Decision Support System for Integrated and Adaptive Water Governance

Zhongyuan Li, Qian Zhang, Feng Wu, and Pei Wang

Contents

Introduction 388
System Design and Implementation 390
    Decision-Making Process 390
    System Architecture 391
    Tools and Technologies Used 392
    Model 394
    Model Integration 398
    Validation of the Water Economic Model Result 399
Application of IAGWR-DSS 401
    Case Study Area 401
    Data Used 403
    Scenario Designs for Impacts of Industrial Transformation on Water Consumption 404
    Results Analysis 407
Discussion and Conclusions 414
References 416

Z. Li (✉)
Faculty of Resources and Environment Science, Hubei University, Wuhan, People's Republic of China

Hubei Key Laboratory of Regional Development and Environmental Response, Hubei University, Wuhan, People's Republic of China

Q. Zhang · F. Wu
Institute of Geographic Sciences and Natural Resources Research, Center for Chinese Agricultural Policy, Chinese Academy of Sciences, Beijing, China

P. Wang
School of Business Administration, Zhongnan University of Economics and Law, Wuhan, People's Republic of China

X. Deng, J. Gibson (eds.), *River Basin Management*, Ecohydrology,
https://doi.org/10.1007/978-981-10-6949-9_8

Abstract

Water resource management has attracted increasing attention, as water has become increasingly regarded as one of the most critical resources in the world's sustainable development, especially in arid areas such as Northwest China. This is the result of a lack of effective administration and management of water resources. In this study, a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS) was designed and developed to support integrated water resource management in river basins. IAGWR-DSS is based on integration of a geographical information system platform (ArcGIS Engine 10.2), a database platform (Microsoft Access), and a plug-in development framework. Some economic models and land use models have been integrated into IAGWR-DSS, such as computable general equilibrium (CGE) models. Four parts are included in IAGWR-DSS: (1) a basic information subsystem including the fundamental geographic information, landform, soil type, land use, hydrology, meteorology, spatiotemporal relations of the social economy, and water attributes of the basin; (2) a scenario simulation environment for the CGE model; (3) a data management subsystem to update the water consumption data, land change data, and socioeconomic data in the database; and (4) a decision support subsystem to visualize and map the results of the simulation and generate a decision report for decision makers. This study focused on the second largest inland river basin in China – the Heihe River Basin, located in an arid area – as an example to illustrate the proposed decision support system prototype for integrated water resource management, coupling the socioeconomic system and the hydrological cycling process. The key tasks of the decision support system for integrated water resource management in the Heihe River Basin are to rationally allocate water resources between the upper, middle, and lower reaches (the spatial dimension) and also between the industrial, living, and ecological sectors (the structure dimension). The change in the regional water resources and arable land can be observed visually, intuitively, and rapidly. The developed DSS is very useful to deal with complex water resource management problems in river basins.

Keywords

Decision support system · Integrated water resource management · Adaptive governance of water resources · System · Model · Database · River Basin

Introduction

With global climate change, sustained population and socioeconomic growth, rapid urbanization, and transition of water resource exploitation, the conflict between the supply of and demand for freshwater resources is increasingly prominent, and the health of water environments and ecological systems is becoming worse and worse, which seriously threatens humans' survival, environment, and food security (Hanjra and Qureshi 2010; Jenerette and Larsen 2006). Worldwide, more than 1.2 billion people living in river basins are facing a shortage of water resources (Karimi et al. 2013; Molden 2007), and now this shortage has become a key limiting factor in social and economic development and environmental protection in these areas (Fedoroff et al. 2010; Oki and Kanae 2006). With contemporary social and economic development and the emergence of this ecological crisis, the need for people to live in harmony with water has become a theme for the development of river basins. The challenges in the management of river water resources are how to protect the water environments and ecological systems that humans and other creatures depend on for their existence, and how to improve the sustainability of basin water resource utilization (Petit and Baron 2009).

Basins are the natural unit for developing a strategy to cope with the shortage of water resources (Simons et al. 2015), which has often been abstracted with regard to the social and ecological aspects of complex systems, so establishing integrated basin water resource management systems is one of the important directions in international water resource management. Meanwhile, decision support systems for the management of basin water resources provide technological support and are powerful tools for sustainable basin water resource development, environmental management, and planning (Anderson and Iyaduri 2003; Giusti and Marsili-Libelli 2015; Pollard and du Toit 2008).

