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Dynamic simulation of water resource management focused on water allocation and water reclamation in Chinese mining cities

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Abstract

Mining cities have undergone the process of extensive exploitation, which always results in a series of water issues. Integrated water resource management is necessary in improving water supply, allocation and quality without damaging economic development. This article constructs a linear optimization model including a 'Top-Down' socio-economic mode, and 'Bottom-Up' water quality control and water supply–demand modes with integrated water resource management focused on water allocation and water reclamation. Based on computer simulation, the model can propose a water resource management under the constraints of water supply–demand and water quality control, and the model can precisely predict the influences of water resource management on economic development, water utilization and water quality. Taking Ordos, a Chinese national resource city, as a case study, this model addresses a detailed water resource management, including a water allocation plan among industries and water reclamation plan with technologies, selection, arrangement and subsidies. The implementation of water resource management can fulfill multiple objectives on water quantity, water quality and sustainable economic development. This study indicates that water resource management with a comprehensive dynamic model can be a maneuverable approach to realize the sustainable development of economic growth and water resource utilization, as well as formulate the regional development plan.

Keywords: Chinese mining cities; Linear optimization model; Water allocation; Water reclamation; Water resource management

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1. Introduction

The rapid development of mining cities requires a large quantity of water resource while most of the mining cities are located in the semi-arid or arid regions (Grundmann *et al.*, 2012), which suffer from water scarcity. Mining cities, which sprang up and flourished relying on mineral resources (Walker & Jourdan, 2003), have undergone the process of extensive exploitation, resulting in a series of water issues such as unreasonable water resource allocation, poor water reclamation and serious water pollution etc. There exists a contradiction between economic development and water utilization in Chinese mining cities. In China, the mining cities account for 20% of all Chinese cities (The State Council, 2013). Take Ordos, a Chinese national resource city, as a case study. Ordos is located in the southwest of Inner Mongolia and holds the core position for national energy supply. However, Ordos belongs to the arid and semi-arid region, which has the characteristics of complex terrain and ecological vulnerability. The plain area, the hill-gully area, the desert area, and the plateau area, respectively, account for 6% in the north, 30% in the east, 40% in the middle, and 24% in the west. Its administrative center and the important manufacturing districts are concentrated in the north-east (Figure 1) due to the impact of these topographic factors.

In Ordos, the resource industries occupy more than 60% of the total output. Tracing back to the last decade, Ordos has experienced a rapid development with an average growth rate of 33.4% annually. However, Ordos will encounter a bottleneck of water resource. In 2012, the sewage treatment rate was 71%, the ratio of water reclamation was 57%, and the removal rate of water contaminants was just 26%. According to the current water allocation and utilizing strategy, the water deficit will reach 809 million m^3 in 2020 (Li, 2011). Water resources cannot guarantee the sustainable development of socio-economics in Ordos (The Twelfth Five-year Plan, 2011). Therefore, water resource management

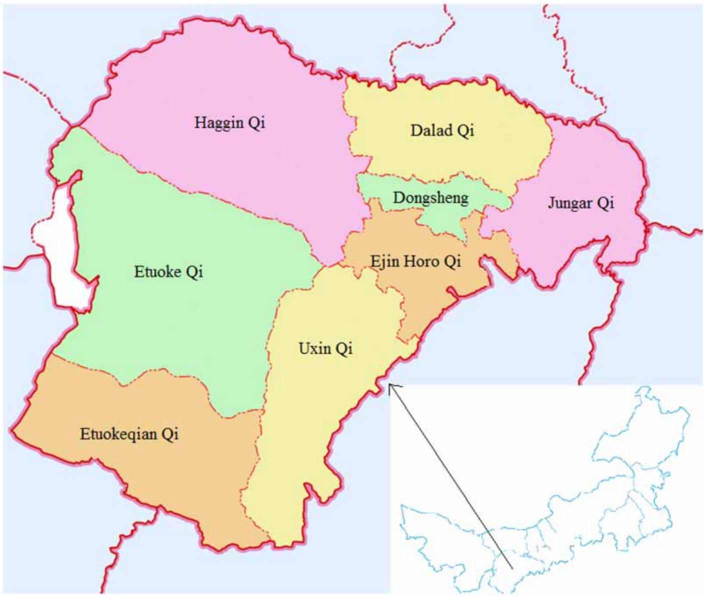

Fig. 1. Location of Ordos.

should be put forward to ensure water supply, enhance water utilization efficiency and improve water quality without damaging economic development of mining cities.

Regarding water resource management, the previous studies mainly focus on the management of water allocation, water reclamation and water quality improvement. First, since the total water resource is limited, a portion of scholars have built linear programing models to discuss how to allocate the limited water resource efficiently among multiple water users to achieve economic, social and environmental benefits with equilibrium constraints (Andrew *et al.*, 2008; Mahdi, 2010; Wolfgang *et al.*, 2013). Secondly, since water reclamation is an effective approach for water exploitation, a group of scholars have utilized a systematic framework to quantify the water reclamation potential to ensure water supply for socio-economic activities (Angelakis *et al.*, 2003; Hong & Abbaspour, 2007; Apostolidis *et al.*, 2011). Thirdly, since the significance of water quality has aroused residents' attention, a series of studies have focused on wastewater treatment with adoption of innovative sewage disposal technology to reduce water contaminants and provide high-quality water to residents (Helen & James, 2008; Zhang *et al.*, 2013). However, even the increase in wastewater treatment will not prevent water companies from experiencing the effects of adverse events; several studies have analyzed the risks and reliability linked to operation of water supply both on quality and quantity (Tchorzewska-Cieslak, 2007; Boryczko & Tchorzewska-Cieslak, 2013; Boryczko & Tchorzewska-Cieslak, 2014). Most of these researches lack the dynamic linkage among socio-economic development, population growth, environmental impact and the intervention of technologies and policies. Furthermore, all of these researches mainly focus on one aspect of water management. Research on integrated water resource management is relatively rare.

