Comprehensive Evaluation of the Regional Environmental and Economic Impacts of Adopting Advanced Technologies for the Treatment of Sewage Sludge in Beijing

Guofeng Zhang, Xiaojing Ma, Jingjing Yan, Jinghua Sha, and Yoshiro Higano

Abstract In recent years, more than one million tons of sewage sludge has been discharged annually in Beijing. The rate of sewage sludge treatment was less than 50% in 2010. Untreated sewage sludge has critically polluted the waterways. The purpose of this paper is to analyze the impact of sewage sludge treatment on the development of the regional economy and on the environment. In this report, we use Lingo software to simulate an economic model and an environmental model with an input-output table and perform a linear optimization of these models. The economic model describes the relationship between economic activities and the emission of water pollutants. The environmental model describes the change in the amount of water pollutants that are generated in the model. Beijing is divided into 11 sub-regions. A comprehensive environmental policy is coupled with the introduction of advanced technology to reduce water pollutants. Based upon the results of the simulation, we can provide detailed information about economic growth, water pollutant reduction, policy subsidies and the number of new sewage and sewage sludge plants needed in each sub-region.

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Introduction

Due to its rapid economic and population growth, Beijing's municipal sewage emissions are increasing each year. In 2010, the city produced more than 1.4 billion tons of sewage emissions (Beijing Environmental Protection Bureau 2011). Many sewage treatment plants that have been constructed by the Beijing municipal government have adopted advanced technologies, and the sewage treatment rate increased to 80% in 2010 (Beijing Water Authority 2011). However, the amount of sewage sludge has also increased. Sewage sludge is the byproduct of sewage treatment, and these byproducts pollute the water environment. If this sewage sludge cannot be treated, 50% of the water pollutants removed by sewage treatment will return to the environment (Yang 2010). However, the need for sewage sludge treatment has not been addressed by the government. The rate of sewage sludge treatment was less than 50% in 2010. More than 20,000 tons of total nitrogen is emitted by untreated sewage sludge every year (Zhou 2011), which accounts for approximately 30% of the total net load of total nitrogen in Beijing.

Recently, the government has realized the importance of environmental protection. Accordingly, *The Twelfth Five-Year Plan of Economic and Social Development* (Beijing Municipal Development and Reform Commission 2011) requires that all sewage sludge be treated by 2015 and load of COD (chemical oxygen demand) be reduced by 8.7% in 2015 compared with 2010. Therefore, the government has adopted an integrated policy that promotes water conservation, forestation, reduction of working capital and the introduction of advanced sewage sludge treatment technologies. To determine the optimal development plan for Beijing, it is beneficial to use a simulation method to evaluate the regional environmental and economic impacts of adopting advanced technologies for the treatment of sewage sludge.

The purpose of this paper is to construct a comprehensive simulation model for optimized solutions, in order to evaluate the regional environmental and economic impacts of adopting advanced technologies for the treatment of sewage sludge, and to develop an optimal policy solution to realize the goal of environmentally sustainable economic development.

The spatial implications of an optimal economic and environmental allocation depend on the time span that is allowed for adjustments. In the short term, only a limited set of adjustments may be feasible. The location of labor and firms may be fixed in the short run, making abatement technology a possibility. Moreover, a regionally uniform policy has different impacts under the different conditions in each sub-region (Siebert 1985). In this study, the simulation duration is 10 years, and the government adopts a uniform water pollutant reduction policy for each

sub-region. Under these conditions, one hypothesis is that water pollutants will be transferred among the sub-regions, but the economy of each sub-region is closed. Another hypothesis is that for both the economic and environmental scope, regional differences should be expected by residents of each sub-region.

Methodology and Data

Methodology

Many studies have estimated the impacts of sewage sludge treatment on economic development and the environment. While some of these studies have performed economic evaluations, which focused on analyses of capital investment and operation cost of sewage sludge treatment (Kim and Parker 2008; Shi 2009a, b); those studies, however, ignore the environmental impacts of sewage sludge treatment. A life cycle assessment is one method that can be used to perform a comprehensive evaluation of the technical, economic and environmental aspects of sludge treatment (Murray et al. 2008; Hong et al. 2009; Enrica et al. 2011). However, this method cannot select the optimal sewage sludge treatment technology. The analytic hierarchy process (AHP) method has been used in China to evaluate the technological and economic impacts of sewage sludge treatment (Mao et al. 2010), but the use of expert scoring in this approach is subjective, as different experts may provide differing evaluations. The establishment of an optimization and comprehensive evaluation model via a computer simulation is a suitable method for evaluating water purification policies (Higano and Sawada (1997); Fumiaki and Yoshiro 2000; Mizunoya et al. 2007 and Yan 2010), but this approach has not yet been used in the evaluation of sewage sludge treatment.

In this study, we construct a comprehensive linear programming model that considers all factors influencing water pollutant emission, such as population growth, gross regional product (GRP) growth, types of land use and industry structure. This comprehensive model consists of one objective function (Maximize GRP) and two sub-models (a water pollutant model and an economic model). The economic model describes the relationship between economic activity and the emission of water pollutants. The water pollutant model describes changes in the level of water pollutants generated. The pollutants measured in this study are T-N (total nitrogen), T-P (total phosphorus) and COD (chemical oxygen demand). In the model, Beijing is divided into 11 sub-regions. The simulation duration is from 2011 to 2020. Simulation for this comprehensive model is performed via Lingo software, which is a fast, efficient and straightforward tool for solving linear and nonlinear optimization problems (Li and Higano 2007). By comparing the simulation results for different scenarios, we can estimate the regional environmental and economic impacts of sewage sludge treatment. Based upon the simulation results, we can provide detailed information about economic growth, water pollutant reduction, policy subsidies and the number of new plants needed in each sub-region.

Data

Three types of data are used in this study. One portion includes published data pertaining to population growth, investment, GRP, economic output values, and the amount of sewage, as well as sewage sludge discharge and treatment. The data of population growth, investment, GRP can be obtained from *"Beijing Statistical Yearbook 2011,"* (Beijing Municipal Bureau of Statistics 2012); the data of economic output values from *"Beijing input-output extension table 2010"* (Beijing Municipal Bureau of Statistics 2011); the data of amount of sewage from *"Beijing Water Resources Bulletin2011,"* (Beijing Water Authority 2012); the data of amount of sewage sludge discharge and treatment from *"Beijing Environment Bulletin 2011,"* (Beijing Environmental Protection Bureau 2012). Another portion is composed of survey data, which include detailed information about advanced sewage and sewage sludge treatment technologies. The technical data of sewage treatment and sewage sludge treatment are based on Gaopidian and Huairou sewage treatment plants located in Beijing, and two sewage sludge treatment plants of Dalian city and Jiaxing city which are the model plants for sewage sludge disposal, respectively. All these treatment plants employ advanced sewage or sludge treatment techniques that are commonly used worldwide and, have more effective on pollutant removal performance than any other existing plants in Beijing. The third portion is composed of calculated data based upon the published data, such as the coefficient of water pollutant emissions, the coefficient of discharged sewage pollutant emissions and others.

Model Description

Structure of the Simulation Model

In this study, we draw on the research of Higano and Sawada (1997), Higano and Yoneta (1999), Hirose and Higano (2000), Mizunoya et al. (2007) and Yan (2010). Based upon these previous studies, we constructed a comprehensive linear programming model. Moreover, this study demonstrates improvements over previous water pollutant models by introducing advanced sludge treatment technologies into the model.

The comprehensive model consists of one objective function (Maximize GRP) and two sub-models (a water pollutant model and an economic model) (Fig. 1). The economic model describes the relationship between economic activities and the emission of water pollutants. The environmental model describes changes in the generation of water pollutants.
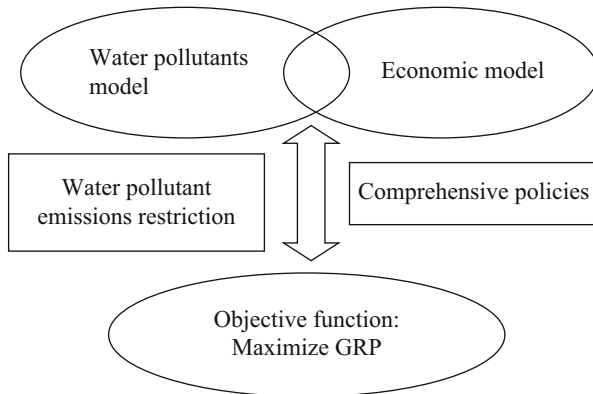
Fig. 1 Composition of the sub-models

We assumed that water pollutants for economic activity flow into the rivers in Beijing (Fig. 2). There are three sources of water pollutant discharge from economic activity: household, industry, and nonpoint sources. Herein, the pollutants contained in rainfall have been examined separately as one part of total water pollutant emissions in the City of Beijing regardless of its amount are very small (Hirose and Higano (2000); Mizunoya et al. 2007; Yan 2010). Consequently, the pollutants emitted via rainfall were excluded from nonpoint sources. A portion of sewage flows into sewage plants through pipes, and sewage sludge is produced during the process of sewage treatment. Finally, the water pollutants contained in the treated and untreated sewage and sewage sludge flow into the rivers. Since it is difficult to collect the water pollutants added by nonpoint sources, we assume that these flow into rivers directly.

