Multi-Scenario Simulation of a Water–Energy Coupling System Based on System Dynamics: A Case Study of Ningbo City

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Abstract: In this work, based on the concept of collaborative water–energy development, a multi-scenario system dynamics simulation model of a water–energy coupling system was constructed by using the system dynamics modeling method. The model was composed of four subsystems: society, economic, water resources, and energy. Taking Ningbo City as the research location to run the simulation model, the analysis of the validity of the model showed that the relative error between the historical data and the simulation results of the model was less than 10%, which proved that the model passed the test. In this paper, based on the scenario of business an usual (BAU), three scenarios of water-saving scenario (WSS), energy-saving scenario (ESS), and comprehensive savings (CS, the comprehensive scenario considers water-saving and energy-saving together) were designed, and the simulation indexes in the three scenarios were refined in order to strengthen the control of water-saving policies, improve the effective use of water, optimize the industrial energy structure, improve the level of energy-saving-related technologies, and advance the urbanization process. The simulation results for Ningbo City from 2010 to 2030 show that the water–energy coupling system is affected by many factors, and the adjustment of a driving factor of any subsystem will have an impact on the water–energy coupling system. There are two driving factors: the first is a constant variable related to water resources, energy, society, and economic, and the second is a variable affected by time. The coupling system is based on the law of real development and is composed of causal and functional relationships between variables. Therefore, within the prediction range of 2030, the driving factors in the coupling system are controllable, and there is no uncontrollable situation. The strengthening of water-saving policies and the improvement of the coefficient of the effective utilization of water will have the optimal saving effects on water resources and energy at both the single and the coupling level; this also demonstrates that the water resource management in Ningbo City plays an extremely important role in the relationship of the water–energy coupling. The results of this study are expected to provide a valuable reference for the management and conservation of water–energy coupling in Ningbo City.

Keywords: water–energy coupling system; system dynamics; multi-scenario simulation

1. Introduction

The coordinated development of water resources and energy is directly related to national security, social stability, and the sustainable development of resources [1]. The extraction, transport, and processing of water require the consumption of energy. Similarly, many processes of refining, processing, and converting various fuels and generating
electricity also require the consumption of water; this connection is called the “hydro-energy relationship” [2]. With the continuous advancement of urbanization, rapid social and economic development, and population growth, the demand for energy is constantly increasing. However, in the process of the development and utilization of energy, water is constantly consumed, and water resources are scarce and unevenly distributed, making the contradiction between the supply and demand of water resources and energy increasingly prominent [3]. According to a report released by the National Intelligence Council in 2012, it is estimated that, by 2030, the global energy demand will increase by 50%, while water demand will increase by 40% [4]; by 2050, the global demand for water and energy will increase by 55% and 80%, respectively, which is particularly evident in China [5]. A total of 97% of China’s electricity production consumes water daily, and without water, there can be no electricity; 95% of coal mining also uses large amounts of groundwater, and 53% of retained coal reserves are in water-scarce areas, while 30% are in water-stressed areas.

The current vertical single-management mode of water resources and energy in China cannot solve the problem of cross-sectoral collaborative water–energy management, and the contradiction between water and energy resources has become an important factor restricting China’s sustainable development [6]. As early as 1977, the United Nations (UN) held a conference on water issues and issued a serious warning to the world: The water crisis will become the next social problem after the oil crisis [4]. The problem of water shortage has long caused visible concern. The theme of the UN’s “World Water Day” in 2014 was “water and energy”. The “World Energy Outlook 2016” released by the IEA also emphasized the Water–Energy Nexus (WEN) [4,7]. These events fully demonstrate that there is an objective connection between water and energy [8]. In this context, it is very important to seek a coupled path for coordinated water–energy development. By combining the LISFLOOD model and DISPA-SET model, Matija et al. analyzed the water–energy dependence relationship in African power pools [2]. Gabriela Shirkey used public data from the United States (US) Energy Information Administration and the US Bureau of Labor Statistics (2014–2019) to generate baseline datasets to assess the interaction between hydropower relationships and society, as well as to establish an environmental and social analysis of the US power industry based on hydropower relationships [9]. Wu et al. studied sustainable, regional water allocation with a water–energy linkage—a chance-constrained probability of mean–variance multi-objective programming [10]. These studies have made great contributions to the exploration of the relationship of water–energy coupling, but there are still few studies of water–energy coupling simulations and multi-scenario simulations on an urban scale [11], especially studies of urban water–energy coupling [12] based on a system dynamics model. System dynamics models can effectively and closely link water resources and energy consumption [13] with other influencing factors, and they can predict water–energy consumption through the interactions of various influencing factors with water resources and energy [14]. Therefore, in this paper, a system dynamics model is applied to the study of water–energy coupling at the urban scale. At the same time, the direct influences of the population and economic system on water resources and the energy system, as well as the mutual influences of water resources and the energy system, are considered in order to construct a water–energy coupling model that integrates four subsystems, which can make the prediction results more accurate and allow more targeted water-saving strategies to be put forward. The results of this paper are expected to provide reasonable policy suggestions for the coordinated management of water–energy resources and an evaluation reference for other urban cases, as well as promote coordinated regional development [15].