Water resource management contains many variables and constraints. In order to achieve more reliable results, it is necessary to take the related factors into full consideration. In recent years, several scholars have applied dynamic models and a simulation approach to conduct studies on integrated urban water resource management. These studies consider the connection of water resource, water pollution and economic development, and evaluate the economic and environmental impacts of integrated water management including wastewater treatment, water utilization and water reclamation (Mizunoya *et al.*, 2006; Akmam & Higano, 2007; Xiang *et al.*, 2014). However, most of these researches concentrate on the developed regions with a focus on water quality; there is a lack of early-warning studies for developing mining cities with consideration of both water allocation and water reclamation.

Therefore, based on these considerations, this paper aims to achieve sustainable economic development under the constraints on water quantity and water quality, with an integrated water resource management focusing on water allocation and water reclamation. There are three main goals to achieve in this paper. (1) This study selects Ordos as a case study, attempting to construct and analyze a comprehensive model with integrated water resource management, which is tailored to suit the characteristics of Chinese growing mining cities. (2) This study tries to explore the optimal water resource management measures, which include water allocation and water reclamation with the introduction of new sewage treatment technologies under the constraints of water resource and water pollutants. (3) This study tries to evaluate and predict the influences of integrated water resource management on economic growth, water utilization and water environment. In this way, the result offers the potential for growing mining cities to avoid development dilemmas and provides references for local policy-makers in other mining cities.

2. Methodology and data

2.1. Methodology

Considering the interactions among water resources, water pollutants, multiple industrial sectors and households, as well as the impacts caused by the implementation of water resource management on macroeconomic variables, industrial output levels, long-term economic growth and other factors (Moffatt & Hanley, 2001), a comprehensive methodology is adopted in this article. The input–output model extended to the field of environment and natural resources was first adopted to evaluate environmental carrying capacity, and later was applied to study the environmental influences of industrial development since it is a very suitable method for conducting environmental assessment (McKenzie & Durango-Cohen, 2010). However, the assessments can provide valuable quantitative information on the anthropogenic environmental loads of economic activities, but the resource and environmental loads can't serve as restrictions to react upon for industrial activities. Linear programing is a useful optimization approach for synthetic decision-making since it can help with identifying an optimal strategy to control the environmental impact and resource consumption related to economic activities. The linear programing method has been already mixed with input–output analysis for solving the problems of environmental impacts and nature resources' utilization (Vogstad, 2009). Therefore, based on the input–output model extended to the field of environment and natural resources (Leontief, 1977; Lee, 1982; Forsund, 1985; Perrings, 1987) with the principles of material balance and value balance (Freeman *et al.*, 1973), the model in our paper uses linear equations and laws of linear algebra (Jin *et al.*, 2003) to set the links between economic activities and related water consumption and pollutant emission, so as to provide an optimal water resource management that can simultaneously ensure water supply and improve water quality without damaging economic development.

To implement comprehensive modeling and simulation, a systematic model is formulated as a linear optimization program, which uses the mathematical software package LINGO (Lindo, Chicago, IL) (Wagner, 1959; Hadley, 1962; Hillier & Gerald, 1967). LINGO, as a linear programing procedure, is always an efficient way to solve optimization dynamic simulation problems (Beroggi, 1999), which enables the simulation of the synthetic system by creating as many linear functions as possible that are close to reality. Finally, a global optimal solution will be obtained through computer operation.

2.2. Model concept and theoretical framework

Based on the basic rules, the model framework is demonstrated in Figure 2, including three sub-modes: Socio-Economic Mode, Water Supply–Demand Mode, and Water Quality Control Mode. These three sub-modes interact with each other, and promote and restrict each other's development. It is a combination of a 'Top-Down' socio-economic mode based on the dynamic input–output model and 'Bottom-Up' water quality control and water supply–demand modes with water resource management. The water supply–demand mode utilizes reclaimed water to gain more water supply (Pandey *et al.*, 2011), whereas the water quality control mode introduces new sewage treatment technologies to reduce water pollutants.

As outlined in Figure 2, water resource management focuses on water allocation and water reclamation. On the one hand, optimal water allocation considers the intensities of both water resource utilization and water pollutants' emission connected to industrial activities, which can improve the

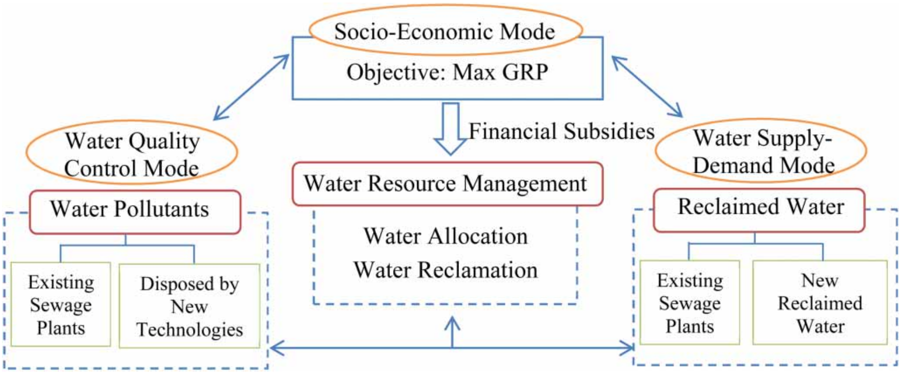

Fig. 2. Model concept and theoretical framework.

utilizing efficiency of limited water resources. On the other hand, water reclamation with the introduction of new sewage treatment technologies, according to the treatment demand of different districts, the treatment capacity and construction costs of different technologies, can improve water quality and gain water supply. Through this integrated water resource management approach, this paper can address the detailed water allocation plan among industries and the water reclamation plan with technologies' selection, arrangement and subsidies, so as to maximize the gross regional product (GRP) of the target area under the particular constraints of water supply limitation and water environmental carrying capacity.

