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Sustainable Development of Typhoon Prone Coastal Areas Based on SD Model

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ABSTRACT

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Sustainable development systems are a dynamic and complicated large systems, that can both be modestly destroyed and restrained by typhoon disasters. System dynamics can be used to study the problems of sustainable development. In this study, based on the theory of sustainable development and targeting typhoon disaster events in Leizhou Peninsula of China, we selected four subsystems (economy, population, environment, and water resource) using the background of typhoon disasters to empirically analyze the effectiveness and practicability of simulation models. Based on this, the restricting factors for sustainable development of the Leizhou Peninsula were assessed via scenario analysis. It was found that typhoon disasters introduced both benefits and harms to the economic development. The existing environmental protection investment did not meet the demands for social development, and the supply-demand contradiction of water resources remained severe. To promote sustainable development of the Leizhou Peninsula, the government has to adjust industrial structure, increase environmental investment, preserve water resources, and improve water quality.

ADDITIONAL INDEX WORDS: *Typhoon disaster, sustainable development, system dynamics, Leizhou Peninsula.*

INTRODUCTION

Extensive and frequent natural disasters have become severe obstacles for socioeconomic development. Statistics show that since this century, natural disasters have led to a death toll of about 5 million, affecting a total of 800 million people, and leading to the loss of -10% of man-made wealth. Although natural disasters are rare, the resulting losses cannot be estimated with simple economic data. Natural disasters might cause a death-blow to the social culture and even affect the moral of an entire country, thus aggravating economic loss.

Over the past decade, large-scale extreme natural disasters have frequently occurred throughout the world, and one of the most severe natural disasters is the typhoon (Schmidt, Kemfert, and Höppe, 2010). Statistics from the Swiss Re-insurance Company show that eight out of ten disasters that caused the largest insurance losses during 1970-2007 were typhoon-related (Ou, Duan, and Chang, 2002). China is one of the most typhoon-prone countries in the world. Between 1988 and 2010, the annual direct economic loss caused by typhoons reached 29.05 billion RMB in China (Xu and Xu, 2010). The economic loss due to typhoon disasters is increasing due to the aggravation of total economic volume (Zhang, Liu, and Wu, 2009). Destructive natural disasters such as typhoons and tsunamis induce successive derivative disasters, which significantly destroy the local affected areas and part of affected industries. The outburst and frequent occurrence of disasters become non-ignorable influence factors for the balance of regional economic development.

The concept of sustainable development originates from ecology and appeared first in the *World Conservation Strategy* in 1980. Since then, it has been widely applied to economics and socioeconomics and has integrated more and new connotations. The World Commission of Environment and Development (WCED), led by the prime minister of Norway Mrs. Brundtland issued *Our Common Future* in 1987, signified the concept and pattern of sustainable development, formally introducing the concept. This report provides a concrete definition: Sustainable development seeks the demands and desires of modern humans; however, it does not hinder the ability of future generations to meet needs and desires, which signifies the birth of sustainable development economics. Sustainable development is based on a compound system that integrates nature, society, and economy, and thus contains three aspects (Wu, Fu, and Cao, 2005). (1) Economic sustainability: Sustainable economic growth can only be achieved through the implementation of clean production and civilized consumption as well as through dependence of science & technology progresses. Thus, economic sustainability is a pre-condition for sustainable development. (2) Environmental sustainability: Sustainable economic growth should be compatible

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with the limited carrying capacity of nature, highlighting the importance of environmental protection that guarantees ecological sustainability. Thus, ecological sustainability is the basis of a sustainable development. (3) Social sustainability: Sustainable development emphasizes social justice, improves life standards, and guarantees equality and freedom. Social sustainability is the target of sustainable development. Thus, sustainable development is the unification of development and sustainability, which complement each other. Thus, ignorance of either element renders sustainable development mere talk. Sustainable development involves all aspects of human society, and is the coordination of society, economy, population, and environment.

Many researchers have conducted profound research on sustainable development. Some of them focused on establishing sustainable development index systems through different methods. Based on sustainable development indices (SDIs) from the European Union (EU), Bolcarova and Kolosta built an aggregation sustainable development index, which generally revealed the positions and situations of sustainable development of 27 EU members (Bolcárová and Kološta, 2015). Van, Kerk, and Manuel (2008) proposed a sustainable society index (SSI) and summarized the development and computation algorithms of SSI. Dong, Wu, and Fu (2015) assessed the pros, cons, opportunities, and threats of sustainable development in the Diqing Tibetan Autonomous Prefecture by using the "strength, weakness, opportunity, and threat" method. Other researchers focused on the influencing factors on sustainable development and discussed relationships among different factors. Valenie (2005) probed into the relationships among renewable resources, technological progress, and economic growth, and summarized the conditions for realizing sustainable economic growth: The social discount rate should be lower than resource regeneration rate and technological progress rate. Based on a time series of the econometric method, Bastola and Sapkota (2015) analyzed and tested relationships among energy consumption, carbon emissions, and economic growth in Nepal. They found that energy consumption stimulus policies cannot effectively activate economic growth, and instead introduced negative environmental impacts. Furthermore, the policies of energy conservation and carbon emission reduction did not hinder economic growth. Based on a dynamic panel data models, Saidi and Hammami (2015) studied the effects of carbon emissions and economic growth on energy consumption from 1990 to 2012 in 58 countries, and found that both factors were positively correlated with energy consumption. With the panel smooth transition regression model (PSTR), Heidari, Katircioğlu, and Saeidpour (2015) analyzed and tested relationships among economic growth, carbon emissions, and energy consumption in five Association of Southeast Asian Nations (ASEAN) countries, and found that the relationships obeyed the environmental Kuznets curve. Omer (2008) discussed the relationships among renewable resources, environment, and sustainable development, and under the urgent demand for clean energy technology, emphasized the potential for developing integrated systems that simultaneously considered environment quality (EQ), energy efficiency (EE), and cost efficiency (CE) via both fixed and portable power markets. Omer (2008) also probed into the expected pattern of energy use and corresponding environmental impacts in future.

The relationship between disasters and economic growth has attracted extensive attention. For instance, the 1979 Nobel Laureate in Economics Lewis (1955) explored the impacts of disasters on economic growth in *The Theory of Economic Growth*, and the 1998 Nobel Laureate in Economics Sen in *Poverty and Famine* (Sen, 1981), which were pioneering works concerning the economic problems of disasters. So far, many research achievements have been made concerning the relationship between disasters and economic growth. However, different views exist: (1) Disasters are negatively correlated with economic growth: The occurrence of disasters hinders economic growth. Most economists support this view, and hold that disasters would cause the decline of GDP and hinder the short-term or even long-term economic growth, introducing severe handicaps to the national or regional economic development. Using the Harrod-Domar model, Zhang and Shen (1995) proposed a method to estimate the relationship between disasters and economic growth from the macroscopic perspective, and used an empirical analysis to show that disasters have a negative impact on economic growth. Analyzing 115 countries from 1960 to 1993, Benseon (2003) studied the correlation between the occurrence frequency of disasters and the real GDP, and found that the GDP growing rates in disaster-prone countries were lower than in those with rare disasters. Rasmussen, Rasmussen, and Robinson (2004) comparatively analyzed the macroeconomic impacts of natural disasters in the Caribbean region in 1970s, and found that the occurrence of natural disasters led to output decline, international payment deterioration, finance condition deterioration, and the increase of poor populations. Noy (2009) studied the macroeconomic impacts of disasters in many countries, and found that disasters caused the most severe impact on agriculture, leading to a 9% decrease in the GDP of a developing country. Moreover, Anderson (1991); Gilbert and Kreimer (1999), Pereira (2009), and Xu (2007) also support this view. (2) Disasters are positively correlated with economic growth: The occurrence of disasters promotes economic growth. Using the endogenous economic growth model, Aghion, Howitt, and Brant-Collett (1998) theoretically explained this view and suggested the occurrence of disasters would destroy the original technology and production systems, forcing the affected areas to urgently renew investments and capital, thus promoting an economic boom. Analyzing 28 disasters in 26 countries between 1960 and 1979, Albala-Bertrand (1993) analyzed the macroeconomic impacts of disasters and found that rates of GDP significantly increased after disasters. He suggested disasters would cause transient negative impacts on the short-term economy; however, that post-disaster reconstruction would accelerate economic operations and thus, the occurrence of disasters would positively contribute to the long-term economy of a country. West and Lenze (1994) found that hurricane Andrew destroyed numerous buildings in Florida, but contributed to local economy in the short run. Moreover, Chang (1983) and Guimaraes (1993) also supported this view. (3) The correlation between disasters and economic growth remains unclear. Gillespie (1991) found that hurricane Hugo did not cause any significant impact on the economic activities in Southern California, because disaster relief plans compensated for the economic loss. Charvériat (2000) analyzed 25 disasters from 1980 to 1996 in Latin America and the Caribbean region, and found real GDP increasing rates in more than 80% of the countries first dropped and then increased. Skidmore and Toya (2002) empirically analyzed the economic impacts of disasters in 89 countries from 1960 to 1990 and found climate disasters to positively contribute to economic growth, but geohazards hindered economic growth.

