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Modelling and evaluating the economy-resource-ecological environment system of a third-polar city using system dynamics and ranked weights-based coupling coordination degree model

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ABSTRACT

The sustainable development of the Tibetan Plateau is vital for Asia and the entire world, as this region is usually referred to as the Asia Water Tower and the Third Pole. Previous studies have focused on the ecological protection of the Tibetan Plateau, largely ignoring the sustainable development of its cities as the carrier of most people on the Tibetan Plateau. In this study, we optimized the economy-resource-ecological environment (ERE) system of the largest city on the Tibetan Plateau, namely Xining. To this end, we first established a system dynamics model of its ERE system, and highlight local policies such as the Yindajihuang Water Transfer Project. Then, we evaluated the coordination of the ERE system under multiple trade-off scenarios, by developing and applying a ranked weights-based coupling coordination degree (CCD) model. This new CCD model avoids accurate and subjective weighting of multiple criteria, thus being more widely applicable and objective. The evaluation results indicate that the resource subsystem should be more emphasized than the economy subsystem, to avoid severe deterioration of the ERE system. Also, the coordination of Xining's ERE system could be effectively improved by setting highest development priority for the ecological environment subsystem.

1. Introduction

The Third Pole, which is also referred to as the Tibetan Plateau, is an immense carbon pool and is the source of many of Asia's major rivers. Its sustainable status significantly influences the stability of Earth's climate system (e.g., Jin et al., 2005) and the resources supply for the living of 40 % of the world's population (Morton, 2011). Therefore, sustainability in the Third Pole is among the critical issues for the entire world. It is necessary to pay attention to sustainable development in the Third Pole and policy-making there.

Regional sustainable development is considered to be a highly complex dynamic process (Cheng et al., 2018; Urbaniec et al., 2017) based on the coordinated development of multiple subsystems within the regional system, especially the economy, resource, and ecological environment subsystems (e.g., Guan et al., 2011; Wang et al., 2020; Wu & Ning, 2018; Xing et al., 2019). Coordinated development of these subsystems refers to the harmonious and consistent development among them (Li et al., 2020), which is difficult to be realized considering their complex interactions. For example, it is a common phenomenon in many regions that economic development has been driven at the expense of unsustainable resource consumption and irreversible ecological environmental deterioration and has brought about severe environmental and resource problems. These problems would in turn put a threat on the sustainability of economic development. However, excessive protective policies on resources and the ecological environment would impede regional economic development and the basic well-being of local residents. Therefore, policy-making that aims for the coordinated development of the economy-resource-ecological environment (ERE) system should be performed considering not only policy effects on each subsystem but the interactions among these subsystems as well.

An effective way to scientifically consider these effects of policy-making is to conduct regional modelling and evaluations in an integrated manner. For regional modelling, system dynamics (SD) is a widely used method that was designed for exploring the interactions

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among several components of a complex system under user-specified scenarios (Ahmadi & Zarghami, 2019; Hu et al., 2020). Through SD, interactive components within a regional system can be abstracted into several subsystems that are composed of interactive variables (Ahmadi & Zarghami, 2019). Then, after adjusting the values of driving variables, the dynamic effects of different policies can be simulated. Therefore, many scholars have established SD models for kinds of regional human-earth systems to deal with various regional problems (e.g., Zuo et al., 2017, Xing et al., 2019, Cui, Chen, et al., 2019). For the Third Pole region, only few scholars have established provincial SD models for tourism development (Zhang et al., 2015) or land changes (Liu et al., 2021) and county-scale SD model for Nitrogen utilization (Wang et al., 2022). None of them has modelled the dynamic sustainability of urban human-earth systems in third-polar cities, which are faced with huge challenges of sustainable development because of the fragile environment, limited resources, and concentrated development pressure. For our concerned ERE system, previous studies of SD modelling were concentrated in metropolises or urban agglomerations (e.g., Guan et al., 2011; Wu & Ning, 2018) considering only land resources and energy resources in models.

This study focuses on the most developed city in the Third Pole, Xining, to answer the following question: How to promote the coordinated development of Xining with policy priorities? To answer this question, this study established an urban-scale SD model of the ERE system of Xining and proposed an improved coupling coordination degree (CCD) model for system evaluation. The model was validated using real data from 2000 to 2020. It was then employed to simulate the development of the ERE system of Xining under different trade-off development scenarios from 2021 to 2030 with a time step of one year. Finally, implications are summarized based on these evaluation results.

It is important to note that although we focused on Xining, our methods are of use to other study areas for two reasons. First, the SD approach for the modelling of Xining's ERE system should be highly applicable to other resource-dependent cities. Second and more important, the improved CCD model is universally applicable both with and without an SD model. CCD has been widely applied with SD to evaluate the coordinated development of a region (Cui, Chen, et al., 2019, Cai et al., 2021). This model could combine the comprehensive development status and the coordination status of the interactive components in the regional system, which are often used to comprehensively reflect the coordinated development level of coupling subsystems (Cui, Chen, et al., 2019, Li & Yi, 2020) into a comprehensive index. Its applications in other studies that are not based on SD also indicate its superiority in the coordination development evaluation of systems (Feng et al., 2021; Hu et al., 2021).

2. Study area, data materials, and methodological and theoretical basis

2.1. Xining as an important city of the Third Pole

Xining (101°30′-101°56′E, 36°30′-36°47′N) is located in the northeast of the Third Pole (as shown in Fig. 1). It is composed of five districts and two counties and covers an area of 7660 km^2. It is a typical plateau valley city. Its central area is located on the valley plains of the Huangshui River surrounded by hilly mountains and has an average elevation of 2261 m. As Xining is located in semiarid inland areas, Xining's average annual precipitation is $<$400 mm, but the average annual evaporation is $>$1300 mm. These special geographical characteristics cause the ecological environment to be very fragile, and urban development is faced with huge resource pressures, especially on the water resource.

Xining can be considered the most developed city in the Third Pole and maintains high urban primacy in this region with a population of 2.37 million and a gross domestic product (GDP) of $>$20 billion dollars in 2021. Its GDP growth rate reached 7.5 % in 2019, which reflected its economic vitality. Xining is the comprehensive centre of Qinghai Province and provides high-quality urban service for $>$3 million people in the surrounding third-polar cities. After a plan was proposed by the Chinese government to build the Lanzhou-Xining urban agglomeration, the radiation range of Xining's urban service further increased. Therefore, the sustainable development of Xining is critical to not only Xining itself but the development of a large surrounding area.

2.2. Data sources and pre-processing

The data used in this study refer to a series of indicators. Their data sources and time sets are shown in Table 1. Time sets of a small portion of indicators are meaningless because the values of these indicators are considered to be fixed in the time scale of this study with reference to related studies (Guan et al., 2011; Xing et al., 2019). For other indicators which vary over time, their time sets are not all same because missing values exist in the data. To address this problem, we adopted the following strategies: trend extrapolation, curve fitting, data interpolation, and computation of historical means. The validation results of the established model proved the reliability of our pre-processed data.

2.3. Methodological and theoretical basis

2.3.1. System dynamic and its application

SD is a useful method for analysis and simulation of complex systems invented by Jay Forrester (Forrester, 1968). It emphasizes the principle

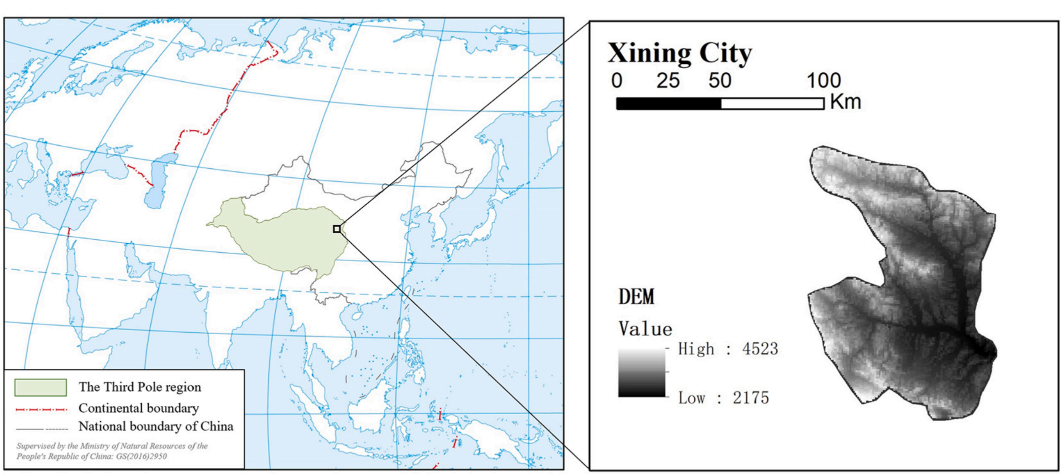

Fig. 1. Location of Xining City in the Third Pole and its elevation.

Table 1
Sources of statistical data used for modelling.

Statistical indicator	Time sets	Sources
Output of three industries	2000–2020	SYX (2001–2021)
Born and death rate	2000–2019	SYX (2001–2021) and SBX (2000–2020)
Variation rate of permanent residents	2000–2020	
Labour force of three industries	2000–2019	
Fixed assets investment of three industries	1990–2019	
Depreciation rate of fixed assets	– (fixed value)	Reference (Wu, 2008)
Areas of cropland, forest land, grassland, impervious land, and other land	2000, 2005, 2010, 2015, 2020	Land cover data at 30 m resolution (Yang & Huang, 2021)
Total area of Xining	– (fixed value)	
Grain production	2000–2020	SBX (2000–2020) and SYX (2001–2021)
Areas of grain yield	2000–2020	
Proven reserves of mineral resources	2002–2013	SYQ (2000–2020)
Output of mineral resources	2002–2013	
Energy consumption of three industries and residents' living	2005–2018	SYX (2001–2021), SYQ (2000–2020), FYPEDQ(12th) (2011), and FYPEDQ(13th) (2016)
Energy consumption structure	2005–2018	
Energy reserve	– (fixed value)	ESYC (2016)
Water consumption for various demands	2000–2020	WRBQ (2000–2020), FYPWRDUP(13th)
Available water resource	2000–2020	
Area of urban green space	2009–2020	SYUC (2012–2020), SYX (2001–2021)
Proportion of urban population	2000–2020	SYX (2001–2021)
Discharge of industrial wastewater, SO2, and solid wastes	2000–2015	SYX (2001–2021) and FYPEPX (12th) (2012)
COD concentration of industrial and living wastewater	2005–2015	
Treatment of industrial solid wastes	2005–2010	
Discharge and treatment of living wastewater	2005–2010	
Emission of living SO2	2005–2015	
Environmental production investment	2006–2017	
Self-purification of environment	– (fixed value)	Reference (Xing et al., 2019)

to observe, analyze, and model behaviors of components of an interactive system using a systematic perspective. This principle enables this method to incorporate components within a general framework and model their dynamic interactions (Guan et al., 2011). Therefore, SD was considered that can effectively deal with problems of predicting large-scale systems (Meadows et al., 1972) in long-term studies (Wu & Ning, 2018) and under multiple scenarios.

SD has been widely applied in the modelling of regional systems in many hot fields around the world. For example, in the field of urban form, Lousada et al. (2021) established an SD model to explore the determinants of urban blight. In the field of land-use changes, scholars have utilized SD to model future regional demands of different land-use types (e.g., Wu et al., 2011). In the field of regional sustainable development, SD has been recognized as a powerful tool to simulate trends of regional systems under various policy scenarios which have different emphases (Cui, Chen, et al., 2019). Such studies have been extensively conducted in many typical regions, especially in developed metropolises (e.g., Yang et al., 2020), and contributed a lot to regional scientific policymaking. However, for cities in the Third Pole, few studies have been conducted.

There are two core tools in SD to explore the structures of the system and conduct system simulation. The first tool is called "causal loop diagram" (CLD). CLD is a conceptual model of the system established to describe the causal structure within this system. Its necessary components include conceptual variables and causal chains that indicate influencing relationships among these variables. The second tool is called "stock-flow diagram" (SFD). SFD is a quantitative model of the system that can describe physical details of the causal structure. It also consists of a series of variables and causal chains, but variables within SFD are measurable and not homogeneous. From the perspective of physical meaning, these variables can be classified into three types: stocks, flows, and auxiliary variables. Stocks are variables that accumulate over time. Flow variables are the inflow or outflow rates of stocks. The other variables are auxiliary variables. From the perspective of influencing factors, these variables can be classified into two types, namely, exogenous variables and endogenous variables. Exogenous variables are variables that are influenced only by factors outside the system in the SD model. Endogenous variables are variables that are determined by the internal status of the system. In this study, these two tools were used to establish an SD model for Xining.

2.3.2. Coupling coordination degree (CCD) model and its weighting problem

The CCD model reflects the degree of coordinated development among multiple coupling subsystems (Cui, Chen, et al., 2019) based on the combination of two parts. The first part evaluates the comprehensive development level of the entire system by calculating the weighted sum of scores of different subsystems. The result is called "comprehensive development degree (CDD)". The second part characterizes the degree of interaction or coordination of these subsystems, namely the "coupling degree (CD)". The geometric mean of CDD and CD is the so-called CCD.

A core of CDD lies in the determination of weights. In existing applications of CCD to SD (e.g., Ariken et al., 2021; Xing et al., 2019), equal weights have been widely adopted to attach the equal importance to different subsystems of a SD model. However, the actual importance varies with the subsystems of a SD model (e.g., Cheng et al., 2018, Cui, Chen, et al., 2019, Xing et al., 2019), meaning that the equal weights is not suitable. Unequal weights can be adopted to solve this problem, but the difficulty lies in how unequal these weights should be. This question was answered by the subjective determination of weights in some pioneering studies (e.g., Li et al., 2012), but it is difficult for a group of decision makers to reach a consensus on weights. Even if only one decision maker is involved, it is not easy to subjectively determine the precise weights for a large number of components (e.g., Wu et al., 2018, Gao, Wang, Cushman, et al., 2020).

2.3.3. Background of the economy-resource-ecological environment (ERE) system and its internal coupling mechanism

In recent decades, understanding regional sustainability problems from systematic and interactional perspectives has gradually become an important consensus, and an increasing number of studies have focused on the coupled human and natural system (CHANS) and its related systems (Liu et al., 2020). Since the CHANS, which is defined as the integrated system in which people interact with natural components (Liu et al., 2007), is conceptually rich in contents, many scholars combined some interconnected components within the CHANS that make differences in concerning processes (e.g., economy and ecological environment) and established models of systems related to the CHANS. Typical examples of these related systems include the social-ecological system, the urbanization-environment system (Cui, Fang, et al., 2019, Fang et al., 2019), the economy-resource-environment system (Li et al., 2018; Wu & Ning, 2018), and so on. Preceding studies on these related systems have made great strides in the understanding and analysis of regional development processes.

For the ERE system, which is one of a rising kinds of system that has been focused on, especially in studies of regions that are faced with sustainable problems, previous studies have conducted lots of discussion on the coupling mechanism among subsystems within the ERE system. A series of studies focused on the relationship between economic development and ecological environment and found that nonlinear relationships exist during the dynamic process of development (Dinda, 2004; Grossman & Krueger, 1995; Zhao et al., 2016). The internal mechanism is that the economic development is often initially realized at the expense of environmental destruction but afterwards conversely being threatened due to health risks and the decline of environmental conditions (Suk William et al., 2016); thus stimulating the awakening of environmental awareness, the increasing of environmental protection invest, the promotion of technical levels, and finally the recovery of eco-environment conditions (Zhao et al., 2016). Existing studies also revealed the essential supporting effects of resources on economic development, which therefore is conversely restricted by conditions of resources in many resources-based regions (Chen et al., 2019; Ruan et al., 2020). For the resources and the ecological environment subsystems, previous studies also indicated their coupling relationships, which are mainly reflected in the influences of resource utilization processes on the eco-environment and purification functions of various natural resources (Engo, 2019; Ye et al., 2022). Preceding relationships among the economy, resources, and the ecological environment make the ERE system a complicated coupled system with massive internal interactions and feedbacks (Xing et al., 2019).

3. System dynamic modelling of ERE system of Xining

3.1. Conceptual modelling of the ERE system: a deeper understanding of Xining

To model the ERE system of Xining, we first analyzed the causal relationship among components of the system. Such an analysis results in a conceptual model for the ERE system, namely CLD. The analysis involves four steps.

1) Establishing a basic framework of the ERE system of Xining

A scientific framework is a basis for accurately modelling and predicting the development of the regional system. In this study, we established the framework of the ERE system, which specifically includes the boundary of the ERE system and the core contents of each subsystem based on the review of previous studies and the consideration of local characteristics of Xining. First, for the boundary of the ERE system in our model, we referred to a series of studies on urban systems (e.g., Guan et al., 2011; Wu & Ning, 2018; Xing et al., 2019) and extracted conditions of urban economic development, population growth, resources consumption, and ecological environment condition under relative policies in Xining as our modelling objects; influences from other conditions are recognized as external factors and remain stable. Then, for the contents of each subsystem, in the economy subsystem, we not only modelled urban economic development but also included the trends of the permanent population considering the vital influence of labour forces on economic production. In the resource subsystem, we analyzed the consumption of various types of resources for productive and domestic demands and the resource pressures. In the ecological environment subsystem, we focused on the condition of the ecological environment in Xining.

2) Concretizing core components within each subsystem

Components are conceptual variables that can represent or significantly influence the conditions of the subsystems, which serve as basic units to clarify interactions within the system. In this study, concrete components within each subsystem are recognized in the following three steps.

First, universal components within each subsystem are initially recognized based on analysis of models of other regions in previous studies. In the economy subsystem, the level of economic development, the population, and the urbanization rate are core components as they are closely related and significantly influence the condition of other subsystems (Fang et al., 2015). In the resource subsystem, energy resources (i.e., fossil energies and new energies such as hydro energy and wind energy) are initially determined to be included considering their essential supporting roles in regional development (Wu & Ning, 2018). Energy consumption and its structure are included as they can reflect energy sustainability and environmental influences (Xing et al., 2019). In the ecological-environment subsystem, polluted conditions of air, water, and solid wastes are commonly considered and included as components.

Second, local components are supplemented to the resource subsystem and the ecological subsystem based on consultations with scholars who are familiar with the actual condition of Xining and analysis of political documents in Xining. For the resource subsystem, as Xining is a typical plateau valley city with extremely limited plain resources, we are concerned about two problems existing in the urban development of Xining, namely the expansion of built-up land and the protection of arable land, and introduced the areas of arable land and built-up land as components of the resource subsystem; grain production was also introduced as it is essential for human life and is closely related to arable land protection; mineral resources pressure and water resource pressure are also innovatively included as components considering the sustainability of industrial development and the problem of severe water resource shortage in Xining, respectively. For the ecological environment subsystem of Xining, we supplemented the condition of ecological lands conservation as components, considering the vital roles played by ecological lands in maintaining and preserving the ecosystem (Feng et al., 2020; Zhang et al., 2021).