2.3. Data

The data collected in this paper consist of national and local published data, survey data and calculated data. The published data include the Ordos Yearbook 2009–2013, Ordos Environment Bulletin in 2013, Emission Coefficient Manuals of Industrial and Urban Residents in 2010, Input–output table of Inner Mongolia in 2007, Water Resource Bulletin in 2013, and Environmental protection 'Twelfth Five-year plan' in Ordos. The survey data are collected from relevant government agencies, such as the Municipal water resources bureau, Environmental protection agency, and Land and resources bureau. Based on the collected data, we calculated the water demand coefficient, sewage water discharge coefficient, chemical oxygen demand (COD) emission coefficient, and input–output coefficients for simulation modeling. All of the coefficients remain unchanged since we assume the technical level would stay the same during the simulation period. The exogenous variables in this model include industrial production, water supply and different kinds of coefficients, all of which are listed in the Appendix (available with the online version of this paper).

3. Modeling and simulation

We divided Ordos city into eight administrative regions (Dongsheng District, Dalad Qi, Jungar Qi, Etuokeqian Qi, Etuoke Qi, Haggin Qi, Uxin Qi, Ejin Horo Qi) and 10 industries in the simulation formulation. In addition, we set two types of decision variables, one endogenous (en) and the other exogenous (ex). The exogenous variables are calculated based on current data sources (listed in the Appendix, available online), whereas the endogenous variables will be derived from simulation. The target term (t) is 13 years, from 2012 to 2025.

3.1. Objective function

As the most important Chinese national resource base, economic growth holds the highest priority in Ordos. Therefore, the objective function was constructed to maximize the total GRP concerning the social discount rate ρ (ex) over the target term to obtain an optimal solution. The objective function is shown below:

$$[OBJ\,]MAX = \sum_{t} \frac{1}{(1+\rho)^{t-1}} GRP(t)\,, \tag{1}$$

$$GRP\,(t) = \sum_{m} \delta_m \;\cdot X^{\,m}(t)\,, \tag{2}$$

where $X^{\,m}(t)$ (en) is the total production of industry m at time t (m $1 \sim 10$, respectively, represents the Primary industry; Coal mining industry; Non-coal mining industry; Petroleum and chemical industries; Metal, non-metal manufacturing industries; Equipment manufacturing industry; Other manufacturing industries; Electricity and water production industries; Construction industry; and Tertiary industry) and $GRP(t)$ is determined by each industry's production and value-added rate δ_{m} (ex).

3.2. Social and economic mode

In this section, the industrial structure, population development and city urbanization work together to construct the socio-economic development of Ordos. The flow balance of market commodities is the foundation of its industrial production. Due to the limited space, we simply demonstrated the formulas for industrial production and adjustment of industrial structure below.

The total production of each industry is decided by a Leontief input–output matrix, which includes parameters such as the inter-industry input–output coefficient, consumption, investment, imports and exports. We assumed that the installation of new sewage treatment technologies will influence the output of each industry, so an impact coefficient and technology investment are added in the Leontief input–output matrix to evaluate the contribution of a new installation:

$$X^{\,m}(t) \;\geq\; A \cdot X(t) \;+\; C(t) \;+\; I^{\,m}(t) \;+\; \beta \cdot I^{\,sp}(t) \;+\; NE(t), \tag{3}$$

where $X^{\,m}(t)$ (en) is the column vector of total production from industry m at time t, A (ex) is the input–output coefficient matrix, $C(t)$ (en) is the column vector of total consumption, $I^{\,m}(t)$ (en) is the column vector of total investment, and $NE(t)$ (en) is the column vector of net export. In this simulation, we introduced new sewage water construction plants to reduce water pollutants and ensure residential and industrial water supply. $I^{\,sp}(t)$ (en) is the column vector of investment for sewage water treatment, whereas β (ex) is the coefficient associated with the production induced by the construction of sewage treatment technologies.

In addition, industrial productions are restricted by the capital stock and curtailment subsidies. The production formula below is derived from the Harrod–Domar model through the relationship between capital accumulation and production. We assume that the industrial structure can be adjusted by residual capital and subsidies for industrial product shrinkage. The capital accumulation depends on investment and capital depreciation.

$$X^m(t) \ \leq \ \alpha^m \cdot (K^m - S^m), \tag{4}$$

$$K^m(t+1) = K^m(t) + I^m(t+1) - d^m \cdot K^m(t), \tag{5}$$

where α^m (ex) is the ratio of capital to output in industry m at time t, K^m (en) is the available capital for industry m at time t, S^m (en) is the subsidy for production curtailment of industry m at term t, and d^m (ex) is the depreciation rate of industry m.

3.3. Water supply and demand mode

In Ordos, water resource can be divided into conventional and unconventional water resource. As Figure 3 shows, conventional water resource contains surface water, groundwater and transfer water, which provides water supply to households, industries and the environment; and unconventional water resource includes reclaimed water and other water resources that are distributed to agricultural

