Integrated optimal allocation model for complex adaptive system of water resources management (I): Methodologies

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\textbf{SUMMARY}

Due to the adaption, dynamic and multi-objective characteristics of complex water resources system, it is a considerable challenge to manage water resources in an efficient, equitable and sustainable way. An integrated optimal allocation model is proposed for complex adaptive system of water resources management. The model consists of three modules: (1) an agent-based module for revealing evolution mechanism of complex adaptive system using agent-based, system dynamic and non-dominated sorting genetic algorithm II methods, (2) an optimal module for deriving decision set of water resources allocation using multi-objective genetic algorithm, and (3) a multi-objective evaluation module for evaluating the efficiency of the optimal module and selecting the optimal water resources allocation scheme using project pursuit method. This study has provided a theoretical framework for adaptive allocation, dynamic allocation and multi-objective optimization for a complex adaptive system of water resources management.

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1. Introduction

Water resources play an important role in the development of socioeconomic and environmental system. Because water resources are dynamic interactions and adaptations with related socioeconomic and environmental factors, water resources allocation is a complex adaptive problem involving population, economy, environment, ecology and policy, etc. (Singh, 2014). The optimal water resources allocation literature mainly treated one or more of the following three elements: (1) complex adaptive allocation of water resources, (2) dynamic allocation of water resources and (3) multi-objective optimization of water resources allocation.

The agent-based on genetic algorithm, i.e., intelligent agent or adaptive agent is one approach that can help decision makers build a complex adaptive model for water resources allocation (Galán et al., 2009; Ng et al., 2011). Zhao et al. (2004) proposed a complex adaptive model for water resources allocation based on genetic algorithm and agent-based. The model was used to analyze the rational amount of diversion water for the West Line of Water Transfer Project from South China to North China and its utilization benefit. Berger et al. (2007) applied multi-agent simulation to capture the complex adaptation of multiple users and their socioeconomic implications within water resources management. Yang et al. (2009) presented a decentralized optimization algorithm for water shed management based on multi-agent simulation with outer river human agent, inner river human agent and ecological agent. Chu et al. (2009) developed an agent-based simulation to capture the complex characteristics of residential water usage. Rieker and Labadie (2012) explored an intelligent agent for optimization of complex river-reservoir system management and long-term operation. Akhbari and Grigg (2013) introduced an agent-based model to resolve and mitigate conflicts of parties participating in water resources management. Giuliani and Castelletti (2013) used multi-agent simulation to model and analyze different levels of cooperation and information exchange among multiple decision makers in order to allow the downstream agents to better adapt to the upstream behaviors in water resource system. Ni et al. (2014) applied an agent-based model to deal with water resources optimal allocation based on genetic algorithm. Yuan et al. (2014) developed an agent-based model for prediction of urban household...
water demand so as to simulate stochastic behavior and feedbacks caused by administrative agent and domestic agent.

System dynamic (SD) is a well-known methodology that supplies a theoretical framework and concepts for modelling dynamic allocation of water resources (Forrester, 1958; Ahmad and Simonovic, 2004; Feng et al., 2008; Willuweit and O’ Sullivan, 2013; Hoekema and Sridhar, 2013). An overview of general dynamic allocation models for water resources has been summarized by Winz et al. (2009). Yang et al. (2008) applied SD to seek a balance between mitigating water shortages and total financial cost in water resources management. Zhang et al. (2008) developed a SD model for making decision on water resources allocation and management. Zhang et al. (2009) developed an integrated dynamic model of water consumption based on SD and water resources carrying capacity theory. Gastélum et al. (2010) explored a SD model for water right transfer with regards to the degree of complexity and uncertainty of the water right allocation process to different economic variables. Rehan et al. (2013) developed a SD model for financially sustainable management of urban water distribution networks. Akhtar et al. (2013) applied SD simulation to present comprehensive response of the society–biosphere–climate–economy–energy system by considering climate, carbon cycle, land use, population, food production, hydrologic cycle, water demand, water quality and energy–economy. Chen and Wei (2014) applied SD method to research on water security including flood security, water resources security, carrying capacity, water environment security. Wang et al. (2014) used a complex system dynamic model to study relationship among population growth, economic development, climate change, management strategies and water resources, and identify the best management strategy to adapt with the changing environment.

The multi-objective algorithm and multi-objective evaluation are alternative methods in solving multi-objective optimization of water resources allocation (Nicklow et al., 2009; Singh, 2014). Nayak and Panda (2001) used multi-objective evaluation to solving water resources allocation for water manager and decision-makers. Srdjevic et al. (2004) used an integrated simulation operation, system performance indices and multi-objective evaluation model to simulate operation of reservoir system. Castelletti et al. (2008) used multi-objective decision to cope with the preference and subjective aspects of the water resources allocation. Shourian et al. (2008) used a multi-objective model to allocate water resources optimally over time and space among competing demands based on particle swarm optimization algorithm. Chang et al. (2009) proposed an integrated multi-objective model for regional water resources allocation and planning problem based on multi-objective genetic algorithm and operating rules. Kilic and Anac (2010) developed a multi-objective planning model for large scale irrigation system in order to increase the benefit from production, increase the size of the total area irrigated and reduce the water losses. Kim and Chung (2013) developed a multi-objective evaluation model for assessing climate change vulnerability of water resources management. Hou et al. (2014) used a multi-objective optimization model for maximizing benefit to the economy, society and environment in water resources allocation. Nouiri (2014) used multi-objective genetic algorithm and Pareto optimality concept to optimize daily management schedule of hydraulic system. Rozzbahani et al. (2014) proposed a multi-objective optimization model for sharing water among stakeholders of a trans boundary river by transforming the multi-objective problem to a three-step single objective problem.

This study is an integrated optimal allocation model of complex adaptive allocation, dynamic allocation and multi-objective optimization, focusing on complex adaptive management of water resources allocation. The paper is organized as follows: Section 2 describes the method adopted in this study, which comprises three parts: introduction of a general framework of integrated optimal allocation model by firstly setup an agent-based module (Section 2.1), secondly setup an optimal module (Section 2.2), and finally setup a multi-objective evaluation module (Section 2.3). The conclusions are drawn in Section 3.