Finally, we supplemented policy factors that greatly influence preceding components, including several characteristic policies of Xining (i.e., “Indajihuang” and other water transfer projects, price-based water conservation rules, China's western development strategy and central economic support, and “Ecology goes first and green development” strategy). Components recognized in this step are displayed in Fig. 2 as words marked in different colours.

3) Concretizing interactions among subsystems according to influencing relationships

Interactions within a system are the basis to simulate the development of this system in SD. To concretize interactions within the ERE system, we analyzed influencing relationships among components based on previous literature and trend analysis of statistic data of Xining. Consumption of energy, land resources, water resources, and of mineral resources, and the emission of pollutants would evidently increase along with the population growth and the development of urbanization and urban economy (Cui, Fang, et al., 2019, Zhao & Zhang, 2018, Fang et al., 2015). The polluted ecological environment then has negative effects on population health and grain production and further threatens economic development (Liu et al., 2016; Lu et al., 2015). However, with the development of the economy, an increasing amount of money could be invested in pollution control and resource protection and effectively ease the environmental pressure and resource pressure (Wei et al., 2012). Preceding relationships formed four core feedback paths shown below.

- Urbanization/economic development and population growth → consumption of land/energy/mineral/water resources → area of arable land → grain production
- Urbanization/economic development and population growth → environmental pollution → grain production/economic development

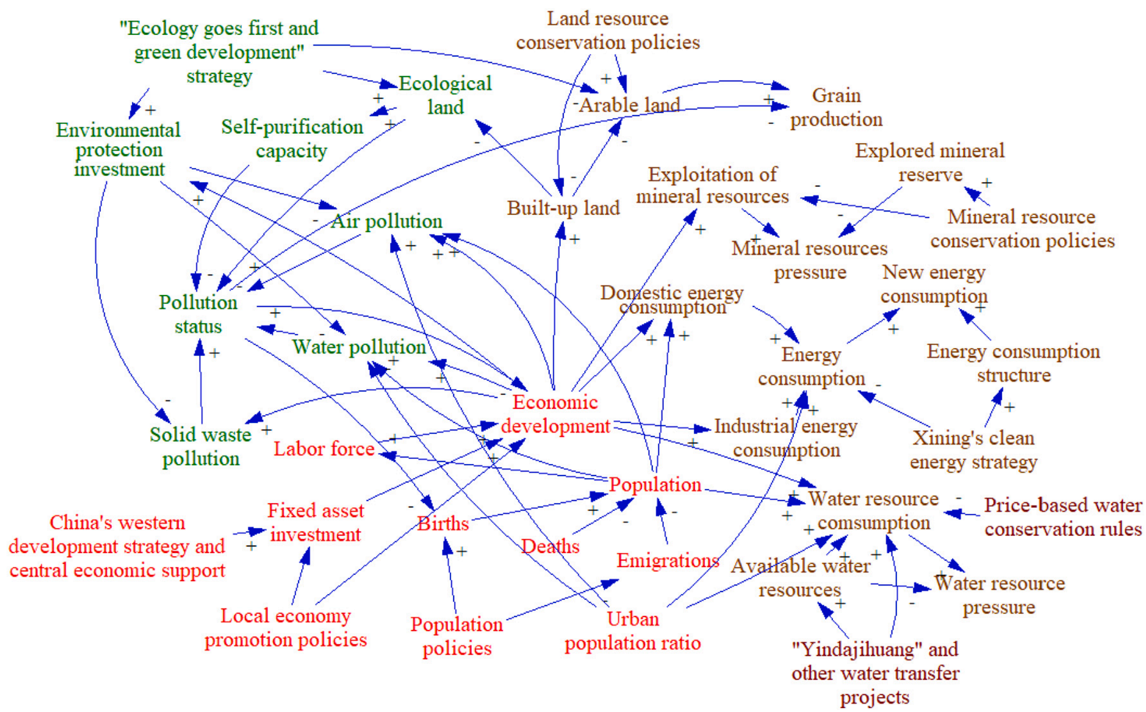

Fig. 2. Conceptual model of the economy-resource-ecological environment system of Xining. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

- Economic development → pollution control investment → environment pollution → grain production/population → economic development
- Economic development → investment in resources exploration or resources conservation → consumption of land/energy/mineral resources→ resource pressure.

We concretized detailed influencing relationships among components according to these feedback paths and completed the conceptual model, which is shown in Fig. 2. A feedback path sometimes represents a non-linear relationship between two components. For example, there is a positive link from "economic development" through "air pollution" to "pollution status", showing that "economic development" can lead to the increase of environmental pollution. Also, the "economic development" component is positively linked with "environmental protection investment", which helps in solving environmental problems (i.e., reduces "pollution status").

The "+" and "−" symbols that are located near the arrows represent the positive and negative influences of the starting components on the ending components. The components that are marked in red, brown, and green belong to the economy, resource, and ecological environment subsystems, respectively.

3.2. *Quantitative description of the causal relationships within the ERE system*

To conduct quantitative simulations, we further quantified the causal relationships within the conceptual model by establishing an SFD for the ERE system. Conceptual variables in the CLD are concretized as several kinds of quantitative variables in SFD (as noted in Section 2.3.1). Values of exogenous variables are determined based on historical data from 2000 to 2020 and scenario settings from 2021 to 2030. Based on the assumption that no time lags exist in the entire process, quantitative functions are defined for each endogenous variable based on the logical relationships among the variables that point to this variable, which are shown in Appendix A. The appendix includes details about our considerations on non-linear relationships between variables and time-dependent, non-linearly evolved variables. To clarify the quantitative structure of the SD model of the ERE system, following we orderly introduce the structure of each subsystem, which are different parts of the entire system. These parts are coupled into an entire system by a series of cross-subsystem variables noted as shadow variables in Figs. 3–5. These cross-subsystem variables appear repeatedly in the entire model. However, only once do they appear as normal variables, and at other times they appear as shadow variables to facilitate the constitution of interactions among different parts.

3.2.1. *The economy subsystem*

Components of the economy subsystem in the CLD and their interactions are concretized into two interactive modules in the economy subsystem: the module of economic development and the module of the permanent population. The SFD of the economy subsystem is shown in Fig. 3.

3.2.1.1. Module1: the module of economic development. In the module of economic development, to calculate the total output of regional economic activities, we adopted a common approach in previous studies of SD modelling (e.g., Du et al., 2018; Xing et al., 2019) to predict economic outputs. In this approach, economic activities that produce goods and services were divided into three industries (primary industry, secondary industry, and tertiary industry) according to the Chinese national industries classification (GB/T 4754—2002). Then, we formulated the annual outputs of each industry based on the well-known Cobb-Douglas production functions (Cobb & Douglas, 1928). Below show the formulas of outputs of the primary, secondary, and tertiary industries in year t as Y_{I_1}, Y_{I_2}, and Y_{I_3}:

$$Y_{I_1}(t) = A_{I_1}(t) \times K_{I_1}(t)^{\alpha_1} \times L_{I_1}(t)^{(1-\alpha_1)} \Big/ (E_{I_1} \times P(t)) \quad (1)$$

$$Y_{I_2}(t) = A_{I_2}(t) \times K_{I_2}(t)^{\alpha_2} \times L_{I_2}(t)^{(1-\alpha_2)} \quad (2)$$

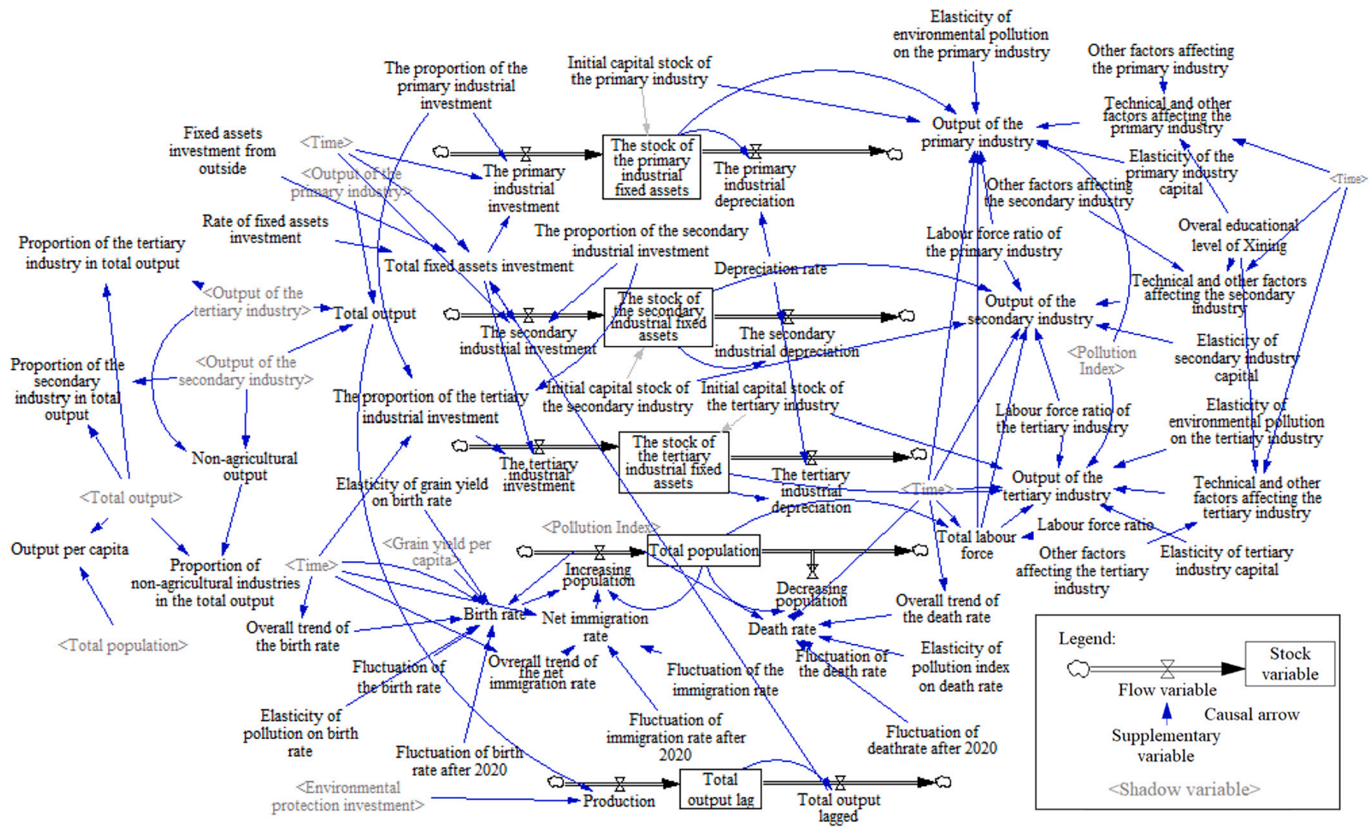

Fig. 3. SFD of the economy subsystem.

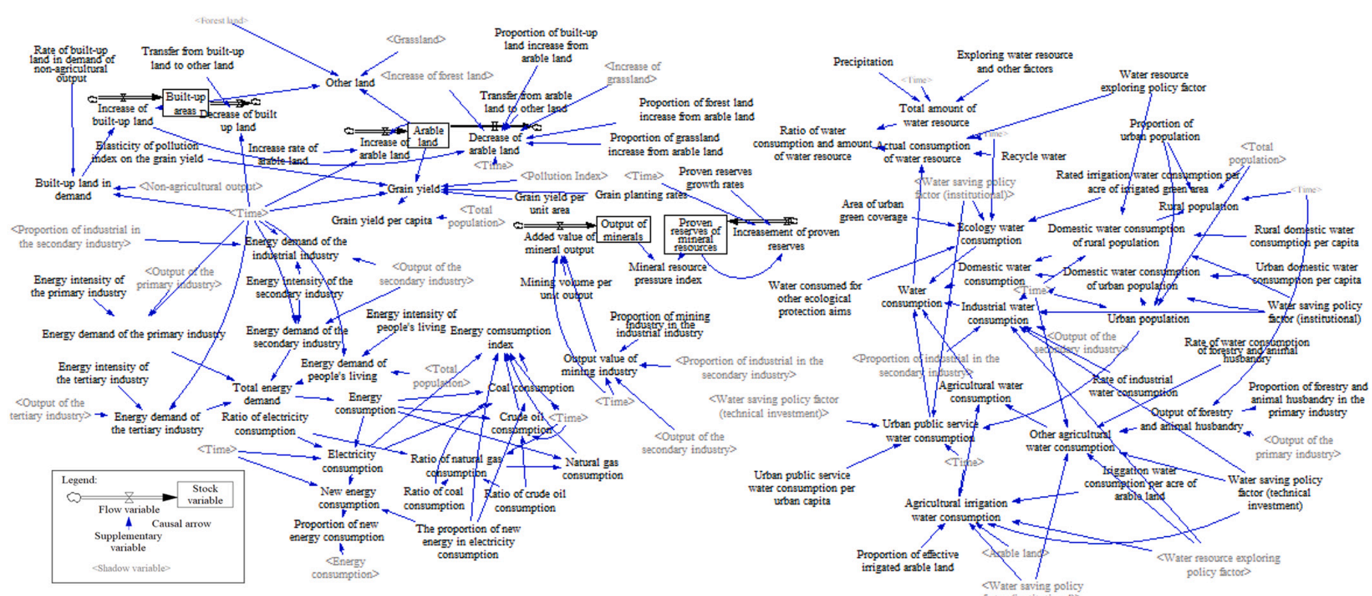

Fig. 4. SFD of the resource subsystem.

$$Y_{I_3}(t) = A_{I_3}(t) \times K_{I_3}(t)^{\alpha_3} \times L_{I_3}(t)^{(1-\alpha_3)} \Big/ \left(E_{I_3} \times P(t)\right) \tag{3}$$

where A_{I_i} $(i = 1, 2, \text{or } 3)$ is the coefficient of total factor productivity. In our model, A_{I_i} is a dimensionless coefficient calculated as the product of the factor of local educational level (represented by the average schooling years referring to (Qu et al., 2020)) and a coefficient which reflects comprehensive conditions of other internal and external factors that are influential on the productive efficiency. P is the pollution index calculated in the ecological environment subsystem (which will be introduced in Section 3.2.3), and E_{I_i} $(i = 1 \text{ or } 3)$ is the coefficient of the influence of pollution conditions on the outputs of the primary and tertiary industries. L_{I_i} $(i = 1, 2, \text{or } 3)$ and K_{I_i} $(i = 1, 2, \text{or } 3)$ are the labour force and fixed assets investment of industry i, respectively, and α_i is the elasticity coefficient of this industry. For L_{I_i} $(i = 1, 2, \text{or } 3)$, we calculated the labour force based on the total number of permanent residents and the labour force ratio in the model. Previous studies have revealed

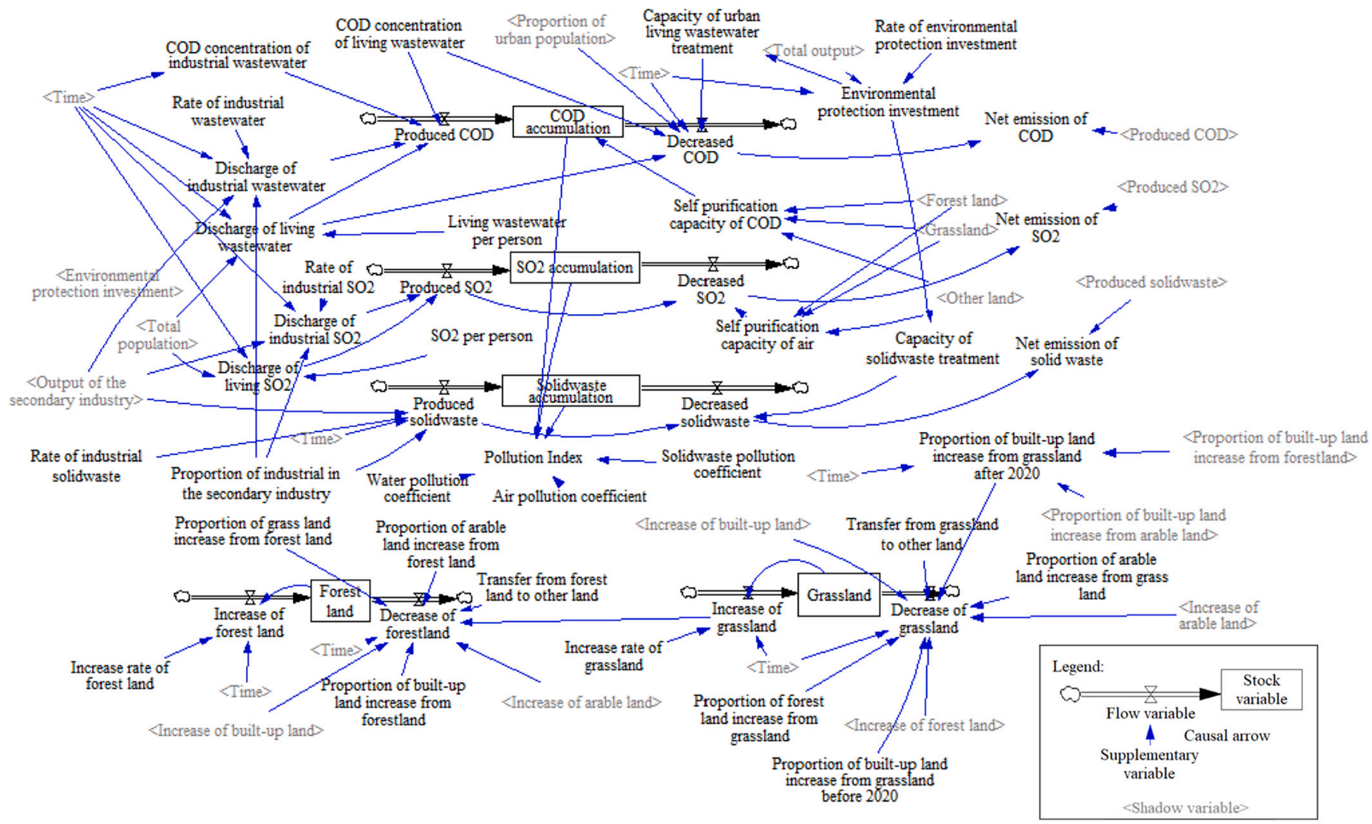

Fig. 5. SFD of the environment subsystem.

strong financial support from the central government to promote the development of western provinces in China (Yang et al., 2022). Therefore, for K_{I_i} ($i = 1, 2,$ or 3), we formulated the total fixed asset investment as the sum of investments from internal sources and external sources (includes central government grants, loans, and foreign investment) (Yang et al., 2022):

$$K(t) = K^E(t) + K^I(t) \tag{4}$$

where K^E is the fixed asset investment from external sources. Benefited from strategies like the western development strategy, external sources provide strong economic support for infrastructure in Xining. K^I is the fixed asset investment from internal sources, which is calculated based on the total output in year $t-1$ and the annual coefficient of fixed asset investment intensity.