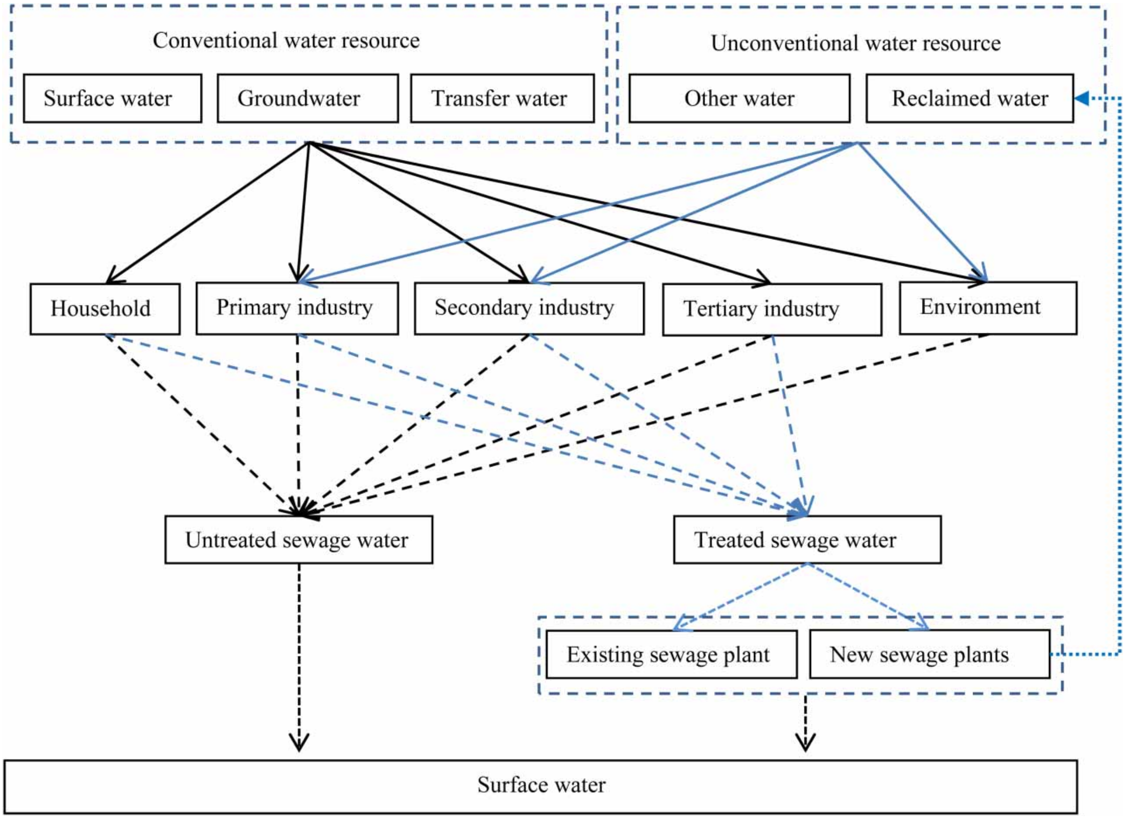

Fig. 3. Water resource flow chart in Ordos.

irrigation, industrial manufacture and environmental maintenance due to their relatively low water quality. After the utilization of water resource, a part of the sewage water directly flows into local surface water without treatment, while the rest is reclaimed by the existing and new added sewage plants, so that the treated water is returned back to the unconventional water resource as reclaimed water. In this mode, by efficient water allocation and water reclamation with new sewage plants, the water supply pressure can be relieved.

3.3.1. Water supply and demand. To ensure household daily life and industrial activities can take place, the total water supply should exceed the total water demand. The total water supply comes from groundwater, local surface water, transfer water, reclaimed water, and other water resources (Sofroniou & Bishop, 2014). The total water demand is generated from households, industry and the environment. We assume that groundwater, local surface water, transfer water and other water resources will remain unchanged because the exploitation of groundwater is under restriction and conventional water sources are limited (Tan *et al.*, 2013). The water demand of the environment is fixed according to the predicted amount announced by the local government. The reclaimed water produced by new sewage treatment technologies will improve the water supply capacity.

$$WST(t) \geq WDT(t)\,, \tag{6}$$

$$WST(t) = GW(t) + LSW(t) + TW(t) + RW(t) + OW(t)\,, \tag{7}$$

$$WDT(t) = HWD(t) + IWD(t) + EWD(t)\,, \tag{8}$$

$$HWD(t) = \sum_j ew^{city} \cdot P_j^{city}(t) + \sum_j ew^{country} \cdot P_j^{country}(t)\,, \tag{9}$$

$$IWD(t) = \sum_j \sum_m ew^m \cdot X_j^m(t)\,, \tag{10}$$

where *WST* (en) is the total water supply at time *t*; *WDT* (en) is the total water demand at time *t*; *GW* (ex), *LSW* (ex), *TW* (ex), *RW* (en), *OW* (ex) are, respectively, groundwater, local surface water, transfer water, reclaimed water and other water resources at time *t*; *HWD* (en), *IWD* (en), *EWD* (ex) are water demand for households, industries and the environment, respectively, at time *t*; *HWD* is determined by the population and coefficients of water demand in city ew^{city} (ex) or in country $ew^{country}$ (ex) in region *j*; and *IWD* is decided by industrial production and water demand coefficients ew^m (ex) of industry *m* in region *j*.

3.3.2. Water reclamation with new sewage treatment technologies. Reclaimed water comes from treated sewage water. Sewage water is generated from social activities. Based on the situation in Ordos, the landscapes of plateau, sand and desert account for 77% of the land (Ordos on Line: Geographical Environment, 2013), so the centralized sewage treatment plants are always built in the city center and industrial areas. Therefore, we assume that sewage discharged by households and industries goes through the centralized sewage treatment whereas the water resources used for the environment remain untreated and flow into the local surface water directly.

$$SWG(t) = HSW(t) + ISW(t)\,, \tag{11}$$

$$HSW(t) = \sum_j es^{city} \cdot P_j^{city}(t) + \sum_j es^{country} \cdot P_j^{country}(t)\,, \tag{12}$$

$$ISW(t) = \sum_j \sum_m es^m \cdot X_j^m(t)\,, \tag{13}$$

where SWG (en) is the sewage water generated at time t; HSW (en) and ISW (en) are the sewage water emitted from households and industries, respectively, at time t; HSW is determined by the population and coefficients of sewage water in city es^{city} (ex) or in country $es^{country}$ (ex) in region j; and ISW is decided by the industrial production and sewage water discharge coefficients es^m (ex) of industry m in region j.