2. Development of methodology

The integrated optimal allocation model (IOAM) for complex adaptive system (CAS) of water resources management consists of following three separately modules: (1) an agent-based module, (2) an optimal module including multi-objective function, constraints and algorithm, and (3) an evaluation module consisting of multi-objective evaluation indices as well as projection pursuit method. The structure of the IOAM is described in Fig. 1. The details of each module are given as follows.

2.1. Agent-based module

Due to the dynamic, multi-objective, multi-reaction and adaption characteristics of CAS of water resources management, SD, agent-based and non-dominated sorting genetic algorithm II (NSGA-II) are used to reveal evolution mechanism of CAS.

2.1.1. Evolution mechanism of CAS

The procedures of applying SD, agent-based and NSGA-II to revealing evolution mechanism of CAS are shown in Fig. 2. CAS of water resources management consists of administrative agent, water supply agent (including reservoir and hydropower station agent), water user agent (including industrial production water agent, agricultural production water agent, domestic water agent, reservoir and hydropower station agent as well as ecological water agent), sewage treatment agent (Zhao et al., 2004). Because functions of reservoir and hydropower station are mainly included flood control, water supply, power generation as well as navigation, etc., reservoir is both water supplier and water user. The details of evolution mechanism of CAS are described as follows:

(1) The planning strategies of society and economy development including population, economy, agriculture and ecology are formulated by administrative agent as well as transmitted to water user agents.

(2) Water demand of water user is predicted by inner stimulus–response of agent and outer feedback relationship between agents based on SD, when the planning strategies of economic and social development are transmitted to water user agents.

(3) Preliminary water supply strategy is formulated by administrative agent and transmitted to reservoir and hydropower station agent according to feedback information of water demand simulated by SD.

(4) Water supply and storage of reservoir as well as hydropower station agent is simulated by inner stimulus–response of agent and outer feedback relationship between agents based on SD according to reservoir operating rules and storage, and then that information is fed back to administrative agent.

(5) The preliminary water supply strategies are simulated by reservoir operation and transmitted to water user agents, at the same time, utilization benefit and sewage discharge of water user agent simulated by SD is fed back to administrative agent and sewage treatment agent, respectively.

(6) Sewage treatment agent is simulated by SD and fed back to administrative agent.
Simulation of inner stimulus-response of agent by SD
Simulation of outer feedback relationship between agents by SD
Revelation of evolution mechanism of CAS based on NSGA-II

Start

Agent-based module
Classification of agent-based
Simulation of inner stimulus-response of agent by SD
Simulation of outer feedback relationship between agents by SD
Revelation of evolution mechanism of CAS based on NSGA-II

Optimal module
Initialization of parent population of decision variables
Evaluation of fitness of of decision variables based on NSGA-II
Evolution of new population based on NSGA-II
Generation of optimal decision set

Multi-objective evaluation module
Selection of multi-objective evaluation indices
Optimization of projection pursuit problem
Selection of optimal scheme of water resources allocation

Stop

Fig. 1. The structure of the integrated optimal allocation model.

Fig. 2. The procedures for revealing evolution mechanism of complex adaptive system.
(7) Fitness function composed of multi-objective function is evaluated by administrative agent according to the feedback of water user agent and sewage treatment agent, and then the strategies of economic and social growth rates as well as water supply are optimized by NSGA-II in order to pursue better adaption of CAS.

2.1.2. Inner stimulus–response of agent and outer feedback relationship between agents based on SD

The basic building blocks for SD method are stock, flow, converter and connector, as shown in Fig. 3. Stock (box shown in Fig. 3) represents accumulations both physical and non-physical. Flow represents actions in a stock which transport quantities into and out of a stock instantaneously or over time. Connector (arrow shown in Fig. 3) establishes relationships between various elements of agent-based and move information as inputs for decisions or actions. Converter (circle shown in Fig. 3) represents agent and its inner stimulus–response function.

Mathematically the state equation (SE) between stock and flow can be described using the following integral form (Sternman, 2000):

\[ \text{Stock}(t) = \int_{t_0}^{t} [\text{Inflow}(s) - \text{Outflow}(s)] ds + \text{Stock}(t_0) \]  \hspace{1cm} (1)

where \( t_0 \) is the initial time, \( t \) is the current time, \( \text{Stock}(t_0) \) is the initial value of the stock, \( \text{Inflow}(s) \) and \( \text{Outflow}(s) \) are flow rates into and out of a stock at any time between the initial time \( t_0 \) and current time \( t \).

The SD method for simulating inner stimulus–response of agent and outer feedback relationship between agents in CAS is developed using VensimPLE Version 5.0a development tool (Ventana System Inc., Harvard, Massachusetts). The water agents include industrial production water agent, agricultural production water agent, domestic water agent, reservoir and hydropower station agent, ecological water agent as well as VAI and IRF are fed back to administrative agent, respectively, and then the WDI is fed back to sewage treatment agent as well as VAI and IRF are fed back to administrative agent.

\[ \text{SE} : \quad \text{WQVAI}_{i,t+1} = \text{WQVAI}_{i,t} + \text{GRWC}_{i,t} \]  \hspace{1cm} (2)

\[ \text{SE} : \quad \text{PVAI}_{i,t+1} = \text{PVAI}_{i,t} \cdot (1 + \text{PGRVA}_{i,t}) \]  \hspace{1cm} (3)

Auxiliary equation (AE) : \[ \text{WDI}_{i,t} = \frac{\text{PVAI}_{i,t} \cdot \text{WQVAI}_{i,t}}{\text{CIPN}_{i,t}} \]  \hspace{1cm} (4)

\[ \text{SE} : \quad \text{VAI}_{i,t+1} = \frac{\text{WSI}_{i,t}}{\text{WQVAI}_{i,t}} \]  \hspace{1cm} (5)

AE : \[ \text{DIS}_{i,t} = \text{WSI}_{i,t} \cdot \text{ISP}_{i,t} \]  \hspace{1cm} (6)

AE : \[ \text{IRF}_{i,t} = \text{WSI}_{i,t} \cdot \text{CIRF}_{i,t} \]  \hspace{1cm} (7)

where \( i \) is the serial number of water-intake, \( t \) is the serial number of time, \( \text{CIPN}_{i,t} \) is coefficient of industrial pipe network of nth water-intake in time \( t \), \( \text{CIRF}_{i,t} \) is coefficient of industrial return-flow of nth water-intake in time \( t \).