More and more researchers have realized that parallel eco-hydrological and socioeconomic water cycling models have limited comprehensive understanding of water circulation and water use because there are interactive feedbacks between eco-hydrological and socioeconomic water cycling processes (models), and the relations between them are not one-way direct impacts or responses. Nevertheless, the mechanisms and spatiotemporal scales of the two streams of models are distinctly different. The majority of socioeconomic models are spatially discrete, relying on administrative boundaries and yearly or monthly statistical data. However, widely used eco-hydrological models are spatially continuous and explicit at the pixel level, and they rely on hourly monitoring data. Consequently, how to integrate the two streams of models and distinctly express the interactive relations between the physical and socioeconomic factors in the upper, middle, and lower reaches is a prominent scientific challenge for coupling human–natural system research (Deng et al. 2017). To date, the need for seamless integration of these two categories of model has been underexamined, and there are few existing successful case studies.

Importantly, without considering eco-hydrological and socioeconomic water cycling simultaneously, any analysis of water circulation will result in partial and potentially misleading conclusions and will ultimately fail to effectively guide sustainable water resource management. To fill the knowledge gaps in model integration, we first summarize the pixel-level geophysical variables and water resource parameters according to administrative units. We then integrate these geophysical and socioeconomic variables into multiregional and dynamic computable general equilibrium (CGE) models (Calzadilla et al. 2008; Jiang et al. 2014; Wu et al. 2015) with the aid of land functional parcel identification and resource (water and land)–embedded input–output tables.

Since decision support systems are widely used in integrated water resource management, the nations of the world have applied them to their own national conditions to carry out a large amount of research (Abramson et al. 2014; Aydin et al. 2015; Chen et al. 2010; Cliburn et al. 2002; Droubi et al. 2008; Ge et al. 2013; Georgakakos 2004; Giupponi 2007; Junier and Mostert 2014; Ling et al. 2014; Lorz et al. 2013; Lang and Gleick 2008; Pallottino et al. 2005; Simons et al. 2015; Zhang et al. 2010), which can provide experience for building an integrated basin water resource management decision support system for reference. However, a basin system is dynamic, changeable, nonequilibrious, open dissipative, and unstructured or semistructured in terms of the dual processes of the natural water cycle and the socioeconomic water cycle, and the existing models and systems inevitably cannot meet the current demand for comprehensive water resource management. In addition, the current research on the integration lacks simulation of a spatially explicit analysis of social and economic systems of water resource utilization, with simulation of the social water cycle and a comprehensive and dynamic design and simulation scenario for social and economic development on a river basin scale. What is more, the models for integration are not adequate, lacking the ability to fully express the relations between the natural and socioeconomic systems, and it is hard to create reasonable forecasts and response options taking into account the dramatic changes that may occur in the climate, water resources, and ways of using water.

In order to support the basin's sustainable development, establishing a watershed integration model combining "natural processes" and "social learning," this paper uses a water–socioeconomic model as a basis to design a framework, structure, and function for a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS) to implement a model coupling the socioeconomic system and eco-hydrological processes. Using a database with high-precision and real-time updates, taking into account climate change, land use changes, basin planning, socioeconomic development, and other scenarios that affect basin water resources, this can not only realize the processes of a socioeconomic and eco-hydrology model based on analysis of simulations but also forecast the evolution of the river basin's water–ecology–social economy coupled systems. What is more, it can improve the precision, reliability, and practicability of the system to solve common problems in the system, using natural geographic data and a combination of social and economic data and different scales of the model, so that it can provide comprehensive decision-making knowledge and technology support for basin water resource management.