3.2.1.2. Module 2: the module of the permanent population. In this module, we modelled the permanent population as the function of historical population, birth rates, death rates, and immigration (Mico et al., 2006) as:

$$\begin{cases} Pop(t) = Pop(t-1) + (IncreaPop(t-1) - DecreaPop(t-1)) \\ IncreaPop(t-1) = Pop(t-1) \times (BR(t-1) + NIR(t-1)) \\ DecreaPop(t-1) = Pop(t-1) \times DR(t-1) \end{cases} \tag{5}$$

where *IncreaPop*(t) and *DecreaPop*(t) represent the increasing population and decreasing population in year t, respectively. $BR(t)$, $DR(t)$, and $NIR(t)$ are the birth rate, death rate, and net immigration rate of the permanent population of Xining in year t, respectively. In our model, annual birth rates, death rates, and net immigration rates are determined by combining their respective overall trends and annual fluctuations. The overall trends are estimated based on regression analysis and influenced by factors of population policies and environmental pollution.

3.2.2. *The resource subsystem*

Based on the structure of the resource subsystem in the CLD, we designed four modules to model the consumption of the four kinds of key resources identified in Xining, namely land resources, energy resources, mineral resources, and water resources. The SFD of the resource subsystem is shown in Fig. 4.

3.2.2.1. Module 1: the module of land resource consumption. The land resource consumption module designed in our SD model concerns two problems existing in the urban development of Xining, namely the expansion of built-up land and the protection of arable land. For the problem of built-up land expansion, we referred to the mechanism in Qu et al. (2020) and modelled the area of built-up land in Xining based on the following equation:

$$A_i(t) = A_i(t-1) + (IA_i(t-1) - DA_i(t-1)) \tag{6}$$

where i (as a subscript) represents different land-use types. A_i is the area of land-use type i (here $i = b$, which represents built-up land). IA_i is the total area of transferred-in pixels of land-use type i from other land-use types in a certain year. DA_i is the total area of transferred-out pixels of land-use type i because of the expansion of other land-use types in a certain year t. Historical land-use data show that only very few pixels were transferred from built-up land to other land-use types. Therefore, we set DA_b as an exogenous variable with small annual values according to historical data and emphasized the determination of annual IA_b. Previous studies have indicated that the development of non-agricultural industries is closely related to the expansion of built-up land (Xing et al., 2019). Therefore, we calculated the annual area of built-up land in demand based on the non-agricultural output:

$$DemandA_b(t) = R_b(t) \times NAO(t) \tag{7}$$

where $DemandA_b$ is the area of built-up land in demand. NAO is the output of non-agricultural industries. R_b is the coefficient of built-up land area in demand per unit of non-agricultural output, which is calculated based on historical impervious surface land cover data provided by Yang and Huang (2021) and the output data. Then, we calculated the total area of transferred-in built-up land pixels (IA_b) in year t through comparing values of $DemandA_b$ and A_b (Qu et al., 2020):

$$IA_b(t) = \begin{cases} DemandA_b(t) - A_b(t); & if\ DemandA_b(t) - A_b(t) > 0 \\ 0; & if\ DemandA_b(t) - A_b(t) \leq 0 \end{cases} \tag{8}$$

For the problem of arable land protection, we similarly modelled variations of the area of arable land based on Eq. (6). First, we modelled annual areas of transferred-in arable land pixels based on the annual increase rates of arable land which are influenced by arable land protection policies. Second, we determined annual areas of transferred-out arable land pixels as the accumulation of conversions because of the expansion of other land-use types (Qu et al., 2020):

$$\begin{cases} DA_a(t) = \sum_{i\ (i \neq a)} IA_i(t) \times P^a_{IA_i}(t) \\ P^a_{IA_i}(t) = A_{a \to i}(t) \Big/ IA_i(t) \end{cases} \tag{9}$$

where a (as a subscript) represents arable land. ${P_{IA_i}}^a$ is the proportion of the land use pixels that are transferred from arable land to land-use type i in the total area of new pixels of land-use type i. Specifically, ${P_{IA_i}}^a$ is calculated as the ratio of the total area of land-use pixels that were transferred from arable land to land-use type i ($A_{a \to i}$) and the total area of new pixels of land-use type i (IA_i) based on historical land cover data (Yang & Huang, 2021) every five years from 2000 to 2020.

3.2.2.2. Module 2: the module of energy consumption. The module of energy consumption is designed to model the total energy consumption and the energy structure. First, we simulated the amounts of categories of energy that are consumed to support production and living activities. Energy consumption is always considered to be closely related to the actual energy demand (Xing et al., 2019). Therefore, we aggregated energy demands for daily living and for economic production as the total energy demand of Xining in the year t (Agnolucci, 2010):

$$ED_t(t) = EI_p(t) \times TP(t) + \sum_{i=1}^{i=3} EI_{I_i}(t) \times Y_{I_i}(t) \tag{10}$$

where EI_p is the annual energy demand for daily living per capita. EI_{I_i} is the annual energy demand for production per unit output of industry i. As Qinghai is an important energy supply base in China, Xining is considered to be self-sufficient in energy consumption. Second, an energy consumption index was designed to reflect the pressure of fossil energy based on the energy consumption and reserves conditions. In ERE system models in previous studies, the pressure of fossil energy was seldom considered. But this pressure is worthy of consideration in the Third Pole considering the regional industrial structure and fragile environment. We expressed the energy consumption index (ECI) in year t as the weighted sum of the consumption of several main categories of fossil energies (Zhang et al., 2010) as below. In addition to directly used fossil energies (i.e., coal, crude oil, and natural gas), indirect utilization during the process of electricity generation was also considered in the function and calculated as the residual proportion beyond new energy.

$$\begin{aligned} ECI(t) = \alpha_{coal} \times Ln\left(EC_{coal}(t) + \left(1 - P^{NE}_{elec}(t)\right) \times EC_{elct}(t)\right) + \\ \alpha_{oil} \times Ln(EC_{oil}(t)) + \alpha_{gas} \times Ln\left(EC_{gas}(t)\right) \end{aligned} \tag{11}$$

where EC_i is the annual consumption of different energy categories. *Coal*, *elec*, *gas*, and *oil* as subscripts represent energy carriers of coal, electricity, natural gas, and crude oil, respectively. P^{NE}_{elec} is the proportion of new energy utilization in electricity generation. α_i is the reserve pressure factor of category i of fossil energy. Since resource pressures were always estimated to decrease with actual reserves (Kong et al., 2017), we quantified α_i based on reserves of these three categories of fossil energies as:

$$\alpha_i = \frac{1}{RE_i} \Big/ \left(\frac{1}{RE_{coal}} + \frac{1}{RE_{oil}} + \frac{1}{RE_{gas}}\right) (i = coal, oil, or\ gas) \tag{12}$$

where RE_i is the latest proven reserve of category i of fossil energy, which is converted to a unit of 10,000 tons of standard coal. Due to data limitations, we utilized reserves data of Qinghai Province to calculate α_i.

3.2.2.3. Module 3: the module of mineral resources consumption. The module of mineral resources consumption was designed to simulate the annual consumption of mineral resources and the consequent pressure on the mineral resources. The pressure on mineral resources is worth attention in Xining because its industrial structure is highly dependent on the exploitation and processing of mineral resources. However, the exploitation of mineral resources and the resource pressure have not been included in related models in previous studies. In this study, we introduced a mineral resource pressure index to reflect the actual pressure faced by the total reserve of mineral resources. The mineral resource pressure index (MRP) is determined by cumulative exploitation and the total proven reserve of mineral resources (Kong et al., 2017) as:

$$MRP(t) = ln(CEA(t))/ln(PMR(t)) \tag{13}$$

where *PMR* is the proven mineral reserve that increases as mineral exploration continues, which was estimated by combining the total proven mineral reserve of Qinghai Province and the latest proportion of exploitation of Xining in Qinghai Province. *CEA* is the cumulative exploitation amount of the mineral resources. Because the annual increasing exploitation amount is related to the annual output of the mining industry (Kong et al., 2017), we calculated *CEA* as:

$$CEA(t) = CEA(t-1) + Y_M(t) \times REA(t) \tag{14}$$

where Y_M is the output of the mining industry. *REA* is the rate of exploitation amount per unit output of the mining industry.

3.2.2.4. Module 4: the module of water resource consumption. The module of water resource consumption is designed to model the pressure of water resources in Xining. Previous studies have estimated regional water resource pressure as the water resources ecological carrying capacity divided by the water ecological footprint (Dai et al., 2019). Here we used the total amount of available water resources to represent the preceding ecological carrying capacity and the total amount of water resource consumption to represent the preceding ecological footprint, considering the consistency of these connotations (Dai et al., 2019). Therefore, the index of the water resource pressure in our model can be calculated as:

$$WPR\ (t) = (TAWC(t) - RWC(t))/TAWR(t) \tag{15}$$

where *TAWC* is the total amount of water consumption. *RWC* is the consumption of recycled water in the total amount of water consumption. The difference between *TAWC* and *RWC* can reflect the actual consumption of water resources taken from nature. *TAWR* is the total amount of water resources. For *TAWC*, we estimated the value of this variable by considering five kinds of water consumption as counted in the water resource bulletin of Qinghai province (WRBQ, 2000–2020), namely domestic water consumption (including urban domestic water consumption and rural domestic water consumption), industrial water consumption, agricultural water consumption (including irrigation water consumption and water consumed for husbandry and forestry industries), ecological water consumption, and urban public service water consumption. For *TAWR*, we estimated the annual amount of water resource based on the statistical relationship between annual precipitation and the amount of water resource and considered the complementary effect of exploring water resource brought by water engineering projects in the meanwhile.

What is more, to simulate possible influences of water resource policies on the water pressure, we first summarized three kinds of effects caused by the implementation of three kinds of water resource policies in Xining after reading all the water resource news published in the water resource bulletin of Qinghai province (WRBQ, 2000–2020) in the past twenty years. The first kind of effect is the trend of water saving that is shown in all kinds of water consumption demands caused by institutional water conservation policies and rules which focused on the water price. The second kind of effect is the improvement of water consumption efficiency in industrial demands, agricultural demands, and urban public service demands promoted by technical investment policies. The third kind of effect is the increase of exploring water resources brought by water engineering projects (e.g., the "Indajihuang" water transfer project), which can conversely release the limit of industrial, rural domestic, and agricultural water consumption and increase the consumption of recycled water in Xining. Future scenario settings are just based on the adjustment of the values of these three kinds of effects as well.

3.2.3. The ecological environment subsystem

In the ecological environment subsystem, we concretized components in the CLD and designed two modules, namely the module of ecological land protection and the module of environmental pollution.

3.2.3.1. Module 1: the module of ecological land protection. In the module of ecological lands protection, we modelled specific areas of grassland and forestland, which are the two most important kinds of ecological lands in Xining considering the area proportions (calculated based on the land-cover data published by Yang and Huang (2021)) and ecological functions (Wu et al., 2020). Areas of grassland and forestland are also calculated based on Eq. (6). Among variables in Eq. (6), increasing areas of grassland and forestland are determined by the historical increasing rates and the future intensity of ecological protection policies, such as the strategy of "ecology goes first and green development" in Xining; decreasing areas of grassland and forestland are calculated based on the expansion of other land-use types and the occupation rates. For the total area of other ecological lands, we referred to the list of land-cover types of ecological land in previous studies (Qi et al., 2017) and calculated it as the residual area in Xining other than built-up land, forest land and grassland, which actually is the sum of the areas of wetland, barren land, snow/ice, water, and shrub lands.

3.2.3.2. Module 2: the module of environmental pollution and pollution control. Considering actual environmental problems as referred to in the 14th Five Year Plan of the ecological environment protection of Xining (FYPEEPX(14th), 2022), we chose three kinds of pollutants which are often considered to reflect the pollution status in existing studies (Guan et al., 2011; Wu & Ning, 2018; Xing et al., 2019) and are available for data collection, namely chemical oxygen demand (COD, which is an indicator utilized in environmental chemistry to reflect the polluted status of wastewater), sulfur dioxide (SO2), and industrial solid wastes. The SFD of the environment subsystem is shown in Fig. 5. The common framework for the accumulation of each type of pollutant in the year t is shown below (Xing et al., 2019):

$$AP_i(\mathrm{t}) = (PP_i(t) - TP_i(t)) \times (1 - f_{P_i}(EL)) + AP_i(\mathrm{t}-1) \tag{16}$$

where i represents different types of pollutants. $f_{P_i}(NL)$ is the function of the self-purification capacity of the environment based on the area of ecological lands referring to previous literature (Guan et al., 2011, Wu & Ning, 2018, Xing et al., 2019). PP_i is the amount of produced pollutants from industrial and domestic sources, which are specifically shown in Fig. 5. TP_i is the amount of centralized treated pollutants, which are quantified as lookup functions based on the environmental protection investment through curve fitting. Finally, the pollution status of the three kinds of pollutants is summarized into a pollution index to reflect the overall status of environmental pollution, which is calculated as:

$$PI = \sum_{i=1}^{i=3} \alpha_i \times ln(AP_i) \tag{17}$$

where α_i is the pollution coefficient of the three types of pollutants, as discussed in previous studies (Guan et al., 2011, Wu & Ning, 2018, Xing et al., 2019).

3.3. Establishment of trade-off development scenarios from 2021 to 2030

In this study, we established a series of trade-off development scenarios to simulate the development of the ERE system from 2021 to 2030, so as to explore the focus and the available optimal policy choice for the local government to promote the coordinated development of the ERE system. Trade-off development scenarios refer to scenarios in which the local government makes trade-offs among development priorities of the three subsystems in the ERE subsystem and adopts different levels of policy intensity to improve the development qualities of these subsystems. Trade-off development scenarios in this study are established in the following steps.

First, we accordingly divided various policies that straightly influence the development of the three subsystems into three types, namely economy and population policies, resource policies, and ecological environment policies. Economy policies included policies that influence the fixes asset investment, employment situation, and factors influencing the total factor productivity, such as the recovery rate of the development of the tertiary industry since the outbreak of covid-19 in 2020; population policies include birth policies and talent introduction policies which make difference on the birth rate and the emigration rate. Resource policies include a series of policies which influence the utilization efficiency and exploration resources, such as the expansion rate of built-up land, energy intensity, and exploring water resources. Ecological environment policies influence the emission and treatment of pollutants and the protection intensity of ecological lands.

Second, we set three levels of policy intensity for each preceding type of policies and determined detailed values of policy-influenced exogenous variables under each policy intensity level. The level of policy intensity indicates the degree of effort of the government to improve the development quality of a certain subsystem. In this study, we set three levels of policy intensity for each subsystem, namely high, middle, and low. Among these three levels of policy intensity, the middle level is set to correspond to the historical policy intensity from 2010 to 2020; the low level and the high level indicate a lower and a higher policy intensity than that from 2010 to 2020, respectively. After that, we determined detailed values of policy-influenced exogenous variables under each level of policy intensity based on the historical changing directions and changing rates from 2010 to 2020 (note that for few variables we adopted data in adjacent years because of data missing, and we also adjusted few future values acquired in this way so as to ensure the numerical rationality), which are shown in Table 2. For the middle level of policy intensity, exogenous variables are set to be changed linearly after 2020 following the changing rate and changing direction from 2010 to 2020. For the high (or the low) level of policy intensity, exogenous variables are set to be changed still following the historical changing direction, but the linear changing rates will be influenced by the policy intensity and increase or decrease by 50 %, which represents that improvement of the system development quality is accelerated (or decelerated in the low level of policy intensity) by 50 %.

Third, we identified seven possible trade-off development scenarios and specified levels of policy intensity of the preceding three types of policies for each scenario. In this step, we first identified all six scenarios (which are numbered as S1-S6) of which development priorities or the three subsystems are all different. We later specified levels of policy intensity for these six scenarios based on the basic principle that a subsystem with a higher development priority will be equipped with a

Table 2
Detailed parameters in different levels of policy intensity and the BAU scenario.