(2) Agricultural production water agent

The inner stimulus–response of agricultural production water agent as well as outer feedback relationship between agricultural production water agent and administrative agent is shown in Fig. 4. Firstly, water quota per 10,000 yuan of economic value-added by industry (WQVAI) is calculated by Eq. (2) according to the values of crop area (CA) and development scale of forest, animal husbandry and fishery production (WDFAFP) formulated by administrative agent, respectively, and then the WDCP and water demand of forest, animal husbandry and fishery production (WSI) are fed back by administrative agent, respectively, and then the WDI is fed back to sewage treatment agent as well as VAI and IRF are fed back to administrative agent.

AE : \[ \text{WDCP}_{i,t} = \sum_{j=1}^{m} \frac{\text{CA}_{ij,t} \cdot f(\text{IPCP}_{ij,t}, \text{P}_{ij,t})}{\text{CCS}_{ij,t}} \]  \hspace{1cm} (8)

AE : \[ \text{WDFAFP}_{i,t} = \sum_{k=1}^{n} \frac{\text{DSFAFP}_{ik,t} \cdot \text{IPCP}_{ik,t}}{\text{CIPN}_{i,t}} \]  \hspace{1cm} (9)

AE : \[ \text{VACP}_{i,t} = \sum_{j=1}^{m} \frac{\text{CA}_{ij,t} \cdot \text{BPUC}_{ij,t} \cdot \text{WSCP}_{ij,t} + \text{CA}_{ij,t} \cdot \text{BPUC}_{ij,t}}{\text{BCP}_{ij,t}} \]  \hspace{1cm} (10)

AE : \[ \text{VAFAF}_{i,t} = \sum_{k=1}^{n} \frac{\text{DSFAFP}_{ik,t} \cdot \text{BPUEAF}_{ik,t} \cdot \text{WSFAFP}_{ik,t}}{\text{WDFAFP}_{i,t}} \]  \hspace{1cm} (11)

Fig. 3. The basic building blocks for SD method.
\[
\text{SE} : \quad \text{VAAP}_{i,t} = \text{VACP}_{i,t} + \text{VAF}_{i,t} \quad (12)
\]
\[
\text{AE} : \quad \text{ARF}_{i,t} = \text{CARF}_{i,t} \cdot (\text{WSCP}_{i,t} + \text{WSF}_{i,t}) \quad (13)
\]

where \( m \) is the number of crop productions, \( n \) is the number of husbandry and fishery productions, \( j \) is the serial number of crop production, \( k \) is the serial number of husbandry and fishery production, \( P_{i,t} \) is the precipitation of \( i \)th water-intake in time \( t \), \( \text{IPCP}_{i,t} \) is the irrigation quota of \( j \)th crop production in \( i \)th water-intake, \( f(\cdot) \) is the function relationship between \( \text{IPCP}_{i,t} \) and \( P_{i,t} \), \( \text{CCS}_{i,t} \) is the coefficient of canal system of \( i \)th water-intake in time \( t \), \( \text{BPUC}_{i,j,t} \) is the benefit per unit \( j \)th crop production of \( i \)th water-intake in time \( t \), \( \text{BCPI}_{i,j,t} \) is the benefit coefficient of \( j \)th crop production-added by irrigation of \( i \)th water-intake in time \( t \), \( \text{BPFAF}_{i,k,t} \) is the benefit per unit \( k \)th production of forest, animal husbandry and fishery of \( i \)th water-intake in time \( t \), \( \text{CARF}_{i,t} \) is the coefficient of agricultural return-flow of \( i \)th water-intake in time \( t \).
(3) Domestic water agent

The inner stimulus–response of domestic water agent as well as outer feedback relationship among domestic water agent, administrative agent and sewage treatment agent is shown in Fig. 6. Firstly, total population (TP), domestic water quota (DWQ) and domestic water demand (DWD) are calculated by Eqs. (14)–(16) according to the values of growth rate of population (GRP), domestic water price (DWP) and income per capita (IPC) formulated by administrative agent, respectively, and then the TP and DWD are fed back to administrative agent, secondly, domestic sewage discharge (DSD) and domestic return-flow (DRF) are calculated by Eqs. (17) and (18) according to domestic water withdrawal (DWW) fed back by administrative agent, respectively, lastly, DSD is fed back to sewage treatment agent as well as DRF is fed back to administrative agent.

\[
\begin{align*}
\text{SE} &: \quad TP_{i,t+1} = TP_{i,t} \cdot (1 + GRP_{i,t}) \quad (14) \\
\text{AE} &: \quad DWQ_{i,t} = g(DWP_{i,t}, IPC_{i,t}) \quad (15) \\
\text{AE} &: \quad DWD_{i,t} = \frac{DWQ_{i,t} \cdot TP_{i,t}}{CDPN_{i,t}} \quad (16) \\
\text{AE} &: \quad DSD_{i,t} = DWW_{i,t} \cdot DSP_{i,t} \quad (17) \\
\text{AE} &: \quad DRF_{i,t} = CDRF_{i,t} \cdot DWW_{i,t} \quad (18)
\end{align*}
\]

where \(g(\cdot)\) is the function relationship among \(DWQ_{i,t}, DWP_{i,t}\) and \(IPC_{i,t}, CDPN_{i,t}\) is the coefficient of domestic pipe network of \(i\)th water-intake in time \(t\), \(DSP_{i,t}\) is the domestic sewage productivity of \(i\)th water-intake in time \(t\), \(CDRF_{i,t}\) is the coefficient of domestic return-flow of \(i\)th water-intake in time \(t\).