System Design and Implementation

Decision-Making Process

The main idea of IAGWR-DSS is a full meta-analysis of basin water resource integrated management of all types of user needs; it brings together a wide range of integrated management of river basin water resources and the wisdom of experts in related fields of scientific research, using computers, software engineering, networking, geographic information systems, remote sensing, and other advanced technologies. It integrates related data on water resource management to provide accurate, convenient, fast, and rich water resources for all types of users, with an integrated watershed management model algorithm and data services. The decision support system for the integrated watershed management framework includes five important parts: users, models, data, scenario simulations, and an interactive user interface (UI). Users can, according to their needs, drive the model by simulating different scenarios of data processing, with output simulation and calculation of results with a visual display at the UI, for decision support to the user. In the whole process, users can propose various models; propose algorithms for the problems and needs of the decision making in a timely manner, in consultation with experts, according to problems and demand issues; constantly refine and improve model algorithms; and create models and algorithms to improve applicability, efficiency, and accuracy, thus forming a virtuous circle of users, models, simulation, data, and decision support, and ultimately providing reliable decision support programs. The design of the decision support system for integrated water resource management of the watershed is shown in Fig. 1.

System Architecture

IAGWR-DSS is a user-friendly, interactive, GIS-based decision support system, which consists of socioeconomic models for sustainable development and management of natural resources and human behavior on a watershed basis. Various data analysis and process techniques have been integrated into development of IAGWR-DSS to handle the models and various data sets. In addition, an integrated socioeconomic simulation model and Dynamics of Land System (DLS) model have been integrated and developed with UIs to support scenario simulation and analysis for water resource management and watershed decision-making processes.

Three-layer architecture is used in the system design, including the UI, application layer (AL), and data layer (DL). Every layer corresponds to a different functionality and role. A concept structure diagram of IAGWR-DSS is shown in Fig. 2.

The DL includes multisource (satellite, GPS, ground, site, report, paper, and statistical yearbook) data sets on the watershed, such as socioeconomic data, water resource data, hydrological data, meteorological data, soil property data, crop data, land use data, vegetation data, ground observation data, etc. The AL is implemented using ArcGIS Engine and .Net Framework, which is a powerful and flexible technology for building the model-running and visualization environment. This provides a user-friendly platform for various modeling environments and data management, processing, analysis, and results visualization functionality. The UI consists of different scenario simulation, parameter configuration, and results display interfaces for models. It also provides various data manifestations (data sheets, charts, graphs, and maps) to help users understand the simulation results of watershed water resource management more efficiently.

Fig. 1 Design philosophy for a decision support system for integrated and adaptive governance of water resources (IAGWR-DSS)

Tools and Technologies Used

- *ArcGIS Engine:* ArcGIS Engine (10.2) is a collection of GIS components and developer resources that can be embedded, allowing addition of dynamic mapping and GIS capabilities to existing applications or building of new custom mapping applications. Developers use ArcGIS Engine to deploy GIS data, maps, and geo-processing scripts in desktop or mobile applications using application programming interfaces (APIs) for COM, .NET, Java, and C++.
- *.NET Framework:* .NET Framework (4.0) is a software framework developed by Microsoft and runs primarily on Microsoft Windows. It includes a large class library, known as the Framework Class Library (FCL), and provides language