However, research on sustainable development in areas prone to natural disasters is rare, especially for typhoon-prone areas. Thus, by targeting typhoon-prone areas, we established a quantitative simulation model underlying sustainable development. We aimed at internal influencing factors and their association mechanisms, and explored the sustainable development patterns suitable for typhoon-prone areas.

System dynamics has been well applied into regional sustainable development. System dynamics is a system simulation method proposed by Prof. W. Forrester of the Massachusetts Institute of Technology in 1956 and can be used to analyze corporate problems, such as production management and stock management (Cheng, Tahar, and Ang, 2010). System dynamics has also been called industrial dynamics and is a subject concerning analysis and study of information feedback systems (Anderson, 1991). System dynamics is based on the idea of system science that "any system must have structures, and that these system structures decide system functions" and adopted the feedback characteristics that the inner system compositional elements are both cause and effect of each other. System dynamics aims to reveal the root of the problem by targeting the inner system structures, rather than explaining systemic behaviors and properties from the perspective of external interference or random events.

Many researchers applied system dynamics to sustainable development. By building simulation models, Jorge, Duran, and Alberto (2009) explored the intrinsic motivation mechanism of urban sustainable development in Puerto Aura, Puebla, Mexico. Xu and Coors (2012) verified the feasibility and practicability of GIS and SD systems in Plieningen, Stuttgart, Baden-Württemberg, south of Germany. In particular, they integrated GIS, SD model, and 3D visualization, thus better explained the inner relationships and changing relations of sustainable indices, which helps decision-makers to more comprehensively and efficiently understand the sustainable level of urban areas (Xu and Coors, 2012). Based on the causality diagram, Halbe, Wostl, and Lange (2015) analyzed the core relationship of the W-E-F Nexus, which formed the basis of the subsequent construction of system dynamics models. Using a system dynamics (SD) model, Oz, Stewart, and Richards (2014) quantified and simulated water-energy-climate correlations, thus efficiently promoting the application of SD models into the W-E-F Nexus. However, these studies only focused on the three elements of water/energy/grains or the natural properties of the Nexus, ignoring the corresponding social attribute elements. The elements of social attributes (e.g. urbanization, globalization, and population scale) all threatened the security of the W-E-F Nexus. These threats could not be weakened, and should be combined with the natural attributes for the global consideration of the W-E-F Nexus (Fu and Liu, 2017; Hoff, 2011; Kollek, Osinski, and Warzynska, 2017; Lawford, Bogardi, and Marx, 2013; Liu, 2017; Wu, 2017).

The sustainable development of typhoon-prone areas is affected by multiple factors and is a typical complex system. In this study, high-order, nonlinear, multi-feedback, and complicated time-variable system dynamics models were developed and used as sustainable development models suitable for typhoon-prone areas. In the empirical study, we targeted the Leizhou Peninsula, China, which frequently suffered from typhoon disasters, and thus tested the effectiveness and practicability of the models. Moreover, the trends of sustainable development in the Leizhou Peninsula from 2011 to 2020 were simulated and predicted. Through simulations, we introduced scientific policies and recommendations that are suitable for the sustainable development of the Leizhou Peninsula.

MODELS

Methodology

The sustainable development system for a typhoon-prone region is a dynamic, complex, and multi-feedback cause-effect system. The number of components, relationships, and relationship complexity add complexity due to the actions of internal and external momentums. Moreover, the between-variable relationships are usually unclear, or more precisely, the relationships among multiple variables cannot be described by traditional methods, and internal and external momentums decide the systemic complexity. However, system dynamics are based on system theory, and absorb the essences of control theory and information theory. Thus, system dynamics focus on both the inner mechanisms and stress the between-unit relationship and information feedback. With system dynamic methods, we screened for the dominant influence factors on sustainable development and analyzed the economic, resource-related, environmental, and ecological impacts that might be induced by different development strategies, aiming to provide a basis for decision-makers.

The system dynamic models were built as follows:

(1) Clarify the target of modeling, or more clearly to understand what to study and solve.

(2) Reasonably determine the system boundaries, or more clearly to delimit the scope of the research problem. All factors that affect the system characteristics should be included into the inner part of the system. The system environment is defined as a part of the boundaries that are associated with the system.

(3) Analyze the system structure, and study the relationships between the system and its components. According to reality, build a causal diagram that can clearly portray the interactions and interrelations among different elements.

(4) Build a system dynamic model, use the language of system dynamics for further description of between-variable relationships, build a mathematical equation set, and determine the values of parameters using parameter estimation method, linear regression, and extrapolation method, and thus plot a system dynamics stock flow diagram.

(5) Use the model to observe relationships between structure and system behaviors, by changing experimental parameters and system institutions. Use the model into simulations, and test model validity. Through simulations, test whether the model has any shortage or defect, thus modifying the model, and continue simulations until satisfactory results have been acquired.

System Analysis

Sustainable development is based on the compound system integrating nature, society, and economy and is characterized as follows: Economic growth is compatible with social progress and based on nature conservation. Social progress, economic development, and environmental change complement each other and are inseparable from each other. Thus, we divided the target system into four subsystems: Economic subsystem, population subsystem, water resource subsystem, and environmental subsystem.

The economic subsystem mainly consists of economic entities, industries, and organizations and is one of the major subsystems of a sustainable development system. The economic subsystem, with its matter reproduction function, provides material and capital support for the development and perfection of other subsystems, and it is the motive force of social development. Without economic development, there is no social development, and resources and the environment for human society are deprived of their social efficacies. Through material and capital support, the economic subsystem increases scientific investment, relieves the pollution stress in the environment subsystem, and enhances the investments for disaster prevention and relief. Pollution discharge can only be reduced through inner technological reconstruction, industrial upgrading, cleaner production, and pollution treatment. The economic subsystem reduces depletion of natural resources through technical innovation, industrial upgrading, and waste recycling. However, the economic subsystem is in a contradictory and coordinative interrelation with both the environment and water resource subsystems. This study focuses on the impacts of typhoon disasters on these three industrial structures.

The population subsystem is also an important part of the sustainable development system, and population is a key factor, restricting regional sustainable development. A larger population is better from the perspectives of industry layout and consumption-driven economic development. However, after reaching a certain scale, a larger population introduces heavier socioeconomic burden and induces a series of socioeconomic problems, such as the reduction of regional development, crowding in regional spaces, insufficient infrastructure, and pollution discharge. Birth and death rates have basic effects on the population. Also included in the population subsystem of a regional system is the machinery growth of population that affects the number of population. Furthermore, the population subsystem offers labor force to the economy subsystem, negatively impacting the environment subsystem.

The water resource subsystem: Due to the scarcity of water resources and the growing water demands by domestic, industrial, and agricultural consumption, the supply-demand contradiction is increasingly prominent due to the aggravation of water pollution, water resource shortage, low use efficiency of water resources, and over-exploitation of groundwater. The water resource subsystem interacts in two ways (conflicting and coordinating) with other subsystems: (1) the reduction of water resource stock due to depletion; (2) the increase of water resource stock due to the deceleration of water resource depletion promoted via technological progress and other measures. Moreover, the situation of water resources highlights that the water utilization rates and water resource saving in the economy and population subsystems are improved, and the increase of water resource utilization rate depends on both technological and environmental investments provided by the economic subsystem.