(4) Reservoir and hydropower station agent

The inner stimulus–response of reservoir and hydropower station agent as well as outer feedback relationship among reservoir and hydropower station agent, administrative agent and other water user agent is shown in Fig. 7. Firstly, reservoir water supply (RWS) and reservoir outflow (RO) are calculated by Eq. (19) according to the values of reservoir required water supply (RRWS) fed back by administrative agent as well as reservoir inflow (RI), reservoir volume (RV) and reservoir constraints, and then the RWS and RO are fed back to administrative agent, lastly, RV, hydropower output (HO) and benefit of hydropower station (BHS) are calculated by Eqs. (19)–(21), respectively, as well as the RV, HO and BHS are fed back to administrative agent.

\[
\begin{align*}
\text{SE} &: \quad RV_{i,t+1} = RV_{i,t} + (RI_{i,t} - RO_{i,t}) \cdot \Delta t - RVL_{i,t} \quad (19) \\
\text{AE} &: \quad HO_{i,t} = CHO_{i,t} \cdot WHHS_{i,t} \cdot RO_{i,t} \quad (20) \\
\text{AE} &: \quad BHS_{i,t} = HO_{i,t} \cdot EP_{i,t} \cdot \Delta t \quad (21)
\end{align*}
\]

where \(\Delta t\) is the time interval, \(RVL_{i,t}\) is the reservoir volume loss of \(i\)th reservoir in time \(t\), \(CHO_{i,t}\) is the coefficient of hydropower output of \(i\)th hydropower station in time \(t\), \(WHHS_{i,t}\) is the water head of \(i\)th hydropower station in time \(t\), \(EP_{i,t}\) is the electric price in time \(t\).

(5) Ecological water agent

The inner stimulus–response of ecological water agent as well as outer feedback relationship among ecological water agent, administrative agent and sewage treatment agent is shown in Fig. 8. Firstly, outer-river ecological water demand (OEWD) is calculated by Eq. (22) according to total population (TP) fed back by administrative agent, and then the OEWD and inner-river ecological water demand (IEWD) are calculated by Eqs. (23) and (24) according to the values of TP fed back by administrative agent.

\[
\begin{align*}
\text{SE} &: \quad \text{OEWD} = TP_{t} \quad (22) \\
\text{AE} &: \quad \text{IEWD} = \frac{TP_{t}}{C_2} \quad (23) \\
\text{AE} &: \quad \text{IEWD} = \frac{TP_{t}}{C_2} \quad (24)
\end{align*}
\]
ecological flow (IEF) are fed back to administrative agent, secondly, ecological water shortage (EWS) is calculated by Eqs. (23)–(25) according to outer-river ecological water withdrawal (OEWW) and IEF fed back by administrative agent as well as the EWS is fed back to administrative agent, lastly, outer-river ecological sewage discharge (OESD) is calculated by Eq. (26) and fed back to sewage treatment agent as well as ecological return-flow (ERF) is calculated by Eq. (27) and fed back to administrative agent.

\[
\text{OEWD}_{it} = \frac{\text{TP}_{it} \cdot \text{EAPC}_{it} \cdot \text{OEWQ}_{it}}{\text{CEPN}_{it}} \\
\text{EWS}_{it} = \text{OEWS}_{it} + \text{IEWS}_{it} \\
\text{OEWS}_{it} = \frac{\text{OEWD}_{it}}{C_0} - \text{OEWW}_{it} \\
\text{IEWS}_{it} = \text{IEWD}_{it} - \text{IEF}_{it} \\
\text{OESD}_{it} = \frac{\text{OESP}_{it} \cdot \text{OEWW}_{it}}{C_1} \\
\text{ERF}_{it} = \frac{\text{OEWW}_{it}}{C_1} - \text{CERF}_{it}
\]

where \(\text{EAPC}_{it}\) is the ecological area per capita of \(i\)th water-intake in time \(t\), \(\text{OEWQ}_{it}\) is the outer-river ecological water quota of \(i\)th water-intake in time \(t\), \(\text{OEWS}_{it}\) is the outer-river ecological water shortage of \(i\)th water-intake in time \(t\), \(\text{IEWS}_{it}\) is the inner-river ecological water shortage, \(\text{OEWD}_{it}\) is the outer-river ecological water demand, \(\text{OEWW}_{it}\) is the outer-river ecological water withdrawal, \(\text{OESP}_{it}\) is the ecological sewage discharge, \(\text{CERF}_{it}\) is the ecological return-flow.
ecological water shortage of ith water-intake in time t. IEWD_{it} is the inner-river ecological water demand of ith water-intake in time t, OESP_{it} is the outer-river ecological sewage productivity of ith water-intake in time t, CERF_{it} is the coefficient of ecological return-flow of ith water-intake in time t.

(6) Sewage treatment agent

The inner stimulus–response of sewage treatment agent as well as outer feedback relationship among water user agent, administrative agent and sewage treatment agent is shown in Fig. 9. Firstly, total sewage discharge (TSD) is calculated by Eq. (28) according to the values of domestic sewage discharge (DSD), secondary industry sewage (SIS), tertiary industry sewage (TIS) and outer-river ecological sewage discharge (OESD) fed back by administrative agent, and then the TSD is fed back to administrative agent, secondly, sewage treatment capacity (STC), sewage treatment fee (STF) and volume of pollutant index of sewage treatment (VPIST) are calculated by Eqs. (29)–(31) according to sewage treatment productivity (STP) and volume of pollutant index of sewage treatment (VPIST), are calculated by administrative agent, respectively, lastly, STC, STF and VPIST are fed back to administrative agent.

\[ AE : \quad TSD_{it} = DSD_{it} + SIS_{it} + TIS_{it} + OESD_{it} \]

\[ SE : \quad STC_{i,t+1} = STC_{i,t+1} + VASTC_{i,t+1} \]

\[ AE : \quad STF_{it} = TSD_{it} \cdot STP_{it} \cdot TCPSD_{it} \]

\[ AE : \quad VPIST_{it} = TSD_{it} \cdot STP_{it} \cdot VPIST_{it} + TSD_{it} \cdot (1 - STP_{it}) \cdot VPIPSD_{it} \]

where TCPSD_{it} is the treatment cost per sewage discharge of ith water-intake in time t, VPIST_{it} is the volume of pollutant index per sewage treatment of ith water-intake in time t, VPIPSD_{it} is the volume of pollutant index per sewage discharge of ith water-intake in time t.

2.2. Optimal module

Water resource is an integral part of the socio-economic–ecological–environmental system, which is a CAS dominated by administrative agent. Optimal module is an extension of the previous multi-objective optimal applications (Hou et al., 2014; Roozbahani et al., 2014), focusing on the social, economic, ecological and environmental objectives optimization of the CAS.