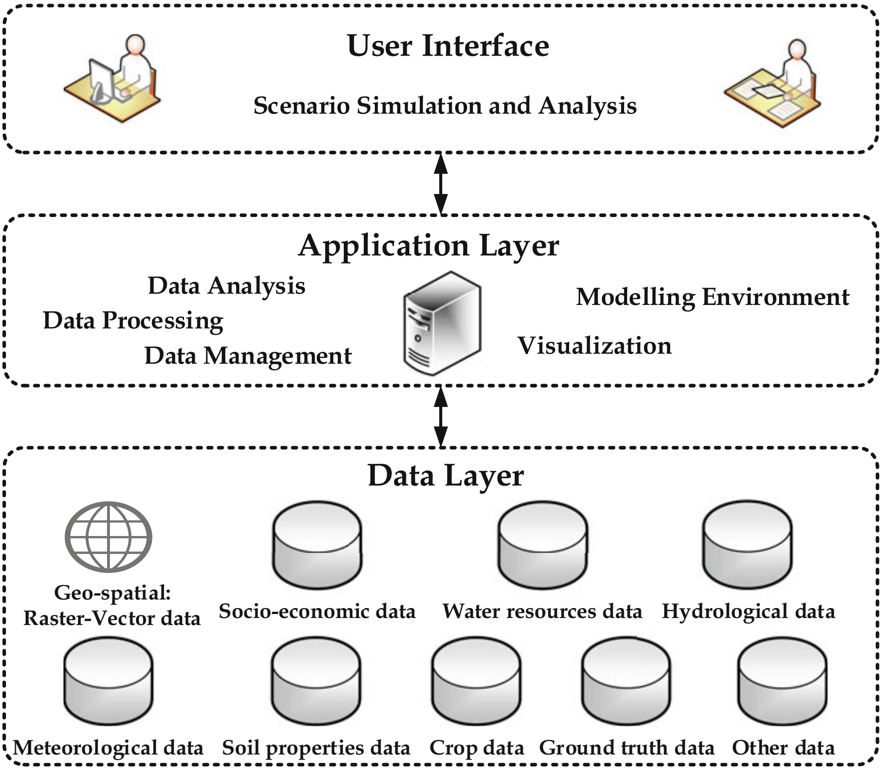

Fig. 2 System architecture of the decision support system for integrated and adaptive governance of water resources (IAGWR-DSS)

interoperability (each language can use code written in other languages) across several programming languages.

- *Microsoft Access:* Microsoft Access is a database management system (DBMS) from Microsoft. It combines the relational Microsoft Jet Database Engine with a graphic UI and software development tools. It is a member of the Microsoft Office suite of applications, included in the Professional and higher editions, or sold separately.
- *Personal Geo-Database:* Personal Geo-Database is a Microsoft Access database with a set of tables defined by Esri for holding geo-database metadata, and with geometry for features held in a BLOB column in a custom format (essentially shapefile geometry fragments). This driver accesses the Personal Geo-Database via ODBC but does not depend on any Esri middle-ware.

IAGWR-DSS is implemented by visual C# based on the ArcGIS Engine 10.2 for .Net 4.0; nonspatial data can be stored in Microsoft Access directly, and geospatial data can be stored and managed in the Personal Geo-Database via the ArcGIS Engine API. Fig. 3 shows the general UI of the system.

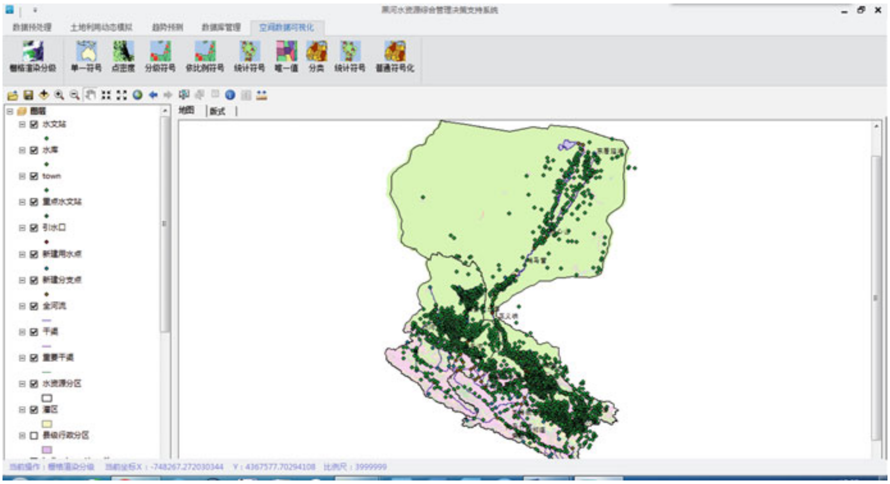

Fig. 3 User interface (UI) of the system

Model

Water resources and socioeconomics are an inseparably integrated system; they rely on each other and influence each other. Water is the foremost productive material in both the economic system and the necessities of life. The conversion, use, protection, and health of water resources have been impacted directly by the economic system's mode of production.

As an important part of this complex and giant system, water resources have a direct impact on the scale and stability of the economic system. The utilization of water resources in socioeconomics has made unceasing progress with the development of human beings' knowledge, production technology level, and social consciousness. Therefore, it is necessary to depict the transfer process of water resources in the socioeconomic system and build subject behavior model equations for socioeconomics, simulating water flow in production, circulation, allocation, and use in the socioeconomic system.