Policies	Detailed variables	BAU	Levels of policy intensity		
			Low	Middle	High
Economy and population policies	Rate of fixed assets investment	0.1403	0.0581	0.0855	0.1129
	Proportion of fixed assets investment in primary industry	0.0129	0.0002	0.0044	0.0087
	Proportion of fixed assets investment in secondary industry	0.1384	0.0010	0.0397	0.0890
	Other factors affecting output of the primary industry	0.9357	0.7020	0.7799	0.8578
	Other factors affecting output of the secondary industry	1.8800	1.9898	2.0996	2.2095
	Other factors affecting output of the tertiary industry	0.9406	1.048 (since 2030)	1.048 (since 2027)	1.048 (since 2024)
	Overall educational level of Xining	1.2650	1.3169	1.3689	1.4208
	Overall trend of variations of the birth rate	(0.0583)	(0.0875)	(0.0583)	(0.0292)
	Overall trend of variations of the net immigration rate	0.1270	0.0635	0.1270	0.1905
	Labour force ratio	0.5800	0.5815	0.5830	0.5845
Resource policies	Required built-up land area per unit of non-agricultural output	4.24E-05	2.93E-05	1.63E-05	3.30E-06
	Grain planting rates	0.4721	0.5795	0.6868	0.7942
	Energy intensity of the secondary industry	80.5555	75.1959	69.8363	64.4767
	Energy intensity of the tertiary industry	22.4716	19.0818	15.6921	12.3023
	Energy intensity of people's living	0.5098	0.8644	0.7462	0.6280
	Ratio of coal consumption	0.2915	0.2702	0.2489	0.2276
	Ratio of crude oil consumption	0.1087	0.1785	0.1553	0.1320
	The proportion of new energy in electricity consumption	0.8650	0.8771	0.8892	0.9012
	Ratio of electricity consumption	0.4360	0.3882	0.4041	0.4201
	Mining volume per unit output	0.6510	0.8258	0.7676	0.7093
	Proven reserves growth rates	0.0020	0.0020	0.0021	0.0021
	Increase rate of arable land	0.0113	0.0165	0.0217	0.0269
	Proportion of forest land increase from arable land	0.0486	0.2015	0.1505	0.0996
	Proportion of built-up land increase from arable land	0.1652	0.1276	0.0901	0.0525
	Proportion of grassland increase from arable land	0.9352	1.0000	0.9700	0.9400
	Water saving policy factor (technical investment)	1	0.7425	0.4851	0.2276
	Water saving policy factor (institutional)	1	0.9032	0.8065	0.7097
	Water resource exploring policy factor	1	1.0278	1.0556	1.0833
Ecological environment policies	Rate of environmental protection investment	0.0034	0.0001	0.0012	0.0023
	Rate of industrial wastewater	171.8000	112.0243	52.2486	4.4260
	Rate of industrial SO2	0.4504	0.3250	0.1997	0.0743
	Rate of industrial solid wastes	36.6700	30.2034	23.7368	17.2702
	SO2 per person	0.0036	0.0146	0.0109	0.0073
	Increase rate of forest land	0.0165	0.0206	0.0248	0.0289
	Increase rate of grassland	0.0159	0.0145	0.0150	0.0154
	Proportion of arable land increased from forest land	0.0019	0.0013	0.0007	0.0002
	Proportion of arable land increased from grass land	0.9971	0.9987	0.9993	0.9998
	Water consumed for other ecological protection aims	1.65E+07	4.71E+07	7.76E+07	1.08E+08
	Proportion of forest land increase from grassland	0.7157	0.9187	0.8510	0.7833
	Proportion of grass land increase from forest land	0.0006	0.0004	0.0003	0.0001

higher level of policy intensity. For example, for a scenario under which the economy has the highest development priority, the level of policy intensity of the economic policies is assigned to be "high". Then, we considered scenarios in which three subsystems have equal priorities and are all equipped with a middle level of policy intensity (which is numbered as S7). All trade-off scenarios and their corresponding levels of policy intensity are shown in Table 3. In addition, we also supplemented a control scenario which is called business as usual (BAU) scenario (numbers as S0) to model the development of the ERE system if no extra measures are adopted and values of policy-influenced exogenous variables remain unchanged after 2020.

Finally, we determined the detailed parameters of each trade-off development scenario. We combined settings of levels of policy intensity of each scenario (as shown in Table 3) and detailed values of policy-influenced exogenous variables under each policy intensity level (as shown in Table 2) for the three types of policies.

3.4. Model validation and sensitivity analysis

Before utilizing the SD model to conduct future simulations, it is essential to test its usefulness, which usually includes its accuracy to reflect the actual situation determined by the reliability of the causal relationships in the model and the sensitivity of the final results to key exogenous variables. Therefore, first, we conducted model validation through a stock-flow test (Cao et al., 2019; Gu et al., 2020). We selected 454 observed values from the simulation results of 27 key endogenous variables from 2000 to 2020 based on two principles: (1) Actual statistical data for the observed variable in the observed year can be acquired.

Table 3
Trade-off scenarios and the levels of policy intensity.

		Scenarios							
		Control scenario	Trade-off scenarios						
		S0 (BAU)	S1	S2	S3	S4	S5	S6	S7
Development priorities orders of subsystems		EC = R = EE	EC > R > EE	EC > EE > R	R > EC > EE	R > EE > EC	EE > EC > R	EE > R > EC	EC = R = EE
Levels of future policy intensity	EC	None (situation remains unchanged since 2020)	High	High	Middle	Low	Middle	Low	Middle
	R		Middle	Low	High	High	Low	Middle	Middle
	EE		Low	Middle	Low	Middle	High	High	Middle

Note: EC, R, and EE represent the economy, resource, and ecological environment, respectively.

(2) The statistical standards for the data should be consistent. We then calculated the error rates of the endogenous variables through the following equation:

$$R_{Q(t)} = \left(Q(t)_O - Q(t)_T\right) / Q(t)_T \tag{18}$$

where $R_{Q(t)}$ is the error rate of variable Q in year t. $Q(t)_O$ and $Q(t)_T$ is the observed value and the true statistical value of variable Q in year t, respectively. Second, we conducted a sensitivity analysis for 37 key exogenous variables in the model referring to existing studies (Gu et al., 2020) through the following equation:

$$\begin{cases} S_{X_Q} = \left| \dfrac{\Delta Q_{(t)}}{Q_{(t)}} \cdot \dfrac{X_{(t)}}{\Delta X_{(t)}} \right| \\ S_X = \dfrac{1}{n} \sum_{i=1}^{n} S_{X_i} \end{cases} \tag{19}$$

where S_X is the final sensitivity level of the exogenous variable X. S_{X_Q} is the sensitivity of variable Q to variable X. $Q_{(t)}$ and $X_{(t)}$ denote the value of variable Q and of variable X in year t, respectively, while $\Delta Q_{(t)}$ and $\Delta X_{(t)}$ denote the variations. n represents the number of tested exogenous variables for the sensitivity of variable X. In this study, 16 key endogenous variables are selected for sensitivity analysis of the exogenous variables.

4. An improved CCD model for evaluating Xining's ERE system under trade-off scenarios based on ranked weights

4.1. Line of thought: incorporation of ranked weights into conventional CCD

In this study, we introduced the ranked weights method (Wu et al., 2018) to improve the conventional CCD model. The ranked weights method is of use here for two reasons. First, it focuses on only the ranks of the weights rather than assigns precise weights for each indicator and avoids possible controversy of determining precise weights (Wu et al., 2018). After determining the rank of weights, the mathematical expression of the numerical range of the weighted sum can be derived, of which the detailed process is shown in the reference (Wu et al., 2018). Second, this method requires enumerating ranks of weights in different scenarios, and the weighted sum is acquired by each scenario. This principle of setting scenarios and acquiring results by each scenario makes it possible to cope with the problem of evaluation under multiple development scenarios.

4.2. Basic preparation: performance evaluation of each subsystem

The performance of each subsystem serves as the basis to calculate the CCD of the ERE system. To objectively evaluate their performance, we adopted a popular and information-theoretic method called the entropy weight coefficient method (Gao, Wang, Wang, et al., 2020). This method resulted in an evaluation score for each subsystem through the following two steps.

1) Preparing representative indicators for subsystems

Representative indicators were first selected for each subsystem with reference to relevant existing research on urban sustainability and ERE system evaluation (Deng et al., 2019; Huovila et al., 2019; Steiniger et al., 2020; Xing et al., 2019; Yang et al., 2020) and the 14th Five Year Plan of Xining with two rules. First, the indicator should be general and widely used in similar cities, which makes the evaluation results comparable. Second, unique indicators to Xining should be included to better reflect its situation. We selected 17 indicators from the three subsystems in the ERE system to reflect the performance of each subsystem, which are shown in Table 4. We determined the direction for each indicator at the same time by referring to relevant indicator systems, which is an essential attribute of these indicators and includes two types: positive (note as "+") and negative (noted as "−"). For positive indicators, the larger the value, the better the performance, and negative indicators are on the contrary. Then, values of indicator j in year i were standardized as follows.

Table 4
Representative indicators of each subsystem for performance evaluation and their weights.

Subsystem	Indicator	Direction	Weights
Economy	Output of the primary industry	+	0.27
	Output per capita	+	0.14
	Output proportion of the non-agricultural industries	+	0.16
	Output proportion of the tertiary industry	+	0.21
	Total population	+	0.22
Resource	Area of arable land	+	0.13
	Area of built-up land	−	0.09
	Grain yield	+	0.23
	Energy consumption index	−	0.11
	Proportion of new energy consumption	+	0.18
	Mineral resource pressure index	−	0.13
	Water resource pressure index	−	0.12
Ecological environment	Area of forest land	+	0.26
	Area of grassland	+	0.21
	Net discharged COD	−	0.10
	Net discharged SO_2	−	0.23
	Net discharged solid wastes	−	0.20

$$s_{ij} = \begin{cases} \left(X_{ij}^{+} - \min_{i,j} X_{ij}{}^{+}\right) \Big/ \left(\max_{i,j} X_{ij}{}^{+} - \min_{i,j} X_{ij}{}^{+}\right) \\ \left(\max_{i,j} X_{ij}{}^{-} - X_{ij}^{-}\right) \Big/ \left(\max_{i,j} X_{ij}{}^{-} - \min_{i,j} X_{ij}{}^{-}\right) \end{cases} \tag{20}$$

where + and – denote positive and negative indicators, respectively. X_{ij} is the value of indicator j in year i.

2) Determining the weight of each indicator

The weight of each indicator was determined based on future temporal variations (specifically the annual mean values of all scenarios from 2021 to 2030), which were quantified using information entropy (i.e., Shannon entropy) according to the following expression:

$$\begin{cases} w_i = (1 - H_i) \Big/ \sum_{i=1}^{n} (1 - H_i) \\ H_i = \dfrac{1}{\ln m} \sum_{j=1}^{m} f_{ij} \cdot \ln \dfrac{1}{f_{ij}} \\ f_{ij} = \dfrac{s_{ij}}{\sum_{j=1}^{m} s_{ij}} \end{cases} \tag{21}$$

where w_i is the weight of indicator i. n is the number of indicators in each subsystem. m is the length of the time series. The results of the weights of each indicator are also shown in Table 4.

Accordingly, the comprehensive weighted index of each subsystem which indicates its performance in year i is calculated as:

$$P_i = \sum_{j=1}^{j=n} w_j s_{ij} \tag{22}$$

4.3. Principles and application of the improved CCD model

The improved CCD model involves four steps. The first steps explained how we incorporate the ranked weights method to improve the conventional CCD model.

1) Enumerating ranks of weights of the three subsystems under each trade-off scenario

With the ranked weights method, we only need to determine the ranks of different subsystems (or components). In our SD model, subsystems have different priorities in a development scenario (Table 3). We employed these priorities as the natural ranks of different subsystems. If there are three subsystems, we have a maximum of six combinations of ranked weights, as follows:

$$S0\ (BAU): \alpha_1 = \alpha_2 = \alpha_3; S1: \alpha_1 > \alpha_2 > \alpha_3; S2: \alpha_1 > \alpha_3 > \alpha_2; S3: \alpha_2 > \alpha_1 > \alpha_3;$$

$$S4: \alpha_2 > \alpha_3 > \alpha_1; S5: \alpha_3 > \alpha_1 > \alpha_2; S6: \alpha_3 > \alpha_2 > \alpha_1; S7: \alpha_1 = \alpha_2 = \alpha_3;$$

where α_1, α_2, and α_3 to represent the weights of three subsystems, i.e., the economy, resource, and ecological subsystems in this study. Each combination corresponds to a development scenario.

2) Calculating the CDD under each scenario

Because we introduced varying scenarios, we need to calculate the CDD under each scenario. To this end, we calculated the geometric means of the lower and upper limits of the weighted sum of the evaluation scores of the subsystems under each scenario. The upper and lower limits under each scenario were calculated based on the mathematical derivation of dual problems (the detailed derivation process can be found in Wu et al. (2018)) as:

$$UT_i = max\left\{P_{i_1}, \frac{P_{i_1} + P_{i_2}}{2}, \frac{P_{i_1} + P_{i_2} + P_{i_3}}{3}\right\} \quad (23)$$

$$LT_i = min\left\{P_{i_1}, \frac{P_{i_1} + P_{i_2}}{2}, \frac{P_{i_1} + P_{i_2} + P_{i_3}}{3}\right\} \quad (24)$$

where UT_i and LT_i are the upper and lower limits in scenario i, respectively. P_{i_j} represents the score of the ranked jth subsystem in weights under scenario i (e.g., P_{1_1} represents the score of the ranked 1st subsystem in weights under scenario S1 and specifically corresponds to the score of the economy subsystem). In scenario i, the CDD can be calculated as:

$$CDD_i = \sqrt{UT_i \times LT_i} \quad (25)$$

3) Calculating the CD

The CD reflects the consistency of the performance of the subsystems. As the consistency level is independent of the importance of the subsystems, the CDs in different scenarios are the same:

$$CD = \left\{\frac{P_{EC} \times P_R \times P_{EE}}{\left[\frac{P_{EC}+P_R+P_{EE}}{3}\right]^3}\right\}^{\frac{1}{3}} \quad (26)$$

where P_{EC}, P_R, and P_{EE} represent the score of the economy subsystem, resource subsystem, and ecological environment subsystem, respectively.

4) Calculating the CCD under each scenario

Based on the preceding evaluation results, the final result of annual CCD in different trade-off scenarios can be calculated as:

$$CCD_i = \sqrt{CD \times CDD_i} \quad (27)$$

where CCD_i is the expression of CCD in scenario i.

5. Results and analysis

5.1. Results of validation and sensitivity analysis of the system dynamic model

As shown in Fig. 6, validation results from the stock-flow test indicate the reliability of the causal relationships within the SD model. According to the overall distribution of the validation results (Fig. 6a), error rates of over 90 % of observed values are below 5 %. According to detailed validation results of different variables (Fig. 6b), the average error rates of 24 out of 27 variables are below 5 %, and that of the other three variables are also below 10 %.

In the meanwhile, results of the sensitivity analysis indicate that modelling results are insensitive to settings of exogenous variables. Other than several variables (variables of "Labor force ratio", "Overall educational level of Xining", "Other factors affecting output of the secondary industry", "Other factors affecting output of the tertiary industry", "Increase rate of grassland", and "Proportion of grassland increase from arable land"), sensitivity levels of 31 out of 37 tested exogenous variables are below 10 %, as shown in Fig. 7. Preceding results of sensitivity analysis are at reasonable levels in SD simulation studies.

5.2. Development of each subsystem of Xining under trade-off scenarios from 2021 to 2030

We simulated the development of the three subsystems in the ERE system in Xining under different trade-off scenarios for the period from 2021 to 2030 and evaluated their comprehensive performance. According to the evaluation results, which are shown in Figs. 8–10, we analyzed trends of the comprehensive performance and specific indicators of each subsystem under multiple scenarios as follows.

5.2.1. Performance of the economy subsystem

According to the comprehensive performance which is indicated by the weighted score (as shown in Fig. 8a), the development of the economy subsystem steadily keeps growing under all trade-off scenarios and performs best under S2. We note that the performance under almost all scenarios is far above that under Scenario BAU except S7 (performance under these two scenarios stays close), which indicates the effectiveness of current economic and population policies.

As for the specific indicators in the economy subsystem, the output proportion of non-agricultural industrials (as shown in Fig. 8f) and the output proportion of the tertiary industry (as shown in Fig. 8e) keep increasing from 2021 to 2030, indicating that the industrial structure remains optimized. The output of the primary (as shown in Fig. 8b) shows slight increasing trends under S1 and S2 but shows decreasing trends in varying degrees under other trade-off scenarios. The reason is that for the primary industry, the input intensity of the fixed asset investment and the coefficient of other environmental factors that influences the total factor productivity keep deteriorating, which puts a threat to the sustainability of the development of the primary industry. The output per capita (as shown in Fig. 8c) under trade-off scenarios shows turning trends in 2024 (S1 and S2) or 2026 (in other trade-off scenarios) because of the continuous increasing trend of the population under S1 and S2 (as shown in Fig. 8d) and the slow economic growth under scenarios of which the economy subsystem has a middle or low development priority (S3-S7). In the last few years, due to the demand for economic development and ecological environment protection, economic inputs are obviously tilted to the tertiary industry.

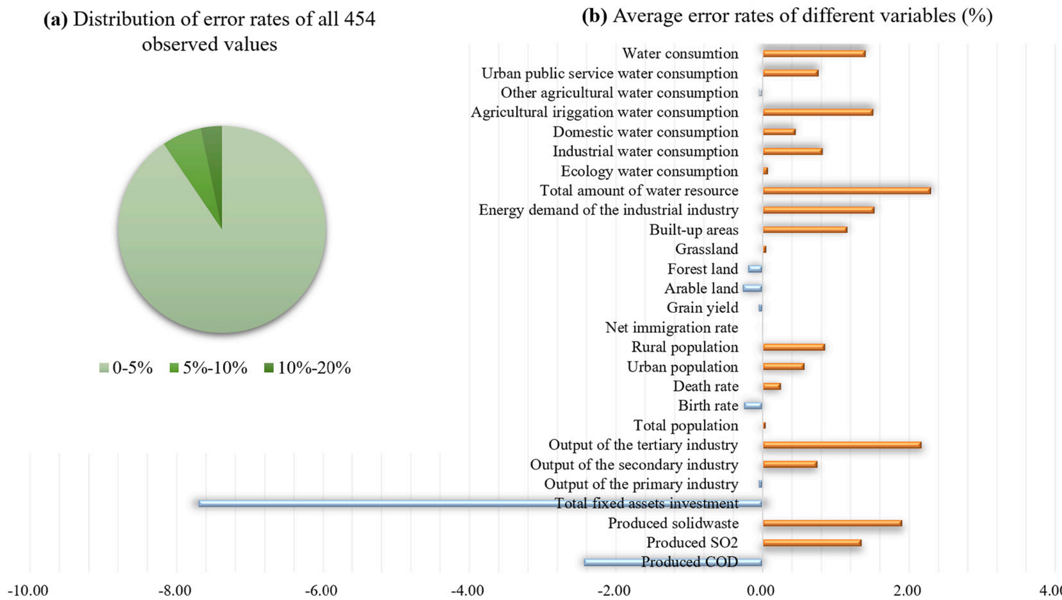

Fig. 6. Validation results of the stock-flow test.