In this study we propose an integrated policy to achieve sustainable development, in both the environmental and economic senses (Fig. 3). Currently, the policies used to reduce water pollutants are named "Forestation for water conservation" and "Reduction of working capital". "Forestation for water conservation" policy is that using government subsidies to encourage foresting on vacant land to enhance soil and water conservation. "Reduction of working capital" policy is that the exploitation of decrease of working capital for achieving water pollutant emission reduction by degrading the sectors with high emissions. In order to further reduce pollution of waterways, we propose the construction of new sewage and sewage sludge treatment plants to manage untreated sewage and sewage sludge in this study. Those are the policy of subsidy for reducing capital stock and subsidy for water conservation, which can decrease the pollution from industry and nonpoint source, respectively, and the policy of installation of new sewage and sewage sludge treatment plants, which can contribute to pollution reduction caused by industry and household.
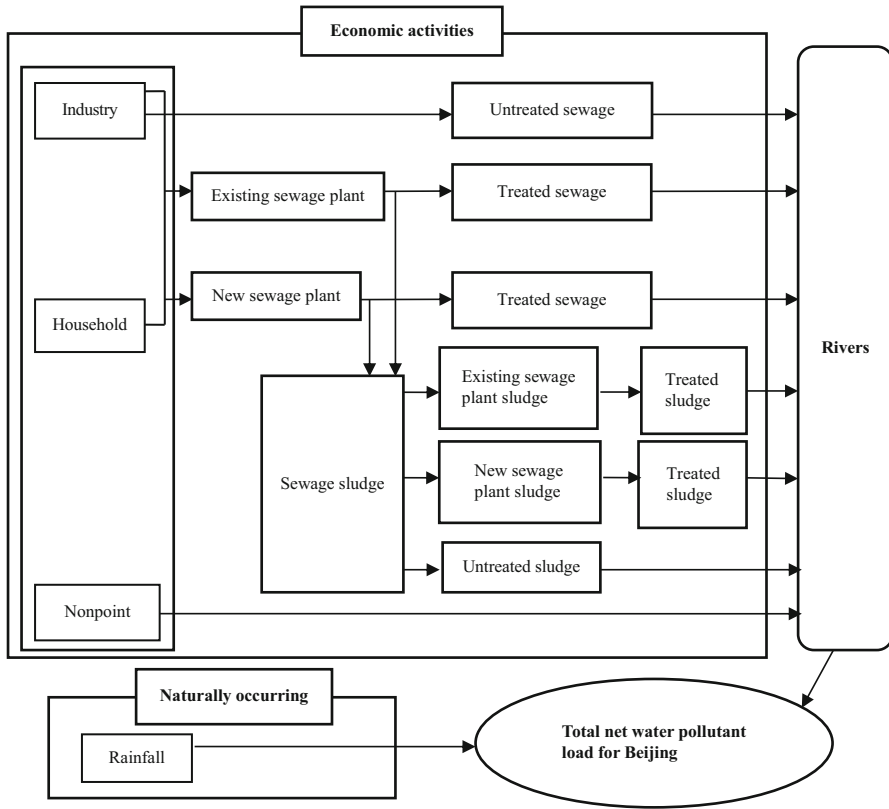
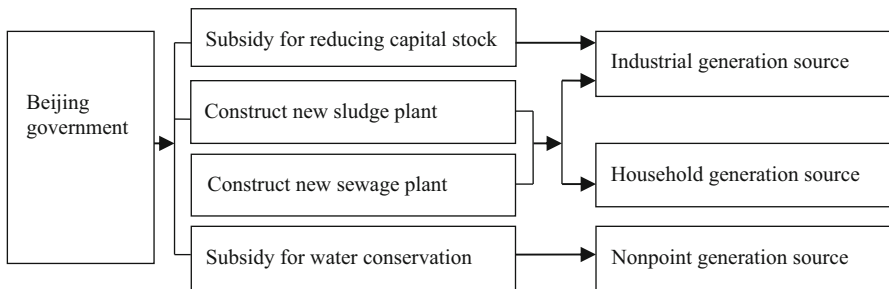**Fig. 2** Framework of the water pollutant model

Fig. 3 The framework of the economic model

The policy variables are represented by coefficients in the simulation model, and the environmental and economic impact of different combinations of policies are discussed based upon the simulation results.

Classification of Water Pollutants

T-P, T-N and COD are commonly used in the literature to describe water pollution (Kyou et al. 1998; Chae and Shin 2007; Wang et al. 2008; Jing et al. 2009). Thus, the model in this study includes organic pollution parameters that are commonly used in the literature to describe water pollution. T-P, T-N and COD coded as water pollutant 1, 2 and 3, respectively, in this analysis.

Sub-Regions of Beijing

To facilitate the collection of data and the implementation of policies, in this analysis Beijing is divided into 11 regions based upon administrative divisions. The Central City sub-region of Beijing, which contains six districts, is regarded as one region because some districts, such as Dongcheng and Xicheng, share sewage and sewage sludge treatment facilities with other districts. The other ten districts each represent a separate sub-region (Table 1 and Fig. 4).

Classification of Water Pollutant Sources

The pollutant sources are divided into three categories: nonpoint, household and industry. Load of water pollutants via nonpoint source is decided by land area and the coefficient of water pollutant emissions for different land use. Land use is categorized into four types based upon the "*Beijing year book 2011*" (Beijing

Table 1 Subdivision of the study area

No.	Sub-region	No.	Sub-region
1	Dongcheng	4	Shunyi
1	Xicheng	5	Changping
1	Haidian	6	Daxing
1	Chaoyang	7	Mentougou
1	Shijingshan	8	Huairou
1	Fengtai	9	Pinggu
2	Fangshan	10	Miyun
3	Tongzhou	11	Yanqing

Fig. 4 The map of Beijing administrative division

Table 2 Coding of land use types

No.	Land use
1	Agricultural area
2	Forest
3	Urban area
4	Other land use

Municipal Bureau of Statistics 2012), (Table 2), and industry is divided into fifteen categories based upon *"Beijing input-output extension table 2010"* (Beijing Municipal Bureau of Statistics 2011), (Table 3).

New Technology

We introduce two types of new sewage treatment technology and two types of new sewage sludge treatment technology. Membrane Bio-Reactor (MBR) technology is a popular sewage treatment technology in China, while the High Turbidity Sewage Purification System (HTSPR) technology is a physical and chemical method of

Table 3 Industry classification and coding

No.	Industry
1	Agriculture
2	Forestry
3	Animal husbandry
4	Fishery
5	Minerals mining
6	Processing of petroleum, Coking and processing of nuclear fuel
7	Chemical industry
8	Metallurgical industry
9	Iron and steel industry
10	Manufacture of communication equipment, computers and other electronic equipment
11	Other manufacturing
12	Production and distribution of electric power and heat
13	Construction
14	Transportation, warehousing and postal service
15	Other services

Table 4 New sewage treatment technologies

Technology	Membrane bio-reactor (MBR)	High turbidity sewage purification system (HTSPR)
Investment for one plant (million CNY)	100	110
Operation cost (CNY/)	0.8	0.6
Sewage sludge treatment scale(tons/day)	500,00	10,000
Influent (mg/L)	T-P: 6	T-P: 7.5
	T-N: 65	T-N: 100
	COD: 450	COD:800
Effluent (mg/L)	T-P: 0.5	T-P: 1
	T-N: 15	T-N: 10
	COD: 30	COD: 30

sewage treatment technology. Anaerobic digestion-fluidized bed drying (A-F) is a German sewage treatment technology that has been used in Dalian, a city in Liaoning province. Finally, fluidized bed drying-combustion (F-C) technology, which uses combustion is a sewage treatment technology that has been used in Jiaxing, a city in Zhejiang province; this technology was developed in Japan. Detailed information about these technologies is presented in Tables 4 and 5.

Table 5 New sewage sludge treatment technologies

Technology	Anaerobic digestion-fluidized bed drying (A-F)	Fluidized bed drying-combustion technology (F-C)
Investment for per plant (million CNY)	150	290
Operation cost (CNY/ton)	893	998
Sewage sludge treatment scale(tons/day)	600	1500

Table 6 Scenario composition

Scenarios	Water pollutant reduction rate (in 2020 compared with 2010)	Advanced sewage technology	Advanced sewage sludge technology	Water conservation (forestation) subsidy	Reduction of working capital
Scenario 1	0%	×	×	○	○
Scenario 2	15%	×	×	○	○
Scenario 3	15%	×	○	○	○
Scenario 4	15%	○	○	○	○

Table 7a Maximum allowable amount of water pollutants for 2011–2020 in scenario 1 (in tons)

Years	Maximum allowable amount of T-P	Maximum allowable amount of T-N	Maximum allowable amount of COD
2011	5387	58,548	202,861
2012	5387	58,548	202,861
2013	5387	58,548	202,861
2014	5387	58,548	202,861
2015	5387	58,548	202,861
2016	5387	58,548	202,861
2017	5387	58,548	202,861
2018	5387	58,548	202,861
2019	5387	58,548	202,861
2020	5387	58,548	202,861

Case Setting

This study explores four scenarios (Table 6). The ○ symbol indicates that a policy was adopted, and the × symbol indicates that a policy was not adopted. We defined the water pollutant reduction rate as the percent decrease in the water pollutant emissions level in 2020 compared with 2010. Since government policy requires that the COD emission rate should be reduced by 8.7% in 2015 compared with 2010, we set a target of a 15% reduction in water pollutant emissions in 2020 compared with 2010. Maximum allowable amount of water pollutant from 2011 to 2020 for every scenario is calculated based upon the real data of 2010 (Tables 7a and 7b).

Scenarios 1 and 2 simulate the current situation, in which no advanced technology is adopted. Scenario 3 simulates the implementation of the integrated

Table 7b Maximum allowable amount of water pollutants for 2011–2020 in scenario 2, 3 and 4 (in tons)

Years	Maximum allowable amount of T-P	Maximum allowable amount of T-N	Maximum allowable amount of COD
2011	5301	57,607	199,596
2012	5216	56,679	196,383
2013	5132	55,767	193,221
2014	5049	54,869	190,110
2015	4968	53,985	187,049
2016	4888	53,116	184,038
2017	4810	52,261	181,075
2018	4732	51,420	178,160
2019	4656	50,592	175,291
2020	4581	49,777	172,469

policy approach, which addresses both economic and environmental aspect, with the introduction of advanced sewage sludge treatment technologies. Scenario 4 simulates the implementation of the integrated policy in conjunction with the introduction of both advanced sewage and sewage sludge treatment technologies.