A CGE model has the advantage of depicting the macroscopic behavior of the socioeconomic system. It is a useful tool for analyzing water prices, water rights, water resource allocation, and the water market, and it is an effective means for analyzing and forecasting water demand with changes in the socioeconomic system. This section focuses on the framework and definition of an integrated model, named the Water Economic Model (WEM), which embeds the water and land resources and the key theory of ecological–hydrological process scenario simulation. The WEM links the key parameters in ecological–hydrological processes and the socioeconomic system, which influence water resource management. The productivity level is influenced by ecological–hydrological processes via the quantity and quality of water resource factor input into the productive process. Changes in the allocation ratio of surface and underground water and land change ecological–hydrological processes by influencing the cyclic process of surface water and underground water in the water and land resource combination of the socioeconomic system. Water resources are affected by socioeconomic subject behavior through land use.

On the basis of the CGE model, the socioeconomic system model decomposes the investment of surface water, underground water, and other water, and increases the price-influencing mechanism for surface water and underground water to analyze the consumption utility of the socioeconomic system. The subjects of the production will allocate the investment combination of the initial factors on the basis of consumption utility. Allocation of water resources can be carried out in the socio-economic system via market mechanisms such as water prices, water rights, and so on. Therefore, the behavior of the socioeconomic system is affected by the water and land resources via the processes of production, consumption, and taxation.

The basic principles of the WEM production module are (1) to allow industrial producers a variety of different types of products at the same time while (2) considering many primary factors in production input such as land, labor, capital, etc., and (3) retain controllability of multiple input–output production modes by a series of separability assumptions.

The decision making of all of the model's production departments is based on production technology principles of cost minimization and stable returns to scale. Multilevel nested functions, named the Leontief function and constant elasticity of substitution (CES), are adopted to describe the framework of the production module. There are different alternative or complementary relationships between inputs into the same nested structure. The Leontief function is used to describe the gross output, which is affected by the combined commodity of intermediate inputs, the combination of the primary elements and other costs, and a fixed ratio of inputs.

$$COM_{c,i} = acom_{c,i} \times XP \tag{1}$$

$$PRIM_i = aprim_i \times XP_i \tag{2}$$

$$OCT_i = aoct_i \times XP_i \tag{3}$$

$$PX_i = \sum_{c \in COM} acom_{c,i} \times PCOM_{c,i} + aprim_i \times PPRIM_i + aoct_i \times POCT_i \tag{4}$$

Each intermediate input can be divided into the combination of a domestic commodity and an imported commodity. The combination between these two products is decided according to the elasticity of substitution and is described by the CES function.

$$DCOM_{c,i} = sdc_{c,i} \cdot \left[\frac{PCOM_{c,i}}{PDCOM_{c,i}}\right]^{\sigma com_c} \tag{5}$$

$$ICOM_{c,i} = sic_{c,i} \cdot \left[\frac{PCOM_{c,i}}{PICOM_{c,i}}\right]^{\sigma com_c} \tag{6}$$

$$PCOM_{c,i} = \left[sdc_{c,i} \cdot PDCOM_{c,i}^{1-\sigma com_c} + sic_{c,i} \cdot PICOM_{c,i}^{1-\sigma com_c}\right]^{\frac{1}{1-\sigma com_c}} \tag{7}$$

The combination of land (LND), capital (CAP), and labor (LAB) is expressed by the CES function.

$$LND_i = slnd_i \cdot \left[\frac{PPRIM_i}{PLND_i}\right]^{\sigma prim_i} \tag{8}$$

$$LAB_i = slab_i \cdot \left[\frac{PPRIM_i}{PLAB_i}\right]^{\sigma prim_i} \tag{9}$$

$$CAP_i = scap_i \cdot \left[\frac{PPRIM_i}{PCAP_i}\right]^{\sigma prim_i} \tag{10}$$

$$PPRIM_i = \left[slnd_i \cdot PLND_i{}^{1-\sigma prim_i} + slab_i \cdot PLAB_i{}^{1-\sigma prim_i} + scap_i \cdot PCAP^{1-\sigma prim_i}\right]^{\frac{1}{1-\sigma prim_i}} \tag{11}$$

The combination of different types of labors (LABO) is also described by the CES function.

$$LABO_{o,i} = slabo_{o,i} \cdot \left[\frac{PLAB_i}{PLABO_i}\right]^{\sigma lab_i} \tag{12}$$

$$PLABO_i = \left[\sum_{o \in OCC} slab_{o,i} \cdot PLABO_{o,i}^{1-\sigma lab_i}\right]^{\frac{1}{1-\sigma lab_i}} \tag{13}$$

A household puts part of its income from capital, land, labor, corporate profits, and deposit interest into productive consumption, and puts another part into investment.