2.2.1. Multi-objective function

Multi-objective functions are described as follows:

(1) Social objective function

Gini coefficient denotes the equity of resources allocation proposed by Gini based on Lorenz curve in 1922. The Lorenz curve is shown in Fig. 10. The letter A denotes area between curve of absolute equity allocation and curve of actual income allocation as well as the letter B denotes area below curve of actual income allocation. Gini coefficient is equal to A/(A + B). The value of Gini coefficient is less, the allocation is tend to be more equity. Three kinds of Gini coefficients are selected as objective function evaluating the equity of resources allocation among society, economy and water resources in different regions, i.e., Gini coefficient between population and water consumption (Gini-P), Gini coefficient between gross domestic product (GDP) and water consumption (Gini-GDP) and Gini coefficient between available water resources (AWR) and water consumption (Gini-AWR).

The annual average of Gini-P is defined as follows:

\[ AGini-P = \frac{\sum_{t=1}^{T_y} Gini-P_{it}}{T_y} \]

\[ = 1 - \sum_{t=1}^{T_y} \sum_{i=1}^{N} \left( CPW_{it} + CPW_{i,t+1} \right) \cdot \left( CPP_{it} - CPP_{i,t+1} \right) / CPW_{it} \]

where AGini-P is annual average of Gini-P, Gini-P_{it} is Gini-P in time t, T_y is the number of years; N is the number of water-intakes, CPW_{it} is the cumulative percentage of water consumption (CPW) of ith water-intake in time t, CPP_{it} is the cumulative percentage of population (CPP) of ith water-intake in time t, as well as CPW_{i,0} and CPP_{i,0} are zero in initial time.

The annual average of Gini-GDP is defined as follows:

\[ AGini-GDP = \frac{\sum_{t=1}^{T_y} Gini-GDP_{it}}{T_y} = 1 - \sum_{t=1}^{T_y} \sum_{i=1}^{N} \left( CPW_{it} + CPW_{i,t+1} \right) \cdot \left( CGP_{it} - CGP_{i,t+1} \right) / CPW_{it} \]

where AGini-GDP is annual average of Gini-GDP, Gini-GDP_{it} is Gini-GDP in time t, CGP_{it} is the cumulative percentage of GDP of ith

[Fig. 9. The inner stimulus–response and outer feedback of sewage treatment agent.]
water-intake in time $t$, as well as $\text{CPA}_{i,0}$ is equal to zero in initial time.

The annual average of Gini-AWR is defined as follows:

$$\text{AGini-AWR} = \frac{\sum_{t=1}^{T} \text{Gini-AWR}_t}{T} = 1 - \sum_{i=1}^{N} \left( \text{CPA}_{i, t} + \text{CPW}_{i, t+1} \right) \left( \text{CPA}_{i, t} - \text{CPA}_{i, t+1} \right) / T,$$

where $\text{AGini-AWR}$ is annual average of Gini-AWR, $\text{Gini-AWR}_t$ is Gini-AWR in time $t$, $\text{CPA}_{i, t}$ is the cumulative percentage of AWR of ith water-intake in time $t$, as well as $\text{CPA}_{i,0}$ is equal to zero in initial time.

In order to consider the effect of water consumption by three kinds of Gini coefficients, weighting method (Fang et al., 2009; Zhou and Guo, 2013) is used to calculate the integrated Gini coefficient (IGC). Therefore, the social objective function, i.e., the equity objective function of water consumption, is shown in

$$f_1(X) = \min \text{IGC} = \min (w_1 \cdot \text{AGini-P} + w_2 \cdot \text{AGini-GDP} + w_3 \cdot \text{AGini-AWR}),$$

where $f_1(X)$ is the equity objective function of water consumption, $X$ is the vector of decision variables including economic and social growth rates and water supply, $w_1$, $w_2$ and $w_3$ are the weighting factors of AGini-P, AGini-GDP and AGini-AWR, respectively, as well as the sum of $w_1$, $w_2$ and $w_3$ is equal to one.

(2) Economic objective function

GDP is generally recognized as an important evaluation index of economic strength and situation for country or region. Thus, GDP is selected as economic objective for evaluating the economic benefit of administrative agent in CAS of water resources. The economic objective function maximizing annual average GDP is shown in

$$f_2(X) = \max \frac{\sum_{t=1}^{T} \text{IGDP}_t}{T}$$

where $f_2(X)$ is economic objective function, $\text{IGDP}_t$ is the integrated GDP including economic value-added by industrial production, agricultural production, hydropower generation and sewage treatment in time $t$.

(3) Ecological objective function

Ecological water shortages are composed of inner-river and outer-river ecological water shortages. Hence, the ecological objective function minimizing ecological water shortage is shown in

$$f_3(X) = \min \frac{\sum_{t=1}^{T} \left( \text{IEWS}_{i,t} + \text{OEWS}_{i,t} \right)}{T}$$

where $f_3(X)$ is ecological objective function, $\text{IEWS}_{i,t}$ and $\text{OEWS}_{i,t}$ are inner-river and outer-river ecological water shortage of ith water-intake in time $t$, respectively.

(4) Environmental objective function

The environmental objective function minimizing VPIST is shown in

$$f_4(X) = \min \sum_{t=1}^{T} \sum_{i=1}^{N} \frac{\text{VPIST}_{i,t}}{T}$$

where $f_4(X)$ is the environmental objective function, $\text{VPIST}_{i,t}$ is the VPIST of ith water-intake in time $t$.

Multi-objective functions can be determined as follows:

$$F(X) = (f_1(X), f_2(X), f_3(X), f_4(X))$$

where $F(X)$ is the vector of multi-objective functions.

2.2.2. Constraints

The multi-objective functions subject themselves to seven kinds of constraints: (1) water conservancy projects including reservoir, hydropower station and water-intake, (2) social development including population and growth rate of population, (3) economic development including growth rate of agriculture and industry, proportion between agriculture and industry as well as water price, (4) production water demand, (5) domestic water demand, (6) ecological water demand and (7) sewage treatment capacity and water environment capacity.