Simulation Model Formulation

Objective Function

The maximization of the objective function places primary importance upon economic activities, are described by the equilibrium solutions of the following structural equation:

$$Max \sum_{t=1}^{10} \frac{1}{(1+\rho)^{(t-1)}} GRP(t) \tag{1}$$

ρ: social discount rate which is a measure used to help guide choices about the value of diverting funds to social projects (exogenous), $\rho = 0.05$;
$GRP(t)$: Gross regional product (endogenous);

The Water Pollutant Model

1. Total water pollutant load for Beijing

$$TQ^p(t) = \sum_{j=1}^{11} WP_j^p(t) \qquad (p = 1, T - P; p = 2, T - N; p = 3, COD) \qquad (2)$$

$TQ^p(t)$: total net load of water pollutant p for Beijing at time t (endogenous);
$WP_j^p(t)$: load of water pollutant p in region j at time t (endogenous);

2. The constraints for the total water pollutant load for Beijing

$$TQ^p(t) \le TQC^p(t) \qquad (3)$$

$TQC^p(t)$: the maximum allowable amounts of water pollutant p at time t;

3. Water pollutant load of sub-region

$$WP_j^p(t) = QR_j^p(t) + RQ_j^p(t) \qquad (4)$$

$QR_j^p(t)$: load of water pollutant p in rivers at time t (endogenous);
$RQ_j^p(t)$: load of water pollutant p from rainfall at time t (endogenous);

4. Water pollutant flow through rivers

$$QR_j^p(t) = (1 - v) \cdot SECQ_j^p(t) \qquad (5)$$

v: river self-purification rate (exogenous);
$SECQ_j^p(t)$: water pollutant p contributed by economic activities in the region j at
    time t (endogenous);

5. Water pollutant contributed by economic activities

$$SECQ_j^p(t) = HQ_j^p(t) + UIQ_j^p(t) + NQ_j^p(t) - SEQ_j^p(t) - SLQ_j^p(t) \qquad (6)$$

$HQ_j^p(t)$: water pollutant p emitted by households in region j at time t (endogenous);
$UIQ_j^p(t)$: water pollutant p emitted by industry in region j at time t (endogenous);
$NQ_j^p(t)$: water pollutant p emitted by nonpoint sources in region j at time t
    (endogenous);
$SEQ_j^p(t)$: water pollutant p reduced by sewage plants in region j at time t (endoge-
    nous);
$SLQ_j^p(t)$: water pollutant p reduced by sewage sludge plants in region j at time t
    (endogenous);

6. Load of water pollutants from nonpoint sources

$$NQ_j^p(t) = \sum_{g=1}^{4} EL^g \cdot L_j^g(t) \qquad (7)$$

EL^g: coefficient of water pollutant p emitted by land use g (exogenous);
$L_j^g(t)$: area of land use g in region j at time t (endogenous);

7. Water pollutants emitted by households

$$HQ_j^p(t) = Z_j(t) \cdot EH^p \tag{8}$$

$Z_j(t)$: number of households in region j at time t (endogenous);
EH^p: emission coefficient of water pollutant p per household (exogenous);

$$Z_j(t+1) = Z_j(t) \cdot (1 + \mu) \tag{9}$$

μ: household growth rate (exogenous);

8. Water pollutants emitted by industry

Level of water pollutants for industry is dependent upon production. We describe relationship of production and emission of water pollutant via coefficient of water pollutants emissions of industry.

$$UIQ_j^p(t) = \sum_{m=1}^{15} x_j^m(t) \cdot EUI^m \tag{10}$$

$x_j^m(t)$: production of industry m in region j at time t (endogenous);
EUI^m: emission coefficient of water pollutant p of industry m (exogenous);

9. Water pollutant reduced by sewage plants

Water pollutant reduced by sewage plants has two portions. One portion is reduced by existing sewage plants. Nine types of technology have been use for these sewage plants. Another portion is reduced by new sewage plants, which will use two types of advanced technologies

$$SEQ_j^p(t) = SEQ_j^a(t) + SEQ_j^b(t) \tag{11}$$

$SEQ_j^a(t)$: load of water pollutant p reduced by the existing sewage plants using original technology a in region j at time t (endogenous);
$SEQ_j^b(t)$: load of water pollutant p reduced by the new sewage plants, which use advanced technology b in region j at time t (endogenous);

$$SEQ_j^a(t) = \sum_{a=1}^{9} QSE_j^a(t) \cdot \alpha^a \tag{12}$$

$QSE_j^a(t)$: the amount of sewage treated by existing plants, which use original technology a, in region j at time t (exogenous);

α^a: coefficient of reduction of pollutant p by original sewage technology a (exogenous);

$$SEQ_j^b(t) = \sum_{b=1}^{2} QSE_j^b(t) \cdot \alpha^b \tag{13}$$

$QSE_j^b(t)$: the amount of sewage treated by new sewage plants, which use advanced technology b, in region j at time t (endogenous);
α^b: coefficient of reduction of pollutant p by advanced sewage technology b (exogenous);

10. Water pollutant reduced by sewage sludge plants

Water pollutant reduced by sewage sludge plants has two portions. One portion is reduced by existing sewage sludge plants. Five types of technology have been use for these sewage plants. Another portion is reduced by new sewage sludge plants, which will use two types of advanced technologies.

$$SLQ_j^p(t) = SLQ_j^c(t) + SLQ_j^d(t) \tag{14}$$

$SLQ_j^c(t)$: load of water pollutant p reduced by the existing sewage sludge plants, which use original technology c, in region j at time t (endogenous);
$SLQ_j^d(t)$: load of water pollutant p reduced by the new sewage sludge plants, which use advanced technology d, in region j at time t (endogenous);

$$SLQ_j^c(t) = \sum_{c=1}^{5} ES^c \cdot QSL_j^c(t) \tag{15}$$

ES^c: coefficient of reduction of pollutant p by original sludge technology c (exogenous);
$QSL_j^c(t)$: amount of sewage sludge treated by existing plants, which use original technology c, in region j at time t (exogenous);

$$SLQ_j^d(t) = \sum_{n=1}^{2} ES^d \cdot QSL_j^d(t) \tag{16}$$

ES^d: coefficient of reduction of pollutant p by new sludge technology d (exogenous);
$QSL_j^d(t)$: amount of sewage sludge treated by new plants, which use advanced technology d in region j at time t (endogenous);

11. Load of water pollutants from rainfall

$$RQ_j^p(t) = ER^p(t) \cdot L_j \tag{17}$$

ER^p: emission coefficient of rainfall for pollutant p (exogenous), $ER^1 = 47$ kg/km²-year, $ER^2 = 1124$ kg/km²-year, $ER^3 = 2091$ kg/km²-year (Hirose and Higano (2000); Yan 2010);

L_j: total area of region j (exogenous);

The Economic Model

Policy Treatment for Nonpoint Sources

The Beijing government converted land that was assigned to other land use into forest land, providing subsidies to improve the water quality.

1. Total land area

$$\overline{L}_j(t) = \sum_{g=1}^{4} L_j^g(t) \tag{18}$$

$\overline{L}_j(t)$: total land area in region j at time t (endogenous);
$L_j^g(t)$: land area comprised of land use g in region j at time t (endogenous);

2. Conservation of land to forest land

Beijing government converted the majority of other land use into forest land to improve the water conservation function.

$$L_j^g(t+1) = L_j^g(t) + \Delta L_j^g(t) \qquad (g = 2) \tag{19}$$

$L_j^g(t+1)$: area of forest in region j at time $t+1$ (endogenous);
$\Delta L_j^g(t)$: increased area of forest that was converted from other land uses in region j at time t (endogenous);

$$\Delta L_j^g(t) = L_j^{42} \tag{20}$$

L_j^{42}: conversion from other land uses $(g = 4)$ to forest $(g = 2)$ in region j at time t (endogenous);

$$L_j^{42} \geq \lambda^4 \cdot S_j^{42}(t) \tag{21}$$

λ^4: reciprocal of the subsidy for one unit of conversion to forest (exogenous);
$S_j^{42}(t)$: subsidy for region j given by the Beijing government for conversion of other land use into forest (endogenous);

Policy Treatment for Production Generation Sources

This production function is derived from Harrod-Domar model through the relationship between capital accumulation and production. The production of industry m is restricted by working capital and subsidy for reducing working capital (Yan 2010). Capital accumulation is dependent upon the investment and depreciation of capital.

$$x_j^m(t) \leq \alpha^m \left\{ k_j^m(t) - s_j^m(t) \right\} \qquad (m = 1, 2, \ldots, 15) \qquad (22)$$

$$k_j^m(t+1) = k_j^m(t) + I_j^m(t+1) - f^m \cdot k_j^m(t) \qquad (23)$$

$x_j^m(t)$: production of industry m in region j at time t (endogenous);
$k_j^m(t)$: working capital available for industry m in region j at time t (endogenous);
$s_j^m(t)$: subsidy given by the Beijing government for industry m at time t (endogenous);
α^m: ratio of capital to output in industry m (exogenous);
$I_j^m(t)$: investment in industry m in region j at time t (endogenous);
f^m: rate of capital depreciation of industry m (exogenous);

Policy Treatment for New Sewage Plant Construction

The investment and maintenance cost of new plants is covered by subsidies from the Beijing government.

1. Total amount of sewage discharge

The total amount of sewage is determined by the amount of industrial and household emissions.

$$TQSE_j(t) = \sum_{m=1}^{15} x_j^m(t) \cdot \eta^m + Z_j(t) \cdot \eta^z \qquad (24)$$

$TQSE_j(t)$: amount of sewage discharge in region j at time t (endogenous);
$x_j^m(t)$: production of industry m in region j at time t (endogenous);
η^m: sewage emission coefficient for industry m (exogenous);
$Z_j(t)$: number of households in region j at time t (endogenous);
η^z: household sewage emission coefficient (exogenous);

2. Total amount of sewage treatment

The total amount of sewage treatment depends upon two quantities. The first amount is the amount of sewage treated by existing sewage plants, which use original technologies, and the second is the amount of sewage treated by new sewage plants, which use advanced technologies.

$$TQSE_j(t) \geq TQSET_j(t) \tag{25}$$

$$TQSET_j(t) = \sum_{a=1}^{9} QSE_j^a(t) + \sum_{b=1}^{2} QSE_j^b(t) \tag{26}$$

$TQSE_j(t)$: amount of sewage discharge in region j at time t (endogenous);

$TQSET_j(t)$: total amount of sewage treatment in region j at time t (endogenous);

$QSE_j^a(t)$: the amount of sewage treated by existing sewage plants, which use original technology a, in region j at time t (exogenous);

$QSE_j^b(t)$: the amount of sewage treated by new sewage plants, which use advanced technology b, in region j at time t (endogenous);

3. Increase in the amount of sewage treatment

The increase in the amount of sewage treatment depends upon the investment in new plant construction.

$$TQSET_j(t+1) = TQSET_j(t) + \Delta TQSET_j(t) \tag{27}$$

$TQSET_j(t+1)$: total amount of sewage treatment in region j at time $t + 1$(endogenous);