To ensure water supply and improve the percentage of disposed sewage, we encourage the treatment of more sewage water with new sewage treatment plants. In Ordos, there are a total of 18 sewage treatment plants (The List of National Urban Sewage Treatment Facilities Operation, 2013), and these mainly adopt the traditional Activated Sludge treatment technology (technology A in Table 1), which is widely used in China at present (Xiang *et al.*, 2014). Water treated by technology A is suitable for agricultural irrigation and environmental maintenance due to its lower removal ability and its operating and maintaining cost. Aiming at the characteristics of emission in mining cities, there are two advanced technologies expected to be introduced. One is the Double Membrane Bio-Reactor (technology B), which is applied in developed areas such as Beijing (Song *et al.*, 2010). Water treated by technology B can be used for industry. The other one is the Ceramic Membrane Bio-Reactor (technology C), which is imported from Japan (Peng, 2010). The reclaimed water produced by technology C can satisfy all kinds of water demands due to its high standard. As demonstrated in Table 1, technology C holds the highest output ratio for reclaimed water production and the best capacity for water pollutant removal, whereas technologies A and B are more efficient on investment.

Table 1. Introduction of traditional and advanced sewage treatment technologies.

	Construction cost (million US$)	Operating & maintaining cost (US$/ton)	Sewage treatment (kiloton)	Reclaimed water production (kiloton)	*Environmental efficiency (kg/kiloton)	**Investment efficiency (kiloton/US$)
Activated sludge (A)	27.4	0.35	30,000	22,000	0.330	0.085
Double membrane bio-reactor (B)	25.2	0.48	36,500	29,200	0.345	0.110
Ceramic membrane bio-reactor (C)	10.7	0.58	10,950	9,300	0.354	0.080

*Environmental efficiency = Removal amount of COD/Sewage treatment.

**Investment efficiency = Sewage treatment/Construction cost.

Generally, not all sewage water can be treated, so the amount of treated water will not exceed the quantity of generated sewage water. The gross volume of treated sewage water includes the existing capacity and the added amount of the new sewage treatment plants:

$$SWG(t) \geq SWT(t)\,, \tag{14}$$

$$SWT(t) = \sum_j ESWT_j(t) + \sum_j (NSWT_j^A(t) + NSWT_j^B(t) + NSWT_j^C(t))\,, \tag{15}$$

where SWT (en) is the treated sewage water at time t; $ESWT_j$ (ex) is the capacity of existing sewage plants; and $NSWT_j^A$ (en), $NSWT_j^B$ (en), and $NSWT_j^C$ (en) are sewage water treated by new technology A, B and C, respectively.

Following the introduction of new technologies, reclaimed water is increased to support the water supply:

$$RW(t) = \sum_j ERWP_j(t) + \sum_j (\rho \cdot NSWT_j^A(t) + \varphi \cdot NSWT_j^B(t) + \omega \cdot NSWT_j^C(t))\,, \tag{16}$$

where $ERWP_j$ (ex) is the existing reclaimed water in region j at time t; and ρ, φ and ω are the coefficients of reclaimed water produced by technology A, B and C, respectively.

There exists the operational risk for water resource management (Tchorzewska-Cieslak, 2007), so the subsidies for new sewage treatment plants not only include the investment, but also consider the operating and maintaining costs in case of risk:

$$\sum_j I_j^{a/b/c}(t) + \sum_j MC_j^{a/b/c}(t) = \sum_j S\_SP_j^{a/b/c}(t)\,, \tag{17}$$

where $I_j^{a/b/c}$ (en) is the total investment of technology A, B or C in region j at time t; $MC_j^{a/b/c}$ (en) is the operating and maintaining cost of technology A, B or C in region j at time t; and $S\_SP_j^{a/b/c}$ (en) is the subsidy for the installation of new technologies in region j at time t.

Understanding how to choose the technologies and how many sewage plants should be built depends on the removal efficiency, investment efficiency, productivity, and operating and maintaining cost of each technology. In addition, the total subsidy for industrial shrinkage and new sewage treatment plants should be restrained by the financial budget:

$$FB(t) \geq S\_SP_j^{a/b/c}(t) + S^m(t)\,, \tag{18}$$

where the total subsidy will not exceed the financial budget FB (en) at time t.

3.4. Water quality control mode

In Ordos, the most significant water pollutant is COD, so COD is used to illustrate water quality. The water pollutant COD is discharged from the wastewater of industries and households. The pollutants that come from non-point sources (farmland, fruit forest, grassland, construction land and others) and rainfall are considered all together. The amount of disposed pollutant increases gradually with the introduction of new sewage treatment facilities:

$$TP\_cod(t) = IWP\_cod(t) + HWP\_cod(t) + NWP\_cod(t) + RP\_cod(t) - SP\_cod(t), \tag{19}$$

$$HWP\_cod(t) = \sum_j ep^{city} \cdot P_j^{city}(t), \tag{20}$$

$$IWP\_cod(t) = \sum_j \sum_m ep^m \cdot X_j^m(t), \tag{21}$$

$$NWP\_cod(t) = \sum_l ep^l \cdot L^k(t), \tag{22}$$

$$RP\_cod(t) = ep^r \cdot L, \tag{23}$$

$$SP\_cod(t) = \sum_j ep^{ex} \cdot ESWT_j(t) + \sum_j (\alpha \cdot NSWT_j^A(t) + \beta \cdot NSWT_j^B(t) + \gamma \cdot NSWT_j^C(t)), \tag{24}$$

where TP_cod (en) is the total COD discharged at time t; IWP_cod (en), HWP_cod (en), NWP_cod (en), and RP_cod (en) are the COD emitted from industries, households, non-point sources and rainfall at time t, respectively; HWP_cod is decided by the coefficient of the pollutant emissions of people who live in city ep^{city} (ex) with city population P_j^{city} (en); IWP is determined by the industrial production and water pollutant discharge coefficients ep^m (ex) of industry m in region j; and ep^l (ex) and ep^r (ex) are the discharged coefficient of non-point sources and rainfall at the target area. SP_cod (en) is the amount of disposed pollutant at time t; ep^{ex} (ex) is the disposed coefficient of existing water treatment; and α, β and γ are the coefficients for pollutant removal of technologies A, B and C, respectively.