Environment subsystem: This subsystem has two major functions: (1) it is a space support for the population and economic subsystems; (2) it achieves the pollutant discharge from these two subsystems. The space support is manifested as an environmental bearing capacity and is a comprehensive ability of all environmental factors. However, in a specific region, the environmental bearing capacity is usually restricted by a certain key factor, or the bottleneck element. Environmental pollution largely reduces the environmental bearing capacity, and through regulating the economy subsystem, it controls the population and pollution discharge, thus guaranteeing that the pollutant discharge is controlled under the environmental self-cleaning ability.

Plotting Causal Loop Diagram

By analyzing the influencing factors on the continuance diffusion system during typhoon disasters, we built causal loop diagrams for analyzing the influence factors on sustainable diffusion. The causal loop diagrams involve four modules: Economic module, water resource module, population module, and environment module.

A causal loop diagram mainly consists of four feedback loops:

(1) GDP->+ science & technology investment ->+ output value of third industry ->+ GDP (positive feedback loop);

(2) Total population ->+ urban population, rural population ->+ domestic water consumption ->+ total water consumption ->- supply-demand ratio ->+ total population (positive feedback loop);

(3) Output value of first industry ->+ agriculture water consumption ->+ total water consumption ->- supply-demand ratio ->+ output value of first industry (positive feedback loop);

(4) Output value of second industry ->+ industrial water consumption ->+ total water consumption ->- supply-demand ratio ->+ output value of second industry (positive feedback loop).

As shown on the causal feedback loop diagram, the sustainable development of a typhoon-affected area is a complicated and

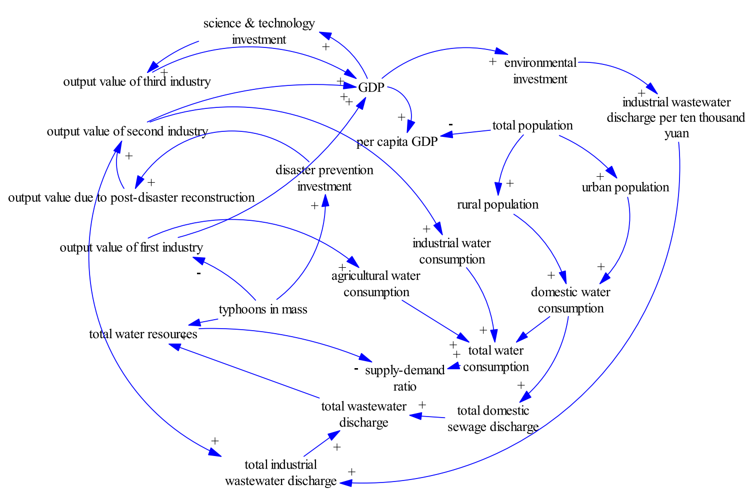


Figure 1. Systematic causal feedback loops.

changeable system. In the general system, the variables among different subsystems are mutually correlated and causal. Change of a certain variable among subsystems might lead to alteration of another irrelevant variable. Causal feedback loops visually reflect this between-variable causality; however, they cannot quantify or embody the change, which can be solved by flow charts.

System Flow Diagram

According to system structure and analysis on causal feedback relations between the four subsystems, the system flow diagram of the SD model is shown in Figure 2.

As shown in Figure 2, the system contains 38 variables. Specifically, there are 6 state variables (total population, output value of first industry, output value of second industry, output value of third industry, total water resources, and output value due to post-disaster reconstruction). There are 8 speed variables (increment of total population, increment of output value of first industry, disaster-caused crop loss, increment of output value of second industry, increment of output value of third industry, precipitation due to typhoon disasters, recycled water use, and water resource depletion). There are 24 assisting variables (science and technology investment, environmental investment, industrial wastewater discharge per ten thousand yuan, per capita GDP, agricultural population, urban population, rate of population growth, industrial water consumption, industrial water consumption per unit, rural domestic water consumption per capita, urban domestic water consumption per capita, domestic water consumption, total water consumption, supply-demand ratio, total wastewater discharge, total industrial wastewater discharge, total domestic sewage discharge, processing rate, agricultural water consumption, agricultural water consumption per unit, typhoons in mass, recycled utilization rate, increments of other industries, and disaster prevention investment).

CASE STUDY

We targeted the Leizhou peninsula in the southernmost part of Mainland China. It faces oceans at three sides and its coastline has a length of 1180 km. The major city Zhanjiang on this Peninsula has a population of 9 million. Leizhou peninsula is located in a typhoon-prone zone at the west of tropical oceans in the southwest North Pacific. It is directly attacked by typhoons from the westward and northwestern paths. This severe typhoon disaster zone suffers from typhoons in summer at a frequency of 2-3 typhoons per year.

Model Parameters

The empirical analysis involved abundant data, which mainly originated from two sources. (1) Yearbooks including the *China Statistical Yearbooks*, the *China Statistical Yearbooks on Science and Technology*, the *Guangdong Statistical Yearbooks*, the *Guangdong Industry Statistical Yearbooks*, the *Guangdong Society Statistical Yearbooks*, the *Guangzhou Statistical Yearbooks*, and the *China Meteorological Disaster Yearbooks* of the past years. (2) Governmental websites included pollution source censuses from the Environmental Protection Bureau of Guangdong Province, the Department of Environmental Resources, at Economic & Information Commission of Guangdong Province and the Statistics Bureau of Guangdong Province.

Simulation Results

After modeling, data processing and fitting were conducted in both SPSS and OriginPro 9.0, aiming to identify the functions of between-variable relationships. Then, system dynamics equations were built according to interactions among different factors. The major equations included:

Agricultural water consumption = output value of first industry × agricultural water consumption per unit;

Disaster-caused crop loss = output value of first industry × number of typhoon disasters / 500;

Output value due to post-disaster reconstruction = INTEG (increment of post-disaster reconstructions, 32);

Increment of post-disaster reconstruction = 1.3 × Disaster prevention investment ^0.2;

Disaster prevention investment = number of typhoon disasters × 0.15 + 0.012;

Increment of output value of third industry = output value of third industry × increasing rate of third industry;

GDP = Output value of first industry + output value of second industry + output value of third industry;

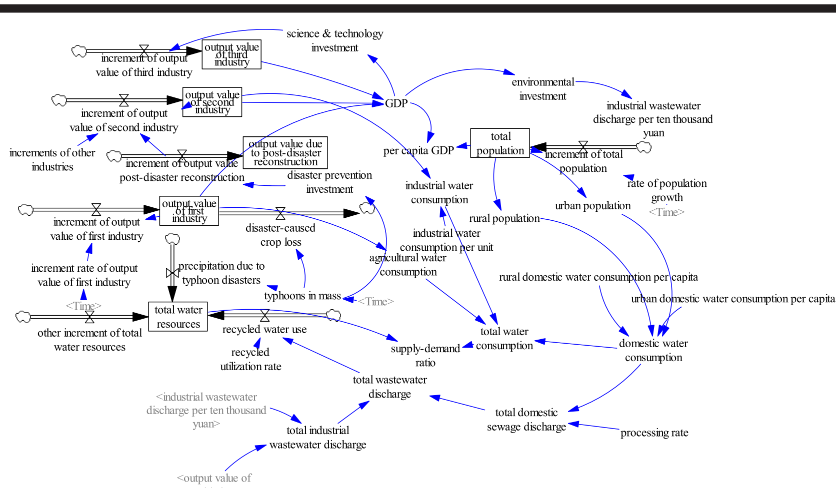


Figure 2. System dynamics flow diagram.