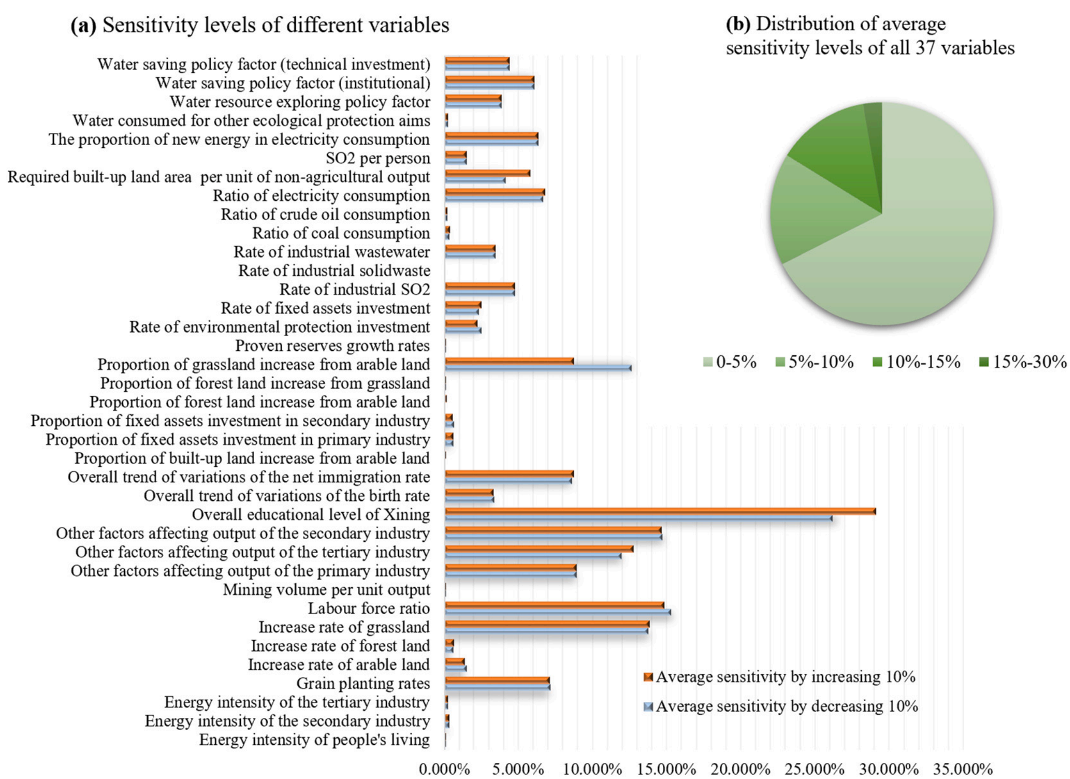

Fig. 7. Results of sensitivity test.

However, the development of the tertiary industry is affected by many factors since 2019, especially the outbreak of the covid-19 epidemic. Although adopting considered intensities of economic policies can keep the overall increasing trends of the comprehensive performance of the economy subsystem, there still exist threats to the economic growth of Xining.

5.2.2. Performance of the resource subsystem

For the comprehensive performance indicated by the weighted score (Fig. 9a), the development of the resource subsystem keeps deteriorating to different degrees under all scenarios from 2021 to 2030. Under scenarios in which the resource subsystem has the highest development priority (S4 and S3), the performance of the resource subsystem can basically keep stable and only show slight deterioration (−12 % under S4 and − 20 % under S3). However, under other scenarios, the performance of the resource subsystem deteriorates rapidly. We also note that under scenarios in which resource conservation is severely neglected (S2 and S7), the development of the resource subsystem is even worse than under the BAU scenario. These results indicate that the low level of policy intensity for resource policies is inadequate for the sustainable

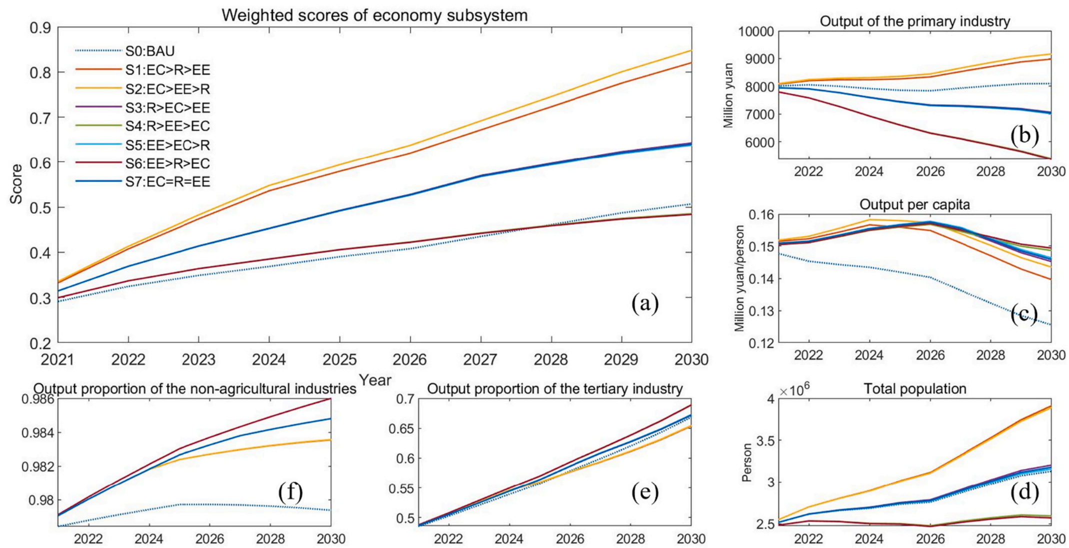

Fig. 8. Comprehensive performance and specific indicators of the economy subsystem under trade-off scenarios.

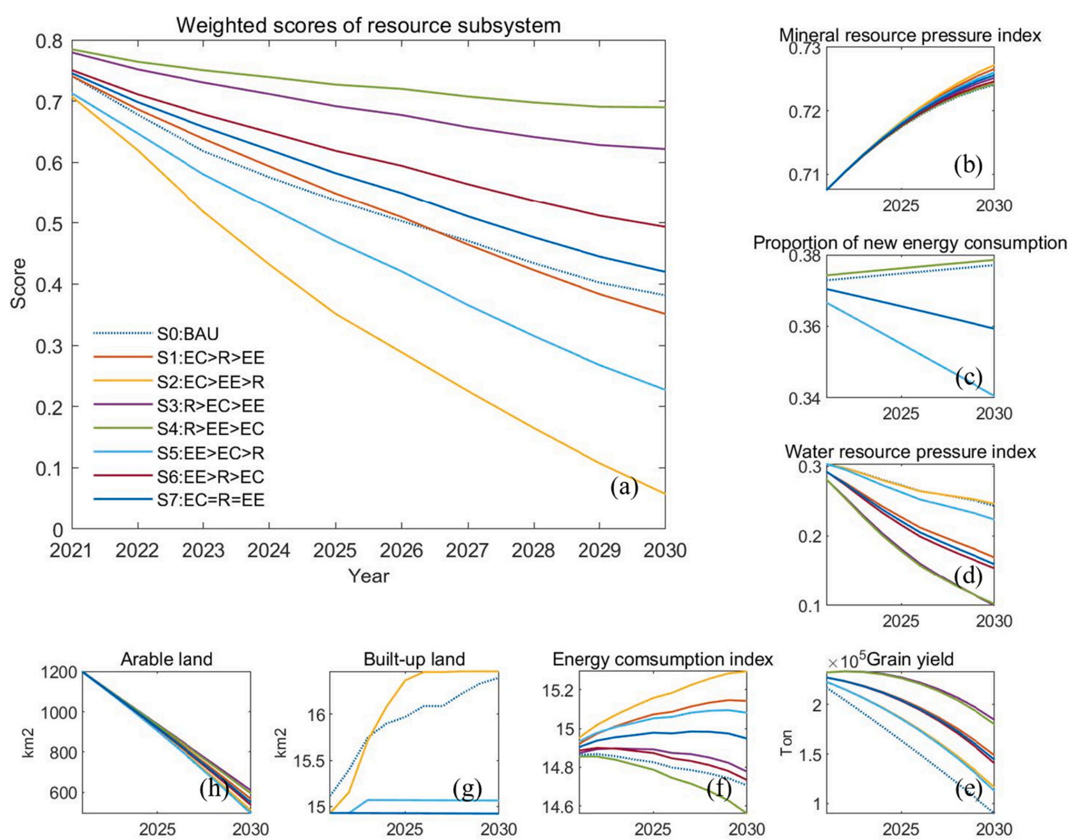

Fig. 9. Comprehensive performance and specific indicators of the resource subsystem under trade-off scenarios

development of the resource subsystem, unless the economic development and population growth are slowed down in the meanwhile.

As for the specific indicators in the resource subsystem, the water resource pressure (as shown in Fig. 9d) is expected to be continuously relieved under all scenarios, but trends for the mineral resource pressure (Fig. 9b) are on the contrary and keep increasing under these scenarios. The area of arable land (Fig. 9h) is faced with a continuous decreasing trend under all trade-off scenarios and subsequently brings threats to the grain yield (Fig. 9e), reflecting that currently considered policy intensities are inadequate for arable land conservation. Huge differences exist among expansion trends of the built-up land (Fig. 9g) under different scenarios, which shows that under scenarios with high intensity for economic and population policies, low intensity for resource policies is inadvisable for the control of built-up land expansion. The energy consumption index (Fig. 9f) shows evident increasing trends under scenarios in which the policy intensity of economy and population policies is higher than that of resource policies, which indicates the importance of the trade-off between the resource and the economy subsystem. What's more, the proportion of new energy consumption (Fig. 9c) shows worrying trends and decreases under scenarios in which

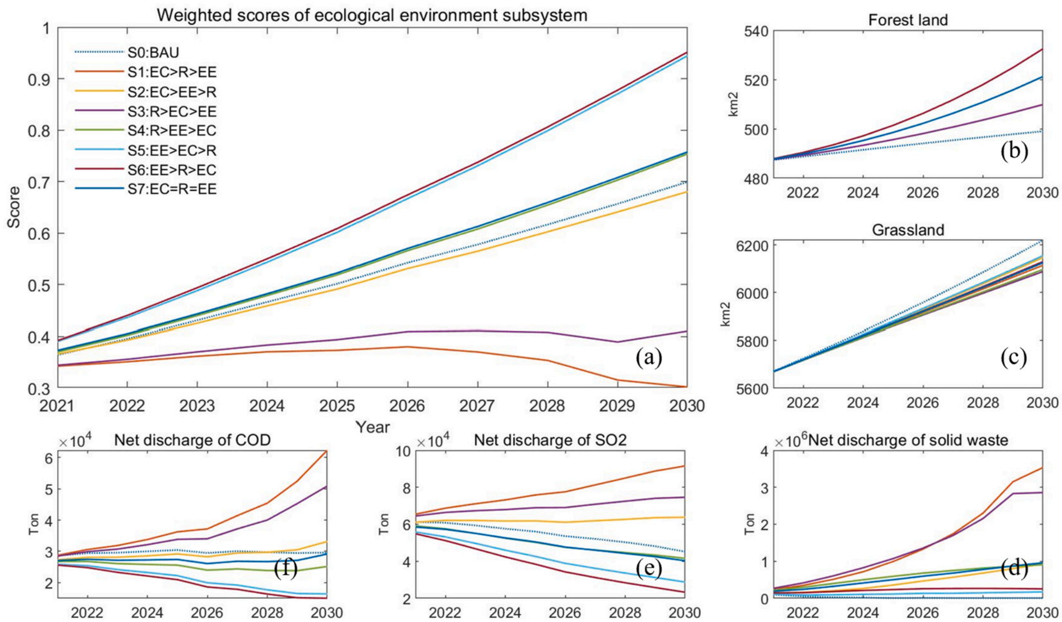

Fig. 10. Comprehensive performance and indicators of ecological environment subsystem under trade-off scenarios.

the resource subsystem has a middle or low level of development priority.

5.2.3. Performance of the ecological environment subsystem

The comprehensive performance indicated by the weighted score (as shown in Fig. 10a) shows varying trends under trade-off scenarios, which reflects the decisive effect of the trade-offs among different subsystems. Under scenarios in which the ecological environment subsystem has the highest or middle level of priority (S2, S4, S5, and S6), the performance of the ecological environment subsystem keeps growing at different rates. However, under scenarios in which the ecological environment subsystem is most neglected (S1 and S3), the performance of the ecological environment subsystem remains stable but shows deteriorating trends from 2028.

For the specific indicators of the ecological environment subsystem, the area of forest land (Fig. 10b) keeps increasing from 2021, and the increasing rate under all trade-off scenarios exceeds that under the BAU scenario, which shows the effectiveness of current policies on the protection of forest land. The area of grassland (Fig. 10b) also keeps increasing from 2021 in all scenarios, but the increasing rates under all trade-off scenarios are smaller than that under the BAU scenario, which indicates that the policy intensity of ecological environment policies should be further strengthened for grassland protection. As shown in Fig. 10d–f, the net discharges of COD, SO2, and solid wastes can be effectively reduced or controlled under scenarios in which the ecological environment subsystem has a highest or middle priority (S2 and S4-S7). However, under scenarios in which the ecological environment is seriously neglected (S1 and S3), net discharges of these pollutants (especially the COD and the solid wastes) show evident increasing trends because of the pressure of economic development, population growth

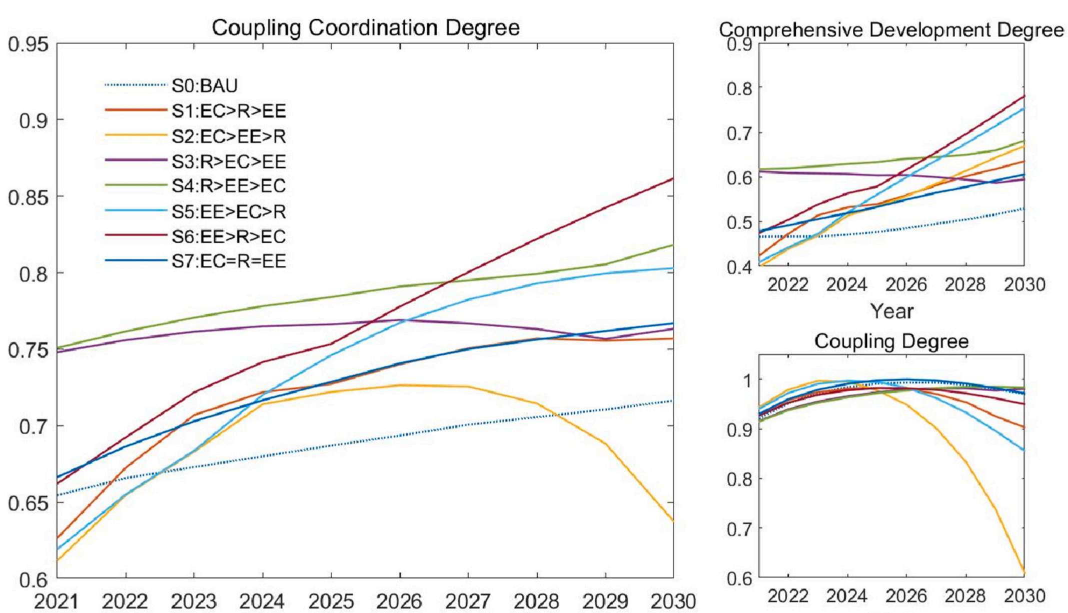

Fig. 11. Trends of the CDD, CD, and CCD calculated with the improved CCD model.

and the low investment intensity on pollutant treatment.

5.3. CCD of Xining's ERE system under trade-off scenarios evaluated by the improved CCD model

Based on the evaluations of the three subsystems, we further calculated the CCDs of the ERE system from 2021 to 2030. Following we analyzed the trends of the two detailed parts in the CCD (specifically are the CDs and the CDDs) and the CCDs under trade-off scenarios, which are shown in Fig. 11.

The CD in the CCD model can effectively reflect the consistency and the degree of interactions of the subsystems. CDs under all trade-off scenarios show turning trends in different degrees, which indicates the inconsistency of the trends of the three subsystems under current policies. Under scenarios in which the resource subsystem is assigned with the highest development priority (S3 and S4), the CDs increase at first and then basically remain stable since 2026. However, under other trade-off scenarios, the CDs first increase from 2021 and then keep decreasing after reaching an inflexion point. Decreasing rates are particularly great under scenarios in which the government emphasizes economic development and weakens the intensity of resource policies (S2). The reason for the preceding results is that under scenarios in which the resource subsystem has the lowest development priority, this subsystem deteriorates seriously from 2021 to 2030, which indicates the great influence of trade-offs among the resource subsystem and other subsystems on the CD of the ERE system.

The CDD in the CCD model indicates the level of the comprehensive performance of the ERE system. Evident differences exist among trends of the CDDs under trade-off scenarios. Under trade-off scenarios in which the development of the ecological environment is most focused (S5 and S6), the CCDs lay behind in the beginning but keep increasing rapidly and exceed that under all other scenarios after 2027. Under scenarios in which the resource subsystem is most focused (S3 and S4), the CDDs remain relatively stable (under S4) or slightly decrease (under S3). Under other trade-off scenarios (S1, S2, and S7), the CCDs overall keep increasing. The reason is that through increasing policy intensity of ecological environmental policies and relieving the environmental pressure from economic development and population growth, the performance of the ecological environment subsystem can be significantly improved, which promoted the comprehensive level of the entire system. We also note that the CCDs under all trade-off scenarios (S1-S7) are greater than that under the BAU scenario (S0) since 2023, which indicating the overall effectiveness of current considering trade-off scenarios. However, current considering trade-off scenarios could just avoid the severe deterioration of the resource subsystem, but could not promote an increasing trend for this subsystem.

The CCD which is the final result of the CCD model can reflect the coordinated development level of the ERE system. We first analyzed trends of CCDs under different trade-off scenarios. Among all these trade-off scenarios, we note that the CCD under the scenario in which the rank of development priorities from large to small is the ecological environment, resource, and economy (S6) grows rapidly and exceeds all other trade-off scenarios after 2027. We also note that the CCD performs worst under the scenario in which the rank of development priorities from large to small is economy, ecological environment, and resource (S2); under this scenario, the CCD first increases from 2021 to 2024 and then shows a turning trend after 2026 because of the severe deterioration of the resource subsystem. Then, we compared trends of CCDs under several pairs of scenarios. Through comparing trends of CCD under S2 with that under S1, S4, and S5 respectively, we found that the trade-off between economy and resource make a great influence on the coordinated development of the ERE system. Fast economic development and population growth will further bring huge pressures on the resource subsystem; if the policy intensity of resources conservation is not strengthened simultaneously, a severe deterioration will happen in the resource subsystem, which leads to a deterioration of the coordinated development level of the ERE system and further threatens urban sustainable development. What is more, we also compared the trend of the CCD under S6 with that under S1, S4, and S5 and found that the trade-off between the ecological environment and the economy evidently influences the growth trend of the coordinated development level of the ERE system in the second half of the study period.

6. Discussion

SD modelling is crucial to the policy-making for sustainable cities and thus has received increasing attention around the world. Recent examples include Ebbsfleet Garden City from UK (Pluchinotta et al., 2021), the City of Mount Gambier from Australia (Zarghami & Dumrak, 2021), and Chongqing City from China (Han et al., 2022), with different considerations in their SD models. Our study established an SD model for the ERE system of Xining and proposed an improved CCD model to evaluate the coordinated development level of the system under multiple trade-off scenarios, so as to propose policy implications to promote the coordinated development of the ERE system of Xining. This section provides discussions on the methods and key results of this study.