$\Delta TQSET_j(t)$: increase in the quantity of sewage treatment in region j at time t (endogenous);

$$\Delta TQSET_j(t) = \sum_{b=1}^{2} \Delta QSE_j^b(t) \tag{28}$$

$\Delta QSE_j^b(t)$: quantity of sewage treatment increased by new sewage plants, which use advanced technology b, in region j at time t (endogenous);

$$QSE_j^b(t+1) = QSE_j^b(t) + \Delta QSE_j^b(t) \tag{29}$$

$$\Delta QSE_j^b(t) \leq \Phi \cdot I_j^b(t) \tag{30}$$

$QSE_j^b(t+1)$: the amount of sewage treated by new sewage plants, which use advanced technology b, in region j at time $t + 1$ (endogenous);

$I_j^b(t)$: investment in new sewage plants construction, which use advanced technology b, in region j at time t (endogenous);

Φ: sewage treatment coefficient per unit of investment (exogenous);

4. Maintenance costs of new sewage plants

The maintenance costs of new sewage plants depend upon the amount of sewage treatment by the new plants.

$$MC_j^b(t) = \zeta_j^b \cdot QSE_j^b(t) \tag{31}$$

$MC_j^{\mathbf{b}}(t)$: Maintenance costs of new sewage plants, which use technology *b*, in region *j* at time *t* (endogenous);

ζ_j^b: maintenance costs per ton of sewage for new sewage plants, which use technology *b*, in region *j* (exogenous);

5. Financial and subsidies constraints

$$I_j^b(t) + MC_j^b(t) \le S_j^b(t) \tag{32}$$

$S_j^b(t)$: subsidies for new sewage plants construction, which use advanced technology *b*, in region *j* by Beijing government at time *t* (endogenous);

Policy Treatment for Sewage Sludge Construction

The investment and maintenance costs of new sewage sludge plants are subsidized by the Beijing government.

1. Total amount of sewage sludge discharge and treatment

The total amount of sewage sludge is determined by the amount of sewage treatment and can be divided into two portions. One portion is the amount of sewage sludge treated by existing sewage sludge plants, which use original technologies, and the other portion is the amount of sewage sludge treated by new sewage sludge plants, which use advanced technologies.

$$TQSL_j(t) \le TQSET_j(t) \cdot ESE \tag{33}$$

$TQSL_j(t)$: total amount of sewage sludge discharged in region *j* at time *t* (endogenous);

$TQSET_j(t)$: total amount of sewage treatment in region *j* at time *t* (endogenous);

ESE: coefficient of sewage sludge discharged by sewage treatment (exogenous);

$$TQSLT_j(t) \le TQSL_j(t) \tag{34}$$

$$TQSLT_j(t) = \sum_{c=1}^{5} QSL_j^c(t) + \sum_{d=1}^{2} QSL_j^d(t) \tag{35}$$

$TQSLT_j(t)$: total amount of sewage sludge treatment in region j at time t (endogenous);

$QSL_j^c(t)$: amount of sewage sludge treated by existing sewage sludge plants, which use original technology c, in region j at time t (exogenous);

$QSL_j^d(t)$: amount of sewage sludge treated by new sewage sludge plants, which use advanced technology d, in region j at time t (endogenous);

2. Increase in the amount of sewage sludge treatment

The increase in the amount of sewage sludge treatment is determined by investment in new sewage sludge plant construction.

$$TQSLT_j(t+1) = TQSLT_j(t) + \Delta TQSLT_j(t) \tag{36}$$

$$\Delta TQSLT_j(t) = \sum_{d=1}^{2} \Delta QSL_j^d(t) \tag{37}$$

$TQSLT_j(t+1)$: total amount of sewage sludge treatment in region j at time $t+1$ (endogenous);

$\Delta TQSLT_j(t)$: increase in the amount of sewage sludge treatment in region j at time t (exogenous);

$\Delta QSL_j^d(t)$: increase in the amount of sewage sludge treatment by new sewage sludge plants, which use advanced technology d, in region j at time t (endogenous);

3. Investment in new sewage sludge plants

$$\Delta QSL_j^d(t) \le \lambda_j^d \cdot I_j^d(t) \tag{38}$$

λ_j^d: sewage sludge treatment coefficient per unit of investment for advanced technology d in region j (exogenous);

$I_j^d(t)$: investment in new sewage sludge plants construction, which use advanced technology d, in region j at time t (endogenous);

4. Maintenance costs of new sewage sludge plants

The maintenance cost of new sewage sludge plants depends upon the amount of sewage sludge treatment by these new plants.

$$MC_j^d(t) = \zeta_j^d \cdot QSL_j^d(t) \tag{39}$$

$MC_j^d(t)$: maintenance costs of new sewage sludge plants, which use advanced technology d, in region j at time t (endogenous);

ζ_j^d: maintenance costs per ton of sewage sludge treatment for new sewage sludge plants, which use advanced technology d, in region j (exogenous);

5. Financial and subsidies constraints

$$I_j^d(t) + MC_j^d(t) \leq S_j^d(t) \tag{40}$$

$S_j^d(t)$: subsidies for new sewage sludge plants construction, which use advanced technology d, in region j, from the Beijing government at time t (endogenous);

6. Subsidies constraints of the Beijing government

$$S(t) \geq \sum_{j=1}^{11} \sum_{m=1}^{15} S_j^m(t) + \sum_{j=1}^{11} S_j^{42}(t) + \sum_{j=1}^{11} \sum_{b=1}^{2} S_j^b(t) + \sum_{j=1}^{11} \sum_{d=1}^{2} S_j^d(t) \tag{41}$$

$S(t)$: total subsidy for water pollutant reduction from the Beijing government at time t (exogenous)

7. Transportation costs for sewage sludge

Based upon the technical characteristics and the amount of sewage sludge, we suggest that sewage sludge plants should be constructed in one sub-region. Sewage sludge from other sub-regions will be transported to this sub-region, and the selection of the optimal region for the construction of new plants is based upon the costs of this transportation. The transportation cost is determined by distance, the amount of sewage and the coefficient of transportation cost. Since, new sewage sludge plant will be constructed nearby the place of sewage plant. We ignore the intra-regional transport of sewage sludge in this analysis.

$$COST_i^j(t) = \sum_{j=1}^{11} DIS_i^j QSL_j^d(t) Et \quad j = 1, 2 \ldots 11; i = 1, 2 \ldots 11 \tag{42}$$

$$T\_COST_i^j = \sum_{t=1}^{10} COST_i^j(t) \tag{43}$$

$COST_i^j(t)$: total transportation cost of moving sewage sludge from region j to region i at time t (endogenous);

DIS_i^j: distance between sub-region i and sub-region j;

Et: coefficient of transportation cost, $Et = 93$, when distance of transportation equal or less than fifty kilometers; $Et = 163$, when distance of transportation more than fifty and less than one hundred kilometers (Zhang et al. 2006);

$T\_COST_i^j$: total transportation cost of moving sewage sludge from region j to region i over 10 years (endogenous);

Market Balance

The total production of each industry is determined by balances between supply and demand (Mizunoya et al. 2007). The production is dependent on the Leontief input-output coefficient matrix, consumption, investment and net export (Yan 2010). We added variables that were related to the investment in advanced technologies to describe the impact of new plant construction on production.

$$X^m(t) \geq A \cdot X^m(t) + C(t) + i^m(t) + \beta_m^b I^b(t) + \beta_m^d I^d(t) + e^t(t) \tag{44}$$

$$I^b(t) = \sum_{j=1}^{11} \sum_{b=1}^{2} I_j^b(t) \tag{45}$$

$$I^d(t) = \sum_{j=1}^{11} \sum_{d=1}^{2} I_j^d(t) \tag{46}$$

$$X^m(t) = \sum_{j=1}^{11} x_j^m(t) \tag{47}$$

$X(t)$: the column vector of the *mth* element is the total product of industry m in the target area at time t (endogenous);

A: input-output coefficient matrix (exogenous);

$C(t)$: total consumption at time t (endogenous);

$i^m(t)$: total investment in industry m at time t (exogenous);

β_m^b: the column vector of the *mth* coefficient is the production in industry m induced by new sewage plant construction (exogenous);

$I^b(t)$: total investment in new sewage plant construction at time t (exogenous);

β_m^d: the column vector of the *mth* coefficient is the production induced in industry m by new sewage sludge plant construction (exogenous);

$I^d(t)$: total investment in new sewage sludge plant construction at time t (exogenous);

$e^t(t)$: column vector of net export at time t (endogenous);

Gross Regional Product

$$GRP(t) = \sum_{m=1}^{15} v^m \cdot X^m(t) \tag{48}$$

v: the row vector of the *mth* element that is the rate of added value in the *mth* industry (exogenous);

$X(t)$: the column vector of the *mth* element is the total product of industry *m* in the target area at time *t* (endogenous);

$v^m \cdot X^m(t)$: economic add value of industry *m* at time *t*;

Simulation Results and Discussion

Economic Effects

Objective Function

In this study, we adopted incorporated integrated policies and introduced advanced technologies into analysis and simulation. A feasible solution was reached for every scenario (Fig. 5). The results of the simulation indicate that the introduction of advanced technologies in sewage and sewage sludge treatment is an effective strategy for increasing GRP growth. The highest value of the objective function is obtained in Scenario 4, which incorporated the policies of adopting both advanced sewage and sludge technologies, as well as subsidy for forestation water conservation and reduction of working capital. When only advanced sewage treatment technologies are adopted along with the two subsidies (Scenario 3), there is a decrease in GRP growth of more than 524 billion CNY compared to Scenario 4. Similarly, when advanced technologies are not adopted and only subsidies are implemented (Scenario 2), there is a decrease in GRP growth of more than 3651 billion CNY. Moreover, under Scenario 1, in which there is no reduction in the
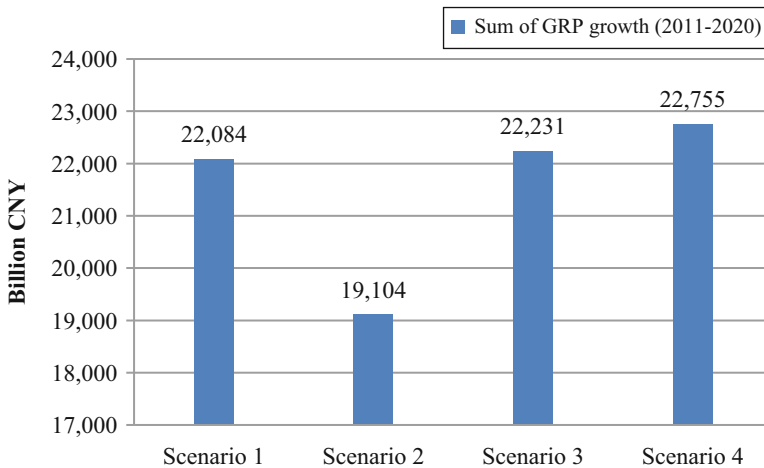