Total population = INTEG (increment of total population, 777.77);

Per capita GDP = GDP / total population;

Supply-demand ratio = total water consumption / total water resources;

Agricultural population = total population × 0.63;

Agricultural water consumption = output value of second industry × industrial water consumption per unit;

Environmental investment = GDP × 0.001;

Total domestic sewage discharge = Domestic water consumption × (1 - processing rate);

Precipitation due to typhoon disasters = 3 × number of typhoon disasters ^2;

Urban population = total population × 0.37;

Total industrial wastewater discharge = industrial wastewater discharge per ten thousand yuan × output value of second industry;

Output value of second industry = INTEG (increment of output value of second industry, 577.6);

Total wastewater discharge = total industrial wastewater discharge + total domestic wastewater discharge;

Recycled water consumption = total wastewater discharge × recycled rate;

Science & technology investment = GDP × 0.001;

Increment of total population = total population × total population growth rate;

Total water consumption = agricultural water consumption + industrial water consumption + domestic water consumption;

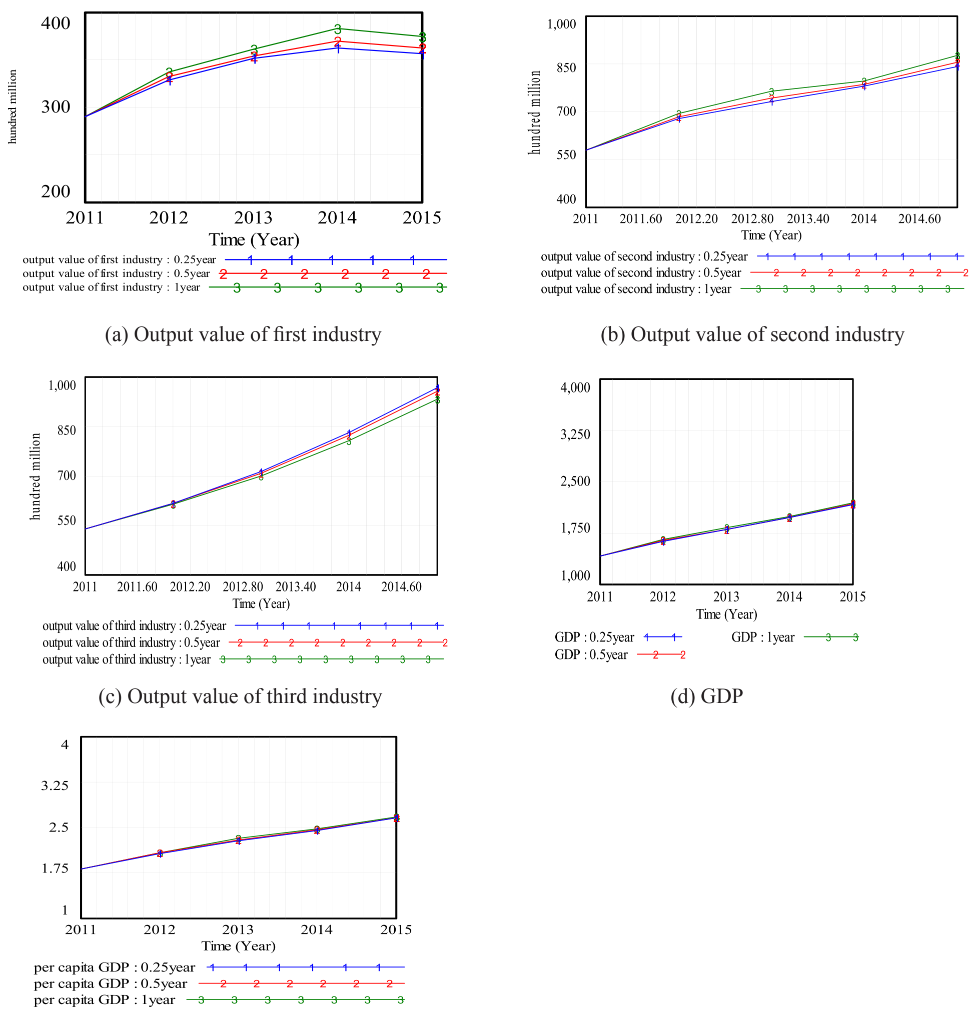
Total water resources = INTEG (increment in other water resources + precipitation due to typhoon disasters + recycled water, 96.06);

Increment of output value of second industry = increment of post-disaster reconstruction + output value of second industry × increasing rates of other industries;

Output value of first industry = INTEG (increment of output value of first industry - disaster-caused crop loss, 289.31);

Domestic water consumption = rural domestic water consumption per capita × agricultural population + urban population × urban domestic water consumption per capita;

Increment of output value of first industry = output value of first industry × increasing rate of output value of first industry;



(a) Output value of first industry

(b) Output value of second industry

(c) Output value of third industry

(d) GDP

(e) Per capita GDP

Figure 3. Simulation of major variables in the economic subsystem under different time intervals.

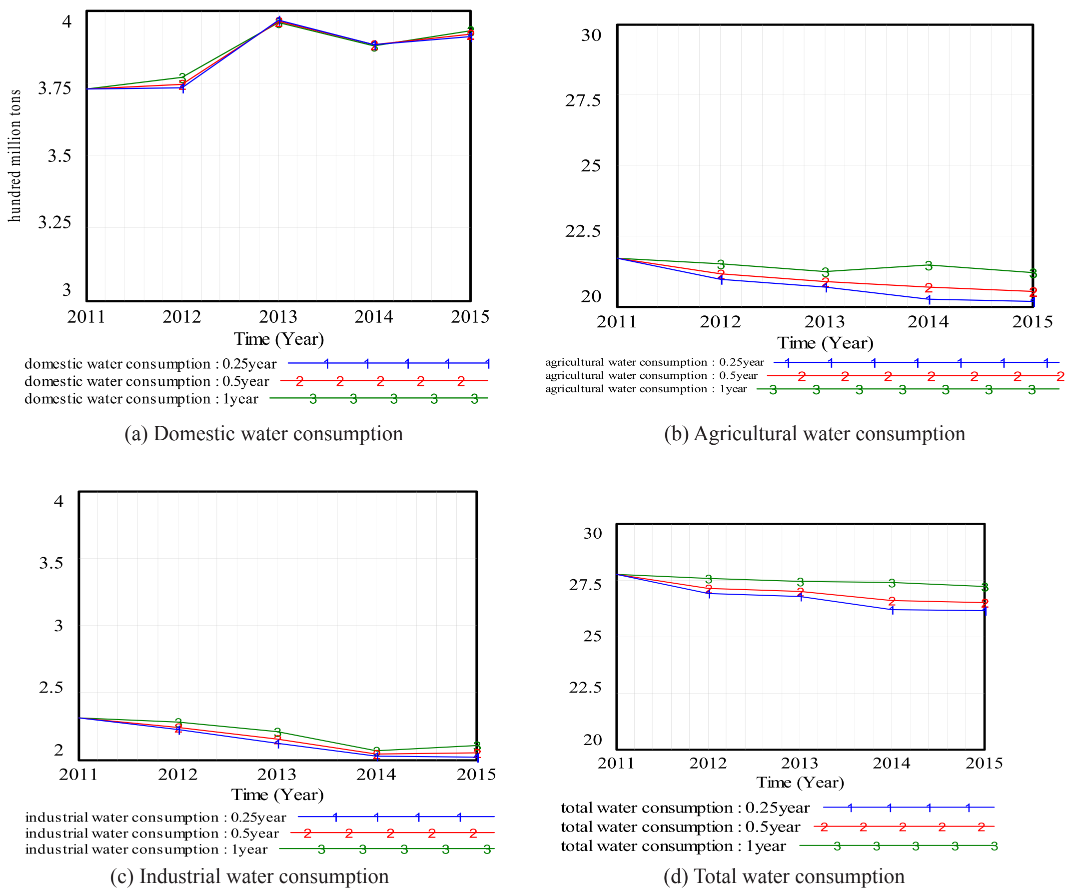


Figure 4. Simulation of major variables in the water resource subsystem under different time intervals.

Output value of third industry = INTEG (increment of output value of third industry, 538.15);

Number of typhoon disasters = IF THEN ELSE (distance < 50, typhoon grade × 1, IF THEN ELSE (distance < 200, typhoon grade × 0.5, IF THEN ELSE (distance < 400, typhoon grade × 0.2, IF THEN ELSE (distance > 400, typhoon grade × 0)))).

After model establishment and with 2005 as the first year and 2015 as the last year (at an interval of 1 year), we simulated on Vensim and obtained output variables of different subsystems.

Model Tests

(1) Running Tests

To test model stability, we selected different time step lengths (DT = 1.0, 0.5, and 0.25 year) for simulations and compared the results of major variables in the economy, water resource, and environment subsystems. As shown in Figures 3 to 5, the system structure and behaviors of the models were basically stable.