In order to assess the contributions of and impacts on economic development and requirements for change in land–water resources in Zhangye City, this study improved the CGE model on the basis of international mainstream research on the relationship between land–water resources and socioeconomic systems. There are not enough land–water resources in Zhangye; the water resource has become the main restricting factor in the development of the local economy. Therefore, it is reasonable to put the land–water resources into the CGE model as production factors. The combination between different types of water resources can be described by the CES function. Water resources are the key limiting factor in the planting structure, development scale, and economic distribution in Zhangye. The Leontief function can express the relationship between land and water resources.

$$SWT_i = sswt_i \cdot \left[\frac{PRWT_i}{PSWT_i}\right]^{\sigma rwt_i} \tag{14}$$

$$UWT_i = suwt_i \cdot \left[\frac{PRWT_i}{PUWT_i}\right]^{\sigma rwt_i} \tag{15}$$

$$OWT_i = sowt_i \cdot \left[\frac{PRWT_i}{POWT_i}\right]^{\sigma rwt_i} \tag{16}$$

$$PRWT_i = \left[srwt_i \cdot PSWT_i^{1-\sigma rwt_i} + suwt_i \cdot PUWT_i^{1-\sigma rwt_i} + sowt_i \cdot POWT^{1-\sigma rwt_i}\right]^{\frac{1}{1-\sigma rwt_i}} \tag{17}$$

$$RWT_i = arwt_i \times LWT_i \tag{18}$$

$$LND_i = alnd_i \times LWT_i \tag{19}$$

$$PLWT_i = arwt_i \times PRWT_i + alnd_i \times PLND_i \tag{20}$$

A static model only depicts a period of economic system subject behavior; all of the endogenous variables just have characteristics of this period. The future climate change scenarios have been predicted until at least 2030; therefore it is necessary to analyze long-term, dynamic, and different years' changes in the endogenous variables of economic agents.

Investment, consumption, and exportation are the three major driving forces of economics. This study researches the dynamic extension mechanism using the WEM. Investment is the main variable for carrying out long-term forecasting of the model in recursive dynamic extensions year after year. The forecasting system contains three kinds of mechanism: (1) the stock–flow relationship of investment and capital; (2) the positive relationship between investment and profit/rate of return; and (3) the relationship between wage growth and employment. The model assumes that domestic production and importation are driving forces of the next round of economic development in investment demand.

The initial capital value for each time interval in the WEM is the economic capital situation at the end of the previous year and the start of the current year. The capital at the beginning of the year, which affects subsequent production, is the sum of the capital stock at the beginning of the previous year and the new capital from the previous year. The growth rate of the capital at the beginning and end of the year is determined by the capital supply curve. Investment is decided by the expected rate of return on capital. The expected rate of return can be convergent with the actual rate of return through a local adjustment mechanism. A recursive dynamic model year by year means that every result of the model stands for the change in the current and next years. The dynamic accumulation mechanism of capital is dynamic recursion according to the benefit of industry sectors. Investors can consider the population increase in the dynamic model for a long time, predict the future employment trend, and change the employment rate according to dynamic adjustment of salaries. Wages will rise if the employment is above the trend level at the end of the term. Therefore, employment and real wages go in opposite directions; this mechanism leads to employment being adjusted according to the trend.

$$\frac{W_{t+1} - W_t}{W_t} = \gamma\left[\frac{L_t}{T_t} - 1\right] + \gamma\left[\frac{L_{t+1}}{T_{t+1}} - \frac{L_t}{T_t}\right] \tag{21}$$

Model Integration

Water use efficiency and management are correlated with land use and cover changes (LUCCs), population distribution, industrial structure, economic development, climate changes, and environmental governance (Deng et al. 2015). The CGE model is integrated into IAGWR-DSS; brief descriptions of the model are given below.