2. Materials and Methods

2.1. Study Area

Ningbo City (Figure 1), an important port city on the southeast coast of China, that was approved by the State Council, and the economic center on the south wing of the Yangtze River Delta, is located in Zhejiang Province and is a “water town south of the Yangtze
River” [16]. It is a water-deficient area where the development of water resources and energy resources is uncoordinated. The water consumption in Ningbo is mainly of surface water, supplemented by groundwater [17], and the supply and consumption of water resources increase year by year [18]. Of the total water consumption (the amount of water taken by various water users, including the loss of water transmission), the proportion of production water is the largest, followed by domestic water, and the proportion of ecological water is the smallest. In 2020, production water accounted for 73.11% of the total water consumption, domestic water for 24.13% and ecological water for 2.76%. Although the utilization rate of water resources in irrigation and in secondary and tertiary industries has been improved [18], the per capita comprehensive annual water consumption is gradually rising, and the difficulty of the development and utilization of water resources in Ningbo will increase year by year in the future. According to international standards, an area with annual per capita water resources of 1000–2000 m$^3$ is considered to have a moderate water shortage. However, in 2019, the per capita water resources of Ningbo (calculated according to the city’s permanent population) were 1430.76 m$^3$, which was about 20% lower than the national per capita level and 1/4 of the international per capita level. Although its economic aggregate accounts for 2/3 of that of the whole province, Ningbo, as a densely populated area in Zhejiang Province, has water resources that only account for 1/5 of the whole province. On the one hand, the spatial and temporal distribution of water resources is extremely uneven; the precipitation from May to September accounts for 60% of the annual precipitation, and the long and heavy Meiyu period leads to frequent droughts after the flood season. On the other hand, the utilization efficiency of water resources is low. The water consumption per 10,000 yuan of GDP is 254 m$^3$, which is more than twice the rate in developed countries, and the water supply and demand are effectively in a weakly balanced state [19]. Although Ningbo has taken a series of measures to relieve the pressure on water resources, such as “reclaimed water”, “sewage reuse”, and the “diversion of water from outside the city”, these measures are insufficient to alleviate the pressure of the demand for water resources caused by the rapid growth of the population and economic aggregation.

![Figure 1. Location of study region in China.](image-url)
In this paper, Ningbo City was selected as the study area, and the development status of the water resources and energy in Ningbo City was considered. The system dynamics method was adopted to explore the coupling of the water–energy system, and the trends of the variations in water resources and energy in different scenarios were analyzed in order to predict water and energy consumption and its availability, as well as to provide a valuable reference for the study of urban water–energy coupling.

2.2. Data Sources

The research data in this paper were taken from the data published in the China Statistical Yearbook (http://www.stats.gov.cn/tjsj/ndsj/ accessed on 30 June 2021), China Energy Statistical Yearbook (https://navi.cnki.net/knavi/yearbooks/YCXME/detail accessed on 30 June 2021), China Environmental Statistical Yearbook (https://navi.cnki.net/knavi/yearbooks/YHJSD/detail accessed on 30 June 2021), Ningbo Statistical Yearbook (https://navi.cnki.net/knavi/yearbooks/YNBTK/detail accessed on 30 June 2021), Ningbo Water Resources Bulletin (http://slj.ningbo.gov.cn/coll1229051263/index.html accessed on 30 June 2021), Ningbo Environmental State Bulletin (http://sthjj.ningbo.gov.cn/coll1229051263/index.html accessed on 30 June 2021).

2.3. Technical Route

This paper presents the method, model and scenario design in the form of technology roadmap (Figure 2).

![Figure 2. Research flowchart based on the system dynamics model for Ningbo.](image)

2.4. Methods for Quantitative Evaluation of Water and Energy

The method for the calculation of mixed water and mixed energy by Yang et al. [1] was applied to the calculation of water and energy consumption in this paper, and this calculation was divided into the total water consumption and total energy consumption. The total water consumption was represented as the sum of the calculation of domestic water, production water, and ecological water. Production water included agricultural water, industrial water (industrial water other than energy-related water), tertiary industry water, and energy-related water consumption (water consumption for the process of the exploitation, use, and development of raw coal, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, heat, and electricity). The total energy consumption included the direct and indirect energy consumption, and the direct energy consumption included raw coal, gasoline, diesel, natural gas, electricity, etc. The indirect energy consumption was expressed as the energy consumption of social water cycle processes [1], including the...
energy consumption for water conveyance, water use, drainage, sewage reuse, and the reclaimed water treatment process.

The total water consumption was computed with the following formula:

$$W = \sum_{m=1}^{w_m}$$

where $$w_m (m = 1, 2, 3)$$ is the water consumption for production, domestic uses, and ecology (ecological water refers to the amount of water provided by human measures to maintain the ecological environment, including the amount of water used for artificial ecological supplement, afforestation, and cleaning), and $$W$$ represents the total water consumption.

The energy-related water consumption is expressed with the following formula:

$$W_1 = \sum_{n=1}^{e_{1n}} \cdot \alpha_n \in W$$

where $$e_{1n} (n = 1, 2, \ldots 8)$$ represents the type of energy that consumes water (raw coal, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, heat and electricity) in the production process, $$\alpha_n (n = 1, 2, \ldots 8)$$ is the water consumption intensity per unit of energy of $$e_{1n}$$, and $$W_1$$ represents the energy-related water consumption.

Direct energy consumption is expressed with the following formula:

$$E_1 = \sum_{n=1}^{e_{1n}}$$

where $$e_{1n} (n = 1, 2, \ldots 8)$$ is the direct consumption of each type of energy and $$E_1$$ represents the total amount of direct energy consumption.

Indirect energy consumption is expressed with the following formula:

$$E_2 = \sum_{k=1}^{w_2k} \cdot \beta_k$$

where $$w_2k$$ represents the five processes of the social water cycle (water conveyance, water use, drainage, sewage reuse and reclaimed water treatment), $$\beta_k (k = 1, 2, \ldots 5)$$ is the energy consumption intensity per unit of water consumption of $$w_2k$$, and $$E_2$$ represents the total amount of indirect energy consumption.

The total energy consumption can be expressed as follows:

$$E = E_1 + E_2$$

where $$E_1$$ represents the total direct energy consumption and $$E_2$$ represents the total indirect energy consumption.