The core simulation tool of this study is an SD model established for the ERE system of Xining, of which the advantages and disadvantages are worth discussing. Advantages of this model lie in the reliable structure with solid theoretical basis, detailed consideration for special characteristics of Xining, and innovative incorporation of water resources and the mineral resources. Worrying trends of pressures on these two kinds of resources under all scenarios (Fig. 9b and d) indicate the importance of maintaining intensities of resource conservation policies and justify the significance of considering these two kinds of resources for Xining. However, since SD is a modelling method that highly depends on the causal relationships among components within a system, the reliability of our model is inevitably influenced by subjectivity in determining internal causal relationships. Although we referred to a series of studies and combined historical trends from data to minimize the influences, subjectivity still exists in some details of the model, such as time lags of the interactions.

Because the improved CCD model is a methodological contribution of this study, it is necessary to demonstrate its advantage over the conventional CCD model. To this end, we performed comparative experiments using these two models, with the results shown in Fig. 12. It can be seen that using the improved model, the influence of the performance of the most focused subsystem can be effectively highlighted, making the effect of the government policies on the coordinated development level of the ERE system more evident than that using the conventional CCD model. Specifically, for scenarios in which policies can effectively promote the coordinated development of the ERE system (like S6), the results of the improved CCD model can highlight the advantage of these measures; for scenarios in which policies may lead to severe deterioration of the ERE system (like S2), turning trends of the final result of the CCD become more evident, which better indicates the potential crisis of the ERE system under this scenario.

Comparison among evaluation results of this study and previous relevant studies further proved the scientific significance of modelling Xining's ERE system. Chen et al. (2018) have analyzed the historical sustainability of the Qinghai Province and found a declining trend largely because of its high dependence on local resources. This study supported the findings of Chen et al. (2018) and further displayed future worrying trends of the urban sustainability of Xining, since, for the CCD of the ERE system, only three scenarios show steadily increasing trends and by 0.10 (S5, S6, and S7) while other scenarios show worrying inverted, declining, or almost unchanged trends in 2021–2030 (Fig. 11). Through modelling and evaluating the ERE system under scenarios, this study also provided solutions of breaking historical declining trends and improving urban sustainability. Moreover, this study found decisive influences of balancing policy intensities of the economy subsystem and resource subsystem on the coordinated development trends of the ERE

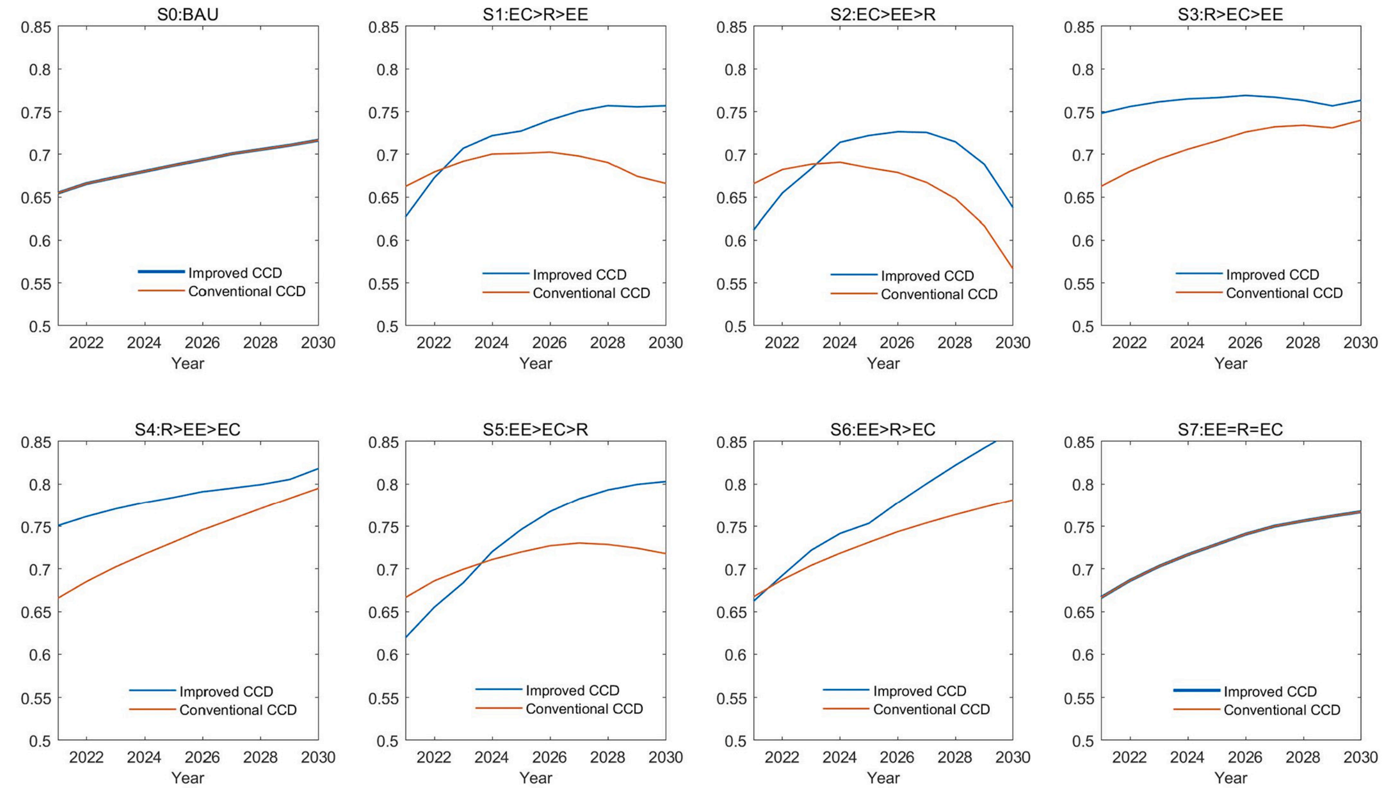

Fig. 12. Comparison of the CCD results of the conventional and improved CCD model.

system. This finding supports the revealed significance of strengthening resource conservation and resource structure optimization in previous studies (Wang et al., 2022; Xing et al., 2019) and indicates the irreversible effects of setting unbalanced policy priorities in a third polar city. What is more, this study also revealed the superiority of scenarios that most emphasizes on ecological environmental protection. This finding is consistent with previous studies on metropolitan cities like Wuhan (Xing et al., 2019) and Chongqing (Guan et al., 2011) but not exactly with that of the coupling system of nitrogen resource, economy, and environment in a typical agricultural and pastoral county in the Third Pole (Wang et al., 2022). This divergence indicates vast differences of geographical characteristics exist within the Third Pole and the necessity of small-scale modelling in representative regions.

7. Conclusions

In this study, we focused on a resource-dependent city on the world's third pole: Xining, by modelling its ERE system using an SD approach. In the approach, we incorporated sections of water and mineral resources to capture the resource characteristics of Xining. The modelling results allowed us to perform predictions for Xining from 2021 to 2030 under seven trade-off scenarios. Then, we introduced the principle of ranked weights obtained from previous studies and proposed an improved CCD model to better evaluate the simulated regional system under multiple scenarios. Model validation, sensitivity analysis, and comparison of the two kinds of CCD models indicate the usefulness of the methods in this study. We draw three conclusions:

- The trade-off relationship between the economy subsystem and the resource subsystem has a decisive influence on the development trend of the ERE system of Xining. Blindly strengthening the intensity of economic and population policies and neglecting resource conservation will lead to a severe deterioration of the coordinated development level of the ERE system.
- Strengthening the intensity of the ecological environment policies is an effective approach for Xining to promote the coordinated development level of the ERE system. The coordinated development level of the ERE system can be further promoted even under scenarios in which the intensity of ecological environment protection is strengthened.
- A part of indicators in the economy subsystem show worrying trends under trade-off scenarios, which become problems that are worthy of attention for Xining. These problems include the population crisis and the emergent needs to boost the development of the tertiary industry.

We could make the following suggestions for the sustainable development of Xining. To efficiently promote the coordinated development of the ERE system, the development priority of the resource subsystem should be higher than that of the economy subsystem, in avoid of severe deterioration of the CCD; setting highest development priority for the ecological environment subsystem could effectively improve the coordinated development level of the ERE system of Xining. What is more, extra efforts are suggested to be made to maintain the development of the tertiary industry and to increase economic inputs in the primary and secondary industries.

CRediT authorship contribution statement

Yuanhui Wang: Conceptualization, Methodology, Software, Writing – original draft. **Changqing Song:** Resources, Supervision, Funding acquisition. **Changxiu Cheng:** Supervision, Project administration. **Haoyu Wang:** Software, Validation, Data curation. **Xiangyu Wang:** Formal analysis, Investigation. **Peichao Gao:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Functions of variables in the SD model

1. Actual consumption of water resource = Water consumption - Recycle water (Time) * Water resource exploring policy factor (Time)
2. Added value of mineral output = Mining volume per unit output (Time) * Output value of mining industry
3. Agricultural irrigation water consumption = Proportion of effective irrigated arable land (Time) * Arable land * Irrigation water consumption per acre of arable land (Time) * 1500 * Water resource exploring policy factor (Time) * Water saving policy factor (institutional) (Time) * Water saving policy factor (technical investment) (Time)
4. Agricultural water consumption = Agricultural irrigation water consumption + Other agricultural water consumption
5. Air pollution coefficient = 0.81
6. Arable land = INTEG (Increase of arable land-Decrease of arable land, 1887.65)
7. Area of urban green coverage = ([(2000, 0) - (2030, 10000)], (2000, 2000), (2007, 2225), (2009, 2730), (2010, 2745), (2011, 2785), (2012, 2823), (2013, 3277), (2014, 3520), (2015, 3647), (2016, 3732), (2017, 3809), (2018, 3894), (2019, 3977), (2020, 4258), (2030, 5000))
8. Birth rate = IF THEN ELSE (Time < 2020, (Fluctuation of the birth rate (Time) + Overall trend of the birth rate) / (1 + Elasticity of pollution on birth rate * Pollution Index) * (1 + Elasticity of grain yield on birth rate * Grain yield per capita), (Fluctuation of birth rate after 2020 + Overall trend of the birth rate) / (1 + Elasticity of pollution on birth rate * Pollution Index) * (1 + Elasticity of grain yield on birth rate * Grain yield per capita))
9. Built-up areas = INTEG (Increase of built-up land-Decrease of built up land, 5.15424)
10. Built-up land in demand = Rate of built-up land in demand of non-agricultural output (Time) * Non-agricultural output
11. Capacity of solid waste treatment = IF THEN ELSE (Environmental protection investment > 17617.7, IF THEN ELSE (Environmental protection investment < = 131495, 0.497 * LN (Environmental protection investment) - 4.859, 0.999), 0)
12. Capacity of urban living wastewater treatment = IF THEN ELSE (Environmental protection investment > 14990.6, IF THEN ELSE (Environmental protection investment < = 224697, 0.369 * LN (Environmental protection investment) -3.548, 0.999), 0)
13. Coal consumption = Energy consumption * Ratio of coal consumption (Time) + Electricity consumption * (1-The proportion of new energy in electricity consumption (Time))
14. COD accumulation = INTEG ((Produced COD-Decreased COD) * (1-Self-purification capacity of COD), 80000)
15. COD concentration of industrial wastewater = 4e-005 * (Time-1999) -4e-005
16. COD concentration of living wastewater = RANDOM UNIFORM (0.000342205, 0.000375, 0)
17. Crude oil consumption = Energy consumption * Ratio of crude oil consumption (Time)
18. Death rate = IF THEN ELSE (Time < 2020, (Fluctuation of the death rate (Time) * 0.75 + Overall trend of the death rate) * (1 + Elasticity of pollution index on death rate * Pollution Index), (Fluctuation of death rate after 2020 * 0.75 + Overall trend of the death rate) * (1 + Elasticity of pollution index on death rate * Pollution Index))
19. Decrease of arable land = Increase of built-up land * Proportion of built-up land increase from arable land (Time) + Increase of forest land * Proportion of forest land increase from arable land (Time) + Increase of grassland * Proportion of grassland increase from arable land (Time) + Transfer from arable land to other land (Time)
20. Decrease of built up land = Transfer from built-up land to other land (Time)
21. Decrease of forestland = Increase of built-up land * Proportion of built-up land increase from forestland (Time) + Increase of arable land * Proportion of arable land increase from forest land (Time) + Increase of grassland * Proportion of grassland increase from forest land (Time) + Transfer from forest land to other land (Time)
22. Decrease of grassland = IF THEN ELSE (Time < = 2020, Increase of built-up land * Proportion of built-up land increase from grassland before 2020 (Time) + Increase of forest land * Proportion of forest land increase from grassland (Time) + Increase of arable land * Proportion of arable land increase from grassland (Time) + Transfer from grassland to other land (Time), Increase of built-up land * Proportion of built-up land increase from grassland after 2020 + Increase of forest land * Proportion of forest land increase from grassland (Time) + Increase of arable land * Proportion of arable land increase from grassland (Time) + Transfer from grassland to other land (Time))
23. Decreased COD = Capacity of urban living wastewater treatment * COD concentration of living wastewater * Discharge of living wastewater * Proportion of urban population (Time)
24. Decreased SO2 = Produced SO2 * Self-purification capacity of air
25. Decreased solid waste = Produced solid waste * Capacity of solid waste treatment
26. Decreasing population = Death rate * 0.01 * Total population
27. Depreciation rate = 0.024
28. Discharge of industrial SO2 = Output of the secondary industry * Proportion of industrial in the secondary industry (Time) * Rate of industrial SO2 (Time)
29. Discharge of industrial wastewater = Output of the secondary industry * Proportion of industrial in the secondary industry (Time) * Rate of industrial wastewater (Time)
30. Discharge of living SO2 = Total population * SO2 per person (Time)
31. Discharge of living wastewater = Total population * Living wastewater per person (Time)
32. Domestic water consumption of rural population = Rural population * 0.001 * Rural domestic water consumption per capita (Time) * 365 * Water saving policy factor (institutional) (Time) * Water resource exploring policy factor (Time)
33. Domestic water consumption of urban population = Urban population * 0.001 * Urban domestic water consumption per capita (Time) * 365 * Water saving policy factor (institutional) (Time)

34. Domestic water consumption = Domestic water consumption of rural population + Domestic water consumption of urban population
35. Ecology water consumption = Area of urban green coverage (Time) * 15 * Rated irrigation water consumption per acre of irrigated green area (Time) * Water saving policy factor (institutional) (Time) + Water consumed for other ecological protection aims (Time)
36. Elasticity of environmental pollution on the primary industry = 0.00053
37. Elasticity of environmental pollution on the tertiary industry = 0.00026226
38. Elasticity of grain yield on birth rate = 1.37888
39. Elasticity of pollution index on death rate = 0.0171509
40. Elasticity of pollution index on the grain yield = 0.000287281
41. Elasticity of pollution on birth rate = 0.00714469
42. Elasticity of secondary industry capital = 0.377012
43. Elasticity of tertiary industry capital = 0.645727
44. Elasticity of the primary industry capital = 0.520321
45. Electricity consumption = Energy consumption * Ratio of electricity consumption (Time)
46. Energy consumption index = LN (Coal consumption + Electricity consumption * (1-The proportion of new energy in electricity consumption (Time))) * 0.072 + LN (Crude oil consumption) * 0.541 + LN (Natural gas consumption) * 0.387
47. Energy consumption = Total energy demand
48. Energy demand of people's living = Total population * Energy intensity of people's living (Time)
49. Energy demand of the industrial industry = Output of the secondary industry * Proportion of industrial in the secondary industry (Time) * Energy intensity of the secondary industry (Time)
50. Energy demand of the primary industry = Energy intensity of the primary industry (Time) * Output of the primary industry
51. Energy demand of the secondary industry = Output of the secondary industry * Energy intensity of the secondary industry (Time)
52. Energy demand of the tertiary industry = Energy intensity of the tertiary industry (Time) * Output of the tertiary industry
53. Energy intensity of people's living = ([(2000, 0) - (2030, 1)], (2000, 0.55), (2005, 0.4357), (2006, 0.42598), (2007, 0.37409), (2008, 0.377196), (2009, 0.334559), (2010, 0.3483), (2011, 0.3545), (2012, 0.37617), (2013, 0.384), (2014, 0.40199), (2015, 0.4445), (2016, 0.4561), (2017, 0.4706), (2019, 0.50983), (2030, 0.7462))
54. Energy intensity of the primary industry = ([(2000, 0) - (2030, 20)], (2000, 13), (2005, 11.1655), (2006, 10.7948), (2007, 8.65908), (2008, 7.09909), (2009, 11.3541), (2010, 9.01143), (2011, 7.98024), (2012, 7.31827), (2013, 6.5001), (2014, 6.481), (2015, 7.5164), (2016, 8.08666), (2017, 6.64822), (2018, 5.86096), (2030, 5))
55. Energy intensity of the secondary industry = ([(2000, 0) - (2030, 300)], (2000, 155), (2005, 145.404), (2006, 147.855), (2007, 133.527), (2008, 110.264), (2009, 114.364), (2010, 92.9158), (2011, 93.7754), (2012, 93.2512), (2013, 88.3728), (2014, 86.7378), (2015, 87.5413), (2016, 78.6609), (2017, 81.1228), (2018, 80.5555), (2030, 69.8363))
56. Energy intensity of the tertiary industry = ([(2000, 0) - (2030, 60)], (2000, 59), (2005, 48.6166), (2006, 43.272), (2007, 42.3607), (2008, 36.1716), (2009, 35.2499), (2010, 32.1768), (2011, 29.1087), (2012, 27.8737), (2013, 22.5472), (2014, 21.468), (2015, 21.8726), (2016, 22.0124), (2017, 22.9335), (2018, 22.4716), (2019, 22.47), (2030, 15.6921))
57. Environmental protection investment = Total output * Rate of environmental protection investment (Time) * 100
58. Exploring water resource and other factors ([(0, 0) - (2030, 10)], (2000, 0), (2015, 0), (2020, 1.89), (2030, 2.56))
59. Fixed assets investment from outside = ([(2000, 0) - (2030, 100000)], (2000, 1504), (2001, 2364.31), (2002, 2645), (2003, 1918.76), (2004, 2518), (2005, 2089.8), (2006, 3676), (2007, 3909), (2008, 6655), (2009, 9044), (2010, 9899.64), (2011, 15198.3), (2012, 21461.5), (2013, 35490.2), (2014, 38398.3), (2015, 37259), (2016, 64029.6), (2017, 49089.5), (2018, 26942), (2019, 20639), (2020, 9358), (2023, 0), (2030, 0))
60. Fluctuation of birth rate after 2020 = RANDOM UNIFORM (-0.6, 0.3, 0.5)
61. Fluctuation of death rate after 2020 = RANDOM UNIFORM (-1, 0.8, 0.5)
62. Fluctuation of immigration rate after 2020 = RANDOM UNIFORM (-2, 2, 0.5)
63. Fluctuation of the birth rate = ([(0, -3) - (2030, 10)], (2000, -0.0019), (2001, 2.4682), (2002, -1.2417), (2003, -0.9716), (2004, 0.00885), (2005, 0.1586), (2006, -0.9013), (2007, 0.1788), (2008, -0.6211), (2009, 0.251), (2010, 0.1309), (2011, 0.3792), (2012, 0.7093), (2013, 0.1394), (2014, 0.2673), (2015, 0.0744), (2016, -0.6561), (2017, 0.3122), (2018, 0.3005), (2019, -0.1512), (2020, 0), (2030, 0))
64. Fluctuation of the death rate = ([(0, -2) - (2019, 10)], (2000, 0.8297), (2001, 0.6832), (2002, -0.0533), (2003, -0.3598), (2004, 0.1337), (2005, 0.4072), (2006, -0.0893), (2007, -0.7358), (2008, -0.9023), (2009, -0.1588), (2010, -1.0253), (2011, 0.1182), (2012, 0.6617), (2013, -0.8548), (2014, -0.0313), (2015, -0.0378), (2016, 0.3057), (2017, 0.8292), (2018, 0.4277), (2019, -0.0638))
65. Fluctuation of the immigration rate = ([(2000, -4) - (2019, 10)], (2000, -0.32), (2001, -2.64), (2002, 0.68), (2003, 0.08), (2004, 0.2), (2005, 0.57), (2006, 1.26), (2007, 0.33), (2008, 0.66), (2009, 0.19), (2010, -0.75), (2011, 1.94), (2012, 1.5), (2013, 0.92), (2014, -1.63), (2015, 1.1), (2016, 0.28), (2017, -0.95), (2018, -1.34), (2019, 1.34))
66. Forest land = INTEG (Increase of forest land-Decrease of forestland, 412.871)
67. Grain planting rates = ([(2000, 0) - (2030, 0.7)], (2000, 0.4945), (2001, 0.461), (2002, 0.4286), (2003, 0.3875), (2004, 0.3534), (2005, 0.369), (2006, 0.3656), (2007, 0.3739), (2008, 0.3284), (2009, 0.3328), (2010, 0.3245), (2011, 0.3313), (2012, 0.3302), (2013, 0.3379), (2014, 0.3372), (2015, 0.3498), (2016, 0.3794), (2017, 0.4184), (2018, 0.455), (2019, 0.4433), (2020, 0.4721), (2030, 0.6868))
68. Grain yield per capita = Grain yield / Total population
69. Grain yield per unit area = ([(2000, 0) - (2030, 2000)], (2000, 265.285), (2001, 349.401), (2002, 312.802), (2003, 334.065), (2004, 333.966), (2005, 365.265), (2006, 343.852), (2007, 378.862), (2008, 423.049), (2009, 418.672), (2010, 397.127), (2011, 402.69), (2012, 418.365), (2013, 413.659), (2014, 413), (2015, 398.262), (2016, 434.479), (2017, 426.617), (2018, 382.767), (2019, 395.495), (2020, 387.133), (2030, 385))
70. Grain yield = Arable land * Grain planting rates (Time) * (Grain yield per unit area (Time) / (1 + Elasticity of pollution index on the grain yield * Pollution Index))
71. Grassland = INTEG (Increase of grassland-Decrease of grassland, 5062.8)
72. Increasement of proven reserves = Proven reserves of mineral resources * Proven reserves growth rates (Time)
73. Increase of arable land = Increase rate of arable land (Time) * Arable land
74. Increase of built-up land = IF THEN ELSE ((Built-up land in demand-Built-up areas) > = 0, Built-up land in demand-Built-up areas, 0)
75. Increase of forest land = Forest land * Increase rate of forest land (Time)
76. Increase of grassland = Increase rate of grassland (Time) * Grassland