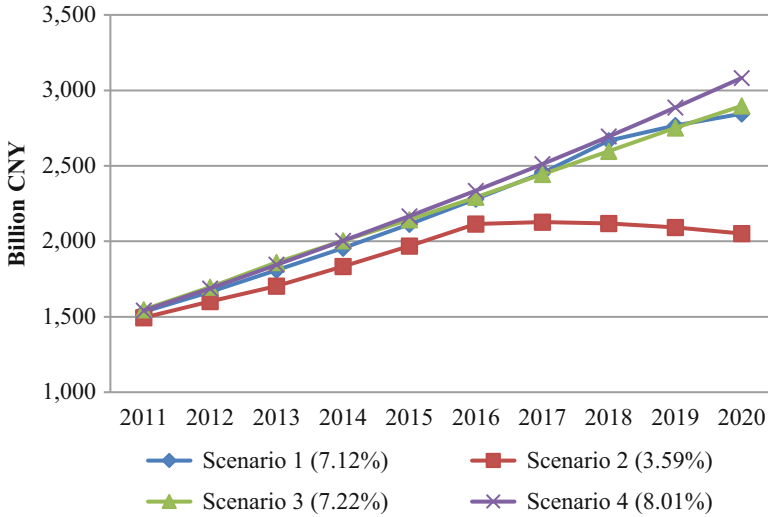**Fig. 5** Sum of GRP growth over 10 years

Fig. 6 Average GRP increase in Beijing, 2011–2020, for each simulation scenario

water pollution in 2020 compared with 2010, no adoption of advanced technologies and only subsidies implemented, there is a difference of more than 671 billion CNY.

Change in GRP for Each Scenario

In this simulation, the average rate of the increase in GRP of Beijing for 10 years is 7.12%, 3.59%, 7.22%, and 8.01% in Scenario 1, 2, 3, and 4, respectively (Fig. 6). A comparison of the results from Scenario 1 and Scenario 2 demonstrate that constraints resulting from high levels of water pollutants will limit economic development. Furthermore, the GRP will decrease after 2016 in Scenario 2. However, if we introduce advanced sewage treatment technologies, as in Scenario 3, the GRP growth rate is demonstrated by the simulation to reach a higher level. It should be noted here that the rates for Scenario 1 and 3 do not differ much, but the load of water pollutant in Scenario 1 is much more than it in Scenario 3 (Figs. 8, 9 and 10). However, the increase in the GRP is greatest when both advanced sewage and sewage sludge treatment technologies are adopted, as in Scenario 4. In this scenario, the GRP in 2020 is more than twice that of 2011.

Economic Value Added by Each Industry Sector

The simulation results for Scenario 3 and 4 indicate that the total combined economic value added of all the industry sectors is increased year by year. (Figs. 7a and 7b). However, we note that:
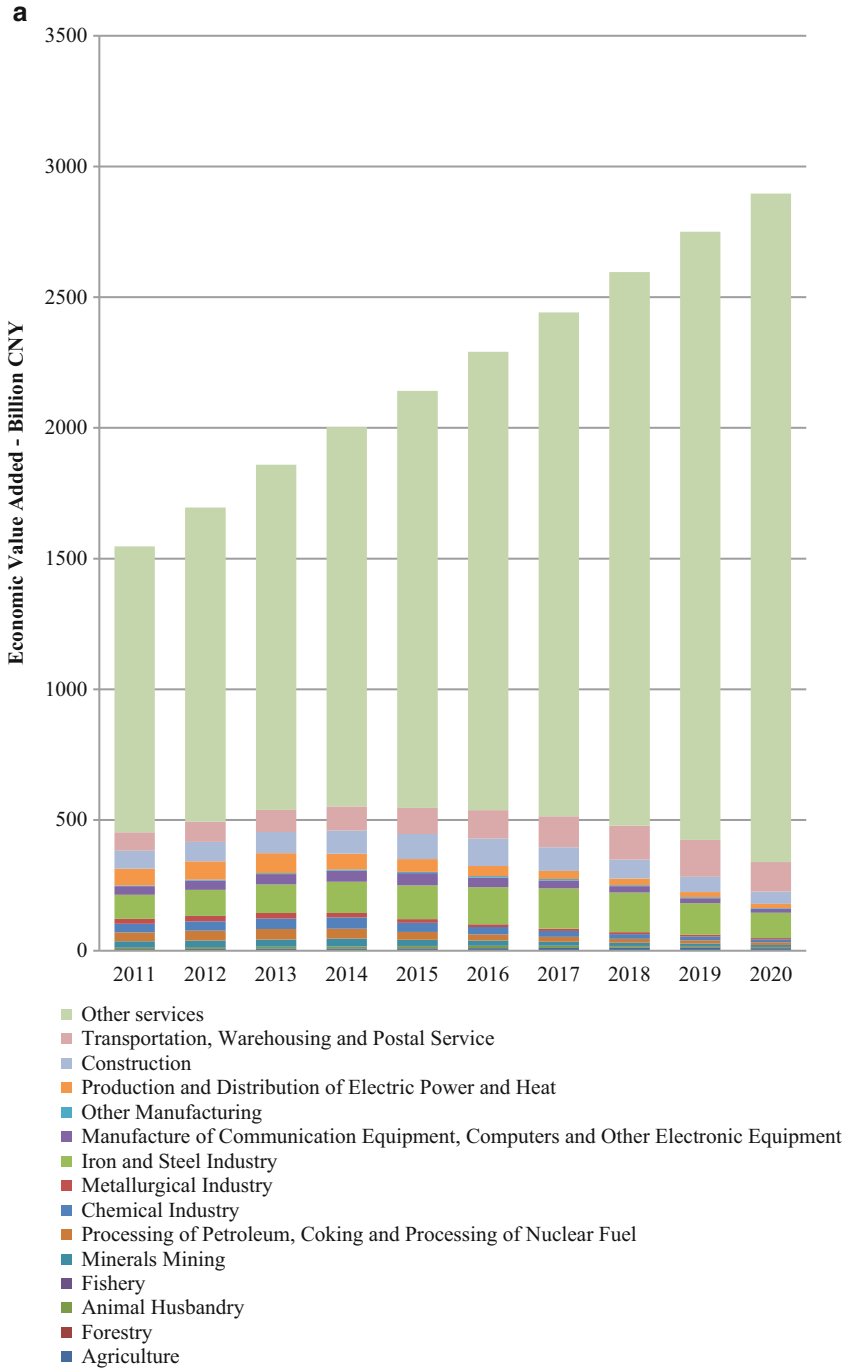
a

Fig. 7a Economic value added for each industry sector in Scenario 3, 2011–2020
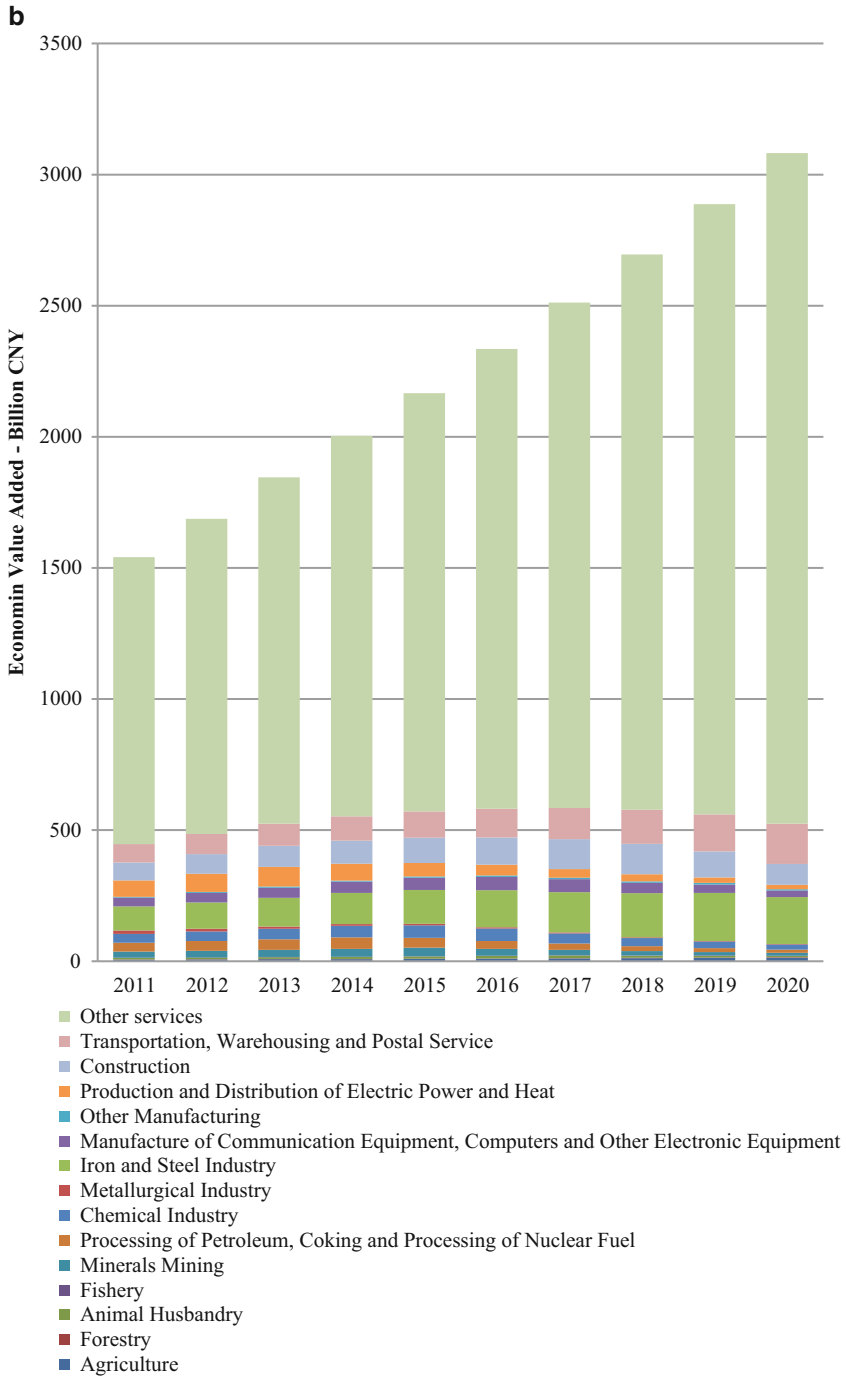
b