2.5. System Dynamics Model

2.5.1. Causal Loop Diagram

System dynamics (SD) can reflect the interactions of the internal elements of a system. With the help of computer modeling, the thought processes and research on complex problems can be completed, making it especially suitable for analyzing and solving a series of nonlinear complex system problems, such as social and economic problems [1]. In this paper, the boundary of the geographical space of Ningbo City was taken as the boundary of the research system. The analysis of the coupling of the systems’ water resources and energy is a complex multi-level system involving population [20], economy, water resources [21], and energy, etc. [22]. Therefore, this paper divides the construction of the water–energy coupling model into four subsystems: society, economy, water resources, and energy. Each variable in the subsystem is both an independent variable and dependent variable in the system, thus forming numerous causal feedback loops (Figure 3).
2.5.2. Variables and Equations

The water–energy coupling system is not the simple sum of the water system and the energy system. The following two problems need to be solved to establish the coupling system by using the SD model. First, two separate subsystems must pass through a bridge or medium to become an integrated system. In this study, water and energy systems are coupled into a system through the two bridges of water-related energy consumption and energy-related water consumption. Second, the integrated system may have overlapping effects, resulting in a total water consumption or total energy consumption that is greater than the actual value. In this case, the structure of the SD model needs to be adjusted to remove data errors caused by overlapping effects. According to the causal loop diagram, 64 indicators were selected from the four dimensions of society, economy, water resources, and energy in order to construct the variable equations (Table 1).

![Causal loop diagram of the water–energy coupling system.](image)

**Table 1.** Core indexes and equations of the subsystems.

| Subsystems | Indexes                      | Equations                                                                 |
|------------|------------------------------|---------------------------------------------------------------------------|
| Society    | Total population             | INTEG (Births—Deaths, 744.3)                                             |
|            | Births                       | Total population × Birth rate                                             |
|            | Deaths                       | Total population × Death rate                                             |
|            | Urban population             | Total population × Urbanization rate × urbanization process/0.7          |
|            | Rural population             | Total population—Urban population                                        |
|            | Urbanization rate            | 0.7 + RANDOM NORMAL (−0.09, 0.09, 0, 0.78, 2)                            |
| Economic   | Gross agricultural production| INTEG (Growth in output value of primary industry, 216.66)                |
|            | Output value of primary industrial | INTEG (Growth in output value of primary industry, 216.66)                |
|            | Gross industrial production  | INTEG (Industrial added value, 2915.09)                                  |
|            | Output value of secondary industrial | INTEG (Industrial added value, 2915.09)                                  |
|            | Gross output value of tertiary industrial | INTEG (Growth in output value of tertiary industry, 2132.95)             |
|            | GDP                          | Output value of primary industrial + Output value of secondary industrial + |
|            | Per capita GDP               | GDP/Total population                                                     |
Table 1. Cont.

| Subsystems              | Indexes                                                                 | Equations                                                                                          |
|-------------------------|------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| Domestic water for urban residents | Urban population \times Urban per capita annual water consumption / 10,000 \times 0.5 / Water-saving policy |
| Domestic water for rural residents | Rural population \times Rural per capita annual water consumption / 10,000                                  |
| Domestic water          | Domestic water for urban residents + Domestic water for rural residents                        |
| Agricultural water consumption | Water consumption per unit agricultural output value \times Output value of primary industrial / Improve the effective utilization coefficient of water |
| Industrial water consumption | Water consumption per unit output value of secondary industry \times Output value of secondary industrial |
| Water consumption of tertiary industry | Water consumption per unit output value of tertiary industry \times Gross output value of tertiary industrial |
| Production water        | Agricultural water consumption + Industrial water consumption + Water consumption of tertiary industry + Energy-related water consumption |
| Ecological water        | WITH LOOKUP (Time, ([2001, 0]—[2030, 10]), (2001, 1.1), (2006, 1.33), (2007, 1.19), (2008, 1.75), (2009, 1.83), (2010, 2.38), (2011, 2.14), (2012, 2.47), (2013, 2.41), (2014, 2.74), (2015, 2.57), (2016, 3.39), (2017, 0.25), (2018, 0.24), (2019, 0.24), (2020, 0.58), (2030, 1.5))) |
| Water consumption       | Domestic water + Production water + Ecological water                      |
| Domestic sewage discharge | Domestic water \times Discharge coefficient of domestic sewage            |
| Production wastewater discharge | Production water \times Discharge coefficient of production wastewater    |
| Total effluent discharge | Domestic sewage discharge + Production wastewater discharge               |
| Sewage treatment        | Total effluent discharge \times Sewage treatment rate                    |
| Reclaimed water         | Total effluent discharge \times Utilization rate of reclaimed water \times Reclaimed water treatment technology / 0.8 |
| Energy consumption of domestic water | Unit energy consumption of domestic water \times Domestic water |
| Energy consumption of production water | Unit energy consumption of production water \times Production water |
| Energy consumption of water | Energy consumption of domestic water + Energy consumption of production water |
| Energy consumption of sewage discharge | Unit energy consumption of sewage discharge \times Total effluent discharge |
| Energy consumption of sewage reuse | Unit energy consumption of sewage reuse \times Sewage reuse \times 0.8 / Sewage reuse technology |
| Energy consumption of reclaimed water | Unit energy consumption of reclaimed water \times Reclaimed water |
| Energy consumption of water conveyance | Domestic water \times Conveyance coefficient of domestic water + Production water \times Conveyance coefficient of production water + Ecological water \times Conveyance coefficient of ecological water |
| Water-related energy consumption | Energy consumption of water + Energy consumption of water conveyance + Energy consumption of sewage discharge + Energy consumption of sewage reuse + Energy consumption of reclaimed water |
| Proportion of water-related energy consumption | Water-related energy consumption / Total energy production |
| Energy-related water consumption | Unit water consumption of energy production \times Total energy production / 10,000 \times (Energy extraction technology \times (0.7 / Clean energy technology)) |
| Proportion of energy-related water consumption | Energy-related water consumption / Water consumption |

2.5.3. Model Building

According to the causal loop diagram and the relationships between the indicators and variables selected above, the SD model was established by using the Vensim software (Figure 4).