77. Increase rate of arable land = ([(2000, 0) - (2030, 0.05)], (2000, 0.015341), (2004, 0.01534), (2005, 0.012087), (2009, 0.01209), (2010, 0.005912), (2014, 0.005912), (2015, 0.011328), (2019, 0.011328), (2030, 0.0217))
78. Increase rate of forest land = ([(0, -0.0005) - (2030, 10)], (2000, 0.008225), (2004, 0.008225), (2005, 0.03012), (2009, 0.03012), (2010, 0.01096), (2014, 0.010957), (2015, 0.016475), (2019, 0.01647), (2030, 0.0248))
79. Increase rate of grassland = ([(2000, 0) - (2030, 0.05)], (2000, 0.007597), (2004, 0.007597), (2005, 0.006422), (2009, 0.006422), (2010, 0.016832), (2014, 0.01683), (2015, 0.015866), (2019, 0.015866), (2030, 0.015))
80. Increasing population = (Birth rate + Net immigration rate) * 0.01 * Total population
81. Industrial water consumption = Rate of industrial water consumption (Time) * 100 * Output of the secondary industry * Proportion of industrial in the secondary industry (Time) * Water saving policy factor (technical investment) (Time) * Water saving policy factor (institutional) (Time) * Water resource exploring policy factor (Time)
82. Initial capital stock of the primary industry = 700
83. Initial capital stock of the secondary industry = 9000
84. Initial capital stock of the tertiary industry = 22000
85. Irrigation water consumption per acre of arable land = ([(2000, 0) - (2030, 800)], (2000, 774.683), (2000, 644), (2001, 708.113), (2002, 682.038), (2003, 727.149), (2004, 712.646), (2005, 714.352), (2006, 732.868), (2007, 678.543), (2008, 713.328), (2009, 691.862), (2010, 644), (2011, 653), (2012, 528), (2013, 523), (2014, 521), (2015, 534), (2016, 536), (2017, 525), (2018, 468), (2019, 485), (2020, 486), (2030, 486))
86. Labour force ratio of the primary industry = ([(2000, 0) - (2030, 1)], (2000, 0.454), (2001, 0.431), (2002, 0.398), (2003, 0.374), (2004, 0.363), (2005, 0.345), (2006, 0.283), (2007, 0.257), (2008, 0.242), (2009, 0.243), (2010, 0.231), (2011, 0.199), (2012, 0.196), (2013, 0.195), (2014, 0.191), (2015, 0.182), (2016, 0.17418), (2017, 0.168), (2018, 0.167), (2019, 0.157), (2025, 0.3), (2030, 0.12))
87. Labour force ratio of the tertiary industry = ([(2000, 0) - (2030, 1)], (2000, 0.312), (2001, 0.359), (2002, 0.388), (2003, 0.401), (2004, 0.406), (2005, 0.418), (2006, 0.457), (2007, 0.481), (2008, 0.474), (2010, 0.474), (2011, 0.49), (2012, 0.486), (2013, 0.529), (2014, 0.53), (2015, 0.556), (2016, 0.57295), (2017, 0.591), (2018, 0.609), (2019, 0.633), (2030, 0.8))
88. Labour force ratio = ([(2000, 0) - (2030, 1)], (2000, 0.479), (2001, 0.5), (2002, 0.513), (2003, 0.533), (2004, 0.534), (2005, 0.55), (2006, 0.556), (2007, 0.563), (2008, 0.57), (2009, 0.57), (2010, 0.577), (2011, 0.597), (2012, 0.558), (2013, 0.559), (2014, 0.559), (2015, 0.561), (2016, 0.561), (2017, 0.56), (2018, 0.56), (2019, 0.558), (2020, 0.58), (2030, 0.583))
89. Living wastewater per person ([(2000, 0) - (2030, 40)], (2000, 26), (2005, 23.96), (2006, 26.1053), (2007, 22.9385), (2008, 22.4669), (2009, 21.9235), (2010, 23.3136), (2011, 31.55), (2012, 32.83), (2013, 33.8), (2014, 33.34), (2015, 33.68), (2019, 33), (2030, 32))
90. Mineral resource pressure index = LN (Output of minerals) / LN (Proven reserves of mineral resources)
91. Mining volume per unit output = ([(2000, 0) - (2030, 10)], (2000, 2.2), (2002, 2.17787), (2003, 2.49401), (2004, 1.91996), (2005, 2.08101), (2007, 1.62967), (2008, 0.809071), (2010, 0.552224), (2011, 0.612045), (2012, 0.502387), (2013, 0.779471), (2019, 0.65104), (2030, 0.7676))
92. Natural gas consumption = Energy consumption * Ratio of natural gas consumption
93. Net emission of COD = Produced COD-Decreased COD
94. Net emission of SO2 = Produced SO2-Decreased SO2
95. Net emission of solid waste = Produced solid waste-Decreased solid waste
96. Net immigration rate = IF THEN ELSE (Time < 2020, Fluctuation of the immigration rate (Time) + Overall trend of the net immigration rate, Fluctuation of immigration rate after 2020 + Overall trend of the net immigration rate)
97. New energy consumption = The proportion of new energy in electricity consumption (Time) * Electricity consumption
98. Non-agricultural output = Output of the tertiary industry + Output of the secondary industry
99. Other agricultural water consumption = Output of forestry and animal husbandry * Rate of water consumption of forestry and animal husbandry (Time) * Water resource exploring policy factor (Time) * Water saving policy factor (institutional) (Time) * Water saving policy factor (technical investment) (Time)
100. Other factors affecting the primary industry = ([(2000, 0) - (2030, 5)], (2000, 1.018), (2001, 0.978), (2002, 0.879), (2003, 0.841), (2004, 0.954), (2005, 0.975), (2006, 0.978), (2007, 1.133), (2008, 1.335), (2009, 1.183), (2010, 1.123), (2011, 1.143), (2012, 1.154), (2013, 1.258), (2014, 1.132), (2015, 1), (2016, 0.924), (2017, 0.967), (2018, 0.894), (2019, 0.912), (2020, 0.936), (2030, 0.7799))
101. Other factors affecting the secondary industry = ([(2000, 0) - (2030, 10)], (2000, 0.999), (2001, 1.071), (2002, 1.068), (2003, 1.194), (2004, 1.298), (2005, 1.376), (2006, 1.467), (2007, 1.658), (2008, 1.827), (2009, 1.718), (2010, 1.683), (2011, 1.84), (2012, 1.872), (2013, 2.117), (2014, 2.023), (2015, 1.955), (2016, 2.014), (2017, 1.949), (2018, 1.73), (2019, 1.812), (2020, 1.88), (2030, 2.0996))
102. Other factors affecting the tertiary industry = ([(0, 0) - (2030, 1000)], (2000, 1.006), (2001, 0.927), (2002, 0.915), (2003, 0.911), (2004, 0.928), (2005, 0.937), (2006, 0.948), (2007, 1.009), (2008, 1.115), (2009, 1.159), (2010, 1.036), (2011, 1.038), (2012, 1.021), (2013, 1.045), (2014, 0.976), (2015, 0.922), (2016, 0.875), (2017, 0.903), (2018, 1.074), (2019, 1.048), (2020, 0.941), (2027, 1.048), (2030, 1.048))
103. Other land = 7659.99 - Built-up areas - Arable land - Forest land - Grassland
104. Output of forestry and animal husbandry = Output of the primary industry * Proportion of forestry and animal husbandry in the primary industry (Time)
105. Output of minerals = INTEG (Added value of mineral output, 400)
106. Output of the primary industry = 1415.66 * Technical and other factors affecting the primary industry / (1 + Elasticity of environment pollution on the primary industry * Pollution Index) * (The stock of the primary industrial fixed assets / Initial capital stock of the primary industry) ˆElasticity of the primary industry capital * ((Labour force ratio of the primary industry (Time) * Total labour force) / 43.07) ˆ (1-Elasticity of the primary industry capital)
107. Output of the secondary industry = 16868.9 * (Technical and other factors affecting the secondary industry * (The stock of the secondary industrial fixed assets / Initial capital stock of the secondary industry) ˆElasticity of secondary industry capital * ((1-Labour force ratio of the primary industry (Time) -Labour force ratio of the tertiary industry (Time)) * Total labour force / 22.15) ˆ (1-Elasticity of secondary industry capital))
108. Output of the tertiary industry = 11849.5 * Technical and other factors affecting the tertiary industry * (The stock of the tertiary industrial fixed assets / Initial capital stock of the tertiary industry) ˆElasticity of tertiary industry capital * (Labour force ratio of the tertiary industry (Time) * Total labour force / 29.57) ˆ (1-Elasticity of tertiary industry capital) / (1 + Pollution Index * Elasticity of environmental pollution on the tertiary industry)
109. Output per capita = Total output / Total population

110. Output value of mining industry = Output of the secondary industry * Proportion of mining industry in the industrial industry (Time) * Proportion of industrial in the secondary industry (Time)
111. Overall educational level of Xining = ([(2000, 0) - (2030, 10)], (2000, 1), (2001, 1.017), (2002, 1.034), (2003, 1.051), (2004, 1.067), (2005, 1.084), (2006, 1.101), (2007, 1.118), (2008, 1.135), (2009, 1.152), (2010, 1.169), (2011, 1.178), (2012, 1.188), (2013, 1.198), (2014, 1.207), (2015, 1.217), (2016, 1.227), (2017, 1.236), (2018, 1.246), (2019, 1.256), (2020, 1.265), (2030, 1.3689))
112. Overall trend of the birth rate = IF THEN ELSE (Time < 2014, -(Time-1999) * 0.301 + 14.362, IF THEN ELSE (Time < = 2020, -(Time-1999) * 0.0583 + 14, - (Time-1999) * 0.0583 + 14))
113. Overall trend of the death rate = (Time-1999) * 0.0155 + 3.5
114. Overall trend of the net immigration rate = IF THEN ELSE (Time < 2020, (Time-1999) * 0.127-7.1657, (Time-1999) * 0.127-7.1657)
115. Pollution Index = Air pollution coefficient * LN (SO2 accumulation) + Water pollution coefficient * LN (COD accumulation) + Solid waste pollution coefficient * LN (Solid waste accumulation)
116. Precipitation = ([(2000, 0) - (2030, 60)], (2000, 33.3), (2001, 33.8), (2002, 32.4), (2003, 44.3), (2004, 39.4), (2005, 40.5), (2006, 40.1), (2007, 44.4), (2008, 37.3), (2009, 43.3), (2010, 39.8), (2011, 41.6), (2012, 45.3), (2013, 34.4), (2014, 46.6), (2015, 35.5), (2016, 43), (2017, 43.71), (2018, 46), (2019, 45.9), (2020, 45.9), (2030, 50))
117. Produced COD = Discharge of industrial wastewater * COD concentration of industrial wastewater + Discharge of living wastewater * COD concentration of living wastewater
118. Produced SO2 = Discharge of industrial SO2 + Discharge of living SO2
119. Produced solid waste = Output of the secondary industry * Rate of industrial solid waste (Time) * Proportion of industrial in the secondary industry (Time)
120. Production = Total output - Environmental protection investment * 0.01
121. Proportion of arable land increase from forest land = ([(2000, 0) - (2030, 0.006)], (2000, 0.002245), (2004, 0.002245), (2005, 0.00124), (2009, 0.00124), (2010, 0.004776), (2014, 0.004776), (2015, 0.001855), (2019, 0.001855), (2030, 0.0007))
122. Proportion of arable land increase from grass land = ([(0, 0) - (2030, 10)], (2000, 0.997236), (2004, 0.9972), (2005, 0.998201), (2009, 0.9982), (2010, 0.992252), (2014, 0.9923), (2015, 0.997101), (2019, 0.997101), (2030, 0.9993))
123. Proportion of built-up land increase from arable land = ([(2000, 0) - (2030, 0.5)], (2000, 0.077178), (2004, 0.07718), (2005, 0.062261), (2009, 0.06226), (2010, 0.302905), (2014, 0.3029), (2015, 0.165171), (2019, 0.1652), (2030, 0.0901))
124. Proportion of built-up land increase from forestland = ([(0, 0) - (2030, 10)], (2000, 0), (2014, 0), (2015, 0), (2019, 0), (2030, 0))
125. Proportion of built-up land increase from grassland after 2020 = 1-Proportion of built-up land increase from arable land (Time) -Proportion of built-up land increase from forestland (Time)
126. Proportion of built-up land increase from grassland before 2020 = ([(0, 0) - (2030, 10)], (2000, 0.585062), (2004, 0.5851), (2005, 0.842329), (2009, 0.8423), (2010, 0.522822), (2014, 0.5228), (2015, 0.802513), (2019, 0.802513), (2020, 0), (2030, 0))
127. Proportion of effective irrigated arable land = ([(2000, 0) - (2030, 0.3)], (2000, 0.189766), (2004, 0.189766), (2005, 0.18826), (2006, 0.1876), (2007, 0.1892), (2008, 0.186), (2009, 0.1866), (2010, 0.2055), (2011, 0.213089), (2012, 0.161036), (2013, 0.173032), (2014, 0.187799), (2015, 0.188411), (2016, 0.19569), (2017, 0.175068), (2018, 0.197), (2030, 0.197))
128. Proportion of forest land increase from arable land = ([(2000, 0) - (2030, 0.2)], (2000, 0.004843), (2004, 0.004843), (2005, 0.004783), (2009, 0.004783), (2010, 0.01569), (2014, 0.01569), (2015, 0.048599), (2019, 0.0476), (2030, 0.1505))
129. Proportion of forest land increase from grassland = ([(2000, 0) - (2030, 1)], (2000, 0.593068), (2004, 0.5931), (2005, 0.538449), (2009, 0.5384), (2010, 0.601823), (2014, 0.6018), (2015, 0.715653), (2019, 0.715653), (2030, 0.7895))
130. Proportion of forestry and animal husbandry in the primary industry = ([(2000, 0) - (2030, 100)], (2000, 40.96), (2001, 42.52), (2002, 46.62), (2003, 46.31), (2004, 51.43), (2005, 52.38), (2006, 50.57), (2007, 50.69), (2008, 53.31), (2009, 51.2), (2010, 43.89), (2011, 47.32), (2012, 48.8), (2013, 48.61), (2014, 50.47), (2015, 49.36), (2016, 50.51), (2017, 51.95), (2018, 54.31), (2019, 55.79), (2020, 58.06), (2030, 75))
131. Proportion of grass land increase from forest land = ([(2000, 0) - (2030, 0.01)], (2000, 0.005798), (2004, 0.005798), (2005, 0.000884), (2009, 0.000884), (2010, 0.001299), (2014, 0.001299), (2015, 0.000589), (2019, 0.000589), (2030, 0.0002673))
132. Proportion of grassland increase from arable land = ([(2000, 0) - (2030, 2)], (2000, 0.653242), (2004, 0.6532), (2005, 0.817975), (2009, 0.818), (2010, 0.792185), (2014, 0.7922), (2015, 0.935174), (2019, 0.935174), (2030, 0.97))
133. Proportion of industrial in the secondary industry = ([(2000, 0) - (2030, 1)], (2000, 0.77), (2001, 0.72), (2002, 0.72), (2003, 0.63), (2004, 0.64), (2005, 0.69), (2006, 0.74), (2007, 0.79), (2008, 0.83), (2009, 0.77), (2010, 0.81), (2011, 0.81), (2012, 0.81), (2013, 0.78), (2014, 0.77), (2015, 0.76), (2016, 0.75), (2017, 0.74), (2018, 0.65), (2019, 0.65), (2020, 0.66), (2030, 0.65))
134. Proportion of mining industry in the industrial industry = ([(2000, 0) - (2030, 0.05)], (2000, 0.047098), (2002, 0.0443766), (2003, 0.0431615), (2004, 0.0244556), (2005, 0.0233883), (2007, 0.0199377), (2008, 0.0298085), (2010, 0.0206872), (2011, 0.0134663), (2012, 0.0136951), (2013, 0.0105594), (2015, 0.004519), (2019, 0.004519), (2030, 0.004))
135. Proportion of new energy consumption = New energy consumption / Energy consumption
136. Proportion of non-agricultural industries in the total output = Non-agricultural output / Total output
137. Proportion of the secondary industry in total output = Output of the secondary industry / Total output
138. Proportion of the tertiary industry in total output = Output of the tertiary industry / Total output
139. Proportion of urban population = ([(2000, 0.5) - (2030, 1)], (2000, 0.5657), (2000, 0.5657), (2001, 0.5684), (2002, 0.557157), (2003, 0.574182), (2004, 0.575957), (2005, 0.58818), (2006, 0.59592), (2007, 0.600111), (2008, 0.610221), (2009, 0.613515), (2010, 0.636981), (2011, 0.654354), (2012, 0.677227), (2013, 0.677986), (2014, 0.686035), (2015, 0.690476), (2016, 0.677227), (2017, 0.677986), (2018, 0.686035), (2019, 0.690476), (2020, 0.786305), (2030, 0.8))
140. Proven reserves growth rates = ([(2000, -0.1) - (2030, 0.5)], (2000, -0.00108), (2002, -0.00108), (2003, 0.00186), (2004, 0.00747), (2005, 0.0077), (2006, 0.0077), (2007, -0.03134), (2008, 0.00198), (2009, 0.00197), (2010, 0.00197), (2011, 0.02401), (2012, -0.06651), (2030, 0.002086))
141. Proven reserves of mineral resources = INTEG (Increasement of proven reserves, 1.9597e + 006)
142. Rate of built-up land in demand of non-agricultural output = ([(0, 0) - (2030, 10)], (2000, 0.000185), (2001, 0.00017719), (2002, 0.0001694), (2003, 0.00015055), (2004, 0.0001371), (2005, 0.0001554), (2006, 0.0001568), (2007, 0.000159), (2008, 0.000127), (2009, 0.00011936), (2010, 0.00011), (2011, 8.9462e-005), (2012, 8.0594e-005), (2013, 6.803e005), (2014, 6.2107e-005), (2015, 5.8068e-005), (2016, 5.2082e-005), (2017,