2.2.3. Optimal algorithm

NSGA-II is elitist and characterized by weak parameter numbers and good distribution of optimal solutions on the Pareto front (Reed et al., 2003; Kapelan et al., 2005). The Pareto optimality concept is used to test the multi-objective genetic algorithm to compare solutions, according to their objective functions, and to select the non-dominated ones. NSGA-II is applied to solve multi-objective optimization of water resources allocation. The details of main procedure are as follows:

(1) Initialization of parent population: parent population of planning growth rates of agricultural and industrial production as well as population is first randomly generated by pseudo-random sampling. Water demand of water user is predicted by inner stimulus–response of agent and outer feedback relationship between agents based on SD, when the planning growth rates are transmitted to water user agents. Initial population of water supply strategy is randomly generated by pseudo-random sampling after the water demand is fed back from administrative agent.

(2) Evaluation of fitness: the multi-objective functions of society, economy, ecology and environment are calculated according to utilization benefit and sewage discharge of water user agent simulated by SD. Then the fitness of decision variables is evaluated for each chromosome by the non-dominated sorting and calculating crowding distance in NSGA-II (Reed et al., 2003).

(3) Evolution of new population: children population is produced by combination children population with parent population.
(4) Stopping iteration: before going on to the next step, make sure the stopping criteria of iteration are satisfied. Otherwise, steps (2) and (3) are repeated. Pareto optimal set based on non-dominated sorting is confirmed as optimal decision set for water resources allocation.

2.3 Multi-objective evaluation module

2.3.1 Multi-objective evaluation indices

Multi-objective evaluation module is used to evaluate the efficiency of optimal module and select out the optimal scheme of water resources allocation. Therefore, the above four multi-objective functions are selected as multi-objective evaluation indices, i.e., (1) minimizing the integrated Gini coefficient, (2) maximizing the annual average GDP, (3) minimizing the VPIST and (4) minimizing the ecological water shortage.

2.3.2 Projection pursuit method

If \( y_{ij} \) (i = 1, 2, ..., n; j = 1, 2, ..., m) (n is the number of samples, m is the number of cluster factors of the samples) is the initial value of the \( j \)th factor of the \( i \)th sample, the procedure of developing the projection pursuit method is described as follows.

(1) Data standardization

In order to eliminate the effect of different ranges of values of cluster factors, the initial data are standardized before they are used in the projection pursuit method. And the standardization formulas used for two kinds of cluster factors are

\[
y_{ij} = \frac{y_{ij} - y_{min,j}}{y_{max,j} - y_{min,j}} \tag{40}
\]

\[
y_{ij} = \frac{y_{max,j} - y_{ij}^*}{y_{max,j} - y_{min,j}} \tag{41}
\]

where \( y_{min,j} \) and \( y_{max,j} \) are the minimum and maximum of samples, respectively, and other notations have the same meaning as above.

(2) Linear projection

Essentially, projection is used to observe data characteristic from all angles. The main purpose of projection pursuit is to find the hidden structure from high dimensional data sets by searching through all their low dimensional projections. If \( \mathbf{a} = (a_1, a_2, \ldots, a_m)^T \) is a \( m \) dimensional unit vector and \( z_i \) is the projected characteristic value of \( y_{ij} \), linear projection can be described as

\[
z_i = \sum_{j=1}^{m} a_j y_{ij} \tag{42}
\]

(3) Projection index

Cluster analysis is a tool for exploratory data analysis that tries to find the intrinsic structure of data by organizing patterns into groups or clusters. In the projection pursuit method, a new projection index is generated on the basis of dynamic cluster principle.

Define \( s(z_i, z_k) = |z_i - z_k| \) as the absolute value of distance between the projected characteristic value \( z_i \) and \( z_k \), namely \( s(z_i, z_k) \) measures the degree to which the data \( z_i \) and \( z_k \) are close. Let \( \Omega = \{z_1, z_2, \ldots, z_n\} \), and define

\[
\text{SS} = \sum_{z_i \in \Omega} s(A_h, z_i) \tag{43}
\]

(4) Projection pursuit optimization

According to the above analysis, it can be found that the projection pursuit optimization can be expressed by

\[
\text{Maximize } \text{SS} \tag{47}
\]

Eq. (25) shows that the projection pursuit method reflects an optimum problem. As Friedman and Turkey (1974) pointed out, projection pursuit method strongly depends on the ability of the optimization algorithm to find substantive optima of the projection index among a forest of dummy optima caused by sampling fluctuations. Therefore, an efficient algorithm is one of the key issues of the projection pursuit method.

2.3.3 Accelerating Genetic Algorithm

Accelerating Genetic Algorithm (AGA) (Wang et al., 2006; Chen and Yang, 2007; Fang et al., 2009) is used to optimize the projection pursuit problem. The steps of AGA are briefly described as follows:

Step 1: Encoding. Transform the intervals of the variables into \([0, 1]\).

Step 2: Initialization of parent population. Generate \( n \) individuals (also called population size) using uniform random numbers. Calculate the objection function and sort them.

Step 3: Fitness evaluation. Calculate the fitness function and retain the first \( n_s \) individuals which are smart individuals.

Step 4: Reproduction. The smart individuals are directly copied to offspring in AGA, while the other \((n - n_s)\) individuals are selected by the selection probability \( p_i \) from the parent population. This will generate the first offspring population.

Step 5: Crossover. Crossover of the parent individuals occurs to generate the second offspring population according to the crossover probability.

Step 6: Mutation. Mutate the poor individuals using a mutation probability \( p_m \) to generate the third offspring population.

Step 7: Evolution and iteration. Sort the three offspring populations by their fitness, and then select the first \( n \) individuals as the new generation. Go back to step 3 and repeat the steps 3–7 twice.

Step 8: Accelerating cycle. Through every other iteration, compress the intervals of the variables until the terminated rules satisfied. As a result, the optimal solution of AGA is obtained.

Generally, the operations of reproduction, crossover and mutation of genetic algorithm (GA) are executed in series. However, these operations are performed in parallel for AGA, which will fur-
ther protect the genetic information of each individual. Thus, AGA may have much more opportunities to reach the global optimal solution to GA. The interval accelerating mechanism in Step 8 accelerates the convergence of the optimization process.