Fig. 7b Economic value added for each industry sector in Scenario 4, 2011–2020

Table 8 Comparison of simulation results with maximum allowable amounts of pollutants in 2020 (in tons)

Scenarios	T-P Maximum allowable amount	T-P Simulation result	T-N Maximum allowable amount	T-N Simulation result	COD Maximum allowable amount	COD Simulation result
Scenario 1	5388	5367	58,548	58,548	202,861	201,606
Scenario 2	4581	4533	49,777	49,777	172,469	142,455
Scenario 3	4581	4571	49,777	49,777	172,469	135,272
Scenario 4	4581	779	49,777	40,471	172,469	172,469

First, outside of the metallurgical industry and the electric and heating power industry, the economic value added of all other industries combined is greater for Scenario 4 than for Scenario 3 in every year. This result, taken in context with the water pollutant emission results presented in Table 8, demonstrates that the level of water pollutants is greatly reduced by the adoption of advanced sewage and sewage sludge treatment technologies, as in Scenario 4. This outcome makes more allowances for the industrial development to emit certain pollutants. However, the development of the metallurgical industry, as well as the electric and heat power industries, is limited in Scenario 4, due to the inefficiency in reduction of COD by sewage sludge treatment technology as compared to sewage treatment technology. The economic value added coefficient for these two industries is lower than that of other industries, while the COD emission coefficient for these two industries is greater than that of other industries.

Second, in Scenario 4, economic value added by the tertiary industry sectors (i.e, transportation and warehousing postal service and other services) is increased year by year, resulting from the low coefficient of water pollutant emission and the high coefficient of economic value added. In contrary, economic value added for the some secondary industry sectors (i.e, minerals mining, processing of petroleum, coking, processing of nuclear fuel, chemical industry, metallurgical industry and production and distribution of electric power and heat power) generally demonstrate a downward trend, due to the low coefficient of economic value added and high coefficient of water pollutant emissions. Yet the other of the secondary industry sectors (i.e, iron and steel industry, manufacture of communication equipment, computers and other electronic equipment and other manufacturing) is increased first and then decreased, owing to the high coefficient of economic value added and high coefficient of water pollutant emissions. The primary industry sectors do not change significantly.

Environmental Effects

Water Pollutant Restrictions and Simulation Results in 2020

The level of water pollutants allowed under the restrictions and the simulation results in 2020 are displayed in Table 8. In this table, it is apparent that, in Scenario 1, 2 and 3, the resulting amount of T-N is equivalent to the maximum level of pollutant allowable under the restrictions, and the resulting amounts of T-P and COD are less than the maximum allowable constrained amounts. However, in Scenario 4, the resulting amount of COD is equivalent to the maximum level of pollutant allowable under the restrictions, and the resulting amounts of T-P and T-N are less than maximum allowable under the restrictions. These results show that the T-N removal efficiencies of the original technologies and the advanced sewage treatment technologies are lower than the removal efficiencies for T-P and COD. In contrast, the COD removal efficiency of advanced sewage sludge treatment technology is lower than the removal efficiencies for T-P and T-N. These findings suggest that the reduction of COD should be considered as the most important factor when adopting both sewage and sewage sludge treatment technologies. The results of this simulation are different from those of previous studies, which did not consider both the economic and environmental impacts of sewage sludge treatment.

Load of Water Pollutant for 2011 to 2020

The resulting total amount of water pollutants for each scenario is presented in Figs. 8, 9 and 10. The largest amount of total water pollutants appears in Scenario 1, in which the water pollutant reduction rate is 0% in 2020 compared with 2010. In scenario 1, the total net loads of T-P, T-N and COD from 2011 to 2020 are 53,832 tons, 583,698 tons and 2,021,044 tons, respectively. In comparing Scenario 2, 3 and 4, the simulation results indicate substantially lower net loads of T-P and T-N form 2011–2020 when sewage sludge treatment technologies are adopted. In Scenario 4, over 10 years, 38,843 and 38,558 fewer tons of T-P is released than in Scenarios 3 and 2, respectively. In Scenario 4, over 10 years, 96,602 and 96,514 fewer tons of T-N is released than in Scenarios 3 and 2, respectively. However, the total net load of COD over 10 years is higher for Scenario 4, by more than 255,733 tons and 198,777 tons as compared to Scenario 3 and 2, respectively. Because the COD removal efficiency of the advanced sewage sludge treatment technology is lower than that of its removal efficiency for T-P and T-N, the removal of COD becomes the objective in Scenario 4.

Subsidy Structure

In this simulation, the Beijing government pays subsidies for water pollutant reduction. Figure 11 presents the subsidy structure. In Scenarios 1 and 2, all
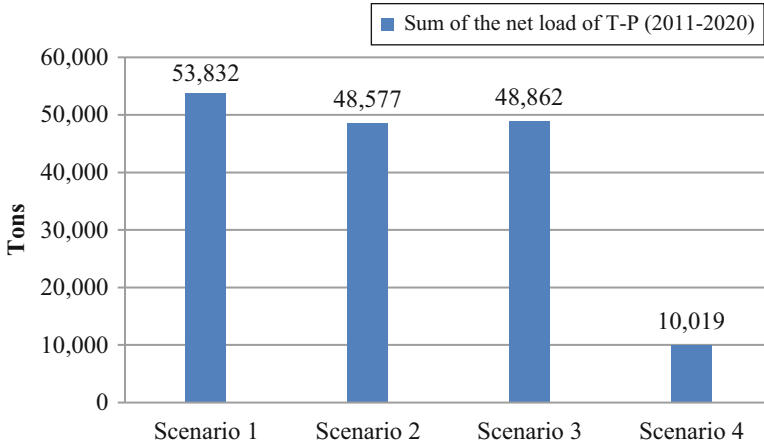
Fig. 8 Total net load of T-P from 2011 to 2020 for each scenario
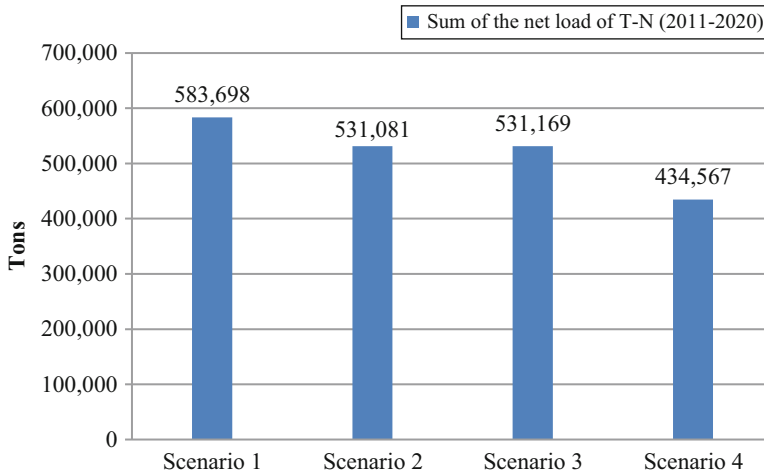
Fig. 9 Total net load of T-N from 2011 to 2020 for each scenario

subsidies are allocated to the policy of reduction of the working capital. The results demonstrate that the water pollutant reduction efficiency of this policy is higher than that of the water conservation by forestation policy. However, the policy of reduction of the working capital is a double-edged sword. As the amount of subsidy granted under this policy increases, GRP decreases. In Scenario 3, in which advanced sewage technology is adopted, the subsidies for water conservation by forestation and the construction of new sewage plants account for 16% and 30% of total subsidies, respectively. Subsidy for the policy of reduction of working capital is 54%, which is 46 percentage points lower in Scenario 3 compared with Scenario 2.

Fig. 10 Total net load of COD from 2011 to 2020 for each scenario
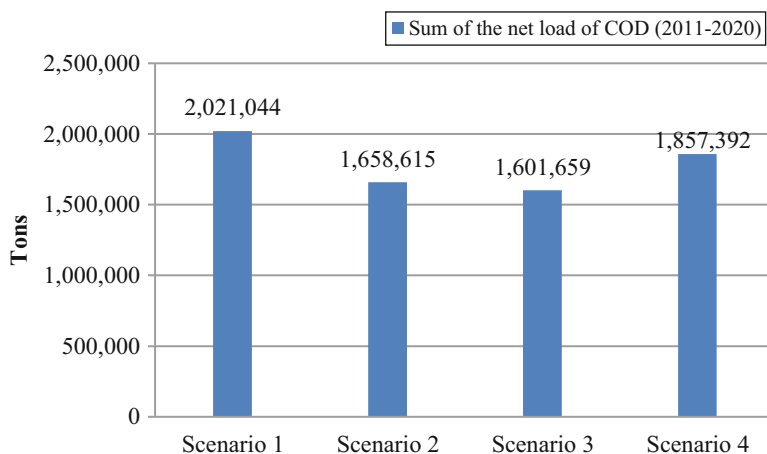
When both advanced sewage and sewage sludge treatment technologies are adopted in Scenario 4, there is no subsidy for the policies of reduction of the working capital and water conservation by forestation. The subsidies for the construction of new sewage and sewage sludge plants account for 24% and 76% of the total subsidy, respectively. This simulation result demonstrates that the construction of new treatment plants is the most efficient tool for water pollutant reduction.

Regional Analysis

To comprehensively consider the impacts upon economic development and the environment, we select Scenario 4 as the optimal scenario. In this section, we will analyze the economic and environmental impacts in each sub-region under the conditions of scenario 4. The model assumes that uniform water pollutant reduction polices are applied throughout the 11 sub-regions by the Beijing government. However, uniform policies do not always lead to identical sub-regional impacts (Siebert 1985).