2.5.4. Model Checking

Unit Consistency Check

The various variables in the SD model have different units. When establishing a variable equation, the units on both sides of the equals sign must be consistent so that the model can run and be simulated correctly. In the Vensim software, the unit error of the model can be effectively checked by using a check model button. In this paper, in
the process of the simulation of the model, the unit maintained good consistency through repeated corrections.

Figure 4. SD model for the water–energy coupling system.

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Structural Rationality Check

Whether the structure of the model is correct can be observed by using the cause hierarchy table or the result hierarchy table of the model. The representative indicators that were selected were the total population (Table 2), water consumption (Table 3), and water-related energy consumption (Table 4). In this paper, we read much of the relevant literature during the analysis of the system and construction of the model, and the model’s structure was essentially consistent with that of the actual system.

Table 2. Result hierarchy for the total population.

| Input Layer    | Middle Layer                          | Result Layer                          |
|----------------|---------------------------------------|---------------------------------------|
| Total population | Per capita GDP                        | /                                     |
|                | Rural population                      | Domestic water for rural residents    |
|                | Births                                | (Total population)                    |
|                | Urban population                      | (Rural population)                    |
|                | Deaths                                | Domestic water for urban residents    |
|                |                                       | (Total population)                    |
Table 3. Cause hierarchy for the water consumption.

| Cause Layer | Middle Layer | Output Layer |
|-------------|--------------|--------------|
| Agricultural water consumption | Production water | Water consumption |
| Industrial water consumption | | |
| Water consumption of tertiary industry | | |
| Energy-related water consumption | Ecological water | |
| Time | | |
| Domestic water for rural residents | Domestic water | |
| Domestic water for urban residents | | |

Table 4. Cause hierarchy for the water-related energy consumption.

| Cause Layer | Middle Layer | Output Layer |
|-------------|--------------|--------------|
| reclaimed water | Energy consumption of reclaimed water | |
| Unit energy consumption of reclaimed water | | |
| Unit energy consumption of sewage reuse | Energy consumption of sewage reuse | |
| Sewage reuse technology | | |
| Sewage reuse | | |
| Total effluent discharge | Energy consumption of sewage discharge | Water-related energy consumption |
| Unit energy consumption of sewage discharge | | |
| Energy consumption of production water | Energy consumption of water | |
| Energy consumption of domestic water | | |
| Production water | | |
| Conveyance coefficient of production water | | |
| Domestic water | | |
| Conveyance coefficient of domestic water | Energy consumption of water conveyance | |
| Ecological water | | |
| Conveyance coefficient of ecological water | | |

Model Validity Check

In order to determine the validity of the simulation results, it was necessary to verify the validity of the model. In the model, the year 2010 was taken as the base year, the data from 2010 to 2018 were used to fit each variable equation, and the key parameters of each subsystem were calibrated. The simulation error of the model was verified by comparing the relative error between the historical data and the simulation results, and the value of each variable in 2019 was further predicted with the historical data from 2010 to 2018. The prediction results were compared with the real values in 2019 to verify the prediction error of the model. The following six indicators were randomly selected, based on the following formula [4], and the simulation results were as follows (Table 5):

$$\delta = \frac{\sigma}{L} \times 100\%$$

\[6\]
\[ \sigma = |S - L| \]  

(7)

where \( \delta \) represents the relative error, \( \sigma \) represents the absolute error, \( S \) represents the simulated value, \( L \) represents the real value, and the corner note of references is added next to the formula.

Table 5. Results of the analysis of the effectiveness of the SD simulation model.

| Index       | Total Population /10,000 People | GDP /10,000 Yuan | Water Consumption /100 Million m³ | Domestic Water /100 Million m³ | Production Water /100 Million m³ | Sewage Reuse/100 Million m³ |
|-------------|---------------------------------|-----------------|-----------------------------------|--------------------------------|---------------------------------|-------------------------------|
| %           | Relative Error                  | Relative Error  | Relative Error                    | Relative Error                  | Relative Error                  | Relative Error                |
| 2010        | 0.00                            | 0.00            | 1.04                              | 4.92                           | 0.02                            | 0.32                          |
| 2011        | 0.04                            | 0.03            | 0.26                              | 4.45                           | 1.75                            | 0.51                          |
| 2012        | 1.98                            | 0.00            | 0.54                              | 0.15                           | 0.86                            | 0.58                          |
| 2013        | 0.14                            | 0.01            | 0.72                              | 0.46                           | 1.22                            | 0.19                          |
| 2014        | 1.96                            | 0.02            | 2.25                              | 0.79                           | 3.58                            | 0.44                          |
| 2015        | 1.45                            | 0.05            | 0.09                              | 0.10                           | 0.10                            | 0.47                          |
| 2016        | 0.47                            | 0.04            | 0.97                              | 0.95                           | 1.59                            | 0.91                          |
| 2017        | 0.35                            | 0.05            | 0.29                              | 1.62                           | 0.12                            | 0.31                          |
| 2018        | 2.00                            | 0.04            | 2.37                              | 1.61                           | 3.72                            | 1.75                          |
| 2019        |                                 |                 |                                   |                                |                                 |                               |

The calculation results in Table 5 show that the errors of each index value were all within 5%. It was proven that the simulated behaviors of the selected water-related indexes in the model were highly consistent with the actual values of the system. When the SD model was used for trend prediction, the error was less than 30%, which meant that the model was effective. Therefore, the SD model of Ningbo City constructed in this study could effectively simulate historical data and predicted data.