3. Conclusions

IOAM for CAS of water resources management is done in three parts, (1) an agent-based module, (2) an optimal module and (3) a multi-objective evaluation module, employing different methods. Firstly, SD, agent-based and NSGA-II are used to reveal evolution mechanism of CAS. Secondly, NSGA-II is employed to solve the optimal module made up of multi-objective function and constraints. Lastly, projection pursuit method and AGA are applied to evaluating the efficiency of optimal module and selecting out the optimal scheme of IOAM. Part 2 of this paper is presented as a case study paper dealing with the execution of these integrated methods for CAS of water resources management.

Acknowledgements

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Appendix A

Abbreviations for variables and parameters in the IOAM.

<table>
<thead>
<tr>
<th>No.</th>
<th>Abbreviation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ARF</td>
<td>Agricultural return-flow</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>2</td>
<td>BCPI</td>
<td>Benefit coefficient of production-added by irrigation</td>
<td>(%)</td>
</tr>
<tr>
<td>3</td>
<td>BHS</td>
<td>Benefit of hydropower station</td>
<td>$10^4 \text{yuan}$</td>
</tr>
<tr>
<td>4</td>
<td>BPUC</td>
<td>Benefit per unit crop production</td>
<td>$10^8 \text{yuan/mu}$</td>
</tr>
<tr>
<td>5</td>
<td>BPUFAF</td>
<td>Benefit per unit production of forest, animal husbandry and fishery</td>
<td>$10^8 \text{yuan/mu}$</td>
</tr>
<tr>
<td>6</td>
<td>CA</td>
<td>Crop area</td>
<td>(mu)</td>
</tr>
<tr>
<td>7</td>
<td>CARF</td>
<td>Coefficient of agricultural return-flow</td>
<td>(-)</td>
</tr>
<tr>
<td>8</td>
<td>CCS</td>
<td>Coefficient of canal system</td>
<td>(-)</td>
</tr>
<tr>
<td>9</td>
<td>CDRF</td>
<td>Coefficient of domestic return-flow</td>
<td>(-)</td>
</tr>
<tr>
<td>10</td>
<td>CDPN</td>
<td>Coefficient of domestic pipe network</td>
<td>(-)</td>
</tr>
<tr>
<td>11</td>
<td>CEPN</td>
<td>Coefficient of ecological pipe network</td>
<td>(-)</td>
</tr>
<tr>
<td>12</td>
<td>CERF</td>
<td>Coefficient of ecological return-flow</td>
<td>(-)</td>
</tr>
<tr>
<td>13</td>
<td>CHO</td>
<td>Coefficient of hydropower output</td>
<td>(-)</td>
</tr>
<tr>
<td>14</td>
<td>CIPN</td>
<td>Coefficient of industrial pipe network</td>
<td>(-)</td>
</tr>
<tr>
<td>15</td>
<td>CIRF</td>
<td>Coefficient of industrial return-flow</td>
<td>(-)</td>
</tr>
<tr>
<td>16</td>
<td>DIS</td>
<td>Discharge of industrial sewage</td>
<td>$10^4 \text{ton}$</td>
</tr>
<tr>
<td>17</td>
<td>DRF</td>
<td>Domestic return-flow</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>18</td>
<td>DSD</td>
<td>Domestic sewage discharge</td>
<td>$10^4 \text{ton}$</td>
</tr>
<tr>
<td>19</td>
<td>DSP</td>
<td>Domestic sewage productivity</td>
<td>(%)</td>
</tr>
<tr>
<td>20</td>
<td>DSFAP</td>
<td>Development scale of forest, animal husbandry and fishery production</td>
<td>(mu)</td>
</tr>
<tr>
<td>21</td>
<td>DWD</td>
<td>Domestic water demand</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>22</td>
<td>DWP</td>
<td>Domestic water price</td>
<td>(yuan)</td>
</tr>
<tr>
<td>23</td>
<td>DWQ</td>
<td>Domestic water quota</td>
<td>(liter/ (people-day))</td>
</tr>
<tr>
<td>24</td>
<td>DWWD</td>
<td>Difference between water withdrawal and demand</td>
<td>(yuan)</td>
</tr>
<tr>
<td>25</td>
<td>DIS</td>
<td>Discharge of industrial sewage</td>
<td>$10^4 \text{ton}$</td>
</tr>
<tr>
<td>26</td>
<td>EAPC</td>
<td>Ecological area per capita</td>
<td>(mu/people)</td>
</tr>
<tr>
<td>27</td>
<td>EP</td>
<td>Electric price</td>
<td>(yuan)</td>
</tr>
<tr>
<td>28</td>
<td>ERF</td>
<td>Ecological return-flow</td>
<td>$10^4 \text{m}^3$</td>
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<tr>
<td>29</td>
<td>EWS</td>
<td>Ecological water shortage</td>
<td>$10^4 \text{m}^3$</td>
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<tr>
<td>30</td>
<td>GRCA</td>
<td>Growth rate of crop area</td>
<td>(%)</td>
</tr>
<tr>
<td>31</td>
<td>GRP</td>
<td>Growth rate of population</td>
<td>(%)</td>
</tr>
<tr>
<td>32</td>
<td>GRWC</td>
<td>Growth rate of water consumption per 10,000 yuan economic value-added by industry</td>
<td>(%)</td>
</tr>
<tr>
<td>33</td>
<td>HO</td>
<td>Hydropower output</td>
<td>(kW)</td>
</tr>
<tr>
<td>34</td>
<td>IEF</td>
<td>Inner-river ecological flow</td>
<td>(m$^3$/s)</td>
</tr>
<tr>
<td>35</td>
<td>IEWD</td>
<td>Inner-river ecological water demand</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>36</td>
<td>IEWS</td>
<td>Inner-river ecological water shortage</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>37</td>
<td>IPCP</td>
<td>Irrigation quota of crop production</td>
<td>$10^4 \text{m}^3$/mu</td>
</tr>
<tr>
<td>38</td>
<td>IPC</td>
<td>Income per capita</td>
<td>$10^4 \text{yuan}/(people)$</td>
</tr>
<tr>
<td>39</td>
<td>IRF</td>
<td>Industrial return-flow</td>
<td>$10^4 \text{m}^3$</td>
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<tr>
<td>40</td>
<td>ISP</td>
<td>Industrial sewage productivity</td>
<td>(%)</td>
</tr>
<tr>
<td>41</td>
<td>OESD</td>
<td>Outer-river ecological sewage discharge</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>42</td>
<td>OESP</td>
<td>Outer-river ecological sewage productivity</td>
<td>(%)</td>
</tr>
<tr>
<td>43</td>
<td>OEWS</td>
<td>Outer-river ecological water shortage</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>44</td>
<td>OEWD</td>
<td>Outer-river ecological water demand</td>
<td>$10^4 \text{m}^3$</td>
</tr>
<tr>
<td>45</td>
<td>OEWQ</td>
<td>Outer-river ecological water quota</td>
<td>$10^4 \text{m}^3$/mu</td>
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### Appendix A (continued)