3.5. Constraints' setting for simulation

In this study, we set a series of constraints for simulation. According to Urban Overall Planning of Ordos (2011–2030): (1) the upper limitation of groundwater, local surface water, transfer water and other water resources supply remains at 2,341 million m^3; (2) the aimed reduced rate of water pollutant COD is 2% each year to fulfill the emission reduction target; (3) the reclaimed water productivity increases year by year; and (4) industry development constraints defined by input–output model and the scope of industrial output will vary around the average growth rate of the last decade.

4. Simulation results, analysis and discussion

Based on the built model and constraints' setting, actual data of Ordos are used to conduct simulation experiments. After repeated trials, this simulation model has passed a consistency test, validity test and sensitivity test. In this section, the optimal water resource management, which focuses on water allocation and water reclamation under the constraints of water quantity and water quality, is explored. The influences of water resource management on economic development, water utilization and water quality are predicted accordingly.

4.1. Endogenous optimal water resource management

Integrated water resource management includes water allocation and water reclamation. Optimizing water allocation and increasing the water reclamation ratio with the introduction of new sewage treatment technologies can improve water supply, water utilization efficiency and water pollutant emission intensity without damaging the economic growth.

4.1.1. Water allocation. Due to different impact intensities of industries on water utilization and pollutant emission, the optimal water allocation is shown in Figure 4. At the beginning of the target period, water utilization structure has been regulated a little because the constraint of limited water resource has not yet appeared. By 2017, water supply will have run short but water requirement would increase significantly if the water distribution remains unchanged. Therefore, the restriction of limited water resource prompts the water allocation to modulate.

According to Figure 4, water demand of the following industries should be curtailed after considering their large amount of water consumption, water pollutant emissions and lower value-added ratios: the primary industry from 73 to 58%; the non-coal mining industry from 0.4 to 0.1%; and the other manufacturing industries from 3.5 to 0.6%. On the contrary, water demand of the following industries should be increased since their higher economic benefits can cover their water pollution loss: the petroleum and chemical industry from 2.5 to 5.9%; the metal, nonmetal manufacturing industries from 0.7 to 1.6%; the equipment manufacturing industry from 0.1 to 1.2%; the electricity and water production industry from 3.8 to 17.2%; and the construction industry from 0.7 to 1.7%.

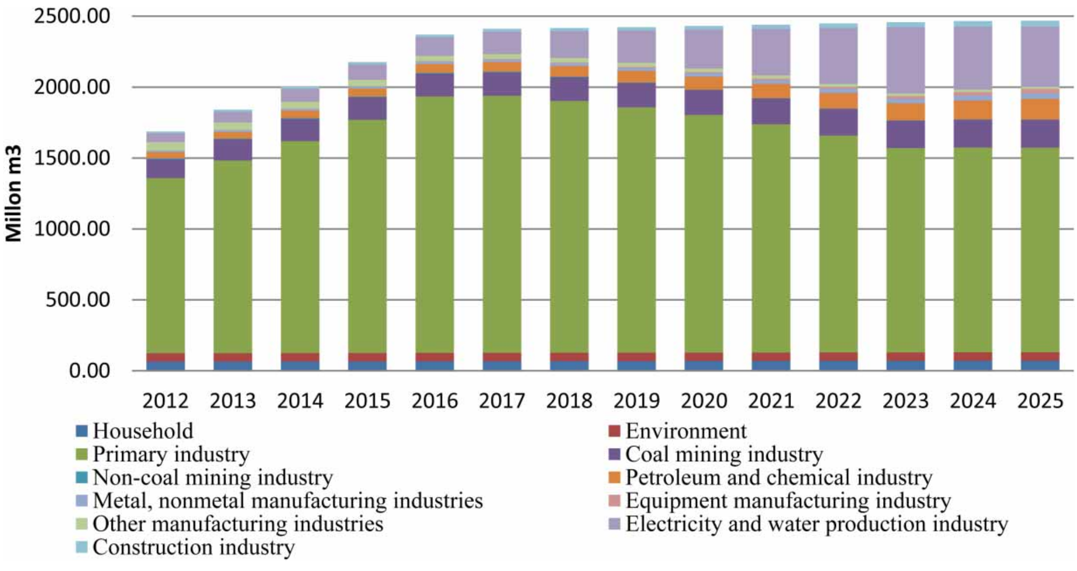

Fig. 4. Water allocation from 2012 to 2025.

Table 2. Technology selection and installation plan.

Technology	Dongsheng District	Dalad Qi	Jungar Qi	Etuokeqian Qi	Etuoke Qi	Haggin Qi	Uxin Qi	Ejin Horo Qi
A	0	0	1	0	0	0	0	0
B	0	0	1	0	0	0	0	0
C	1	0	6	0	0	0	0	0

4.1.2. Water reclamation. In order to increase the water reclamation ratio, an optimal selection of sewage treatment technologies and installation plan is derived from the simulation. As shown in Table 2, a total of nine instances of new sewage plants with technologies A, B and C are suggested to be built, mainly in Dongsheng District and Jungar Qi with fiscal subsidy of US$512.6 million including US$107.5 million for construction and US$405.1 million for operation and maintenance.

The Dongsheng District, as the administrative center of Ordos, is undergoing rapid urbanization. The natural growth rate of the population is 9.66%, and the proportion of the construction industry and the tertiary industry is over 70%, which will boost the pressure on both water demand and water contamination. Therefore, one instance of technology C is suitable to be introduced in Dongsheng District because technology C holds the advantages of a lower construction cost, a smaller sewage treatment amount, a higher removal rate and better water quality.

In addition, Jungar Qi is the important manufacturing district in Ordos, the scale of the coal mining industry and the electricity and water production industry accounts for 58%. These industries require large water consumption. Combined with the growing population and rapid industrialization and urbanization, Jungar Qi will face great pressure on water quality. To address the shortage, eight sewage plants with one instance of technology A, one instance of technology B, and six instances of technology C are suggested to be built in Jungar Qi. Technology C is chosen at the beginning of the target period due to its high removal ratio. To guarantee further economic development, the mathematical modeling elects technologies A and B due to their high efficiency of investment.