Sub-regional Economic Trends

Figures 12 and, 13 show the economic trends for each sub-region. Figure 12 demonstrates that the GRP increases annually in each sub-region. In terms of the GRP size of each region, the GRP of the Central City sub-region accounts for more than 70% of total GRP in Beijing each year. This denotes that the Central City sub-region plays an important role in the economic development of Beijing. Figure 13
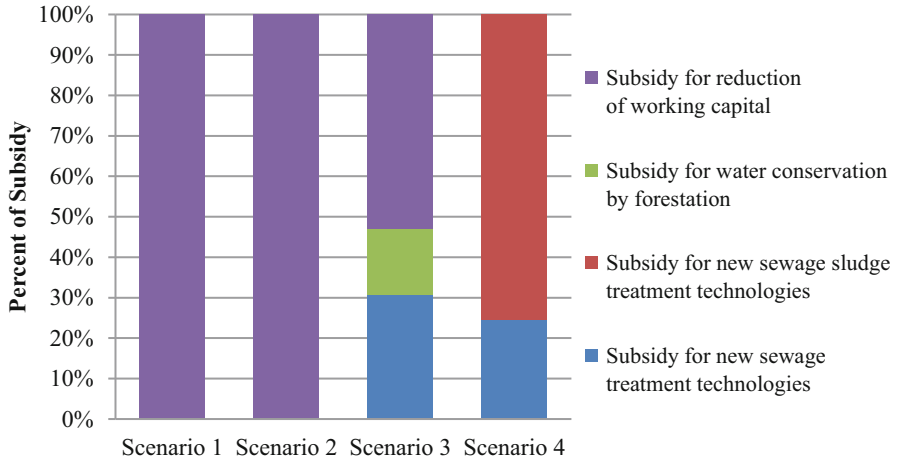
Fig. 11 Allocation of Beijing government subsidy to various water pollutant reduction policies in four scenarios

demonstrates that the rate of economic growth differs for each sub-region. In five of the sub-regions, the annual average GRP grows faster than the average rate in Beijing from 2011 to 2020 (8.01%). In particular, the annual average GRP growth rate of Changping is the highest, at 9.31%.

Environment Intensity Trend

Based upon the analysis above, the COD constraint becomes the target of interest for scenario 4. Therefore, in this section, we select COD intensity as a proxy for environmental impact (Table 9); this metric is an important indicator of environmentally sustainable regional economic development.

This simulation result indicates that COD levels decrease from year to year in each sub-region. Simultaneously, the capacity for sustainable development in each sub-region increases each year. The average COD intensity is related to the efficiency of environmental protection and economic development of each sub-region. However, compared to the average COD intensity of Beijing (82 tons/billion CNY of GRP), only Changping, Central City and Shunyi sub-regions have more efficient environmental protection and economic development. This result also demonstrates that the implementation of a uniform policy does not result in a uniform capacity for sustainable development. The imbalances in capacity can be explained by differences in the initial capital accumulation, population and industry structure and the limitation of labor and firms migration.
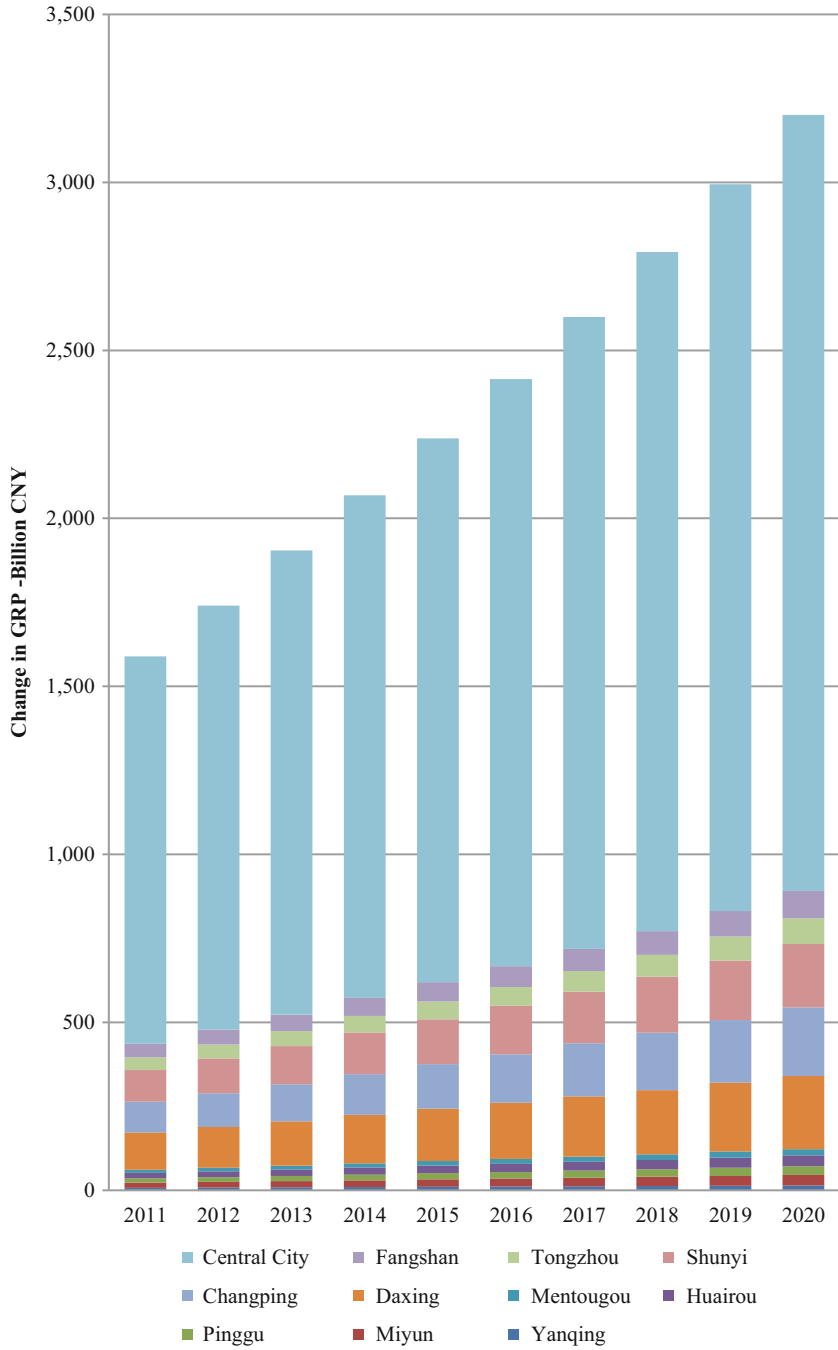
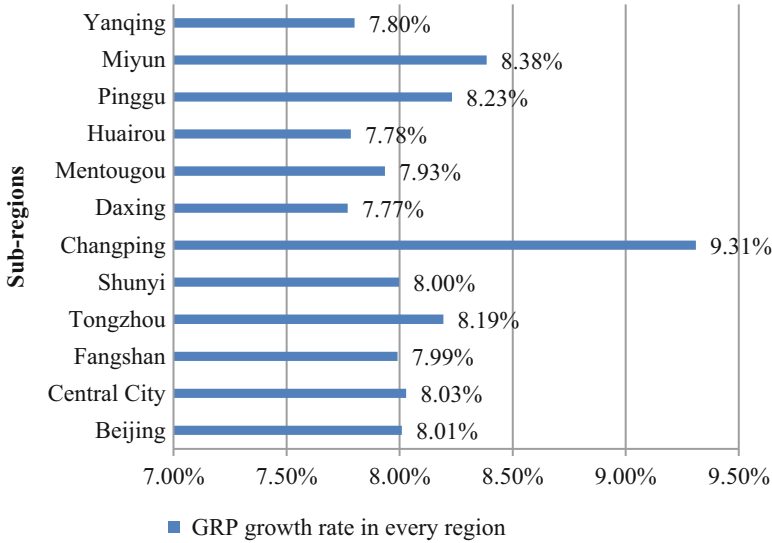**Fig. 12** Change in GRP for each sub-region

Fig. 13 Rate of GRP growth for each sub-region

Table 9 COD intensity trend from 2011 to 2020 (in tons/billion CNY)

Sub-regions	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Average intensity	Ranking (low to high)
Changping	111	107	103	99	51	47	44	39	36	33	67	1
Central City	107	91	89	81	76	69	65	59	55	51	74	2
Shunyi	174	171	66	62	59	54	50	47	43	40	77	3
Fangshan	170	168	111	104	99	91	85	77	72	67	104	4
Daxing	144	143	138	136	129	121	85	78	62	57	109	5
Huairou	179	176	172	170	160	148	138	127	119	93	148	6
Mentougou	236	228	220	141	135	122	113	105	100	92	149	7
Tongzhou	261	251	242	151	143	131	124	116	111	97	163	8
Pinggu	219	212	206	200	190	147	136	127	120	109	167	9
Yanqing	480	452	198	182	172	160	149	138	129	120	218	10
Miyun	369	349	332	284	262	242	227	209	193	180	265	11

Optimal Regions for New Sewage Sludge Plant Construction

We selected the optimal regions for the construction of new sewage sludge plants based upon transportation costs (Fig. 14). Since new sewage sludge plant will construct in the place of sewage plants, we do not consider intra-regional transport of sludge.

In this simulation, the transportation costs associated with of building new sewage sludge plants in Central City sub-regions is 2965 million CNY, which is lower than those associated with construction of plants in other sub-regions in
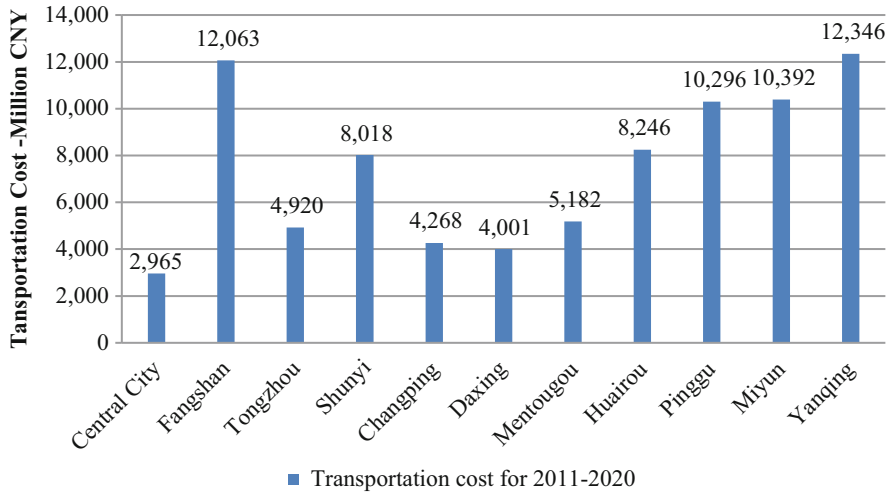
Fig. 14 Transportation costs associated with proposed Central City sub-region sludge plant from the sub-regions of Beijing

Beijing. Therefore, the optimal location for new sewage sludge plants is Central City sub-region.