2.6. Scenario Analysis

Water resources and energy, as the output system of the target of investigation and the effective expression of policy measures, were affected by multiple driving factors, such as the society and economy. In order to investigate and compare the influences of different policy regulations and driving factors on the coupling system, this paper set up four different scenarios (Table 6) by using a scenario analysis (SA) based on the relevant development plans, policies, and regulations of Ningbo and the analysis of the development status quo (Table 6)—BAU, WSS (Scenario 1), ESS (Scenario 2), and CS (Scenario 3), as well as different dimensions of the regulatory scheme—in order to evaluate the extent of the impact on the target.

2.6.1. Water-Saving Scenario Setting

Since 2005, Ningbo has reviewed and approved a number of water-saving schemes: the Management Regulations of Ningbo City on Urban Water Supply and Water Conservation [23] and the Comprehensive Planning of Ningbo City on Water Resources, Management Regulations of Ningbo City on Water Resources, etc. The control of water-saving policies was continuously strengthened, and the institutional system was continuously improved. Therefore, water-saving policies were taken as one of the indicators of WSS, and the overall goals of the water-saving actions of Ningbo were referred to as follows: In 2022, the target values of water consumption per 10,000 yuan of GDP and water consumption per 10,000 yuan of value added by industry will be less than 17 and 12 m³, respectively, and the total water consumption of the whole city will be maintained under 2.2 billion m³; in 2025, the target values of water consumption per 10,000 yuan of GDP and water consumption
per 10,000 yuan of value added by industry will be less than 16 and 11 m$^3$, respectively, and the total water consumption of the whole city will be kept under 2.4 billion m$^3$. As a result of the correlation of the target data and the trendline analysis, the water-saving policy coefficient of Scenario 1 increased from 0.5 to 0.6 (Table 6).

For Ningbo, the highest proportion of water consumption [19] was due to crop irrigation [24]. By 2019, the effective irrigation area of crops in Ningbo was 175.18 thousand hectares, the effective irrigation rate was 90.31%, and the water-saving irrigation rate was 74.16%. Therefore, in the first scenario, crop irrigation [25] was also included in the WSS index. With the continuous advancement of agricultural modernization [26], the irrigation efficiency for agricultural water in Ningbo was improved. As a result of the analysis of the correlation of irrigation efficiency and the coefficient of effective utilization of water [27], as well as the influence of the coefficient of effective utilization of water on the changes in agricultural water consumption in their ranges of variation, the coefficient of effective utilization of water increased to 1.1 in Scenario 1 (Table 6).

### 2.6.2. Energy-Saving Scenario Setting

Energy development is a complex systematic project and an important foundation for ensuring the comprehensive, coordinated, and sustainable development of the economy and society. In recent years, Ningbo has intensified the development and utilization of clean energy [28] and renewable energy; it has taken the construction of a clean, low-carbon, safe, and efficient energy system as the starting point and foothold, adjusted the energy industry’s structure [29], and promoted the high-quality development of energy in the whole city. Considering the current energy structure and the proportion of clean energy with respect to the total energy consumption, Scenario 2 improved the coefficient of clean energy technology to reach 0.85 (Table 6).

It is important to realize the coordinated development of water and energy in order to promote technological progress in saving water and energy, to improve the rates of the reuse of water and sewage and the yield of reclaimed water through scientific management and technological transformation, and to save water and reduce its consumption. The southeast coast of Ningbo is a typical seaport city with rich natural resources in the sea area. Ningbo needs to improve its energy extraction technologies, enrich the types of mineral resources, reduce the consumption of water resources in mining processes, and make intensive use of resources. Therefore, the improvement of the energy-saving-related technology level is regarded as one of the indicators of the ESS. According to the country’s Plan for the Development of the Energy Conservation and Environmental Protection Industry in the 13th Five-Year Plan [30] and the 13th Five-Year Plan for the Energy Saving of Ningbo City, as well as other relevant policy documents and plans, through the data correlation analysis and the trendline prediction for Ningbo’s sewage treatment rate, sewage reuse, reclaimed water production from 2010 to 2019, the coefficients for the sewage reuse technology, reclaimed water treatment technology, and energy extraction technology increased to 0.9, 1.1, and 1.15, respectively (Table 6), and these values were also set in Scenario 2.

### 2.6.3. Comprehensive Scenario Setting

According to the analysis of the statistical data, the rapid economic development, water resource consumption, and energy consumption of Ningbo are closely related to the total population, and the urban population of Ningbo accounts for a large proportion of the total population. As shown by the growth of the urban population from 4,782,300 in 2010 to 6,287,000 in 2019, the urbanization rate is continuously increasing; it increased from 64.3% in 2010 to 73.6% in 2019, so the continuous advancement of the urbanization process [31] was integrated into the comprehensive scenario. According to the trend and the prediction of the urbanization rate during 2010–2019, the value for the urbanization process increased from 0.7 to 0.85 (Table 6). At the same time, the correlation coefficient used for the WSS and ESS was also set in Scenario 3.
Table 6. Parameter settings of different scenarios.

| Scheme | First-Level Indicators | Second-Level Indicators (Coefficient) | Parameter Setting [1,27–29,31] |
|--------|------------------------|---------------------------------------|-------------------------------|
| BAU    | /                      | /                                     | /                             |
| Scenario 1 | WSS                   | Strengthening the control of         | Water-saving policy 0.6       |
|         |                        | water-saving policies                 |                               |
|         |                        | Improve the coefficient of           | Coefficient of the            |
|         |                        | effective utilization of water       | efficient utilization of water|
|         |                        | Optimization of industry             | Clean energy technology 0.85  |
|         |                        | energy structure                     |                               |
|         |                        | Improvement of the                  | Sewage reuse technology 0.9   |
|         |                        | energy-saving-related technology     |                               |
|         |                        | deal level                           | Reclaimed water                |
|         |                        |                                         | treatment technology 1.1      |
|         |                        | WSS + ESS + Continuous               | Urbanization is advancing 0.85|
|         |                        | advancement of the urbanization       |                               |
|         |                        | process                              |                               |

3. Results

According to the model constructed in the previous section, the data were processed and then input into the Vensim software to simulate the water–energy coupling system of Ningbo City from 2010 to 2030.