(2) Goodness-of-fit Test

In the historical goodness-of-fit test, we compared the model-simulated results with real data, tested the rationality and validity of the fitted results, and thus repeatedly modified the models. We selected representative indices from the subsystems and computed the Pearson correlation coefficients between the simulated results and real values (Tables 1-3).

The major variables of the SD model were selected, and the real values were compared to the simulated data from 2011 to 2015 (Tables 1-3). Clearly, the relative errors were basically all below 6% (Table 3). Considering randomness and volatility of social policy and natural environment as well as the complexity and comprehensiveness of system dynamics, we involved in the model all influencing factors on the indices, which improved both effectiveness and simulating performance.

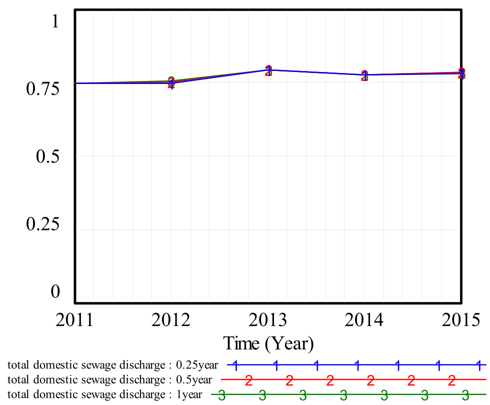
Scenario Setting and Simulation Analysis

The system dynamics models could be used to predict prediction system behaviors through simulations. Different simulation results were obtained according to the potential policy changes and parameter adjustment. By comparing the system behaviors under different policies, we selected the optimal solution and thus presented recommendations for decision makers.

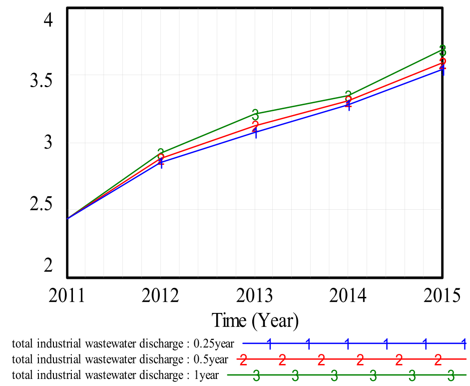
Four scenarios were considered:

Scenario A – the baseline scenario, which followed the existing development rules;

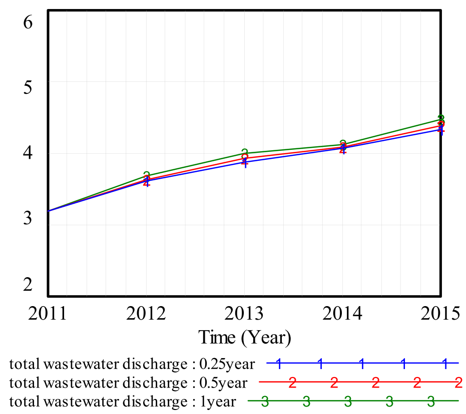
Scenario B – based on Scenario A, proportions of different industries in the economic structure were changed (the proportion



(a) Total domestic sewage discharge



(b) Total industrial wastewater discharge



(c) Total wastewater discharge

Figure 5. Simulation of major variables in the environment subsystem under different time intervals.

Table 1. *Error rates between real data and simulated data in the economic subsystem.*

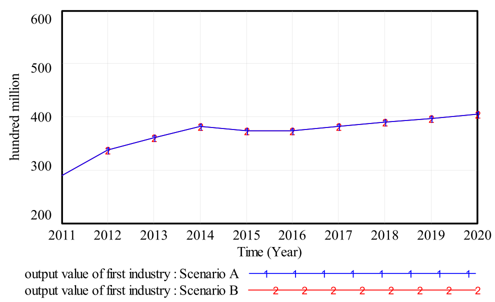
Time (Year)	Output Value of Second Industry			Output Value of Third Industry		
	Real Data	Simulated Data	Error Rates (%)	Real Data	Simulated Data	Error Rates (%)
2011	577.60	577.60	0.00	538.15	538.15	0.00
2012	710.24	694.44	-2.25	645.65	612.34	-5.16
2013	723.13	762.11	5.39	752.15	727.59	-3.27
2014	814.03	794.14	-2.44	824.00	806.51	-2.12
2015	894.15	875.19	-2.12	935.46	932.44	-0.32

Table 2. *Error rates between real data and simulated data in the water resource subsystem.*

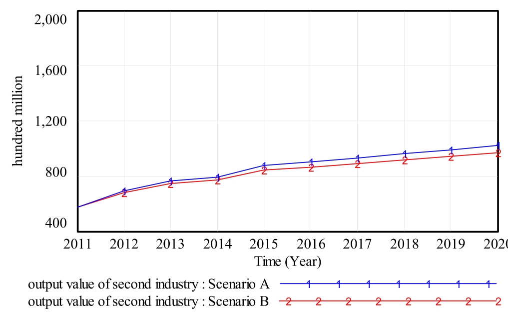
Time (Year)	Total Water Consumption			Total Water Resources		
	Real Data	Simulated Data	Error Rates (%)	Real Data	Simulated Data	Error Rates (%)
2011	27.67	27.74	0.25	96.06	96.06	0.00
2012	27.15	27.55	1.48	86.71	85.01	-1.96
2013	27.03	27.42	1.45	103.28	99.57	-3.59
2014	27.01	27.40	1.46	110.00	104.14	-5.33
2015	26.88	27.23	1.29	78.46	78.15	-0.40

Table 3. *Error rates between real data and simulated data in the environment subsystem.*

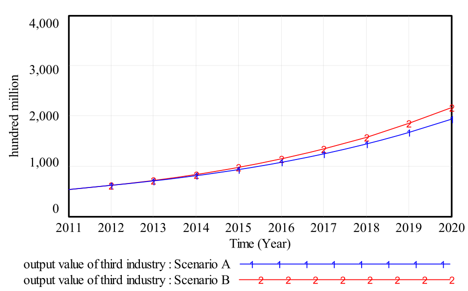
Time (Year)	Total Industrial Wastewater Discharge			Total Domestic Sewage Discharge		
	Real Data	Simulated Data	Error Rates (%)	Real Data	Simulated Data	Error Rates (%)
2011	0.54	0.54	0.00	0.75	0.75	-0.27
2012	0.68	0.69	0.00	0.75	0.75	0.27
2013	0.81	0.82	-0.01	0.79	0.79	0.67
2014	0.62	0.62	-0.01	0.77	0.78	0.23
2015	0.66	0.66	0.00	0.78	0.79	0.45



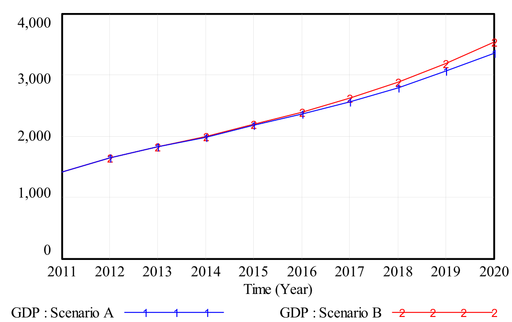
(a) Output value of first industry



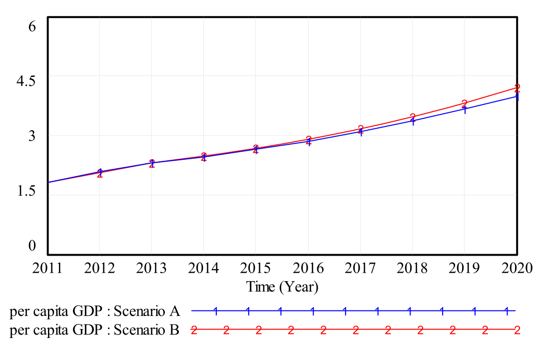
(b) Output value of second industry



(c) Output value of third industry



(d) GDP



(e) Per capita GDP

Figure 6. Comparison of Scenarios A and B in the economic subsystem.

of the second industry was reduced and the proportion of third industry was increased);

Scenario C – based on Scenario A, the natural population-increasing rate was changed (increment of 2%);

Scenario D – based on Scenario A, the influence of typhoon disasters was changed (the maximum influence of typhoon disasters in past years was selected).

(1) Analysis of Scenario B

Based on the SD model, we compared Scenarios A and B in the subsystems.