The Amount of Sewage Sludge Transportation in Sub-regions

Sewage sludge is the source of the water pollutants. Based on the simulation results, sewage sludge discharge in other regions should be treated Central City sub-region. Table 10 show the amount of sewage sludge transportation from the other sub-regions to Central City sub-region. The simulation results predict that approximately 8,084,288 tons of sewage sludge will be transported to Central City sub-region from the other sub-regions over 10 years.

Compensation for Environmental Costs

However, the "polluter pays" principle requires a region to bear the environmental cost that it causes in another region (Siebert 1985). This principle also plays an important role in China. The environmental cost is the damage caused by water pollutants. The compensation for Central City sub-region equals the sum of sewage sludge treatment cost (including investment and maintenance cost) of all sub-regions (Table 11). This simulation result predicts that from 2011 to 2020 approximate 7569 million CNY would be compensated to Central City sub-region by the other sub-regions.

Table 10 Amount of sewage sludge transported to Central City from other sub-regions (in tons)

Sub-regions	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Central city	287,297	349,976	374,820	403,756	421,236	442,543	442,543	453,459	453,459	453,459	4,082,548
Fangshan	50,589	50,589	59,215	60,866	60,866	60,866	60,866	60,866	60,911	61,335	586,969
Tongzhou	50,589	50,589	50,589	63,011	63,011	63,600	63,600	63,600	63,600	65,436	597,625
Shunyi	39,749	39,749	77,465	81,681	81,713	81,713	81,713	81,713	81,713	81,713	728,922
Changping	47,874	47,874	47,874	47,874	65,643	65,643	65,643	65,643	65,643	66,166	585,877
Daxing	50,589	50,589	59,215	60,866	60,866	60,866	60,866	60,866	60,911	50,589	576,223
Mentougou	14,454	14,454	14,454	17,415	17,415	17,572	17,572	17,572	17,572	17,572	166,052
Huairou	20,790	20,790	20,790	20,790	20,790	20,790	20,790	20,790	20,790	20,790	207,900
Pinggu	19,998	19,998	19,998	19,998	19,998	21,937	22,039	22,076	22,076	22,325	210,443
Miyun	16,261	16,261	16,261	18,265	18,454	18,454	18,454	18,454	18,454	18,590	177,908
Yanqing	10,841	10,841	17,427	17,786	17,821	17,821	17,821	17,821	17,821	17,821	163,821
Total	609,031	671,710	758,108	812,308	847,813	871,805	871,907	882,860	882,950	875,796	8,084,288

Table 11 Compensation to Central City sub-region (in million CNY)

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Central city	434	356	352	381	389	410	396	413	406	406	3943
Fangshan	78	45	59	56	54	54	54	54	54	55	563
Tongzhou	78	45	45	65	56	57	57	57	57	60	577
Shunyi	61	36	95	76	73	73	73	73	73	73	706
Changping	73	43	43	43	71	59	59	59	59	60	569
Daxing	33	21	21	21	21	21	46	35	47	42	308
Mentougou	22	13	13	18	16	16	16	16	16	16	162
Huairou	32	19	19	19	19	19	19	19	19	21	205
Pinggu	31	18	18	18	18	21	20	20	20	20	204
Miyun	24	15	15	18	17	17	17	17	17	17	174
Yanqing	16	10	20	16	16	16	16	16	16	16	158
Total	882	621	700	731	750	763	773	779	784	786	7569

Table 12 Subsidy scheme for new sewage plant construction (in million CNY)

Sub-regions	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Central city	82	376	135	163	145	168	116	149	122	122	1577
Fangshan	0	0	26	10	6	6	6	6	6	8	75
Tongzhou	0	0	0	38	8	9	8	8	8	13	92
Shunyi	0	0	115	36	26	25	25	25	25	25	303
Changping	0	0	0	0	54	11	11	11	11	12	110
Daxing	37	5	5	5	5	5	54	14	37	19	184
Mentougou	0	0	0	9	2	2	2	2	2	2	21
Huairou	0	0	0	0	0	0	0	0	0	6	6
Pinggu	0	0	0	0	0	6	1	1	1	2	12
Miyun	0	0	0	6	2	1	1	1	1	2	15
Yanqing	0	0	16	1	0	0	0	0	0	0	17
Total	119	381	297	268	248	233	224	217	213	211	2412

Subsidy Trend for New Sewage Plant Construction

Table 12 presents the optimal subsidy scheme for new sewage plant construction. The subsidy consists of investments in new plant construction and maintenance costs. This simulation result assumes that the subsidy for the Central City sub-region is in the greatest among all the sub-regions; this subsidy accounts for 65% of the total subsidies for sewage plant construction in Beijing. The population and GRP of the Central City sub-regions accounts for 60% and 70% of the total population and GRP of Beijing, respectively, in 2010. Although the rate of sewage treatment reached 95% in 2010, a large amount of new sewage is discharged as the population and GRP continue to grow.

Table 13 The number of new plants to be constructed in each region

Sub-regions	Sewage plants (MBR)	Sewage plants (HTSPR)	Sewage sludge plants (A-F)	Sewage sludge plants (F-C)	Total
Central city	2	3	2	1	8
Fangshan	0	3	–	–	3
Tongzhou	0	12	–	–	12
Shunyi	0	5	–	–	5
Changping	0	7	–	–	7
Daxing	1	1	–	–	2
Mentougou	0	1	–	–	1
Huairou	0	2	–	–	2
Pinggu	0	7	–	–	7
Miyun	0	6	–	–	6
Yanqing	0	2	–	–	2
Total	3	49	2	1	55

The Number of New Sewage and Sewage Sludge Plants to be Constructed in Each Region

The number of new sewage and sewage sludge plants that are proposed to be constructed over 10 years is shown in Table 13. MBR and SPR represent the advanced technologies that will be used in the new sewage plants, while A-F and F-C represent the advanced technologies that will be used in the new sewage sludge plants. In this simulation, it is necessary to construct three new sewage plants featuring the MBR technology and forty-nine plants featuring the HTSPR technology in Beijing. Two sewage sludge plants with the A-F technology and one sewage sludge plant with the F-C technology will need to be constructed in Central City sub-region.

Conclusion

In this study, we create an integrated (economic-environment) model and use a computer simulation to analyze the regional environmental and economic impacts of adopting advanced technologies for the treatment of sewage sludge. Moreover, we discuss the issues of economic development, environmental conservation, environmental allocation and the compensation of each sub-region. The following conclusions are based upon the simulation results.

1. When both advanced sewage and sewage sludge technology are adopted, this policy becomes a very effective tool for reducing environmental pollutants and improving economic development. In the optimal scenario (Scenario 4), the total GRP for 2011–2020 is 22,755 billion CNY. This figure is 3651 billion CNY

more than the total GRP for 2011–2020 under Scenario 2, in which advanced sewage sludge treatment technology is not adopted. In the optimal scenario, the average rate of economic growth from 2011 to 2020 is 8.01%, which is 4 percentage points higher than that of Scenario 2 (3.59%). Moreover, the total net loads of T-P and T-N are 10,019 tons, and 434,567 tons, respectively, in Scenario 4. These numbers are 79%, 18%% lower, respectively, than the net loads for Scenario 2. The total net load of COD is 1,857,392 tons which is 12% higher than in Scenario 2.

2. The optimal budget expenditures for the policy are 2.4 billion CNY for new sewage plant construction and 7.6 billion CNY for new sewage sludge plant construction. The optimal location for new sewage sludge plants is Central City sub-region. Approximately 8,084,288 tons of sewage sludge is transported to Central City sub-region from other sub-regions over 10 years. Thus, the other sub-regions should compensate Central City sub-region approximately 7569 million CNY for 10 years.

3. The pollutant removal efficiency of advanced sewage and sewage sludge technology are different. The COD removal efficiency of advanced sewage technology is higher than that of sewage sludge technology. Thus, COD should be selected as a limiting factor when advanced sewage sludge technology is adopted. This finding differs from those of other studies, which only considered sewage treatment.

4. In the short run, since the location of labor and firms fixed, the adoption of a uniform water pollutant reduction policy by the Beijing government has different impacts on sub-regional economic development and environmental conservation. For example, the capacity for sustainable development in Changing sub-region, Central City sub-region and Shunyi sub-region are much higher than in the other sub-regions. However, in the long run, with labor and firms migration in sub-regions, economic and environmental development of each sub-region will in the same level.

5. In this study, an assumption of the analysis was that the Beijing economic system function as a closed sub-national region, we conducted the model with a short-run 10 years prediction. Our ultimate goal is to reconstruct the model as an open system using a long-run perspective, extending the study area to encompass north China, and eventually a national or global study area. In that case we would consider both the pollution flow and the economic relations among sub-regions.

6. Sewage sludge recycling is an important future extension of our research. Using current technology, power and biogas can be generated during the process of sewage sludge treatment. In further research, this model will be expanded to four sub-models: (1) the energy balance model; (2) the greenhouse gas (GHG) balance model; (3) the water pollutants model; and, (4) the socioeconomic model.

7. This study focuses only on organic pollution measures (T-P, T-N and COD) commonly used in the literature to describe water pollution. As it is important for public health, other toxic waste, such as heavy metal, should be investigated further, though this is outside of the research scope. Additionally, about the problem of the inefficiency in reduction of COD lower than which of T-P and T-N in Scenario 4, introduction of new techniques and application of a mixed policy leading to higher COD emission reduction are two assignments remain in the future work.

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