3.1. Analysis of the Simulation Results of the BAU

According to the current development trend, the representative indexes of each sub-system were selected, and the simulation results are shown in Figure 5.

According to the prediction results of the model, for the BAU, the total population would continue to grow from 2010 to 2030. Although there was a small range of fluctuations in the middle, the overall trend would significantly increase. It was estimated that by 2030, the total population would reach 1.6 times that of 2010. As seen in Figure 5a, with the continuous increase in the population, the water consumption would also rise. However, the per capita comprehensive annual water consumption decreased from 370 m$^3$ in 2010 to 239 m$^3$ in 2019. The only turning point occurred in 2016–2017, during which the per capita comprehensive annual water consumption plummeted by 140 m$^3$. According to the data analysis, the 13th Five-Year Development Plan of Ningbo clearly stipulated that the management of water resources should be strengthened and the effective utilization rate of water should be improved. In 2017, the precipitation of Ningbo decreased by 16.1% compared to the previous year, and the uneven distribution of precipitation in the whole city was very significant. Therefore, there were three reasons for the turning point of the per capita comprehensive annual water consumption: 1. The precipitation decreased and the spatial and temporal distribution was uneven. The amount of surface water resources decreased by 26.3% compared with the previous year, resulting in a decrease in per capita water consumption. 2. The control of water-saving policies was strengthened and residents’ awareness of water saving was improved. 3. The economic development (the per capita GDP continued to increase) was accompanied by population growth, and the population base became larger. In Figure 5b, per capita GDP is taken as the representative index of the economic subsystem. With the continuous increase in the total population, the per capita GDP also shows a positive growth, which indicates that the trend of the development of various industries in Ningbo will be positive in the future. It is estimated that by 2030, the per capita GDP will reach 183,500 yuan, an increase of 2.6 times compared with the base year of 2010. It can be seen in Figure 5c that with the increase in population, the total energy consumption increases. According to the analysis of the data over the years,
there is a strong correlation between the energy consumption and the total population. In Figure 5d, the energy-related water consumption is seen to fluctuate in a small range; the overall trend increases and tends to be stable from 2020 to 2030. The water-related energy consumption fluctuated significantly from 2010 to 2012. On the one hand, in the early stages, the utilization rate and energy consumption of reclaimed water in Ningbo City were low, and the reclaimed water treatment technology and sewage reuse technology needed to be improved. In 2012, the water consumption for production decreased by 5.9% compared with that of the previous year, which led to a reduction in the energy consumption of water used for production. The combined effects of the two caused the water-related energy consumption to fluctuate greatly. From 2012 to 2030, the sewage treatment volume and reclaimed water consumption will increase, and the water-related energy consumption will gradually increase, with the growth rate tending to be stable.

3. Results

According to the model constructed in the previous section, the data were processed and then input into the Vensim software to simulate the water–energy coupling system of Ningbo City from 2010 to 2030.

3.1. Analysis of the Simulation Results of the BAU

According to the current development trend, the representative indexes of each subsystem were selected, and the simulation results are shown in Figure 5.

Figure 5. (a) Trend analysis chart of the total population (10,000 people) and water consumption (100 million m$^3$). (b) Trend analysis chart of the total population (10,000 people) and per capita GDP (10,000 yuan). (c) Trend analysis chart of the total population (10,000 people) and total energy consumption (10,000 tce). (d) Trend analysis chart of the water-related energy consumption (10,000 tce) and energy-related water consumption (100 million m$^3$).

3.2. Analysis of the Simulation Results of the WSS

The simulation model was run under the joint action of the water-saving policy and the improvement of the coefficient of effective utilization of water, and the results are shown in Figure 6.
The promotion of water-saving policies was strengthened, and the domestic water consumption and the energy consumption thereof were significantly reduced compared with those in the BAU. Adhering to the principle of “broaden sources of income and reduce expenditures” [32] was a basic policy of water resource management and solved the problem of urban water supply in Ningbo [33]. In 2020, Ningbo City issued the Implementation Plan of Water-Saving Action; the project proposes the implementation of the simultaneous control of total water consumption and intensity, as well as the units of water consumption, the implementation of the management of water consumption throughout the whole process, the deepening of the comprehensive reform of water pricing, the improvement of the standard water-saving system and incentive methods, the establishment of water-saving statistics and an information-sharing mechanism, the implementation of a water-efficiency labeling system, and other comprehensive promotions of the construction of society’s water-saving capacity. The reduction in water consumption [34] leads to the reduction in energy consumption, thus achieving the purpose of coordinated management and the saving of water and energy.

The infrastructure of farmland water conservancy in Ningbo is relatively weak, and the utilization rate and efficiency for water irrigation are generally low. It can be seen that, with the increase in the coefficient of the effective utilization of water, the agricultural water consumption and production water consumption are significantly reduced compared with those in the BAU, and the total water consumption, energy consumption of production water, and water-related energy consumption are also slightly reduced under the joint effects of water-saving policies and the improvement of the coefficient of the effective utilization of water. Ningbo should further adjust the structure of the planting industry,
promote the use of water-saving agricultural technology, vigorously develop water-saving irrigation projects, and reduce the proportion of agricultural water consumption in the total water consumption of the entire society. It is estimated that the proportion of agricultural water consumption could be reduced to 24.29% by 2030.

3.3. Analysis of the Simulation Results of the ESS

The simulation model was run under the joint action of the optimization of the industrial energy structure and the improvement of the level of energy-saving-related technology, and the results are shown in Figure 7.