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<thead>
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<th>No.</th>
<th>Abbreviation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>46</td>
<td>OEWW</td>
<td>Outer-river ecological water withdrawal</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>47</td>
<td>P</td>
<td>Precipitation</td>
<td>(mm)</td>
</tr>
<tr>
<td>48</td>
<td>PGRVA</td>
<td>Planning growth rate of economic value-added by industry</td>
<td>(%)</td>
</tr>
<tr>
<td>49</td>
<td>PVAI</td>
<td>Planning economic value-added by industry</td>
<td>(10^8 yuan)</td>
</tr>
<tr>
<td>50</td>
<td>RI</td>
<td>Reservoir inflow</td>
<td>(m^3/s)</td>
</tr>
<tr>
<td>51</td>
<td>RO</td>
<td>Reservoir outflow</td>
<td>(m^3/s)</td>
</tr>
<tr>
<td>52</td>
<td>ROR</td>
<td>Reservoir operating rules</td>
<td>(–)</td>
</tr>
<tr>
<td>53</td>
<td>RRWS</td>
<td>Reservoir required water supply</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>54</td>
<td>RTWL</td>
<td>Reservoir tail water level</td>
<td>(m)</td>
</tr>
<tr>
<td>55</td>
<td>RWL</td>
<td>Reservoir water level</td>
<td>(m)</td>
</tr>
<tr>
<td>56</td>
<td>RWS</td>
<td>Reservoir water supply</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>57</td>
<td>RV</td>
<td>Reservoir volume</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>58</td>
<td>RVL</td>
<td>Reservoir volume loss</td>
<td>(10^4 m^3)</td>
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<tr>
<td>59</td>
<td>SIS</td>
<td>Secondary industry sewage</td>
<td>(10^4 ton)</td>
</tr>
<tr>
<td>60</td>
<td>STC</td>
<td>Sewage treatment capacity</td>
<td>(ton/d)</td>
</tr>
<tr>
<td>61</td>
<td>STF</td>
<td>Sewage treatment fee</td>
<td>(10^4 yuan)</td>
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<tr>
<td>62</td>
<td>STP</td>
<td>Sewage treatment productivity</td>
<td>(%)</td>
</tr>
<tr>
<td>63</td>
<td>TCPSD</td>
<td>Treatment cost per sewage discharge</td>
<td>(yuan/ton)</td>
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<tr>
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<td>TIS</td>
<td>Tertiary industry sewage</td>
<td>(10^4 ton)</td>
</tr>
<tr>
<td>65</td>
<td>TP</td>
<td>Total population</td>
<td>(10^4 people)</td>
</tr>
<tr>
<td>66</td>
<td>TSD</td>
<td>Total sewage discharge</td>
<td>(10^4 ton)</td>
</tr>
<tr>
<td>67</td>
<td>VAAP</td>
<td>Economic value-added by agricultural production</td>
<td>(10^8 yuan)</td>
</tr>
<tr>
<td>68</td>
<td>VACP</td>
<td>Economic value-added by crop production</td>
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<tr>
<td>69</td>
<td>VAFAF</td>
<td>Economic value-added by forest, animal husbandry and fishery production</td>
<td>(10^8 yuan)</td>
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<td>VAI</td>
<td>Economic value-added by industry</td>
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<tr>
<td>71</td>
<td>VASTC</td>
<td>Economic value-added by sewage treatment capacity</td>
<td>(ton/d)</td>
</tr>
<tr>
<td>72</td>
<td>VPIPSD</td>
<td>Volume of pollutant index per sewage discharge</td>
<td>(m^3/ton)</td>
</tr>
<tr>
<td>73</td>
<td>VPIPST</td>
<td>Volume of pollutant index per sewage treatment</td>
<td>(m^3/ton)</td>
</tr>
<tr>
<td>74</td>
<td>VPIST</td>
<td>Volume of pollutant index of sewage treatment</td>
<td>(m^3)</td>
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<td>WDCP</td>
<td>Water demand of crop production</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>76</td>
<td>WDFAFP</td>
<td>Water demand of forest, animal husbandry and fishery production</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>77</td>
<td>WDI</td>
<td>Water demand of industry</td>
<td>(10^4 m^3)</td>
</tr>
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<td>78</td>
<td>WHHS</td>
<td>Water head of hydropower station</td>
<td>(m)</td>
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<td>79</td>
<td>WQFAFP</td>
<td>Water quota of forest, animal husbandry and fishery production</td>
<td>(10^4 m^3/mu)</td>
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<td>80</td>
<td>WQVAI</td>
<td>Water quota per 10,000 yuan of economic value-added by industry</td>
<td>(m^3/10^4 yuan)</td>
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<td>81</td>
<td>WSCP</td>
<td>Water supply for crop production</td>
<td>(10^4 m^3)</td>
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<tr>
<td>82</td>
<td>WSFAFP</td>
<td>Water supply for forest, animal husbandry and fishery production</td>
<td>(10^4 m^3)</td>
</tr>
<tr>
<td>83</td>
<td>WSI</td>
<td>Water supply for industry</td>
<td>(10^4 m^3)</td>
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### References


Yang, C.C., Chang, I.C., Ho, C.C., 2008. Application of system dynamics with impact analysis to solve the problem of water shortages in Taiwan. Water Resour. Manage. 22 (11), 1561–1577.