With the introduction of new sewage treatment plants, see Figure 5, the ratio of water reclamation rises steadily from 57.4% in 2012 to 73.9% in 2025, and the reclaimed water increases from 34.2 million m^3 to 128.3 million m^3, which will make up for the deficit between water supply and demand.

4.2. Influences of the optimal water resource management

4.2.1. Influence on economic development. Restricted by the water allocation of industries, the industrial structure is adjusted according to the industries' water utilization intensities. As shown in Figure 6, the following industries should be curtailed: the primary industry from 2.17 to 0.96%; the coal mining industry from 33.46 to 18.72%; the non-coal mining industry from 6.43 to 0.62%; and the other manufacturing industry from 2.65 to 0.25%. On the contrary, the following industries should be encouraged: the petroleum and chemical industry from 7.23 to 9.42%; the metal, nonmetal manufacturing industry from 3.65% to 4.76%; the equipment manufacturing industry from 0.34 to 3.91%; the electricity and water production industry from 3.24% to 8.16%; the construction industry from 7.33 to 9.55%; and the tertiary industry from 33.49 to 43.65%.

Based on this industrial structure, GRP in Ordos continues to rise steadily from US$68,220 million in 2012 to US$170,674 million in 2025, and the average annual growth rate remains at 7.6%. We can see

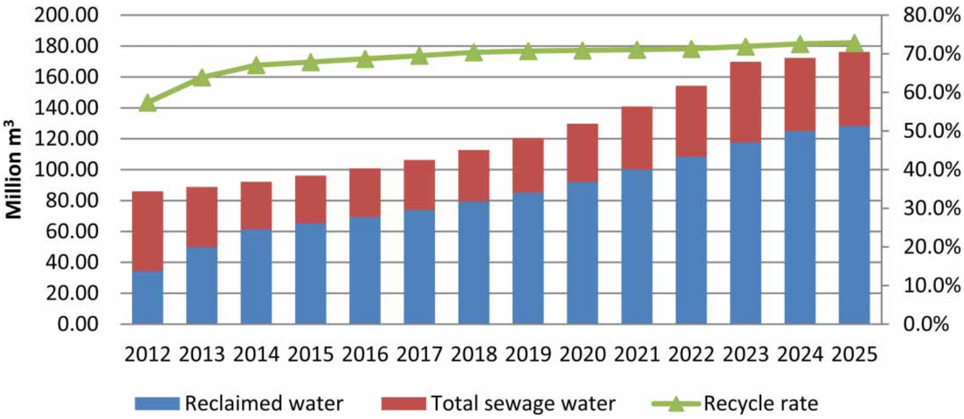

Fig. 5. Water reclamation from 2012 to 2025.

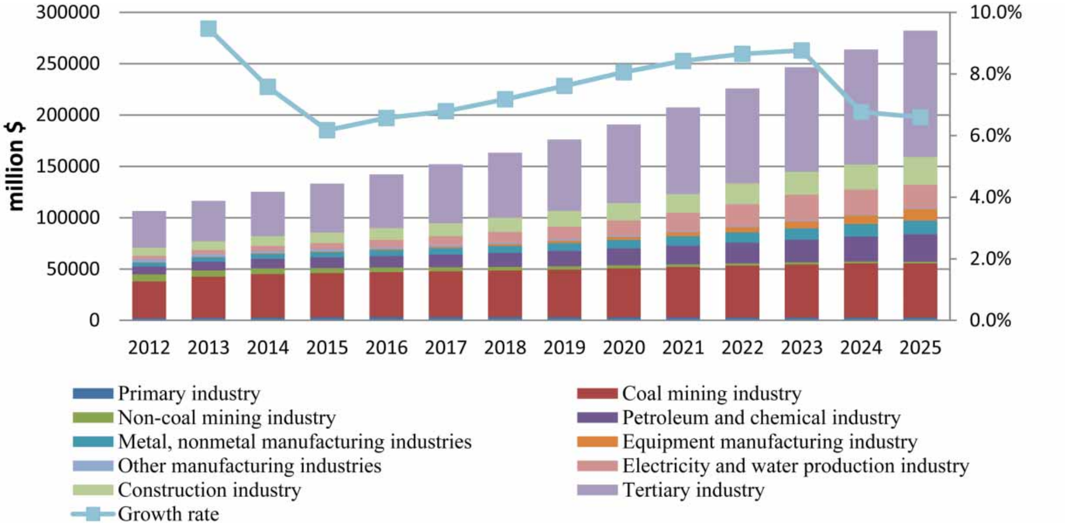

Fig. 6. Estimated GRP and growth rate from 2012 to 2025.

from Figure 6 that in 2013, the fiscal subsidy for water resource management is not executed, so the economic growth rate reaches 9.5%. From then, the industrial structure is influenced by water allocation and the subsidy used for sewage water treatment, making the economic growth rate drop back to a minimum percentage of 6.2% in 2015. After 2015, due to the further optimization of industrial structure, the growth rate rises solidly to 8.8% in 2023 but ultimately falls to 6.6% in 2025. The reason for this is that the introduction of new sewage plants does not mean a win–win situation for economic growth and environmental improvement simultaneously in the later stage of the target period under the restriction of water supply and water pollutant carrying capacity.