The comparative analysis of the economy subsystem is shown in Figure 6.

Table 4 shows the increments of output values, DGP, and per capita GDP of different industries in Scenarios A and B.

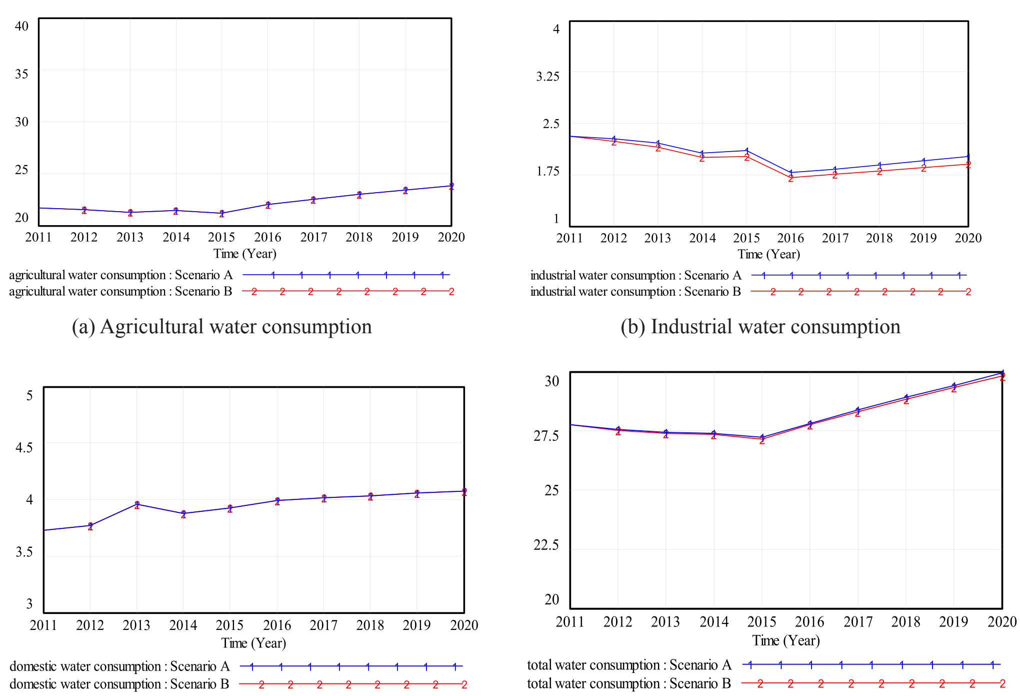
Clearly, GDP and per capita GDP both increased after the proportions of different industries were changed (the proportion of second industry was reduced, the proportion of third industry was increased) (Table 4). Consequently, increasing the proportion of third industry contributed to the increments of both GDP and per capita GDP. The comparative analysis of the water resource subsystem is shown in Figure 7.

Table 5 shows the data of agricultural water consumption, industrial water consumption, total water consumption, and domestic water consumption after the proportions of industries were changed.

Clearly, agricultural water consumption did not change, but the average industrial water consumption dropped by 4% after the proportion of the second industry was reduced, the proportion of third industry was increased (Table 5). Therefore, increasing

Table 4. *Comparison between Scenarios A and B at different years in the economy subsystem.*

Time (Year)		2016	2017	2018	2019	2020
	GDP	2,355	2,561	2,792	3,055	3,354
	per capita GDP	2.862	3.096	3.36	3.659	3.997
Scenario A	output value of first industry	373.81	382.37	389.6	396.96	404.46
	output value of third industry	1,078	1,246	1,441	1,666	1,926
	output value of second industry	903.21	931.89	961.47	991.93	1,023
	GDP	2,389	2,620	2,884	3,188	3,540
	per capita GDP	2.903	3.168	3.47	3.818	4.219
Scenario B	output value of first industry	373.81	382.37	389.6	396.96	404.46
	output value of third industry	1,149	1,347	1,578	1,849	2,166
	output value of second industry	865.94	890.75	916.26	942.45	969.36



(a) Agricultural water consumption (b) Industrial water consumption

(c) Domestic water consumption (d) Total water consumption

Figure 7. Comparison of Scenarios A and B in the water resource subsystem.

the proportion of the third industry could effectively reduce the industrial water consumption and save water resources. A comparative analysis of the environment subsystem is shown in Figure 8.

Table 6 shows the data of total industrial wastewater discharge, total wastewater discharge, and total domestic sewerage discharge after the proportions of industries were changed.

Clearly, the total domestic sewerage discharge did not change, but the total industrial wastewater discharge decreased by 3%, while the total wastewater discharge decreased by 1.7% after the proportion of the second industry was reduced and the proportion of the third industry was increased (Table 6). Therefore, increasing the proportion of the third industry could effectively reduce the wastewater discharge and improve the environmental quality.

(2) Analysis of Scenario C

Based on the SD model, we compared Scenarios A and C in the subsystems.

The comparative analysis of the population subsystem is shown in Figure 9.

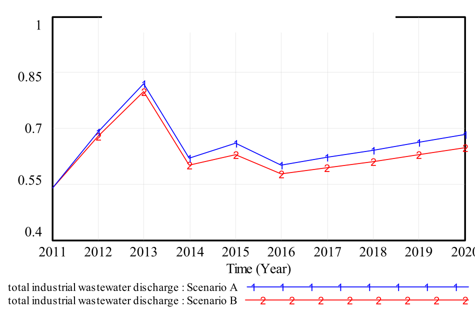
Table 7 shows the data of agriculture population, urban population, and total population after the natural population-increasing rate was changed.

Clearly, the agriculture population, urban population, and total population increased to different extent after the natural population-increasing rate was changed (increment of 2%), and the absolute values of population growth increased with time.

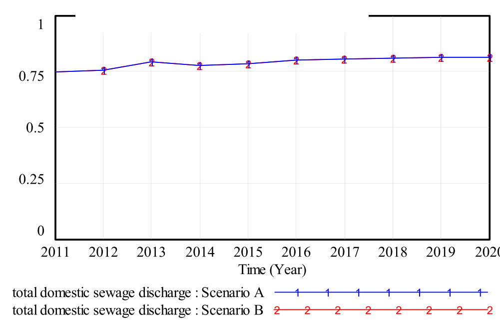
A comparative analysis of the water resource subsystem is shown in Figure 10.

Table 5. *Comparison between Scenarios A and B at different years in the water resource subsystem.*

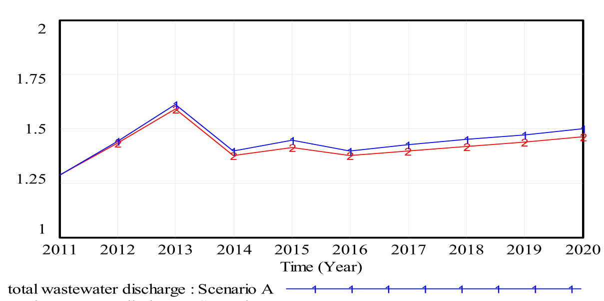
Time (Year)		2016	2017	2018	2019	2020
Scenario A	agricultural water consumption	22.04	22.54	22.97	23.4	23.84
	industrial water consumption	1.78	1.837	1.895	1.955	2.017
	total water consumption	28	28	29	29	30
	domestic water consumption	3.995	4.015	4.034	4.054	4
Scenario B	agricultural water consumption	22.04	22.54	22.97	23.4	23.84
	industrial water consumption	1.707	1.756	1.806	1.858	1.911
	total water consumption	28	28	29	29	30
	domestic water consumption	3.995	4.015	4.034	4.054	4.074