4.7788e-005), (2018, 4.395e-005), (2019, 4.2373e-005), (2030, 1.632e-005))

143. Rate of environmental protection investment = ([(2000, 0) - (2030, 0.01)], (2000, 0.0055), (2005, 0.006442), (2006, 0.006459), (2007, 0.007052), (2008, 0.008272), (2009, 0.007211), (2010, 0.009436), (2011, 0.0075216), (2012, 0.00663689), (2013, 0.00987539), (2014, 0.00634924), (2015, 0.0062746), (2016, 0.00503912), (2017, 0.00435136), (2018, 0.00372708), (2019, 0.0037155), (2020, 0.0033938), (2030, 0.0012))
144. Rate of fixed assets investment = ([(2000, 0) - (2030, 0.8)], (2000, 0.1407), (2001, 0.1472), (2002, 0.143299), (2003, 0.149485), (2004, 0.140042), (2005, 0.154379), (2006, 0.142103), (2007, 0.154288), (2008, 0.135599), (2009, 0.182365), (2010, 0.230278), (2011, 0.231263), (2012, 0.268148), (2013, 0.264392), (2014, 0.33694), (2015, 0.36573), (2016, 0.269356), (2017, 0.35842), (2018, 0.154284), (2019, 0.170697), (2020, 0.140271), (2030, 0.0855))
145. Rate of industrial SO2 = ([(2000, 0) - (2030, 5)], (2000, 1.053), (2001, 1.27882), (2002, 1.06106), (2003, 2.307), (2004, 1.94867), (2005, 2.6667), (2006, 2.07576), (2007, 1.479), (2008, 1.0637), (2009, 1.1571), (2010, 1.01592), (2011, 0.793219), (2012, 0.698), (2013, 0.618869), (2014, 0.536058), (2015, 0.4504), (2019, 0.4504), (2030, 0.1997))
146. Rate of industrial solid waste = ([(2000, 0) - (2030, 80)], (2000, 50.247), (2001, 68.2057), (2002, 50.037), (2003, 57.6831), (2004, 54.3927), (2005, 69.9115), (2006, 47.0488), (2007, 43.2513), (2008, 37.0446), (2009, 41.09), (2010, 56.648), (2011, 54.904), (2012, 49.364), (2013, 46.347), (2014, 43.513), (2015, 36.669), (2019, 36.67), (2030, 23.7368))
147. Rate of industrial wastewater = ([(2000, 0) - (2030, 2000)], (2000, 1835.18), (2001, 1749.36), (2002, 1497.73), (2003, 1228.59), (2004, 961.099), (2005, 1650.14), (2006, 1191.9), (2007, 928.518), (2008, 652.458), (2009, 721.048), (2010, 564.88), (2011, 344.544), (2012, 311.3), (2013, 241.038), (2014, 205.12), (2015, 171.75), (2019, 171.8), (2030, 52.2486)) Ton / Hundred million yuan
148. Rate of industrial water consumption = ([(2000, 0) - (2030, 200)], (2000, 160.141), (2001, 163.446), (2002, 147.975), (2003, 120.142), (2004, 118.673), (2005, 98.4004), (2006, 82.4465), (2007, 74.4945), (2008, 32.1232), (2009, 23.423), (2010, 22.0697), (2011, 17.4442), (2012, 9.01351), (2013, 8.97477), (2014, 8.13898), (2015, 8.40639), (2016, 6.40257), (2017, 7.05103), (2018, 8.08356), (2019, 7.51361), (2020, 4.756), (2020, 4.75599), (2030, 4.756))
149. Rate of water consumption of forestry and animal husbandry = ([(2000, 0) - (2030, 700)], (2000, 532.893), (2001, 495.85), (2002, 463.164), (2003, 600.68), (2004, 457.775), (2005, 363.273), (2006, 399.695), (2007, 311.603), (2008, 236.516), (2009, 244.421), (2010, 310.337), (2011, 283.026), (2012, 289.419), (2013, 230.582), (2014, 213.845), (2015, 218.524), (2016, 238.103), (2017, 335.108), (2018, 345.294), (2019, 321.294), (2020, 280.034), (2030, 280))
150. Rated irrigation water consumption per acre of irrigated green area = ([(0, 0) - (2030, 200)], (2000, 200), (2020, 200), (2030, 200))
151. Ratio of coal consumption = ([(2000, 0) - (2030, 1)], (2000, 0.3018), (2001, 0.2802), (2002, 0.2642), (2003, 0.2872), (2004, 0.2756), (2005, 0.442), (2006, 0.4518), (2007, 0.4756), (2008, 0.4372), (2009, 0.4299), (2010, 0.3414), (2011, 0.2858), (2012, 0.3143), (2013, 0.3167), (2014, 0.2977), (2015, 0.3253), (2016, 0.3628), (2017, 0.3212), (2018, 0.3009), (2019, 0.2915), (2030, 0.2489))
152. Ratio of crude oil consumption = ([(2000, 0) - (2030, 0.52025)], (2000, 0.1896), (2001, 0.1805), (2002, 0.1577), (2003, 0.1347), (2004, 0.1407), (2005, 0.0863), (2006, 0.0775), (2007, 0.0809), (2008, 0.0895), (2009, 0.0779), (2010, 0.0761), (2011, 0.1068), (2012, 0.094), (2013, 0.0824), (2014, 0.0821), (2015, 0.0852), (2016, 0.0992), (2017, 0.1112), (2018, 0.1029), (2019, 0.1087), (2030, 0.1553))
153. Ratio of electricity consumption = ([(2000, 0) - (2030, 2)], (2000, 0.4603), (2001, 0.4641), (2002, 0.4456), (2003, 0.4274), (2004, 0.4258), (2005, 0.3917), (2006, 0.3861), (2007, 0.3606), (2008, 0.3513), (2009, 0.3653), (2010, 0.4704), (2011, 0.4777), (2012, 0.4457), (2013, 0.4614), (2014, 0.4916), (2015, 0.4467), (2016, 0.3883), (2017, 0.4107), (2018, 0.4369), (2019, 0.43), (2030, 0.4041))
154. Ratio of natural gas consumption = 1-Ratio of coal consumption (Time) -Ratio of crude oil consumption (Time) -Ratio of electricity consumption (Time)
155. Ratio of water consumption and amount of water resource = Actual consumption of water resource / Total amount of water resource
156. Recycle water = ([(2000, 0) - (2030, 0.5)], (2000, 0), (2013, 0), (2014, 0.0144), (2015, 0.0301), (2016, 0.0301), (2017, 0.0793), (2018, 0.106), (2019, 0.2991), (2020, 0.1974), (2030, 0.1974))
157. Rural domestic water consumption per capita = ([(2000, 0) - (2030, 300)], (2000, 56.1652), (2001, 69.8838), (2002, 59.6334), (2011, 90), (2012, 50), (2013, 50), (2014, 57), (2015, 56), (2016, 71), (2017, 73), (2018, 64), (2019, 71), (2020, 95), (2030, 95))
158. Rural population = Total population * (1-Proportion of urban population (Time))
159. Self-purification capacity of air = 0.247 / LN (7659.99- (Other land + Forest land + Grassland))
160. Self-purification capacity of COD = 0.392 / LN (7659.99- (Other land + Forest land + Grassland))
161. SO2 accumulation = INTEG (Produced SO2-Decreased SO2, 75000)
162. SO2 per person = ([(2000, 0) - (2030, 0.02)], (2000, 0.0007), (2005, 0.000747), (2006, 0.000782), (2008, 0.001048), (2009, 0.001068), (2010, 0.001193), (2011, 0.00267729), (2012, 0.00304975), (2013, 0.00314385), (2014, 0.00360545), (2015, 0.00361385), (2019, 0.003614), (2030, 0.00728))
163. Solid waste accumulation = INTEG (Produced solid waste-Decreased solid waste, 500000)
164. Solid waste pollution coefficient = 0.66
165. Technical and other factors affecting the primary industry = Other factors affecting the primary industry (Time) * Overall educational level of Xining (Time)
166. Technical and other factors affecting the secondary industry = Other factors affecting the secondary industry (Time) * Overall educational level of Xining (Time)
167. Technical and other factors affecting the tertiary industry = Other factors affecting the tertiary industry (Time) * Overall educational level of Xining (Time)
168. The primary industrial depreciation = Depreciation rate * The stock of the primary industrial fixed assets
169. The primary industrial investment = Total fixed assets investment * The proportion of the primary industrial investment (Time)
170. The proportion of new energy in electricity consumption = ([(2000, 0) - (2030, 1)], (2000, 0.7), (2005, 0.7976), (2010, 0.8415), (2015, 0.81), (2018, 0.865), (2030, 0.8892))
171. The proportion of the primary industrial investment = ([(2000, 0) - (2030, 0.1)], (2000, 0.034471), (2001, 0.02933), (2002, 0.018), (2003, 0.014122), (2004, 0.017014), (2005, 0.033651), (2006, 0.034636), (2007, 0.029645), (2008, 0.036119), (2009, 0.040848), (2010, 0.037562), (2011, 0.030784), (2012, 0.026685), (2013, 0.029816), (2014, 0.038965), (2015, 0.041315), (2016, 0.019538), (2017, 0.026012), (2018, 0.028709), (2019, 0.01405), (2020, 0.0128941), (2030, 0.0044))

172. The proportion of the secondary industrial investment = ([(2000, 0) - (2030, 1)], (2000, 0.236255), (2001, 0.257912), (2002, 0.3477), (2003, 0.336787), (2004, 0.364941), (2005, 0.408696), (2006, 0.454077), (2007, 0.472609), (2008, 0.462148), (2009, 0.441686), (2010, 0.482649), (2011, 0.514066), (2012, 0.505669), (2013, 0.486742), (2014, 0.450161), (2015, 0.454733), (2016, 0.3385), (2017, 0.304851), (2018, 0.188026), (2019, 0.183679), (2020, 0.138433), (2030, 0.0397))
173. The proportion of the tertiary industrial investment = 1-The proportion of the secondary industrial investment (Time) -The proportion of the primary industrial investment (Time)
174. The secondary industrial depreciation = Depreciation rate * The stock of the secondary industrial fixed assets
175. The secondary industrial investment = The proportion of the secondary industrial investment (Time) * Total fixed assets investment
176. The stock of the primary industrial fixed assets = INTEG (The primary industrial investment-The primary industrial depreciation, Initial capital stock of the primary industry)
177. The stock of the secondary industrial fixed assets = INTEG (The secondary industrial investment-The secondary industrial depreciation, Initial capital stock of the secondary industry)
178. The stock of the tertiary industrial fixed assets = INTEG (The tertiary industrial investment-The tertiary industrial depreciation, Initial capital stock of the tertiary industry)
179. The tertiary industrial depreciation = Depreciation rate * The stock of the tertiary industrial fixed assets
180. The tertiary industrial investment = The proportion of the tertiary industrial investment * Total fixed assets investment
181. Total amount of water resource = (0.4957 * Precipitation (Time) - 7.139 + Exploring water resource and other factors (Time)) * 1e + 008
182. Total energy demand = Energy demand of people's living + Energy demand of the secondary industry + Energy demand of the tertiary industry + Energy demand of the primary industry
183. Total fixed assets investment = Total output lagged * Rate of fixed assets investment (Time) + Fixed assets investment from outside (Time)
184. Total labour force = Labour force ratio (Time) * Total population / 10000
185. Total output lag = INTEG (Production-Total output lagged, 21321.4)
186. Total output lagged = Total output lag
187. Total output = Output of the primary industry + Output of the secondary industry + Output of the tertiary industry
188. Total population = INTEG (Increasing population - Decreasing population, 1.9792 * 10^6)
189. Transfer from arable land to other land = ([(2000, 0) - (2030, 1)], (2000, 0.277555), (2004, 0.277555), (2005, 0.072686), (2009, 0.07269), (2010, 0.079586), (2014, 0.07959), (2015, 0.071919), (2019, 0.071919), (2030, 0.08))
190. Transfer from built-up land to other land = ([(2000, 0) - (2030, 0.005)], (2000, 0.00138), (2004, 0.00138), (2005, 0.002607), (2009, 0.002607), (2010, 0.002607), (2014, 0.002607), (2015, 0.000767), (2019, 0.000767), (2030, 0.00075))
191. Transfer from forest land to other land = ([(2000, 0) - (2030, 10)], (2000, 4.32786), (2004, 4.328), (2005, 1.48024), (2009, 1.48), (2010, 1.92862), (2014, 1.9286), (2015, 6.43712), (2019, 6.43712), (2030, 7))
192. Transfer from grassland to other land = ([(2000, 0) - (2030, 20)], (2000, 5.72698), (2004, 5.72698), (2005, 8.04126), (2009, 8.04126), (2010, 5.62976), (2014, 5.62976), (2015, 16.1238), (2019, 16.1238), (2030, 17))
193. Urban domestic water consumption per capita = ([(2000, 0) - (2030, 300)], (2000, 224.522), (2001, 222.91), (2002, 221.508), (2003, 150), (2011, 124), (2012, 80), (2013, 80), (2014, 86), (2015, 89), (2016, 111), (2017, 109), (2018, 114), (2019, 115), (2020, 100), (2030, 100))
194. Urban population = Total population * Proportion of urban population (Time)
195. Urban public service water consumption per urban capita = ([(2000, 0) - (2030, 100)], (2000, 25), (2003, 25.91), (2004, 26.7), (2005, 25.9), (2006, 20.08), (2007, 25.03), (2008, 22.57), (2009, 22.94), (2010, 23.48), (2011, 25.1), (2012, 44.62), (2013, 48.13), (2014, 47.75), (2015, 44.49), (2016, 40.18), (2017, 39.97), (2018, 43.7), (2019, 41.17), (2020, 26.75), (2030, 26.75))
196. Urban public service water consumption = Urban public service water consumption per urban capita (Time) * Urban population * Water saving policy factor (institutional) (Time) * Water saving policy factor (technical investment) (Time)
197. Water consumed for other ecological protection aims = ([(2000, 0) - (2030, 2e + 008)], (2000, 3.4e + 006), (2003, 3.98071e + 006), (2004, 3.99429e + 006), (2005, 3.99786e + 006), (2006, 9.71143e + 006), (2007, 1.0995e + 007), (2008, 4.53e + 006), (2009, 3.45e + 006), (2010, 3.525e + 006), (2011, 5.715e + 006), (2012, 3.219e + 006), (2013, 2.079e + 006), (2014, 3.55e + 006), (2015, 4.479e + 006), (2016, 7.604e + 006), (2017, 1.0943e + 007), (2018, 1.1568e + 007), (2019, 1.6539e + 007), (2030, 7.75996e + 007))
198. Water consumption = Agricultural water consumption + Domestic water consumption + Ecology water consumption + Industrial water consumption + Urban public service water consumption
199. Water pollution coefficient = 0.35
200. Water resource exploring policy factor = ([(0, 0) - (2030, 10)], (2000, 1), (2020, 1), (2030, 1.0556))
201. Water saving policy factor (institutional) = ([(0, 0) - (2030, 10)], (2000, 1), (2020, 1), (2030, 0.8065))
202. Water saving policy factor (technical investment) = ([(0, 0) - (2030, 10)], (2000, 1), (2020, 1), (2030, 0.4851))

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