4.2.2. Influence on water utilization. The implementation of integrated water resource management will create a positive impact on water utilization. We can see from Figure 7 that water supply keeps

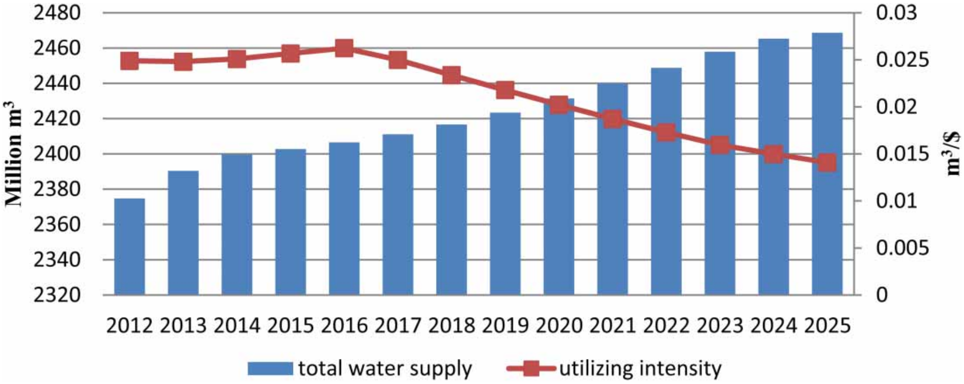

Fig. 7. Estimated water supply and utilizing intensity from 2012 to 2025.

growing gradually from 2,374 million m^3 in 2012 to 2,469 million m^3 in 2025, which means that the water supply can effectively meet the basic demand of socio-economic development. Moreover, thanks to the water allocation, the utilizing intensity of water resources (water consumption per US$) will climb to a peak of 0.0258 m^3 per US$ in 2016 and then decline to 0.1385 m^3 per US$ in 2025, which means that the water allocation can improve the utilization efficiency of water resources.

4.2.3. Influence on water quality. The implementation of water resource management also has an influence on the water environment. As revealed in Figure 8, water pollutant COD emissions drop from 103,400 tons to 79,518 tons with a falling rate of 23% from 2012 to 2025 and water quality is greatly improved. Similarly, the contaminant discharge intensity (water pollutant emission per US$) decreases significantly from 1.516 to 0.45 t/US$, alleviating the restriction brought by water pollution on economic development.

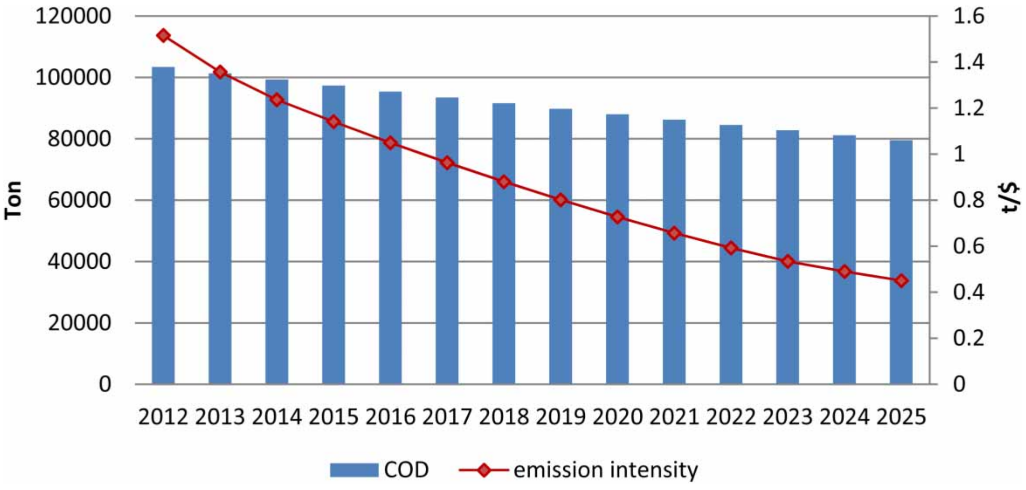

Fig. 8. Water pollutant COD and emission intensity from 2012 to 2025.

The simulation result demonstrates that with an annual GRP growth rate of 7.6%, the implementation of water resource management focused on water allocation and water reclamation can realize the trade-off between supply and demand and fulfill the task of 2% emissions' reduction each year during the target period.

5. Conclusions

To ensure water supply, enhance water utilization efficiency and improve water quality without damaging economic development in mining cities, this research constructs a comprehensive dynamic linear optimization model, including a socio-economic mode, water supply–demand mode and water quality control mode with interaction among the three sub-modes, to explore optimal water resource management that focuses on water allocation and water reclamation, and observe the consequences of water resource management on economic development, water utilization and water quality.

After modeling and simulating a typical area, Ordos, the results contain detailed water resource management measures, including a water allocation plan, water reclamation plan with technologies' selection, arrangement and subsidies. During the target term (from 2012 to 2025), water demand of the primary industry, the non-coal mining industry, and the other manufacturing industries is recommended to be cut by 15%, 0.3%, and 2.9%, respectively. Nine wastewater treatment plants of three technologies are suggested to be built mainly in Dongsheng District and Jungar Qi with fiscal subsidy of US$512.6 million including US$107.5 million for construction and US$405.1 million for operation and maintenance. After implementation of water resource management, the following objectives are foreseen simultaneously by 2025: the ratio of water reclamation reaches 73.9%, reclaimed water production increases by 93.95 million m^3, the emissions of water pollutant COD decrease by 23%, and the economic growth rate remains at 7.6% annually.

However, there are still some limitations that need to be considered for future extensions. For example, the classification of water pollutant materials may not be sufficient to manifest the unique characteristics of mining cities. Furthermore, water price can also influence the decisions of water policy, and we will continue this study and try to manipulate the Computable General Equilibrium (CGE) model to investigate the impact on water price caused by integrated water resource management (Llop & Ponce-Alifonso, 2012) as well as the response of different economic factors according to the variation of relative price, subsidy and progress of water-using technology (Li *et al.*, 2014), to put forward a more specific regional plan for policy-makers.

The research concludes that the proposed comprehensive dynamic linear optimization model can elaborate the interrelations among industries with water resource utilization and water pollutant emission by drawing linear equations, and can precisely simulate and predict the policy effects of applicable approaches and technology introductions under the precondition of satisfying multiple goals of socio-economic development, resource saving and environmental conservation. Therefore, this synthetic methodology can serve as a pre-evaluation approach for conducting early-warning research for mining cities in a growing stage to avoid a series of inharmonious problems, offering feasible suggestions for government decision-making. Moreover, on account of the openness of modeling, this model can be replicated by adding substance to solve coordinated development issues in socio-economics, resources and the environment in other regions.

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Conflicts of interest

The authors declare no conflict of interest.

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