(a) Total industrial wastewater discharge



(b) Total domestic sewage discharge

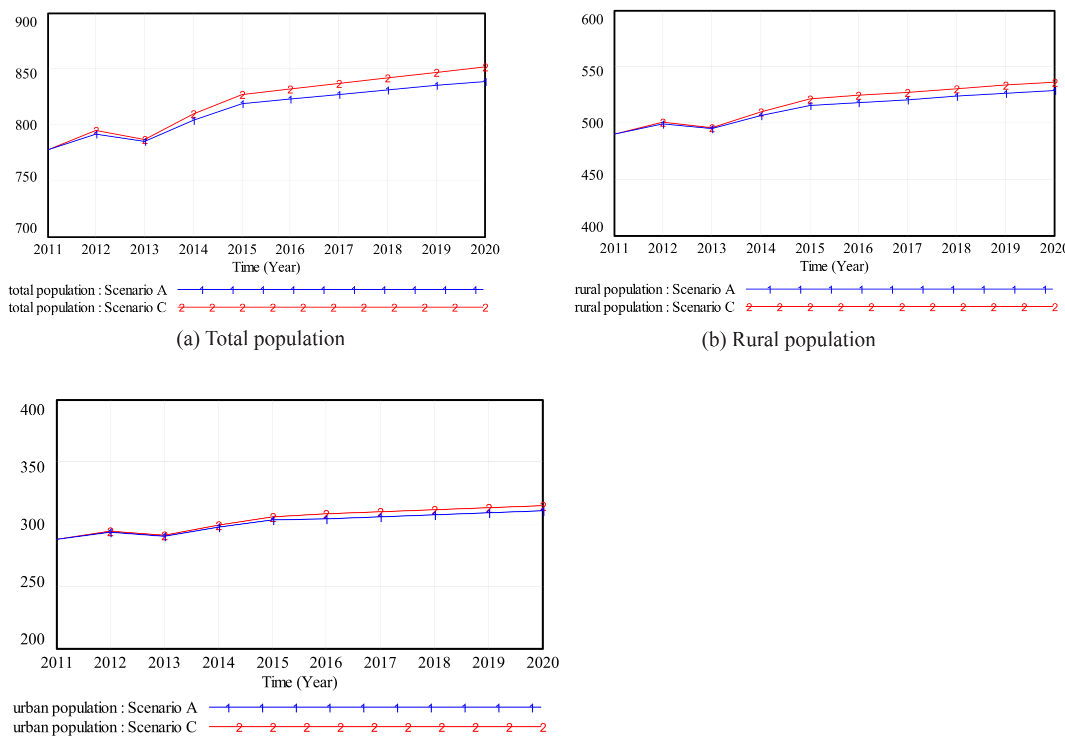


(c) Total wastewater discharge

Figure 8. Comparison of Scenarios A and B in the environment subsystem.

Table 6. *Comparison between Scenarios A and B at different years in the environment subsystem.*

Time (Year)		2016	2017	2018	2019	2020
	total industrial wastewater discharge	0.6	0.6221	0.6418	0.6622	0.6831
Scenarios A	total wastewater discharge	1.399	1.425	1.449	1.473	1.498
	total domestic sewage discharge	0.799	0.803	0.8069	0.8108	0.8147
	total industrial wastewater discharge	0.5769	0.5946	0.6116	0.6291	0.6471
Scenarios B	total wastewater discharge	1.376	1.398	1.419	1.44	1.462
	total domestic sewage discharge	0.799	0.803	0.8069	0.8108	0.8147



(a) Total population

(b) Rural population

(c) Urban population

Figure 9. Comparison of Scenarios A and C in the population subsystem.

Table 7. *Comparison between Scenarios A and C at different years in the population subsystem.*

Time (Year)		2016	2017	2018	2019	2020
	agricultural population	518.47	520.97	523.5	526.03	528.57
Scenario A	urban population	304.5	305.97	307.45	308.94	310.43
	total population	822.96	826.94	830.95	834.97	839.01
	agricultural population	524.27	527.32	530.38	533.46	536.56
Scenario C	urban population	307.91	309.69	311.49	313.3	315.12
	total population	832.18	837.01	841.87	846.76	851.68

Table 8 shows the data of total water consumption and domestic water consumption after the natural population-increasing rate was changed.

Clearly, the total water consumption and domestic water consumption increased to different extent after the natural population-increasing rate was changed (increment of 2%), and the absolute value of population growth increased with time. Specifically, the domestic water consumption and total water consumption increased by 1.3% and 0.18%, respectively, on average.

A comparative analysis of the environment subsystem is shown in Figure 11.

Table 9 shows the data of total wastewater discharge and total domestic sewerage discharge after the natural population-increasing rate was changed.

Clearly, the total wastewater discharge and total domestic sewerage discharge increased to different extent after the natural population-increasing rate was changed (increment of 2%), and the absolute values of population growth increased with time. Specifically, the total domestic sewerage discharge and total water consumption increased by 1.3% and 0.071%, respectively on average, indicating that population growth would aggravate environmental pollution.

(3) Analysis of Scenario C

Based on the SD model, we compared Scenarios A and D in the subsystems.

A comparative analysis of the economy subsystem is shown in Figure 12.

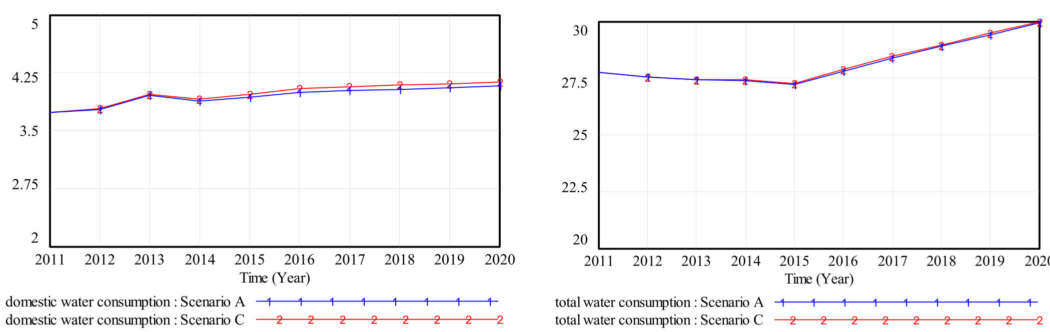
Table 10 shows the GDP, output value due to post-disaster reconstruction, and output value of first industry after the influence of typhoon disasters had been changed.

Clearly, both the GDP and output value of the first industry were reduced, while the output value increased due to post-disaster reconstruction after the influence of typhoon disasters was aggravated. Specifically, GDP and output value of the first industry decreased by 0.72% and 5%, respectively, while the output value increased by 0.9% due to post-disaster reconstruction. This indicates that the increase of economic influence of typhoon disasters largely affects the first industry, and promotes the output value of post-disaster reconstruction.

A comparative analysis of the water resource subsystem is shown in Figure 13.

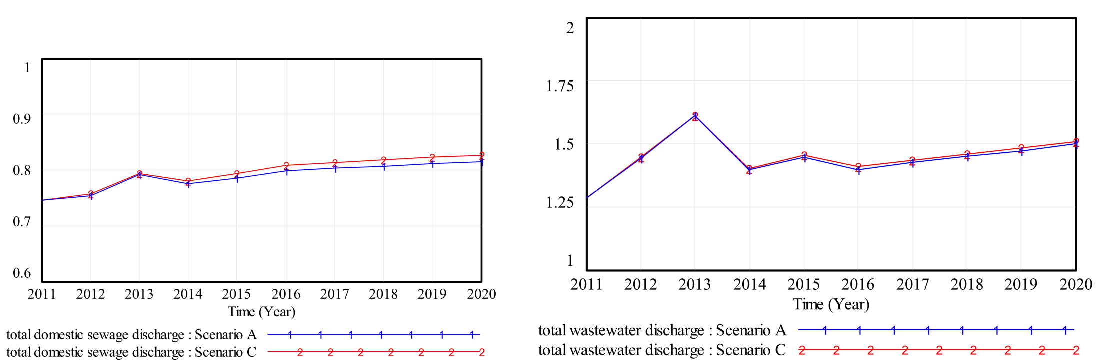
Table 8. *Comparison between Scenarios A and C at different years in the water resource subsystem.*

Time (Year)		2016	2017	2018	2019	2020
Scenario A	total water consumption	27.81	28.39	28.9	29.41	29.93
	domestic water consumption	3.995	4.015	4.034	4.054	4.074
Scenario C	total water consumption	27.86	28.44	28.95	29.47	29.99
	domestic water consumption	4.04	4.064	4.087	4.111	4.135



(a) Domestic water consumption (b) Total water consumption

Figure 10. Comparison of Scenarios A and C in the water resource subsystem.



(a) Total domestic sewage discharge (b) Total wastewater discharge

Figure 11. Comparison of Scenarios A and C in the environment subsystem.