As can be seen in Figure 7, with the improvement of the coefficient of clean energy technology, energy-related water consumption and the proportion of energy-related water consumption are significantly reduced compared with those in the BAU. In 2020, Ningbo launched the “14th Five-Year” energy plan, which comprehensively analyzes the energy status and industrial base, adjusts the energy structure, vigorously develops renewable energy and new energy, strictly controls the total coal consumption, reduces unreasonable and inefficient heat demand, and accelerates the construction of the infrastructure of the “last mile” of natural gas utilization. In 2020, the city’s industrial sector will free up 300,000 tce through energy-saving transformations, and the reduction in energy consumption will cause a reduction in energy-related water consumption. It is estimated that in 2020–2030,
the energy-related water consumption will abandon the quick growth of the old model, and the proportion of energy-related water consumption will continue to decrease.

The improvement of sewage reuse technology can effectively reduce the energy consumption of sewage reuse. The improvement of reclaimed water treatment technology also increases the amount of reclaimed water. Under the condition that the unit energy consumption of reclaimed water remains unchanged, the increase in the amount of reclaimed water will lead to an increase in energy consumption in the process of production of reclaimed water. Therefore, the next steps should be to reduce the unit energy consumption of reclaimed water, to increase the amount of reclaimed water while reducing its total energy consumption, and to realize synergistic water–energy saving. It can be seen in Figure 7 that the improvement of the technological level does not bring about a significant reduction in water-related energy consumption. In the case of the reduction in energy-related water consumption, the energy consumption of sewage reuse and reclaimed water continues to rise, and the combined effects of the three cause the total water-related energy consumption to remain almost unchanged. The production of reclaimed water and the reuse of sewage can effectively alleviate the shortage of water resources, and the improvement of energy exploitation technologies can effectively reduce the water consumption in the process of energy exploitation, which indicates that there is a great potential for water saving in the field of energy exploitation. The investment in energy exploitation can be appropriately increased to further improve energy exploitation technologies.

### 3.4. Analysis of the Simulation Results of the CS

The simulation model was run in a comprehensive scenario, and the results are shown in Figure 8.

![Figure 8](image_url)

**Figure 8.** Simulation results of water-related indicators and energy-related indicators under CS: domestic water for urban residents, domestic water, production water, water consumption, energy-related water consumption, and water-related energy consumption.

From the above modeling process and the analysis of the simulation results in the BAU, it can be seen that, with the continuous advancement of urbanization, the number of urban residents, the quality of the living environment, and the continuous improvement of quality of life increase, resulting in a small increase in the domestic water consumption of urban residents compared with that in the BAU; it continues to increase, but the total domestic water consumption does not increase. Instead, it decreases compared with that in the BAU, which shows that the strengthening of water-saving policy controls plays a strong positive role in promoting the reduction in domestic water consumption. Compared with the BAU, the improvement of energy extraction technology and clean energy technology brings about the reduction in energy-related water consumption, and the overall trend will slowly decrease and become stable from 2020 to 2030. The improvement of sewage reuse technology and reclaimed water treatment technology also shows clear effectiveness for the reduction in water-related energy consumption. The increase in urban population further promotes the development of the industrial economy and brings about an increase...
in the energy consumption of production water, which is also one of the reasons for the continuous increase in water-related energy consumption in the ESS from 2020 to 2030. Under the dual effects of water saving and energy saving, although the overall trend of water consumption is on the rise, it significantly decreases compared with that in the BAU. Moreover, with time, the output values of the comparison with the baseline scenario gradually increase, and the space for water saving and energy saving gradually enlarges. It is estimated that, by 2030, the total amount of water saving will increase by 27.69% compared with that in the BAU.

3.5. Analysis of Multi-Scenario Simulation Results

The different scenarios have different water-saving and energy-saving effects (Figure 9). A comparison showed that the rankings of water-saving effects are as follows: CS > WSS > ESS; the rankings of energy-saving effects are CS > WSS > ESS. Therefore, in the CS—that is, under the five parallel measures for strengthening the control of water-saving policies, improving the effective use of water, optimizing the industrial energy structure, improving the level of energy-saving-related technologies, and the continuous advancement of urbanization—the energy-saving and water-saving effects will reach the optimal level, and the purpose of the coordinated management and conservation of water and energy can be achieved. Compared with the CS, the water-saving and energy-saving effects are slightly different in the WSS, indicating that the constraints of the water-saving policy and the improvement of the effective use of water have a good cooperative water-energy-saving effect on both the single level and the coupling level [35]. Compared with the CS, the rates of the contributions (Table 7) of the optimization of the industrial energy structure and the improvement of the energy-saving-related technology level to water saving and energy saving are 2.94% and 0.32%, respectively, which are very different from the values of 50.8% and 50.97% in the CS, indicating that the two energy-saving measures can bring neither obvious water-saving effects nor weak energy-saving effects. The continuous advancement in urbanization [36] is an irreversible process, and it will lead to the continuous increase in water consumption and energy consumption. Therefore, with the continuous improvement of the urbanization rate, it is necessary to adjust and strengthen water-saving and energy-saving policies, improve the coefficient of the effective utilization of water, and promote efficient water-saving technology in order to continuously optimize the water–energy coupling system in the CS.
Table 7. The effects of water saving and energy saving in the three simulation scenarios.

| Scenario Setting | Changes in Water and Energy Consumption | WS and ES Effect |
|------------------|-----------------------------------------|-----------------|
|                  |                                         | Water-Saving    | Energy-Saving |
| WSS              | Water-saving policy                     | All decrease    | 46.26%        | 48.71%        |
|                  | Improve the coefficient of the effective utilization of water |                |                |
| ESS              | Optimization of industry energy structure | All decrease    | 2.94%         | 0.32%         |
|                  | Improvement of energy-saving-related technology |                |                |
| CS               | WSS + ESS + Continuous advancement of the urbanization process | All decrease    | 50.8%         | 50.97%        |