Table 9. *Comparison between Scenarios A and D at different years in the environment subsystem.*

Time (Year)		2016	2017	2018	2019	2020
Scenario A	total wastewater discharge	1.399	1.425	1.449	1.473	1.498
	total domestic sewage discharge	0.799	0.803	0.8069	0.8108	0.8147
Scenario C	total wastewater discharge	1.408	1.435	1.459	1.484	1.51
	total domestic sewage discharge	0.808	0.8128	0.8175	0.8222	0.827

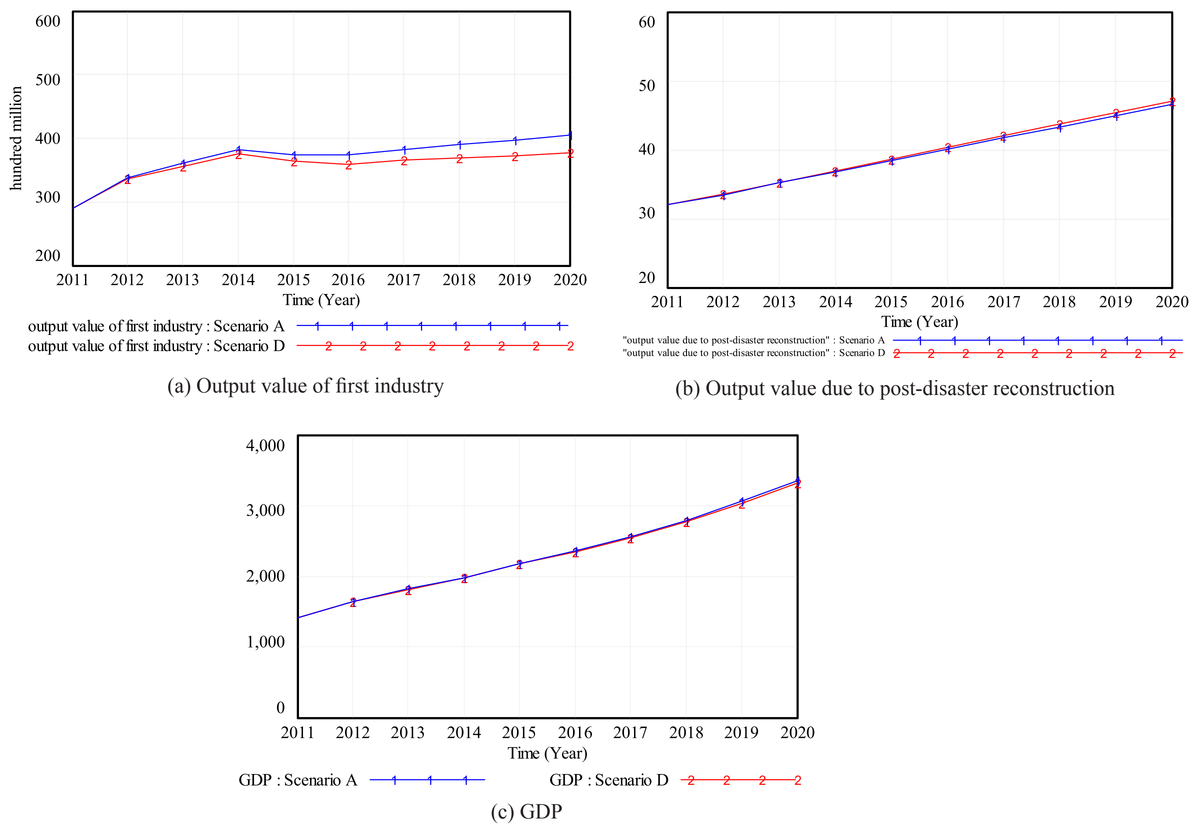


Figure 12. Comparison of Scenarios A and D in the economic subsystem.

Table 11 shows the precipitation due to typhoon disasters, and total water resource after the influence of typhoon disasters had been changed.

Clearly, the precipitation after typhoon disasters and thus, the total water resource increased after the influence of typhoon disasters was aggravated (Table 11). When the maximum influence of typhoons during the past years was selected, the precipitation due to typhoon disasters and the total water resource increased by 10.25% and 6.19%, respectively. It is indicated that typhoon disasters have significant effects on water resources, and the occurrence of typhoon disasters would intensify the precipitation in the affected areas, which in turn improved total water resources.

CONCLUSIONS

System dynamics is a discipline that qualitatively and quantitatively studies complex system problems with the help of computer simulations. It is good at solving problems of multivariate, high-order, multi-feedback, and nonlinear complex systems, which contribute to research on sustainable development. The simulation of sustainable development on the Leizhou Peninsula was conducted on Vensim.

(1) The population growth in Leizhou Peninsula was very slow, and the total population was under the controlled range.

(2) The economic growth was slow in the simulations. To accelerate economic development, the governments should optimize the industrial structure, and based on the revitalization of industry, pay attention to technologic innovation and emerging industries, thus improving resident incomes and quality of life, while promoting the service industry. Especially, increasing the output value of third industry would elevate GDP and per capita GDP.

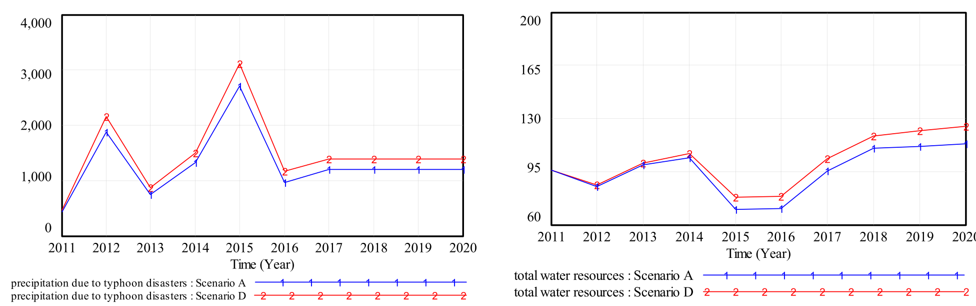
(3) Increasing the proportion of the third industry would improve the environmental quality. However, if the population growth would be too rapid, it would aggravate environmental pollution. Thus, environmental investment and the proportion

Table 10. *Comparison between Scenarios A and D at different years in the economic subsystem.*

Time (Year)		2016	2017	2018	2019	2020
Scenario A	GDP	2,355	2,561	2,792	3,055	3,354
	output value due to post-disaster reconstruction	40.1	41.69	43.31	44.93	46.55
	output value of first industry	373.81	382.37	389.6	396.96	404.46
Scenario D	GDP	2,341	2,543	2,771	3,031	3,327
	output value due to post-disaster reconstruction	40.39	42.04	43.72	45.4	47.08
	output value of first industry	359.45	364.8	368.78	372.8	376.86

Table 11. *Comparison between Scenarios A and D at different years in the water resource subsystem.*

Time (Year)		2016	2017	2018	2019	2020
Scenario A	precipitation due to typhoon disasters	972	1200	1200	1200	1200
	total water resources	70.67	95.46	110.44	111.75	113.07
Scenario D	precipitation due to typhoon disasters	1072	1323	1323	1323	1323
	total water resources	73.66	100.22	116.82	119.82	122.95



(a) Precipitation due to typhoon disasters (b) Total water resources

Figure 13. Comparison of Scenarios A and D in the water resource subsystem.

of environmental investment in GDP should be improved, to improve the environmental quality.

(4) Typhoon disasters largely influence economy and water resources. In case of severe typhoon disasters, the first industry was largely affected, leading to a decline of GDP. Moreover, typhoon disasters brought more precipitation to the affected areas, thus increasing local water resources.

In summary, based on the current economic and social developmental rules, the second industry will dominate the economic development of the Leizhou Peninsula by the end of 2020. The demand for water resources was increasingly intensified, and in particular, industrial water use was the major cause for the severe depletion of water resources. Typhoon disasters largely affected the economic development and water resources. By comparing different scenarios, we found the coordinated development scenario B to be optimal. This scenario is based on the standard scenario with optimized industrial structure. Specifically, the proportion of the second industry is reduced, the proportion of the third industry is increased, and the demand and consumption of water resources are reduced, consequently largely relieving the environmental burden and promoting sustainable development of the Leizhou Peninsula.

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