4. Discussion

This paper provides a new perspective for exploring the coordinated management and conservation of an urban water–energy coupling system. The simulation results of the water–energy coupling system in this paper prove that the SD model of the water–energy coupling system can bring about the coordinated saving of water and energy. The resource planning based on water-saving may ignore the energy consumption, and the resource planning based on energy-saving may increase the consumption of water resources, and both can achieve the purpose of common saving. This also shows that the saving efficiency of the coupled system is stronger than that of the single subsystem. In exploring the internal driving mechanism of the coupling system, adjusting a driving factor will bring about the change in total water consumption and total energy consumption, which reflects the structural flexibility of the coupling system. The SD model created in the Vensim software can predict the long-term future situation according to the current situation, which reflects the sustainability of the coupling system. With the development of economy and technology and the improvement of environmental conditions, the improvement of related technologies such as sewage reuse technology and clean energy technology will also bring about the sustainable development of water and energy. Yang et al. discussed the effects of the restriction of various resources and environmental factors on the development of Ningbo City by identifying the limiting factors of the UECC, concluding that the shortage of water resources is the prominent limiting factor for the sustainable development of Ningbo City [37], which is consistent with the conclusion of this paper. The simulation study by Lu et al. on the cooperative control of energy and water policies at the national scale [4] provided ideas and references for the construction of the subsystems of the SD model in this paper. Based on the scenario analysis method, Wu et al. analyzed the WRCC and its regional change characteristics in Ningbo in 2020 and 2030, and the results showed that, against the general background of 2020 and 2030, the total water resources of Ningbo City will gradually approach the level of abundance [38], which is consistent with the change trends obtained in this paper for the total water consumption in the CS.

Due to the limited data availability, the index data used to construct the SD model were lacking and incomplete, and the quality of this aspect of the study must be further improved. Another limitation is that only the representative second-level indicators of water saving and energy saving were selected, and the number of indicators needed to be further expanded and refined. Based on the results of this study, it is expected that the coordinated development of water resources and energy will be achieved under the guidance of the planning of the study area. However, the development of the coupling system is undergoing complex and dynamic changes that require more analysis and research. In future studies, the optimization of the coupling systems of urban agglomerations may be
carried out by considering the spatial influences of neighboring regions on the study area on the basis of expanding the system boundaries.

5. Conclusions

Ningbo is the economic center of the south wing of the Yangtze River Delta. Since the reform and opening up, Ningbo’s economy has been developing continuously and rapidly [39], showing great vitality and potential, and becoming one of the most active regions in the domestic economy. However, the spatial and temporal distribution of water resources in Ningbo is uneven, and the rate of effective utilization of water is low. With continuous economic development and the increasing consumption of energy resources, water resource, as a follow-up power resource, has become a short board in the coordinated development of water and energy. In order to ensure the coordinated management and conservation of water resources and energy, in this paper, a path for the coupling of the coordinated development of water resources and energy was explored by using the system dynamics method, for which the water and energy consumption were quantitatively calculated and three scenarios were established. Through data validation and the developmental trends of water resources and energy, the water–energy coupling system was predicted and evaluated, and the following conclusions were obtained.

(1) From 2010 to 2019, the water consumption and energy consumption in Ningbo fluctuated in a small range and showed an overall upward trend. From 2010 to 2015, the total water consumption increased by 141 million m$^3$ and the energy consumption increased by 5.06 million tons of standard coal. After 2015, the growth rate gradually accelerated, and the per capita annual water consumption decreased year by year; it decreased from 392 m$^3$ in 2015 to 246 m$^3$ in 2020, highlighting the contradiction between water supply and demand. The fluctuation of water-related energy consumption was obvious in the early stage; it tended to be level and gradually decreased in the later stage due to the improvement of the sewage reuse technology and reclaimed water treatment rate. From 2015 to 2020, water-related energy consumption fluctuated by only 0.0066 million tons of standard coal. Energy-related water consumption increased year by year as energy consumption increased, and the progress of clean energy technology played a buffer role in the growth curve.

(2) In the simulations of the three scenarios, water-saving policy and the improvement of the coefficient for the effective utilization of water had the largest rates of contribution to water saving and energy saving, they had the most significant effects on the reduction in water consumption and energy consumption, and promoted the water saving and energy saving effect to reach 46.26% and 48.71% in the water-saving scenario, and 50.8% and 50.97% in the comprehensive scenario. This showed that water-related energy consumption accounted for a large proportion of the total energy consumption. If the consumption of water resources, domestic water, production water, and ecological water was reduced, the energy consumption would also be reduced [40]. Strengthening the control of water-saving policies and the improvement of the coefficient of effective utilization of water are strategies that positively promote the collaborative management and conservation of water and energy. In the coordinated management of water and energy in Ningbo in the future, priority should be given to water resource management in order to realize the win–win situation of water saving and energy saving.

(3) When formulating and implementing a sustainable development strategy for Ningbo, it is necessary to focus on water resource safety [41]. Under the conditions of the weak growth of the supply space of water resources, it is necessary to speed up the development of industrial sewage reuse and reclaimed water treatment technology, promote high-efficiency water-saving irrigation technology, reduce the difference in water supply and demand and the pressure to develop new water sources, and improve the utilization efficiency of water resources in the process of the social water cycle. It is also necessary to reduce water consumption while reducing energy consumption in the development and utilization of water resources, thereby reducing the proportion of water-
related energy consumption in the total energy consumption. Under the above conditions, from 2010 to 2020, the proportion of water-related energy consumption in Ningbo city reduced by 0.08%, which achieved results. Technological development can reduce water and energy consumption to a certain extent [42], optimize the energy structure, speed up the development and application of new energy, promote the development of low-water-consumption energy extraction technology and clean energy technology, and support the implementation of a strategy for the parallel improvement of the policy and technology level, which is an important way to realize the coordinated management and development of a coupled water–energy system [43].

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