The CGE model is an effective tool to reallocate the primary factors across sectors for different industrial transformation scenarios. It is widely used to evaluate the impact of external shocks on water utilization efficiency at different scales, especially the impacts of socioeconomic policies on water flow across sectors (Wu et al. 2014). Most studies of the CGE model have mainly focused on the effects of shifting water rights and water allocation across sectors, regulation of surface and groundwater resources, and water resource management (Çirpici 2009; Horridge and Wittwer 2008).

This water CGE model is an extended standard CGE model, so it usually includes the components of the factor market, consumption market, production market, government market, trade flow, and commodity exchanges as an intermediate input–output process. Commodities are produced by all firms in a sector that present both market demand for consumption and market supply of production. Thereby, the regional economic structure can be aggregated by a series of production functions to represent a practical and specific economic scale, and water may also be considered as a factor in production. The consumption market is formed by all households, which represents all family earnings and purchases. Their incomes are divided into two parts: one part comes from all-factor income and the other part comes from their salaries. For money flows in a well-constructed circulation, household purchases connect the factor market and commodity market. Water commodities purchased in the product market may not include all water use for all production processes in every sector (Wu et al. 2014). The conceptual water flow in a CGE model is presented in Fig. 4.

The CGE model was used to determine the future water demand and to optimize and assess the water allocation in the forecasted urbanization scenarios. In the model, the circular flow of the economy and water were represented by a set of financial transactions. The value of water changes substantially with time and space. The production and consumption functions were used to represent the economic activities of primary, secondary, and tertiary industries. In the nested structure of production function, land and water were considered as part of the primary factors. The CGE model is modified to embed water, and the economic activities of primary,

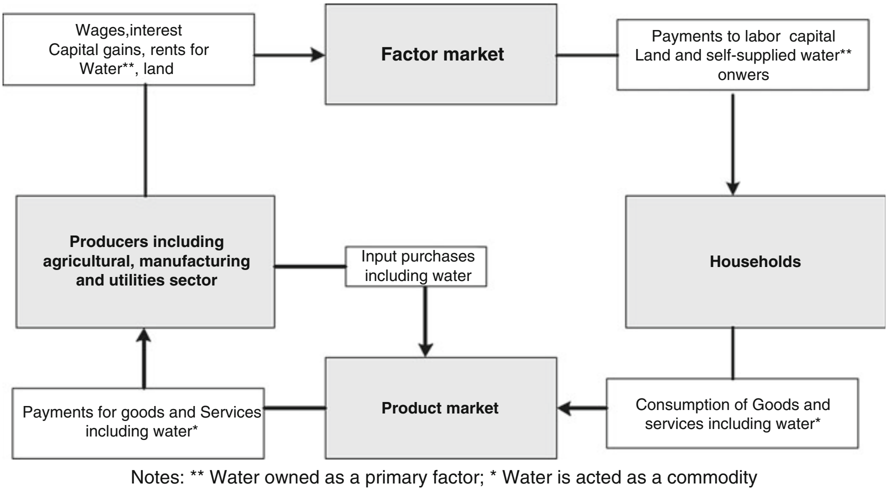

Fig. 4 Framework of economic activities embedding water resources in the computable general equilibrium (CGE) model (Reprinted from Wu et al. (2014) with permission of Sustainability)

secondary, and tertiary industries are included in the water-embedded CGE model with the production and consumption functions. A detailed description of production function and the variables of input–output are reported in Wu et al. (2014).

The Global Trade Analysis Project – Water (GTAP-W) model is a very famous model based on the Global Trade Analysis Project (GTAP) model for water use in agriculture (Calzadilla et al. 2011), which was implemented using GEMPACK software (Hertel 1996). In the GTAP-W model, the original land endowment has been split into pasture land, rain-fed land, irrigable land, and irrigated land. Irrigation water is nested into a value-added part, which implies substitution possibilities with irrigable land and all other factors of production. By combining irrigated land and its water supply, production factors are set into a value-added nest through a CES function. The nest structure of GTAP-W is relatively simpler but more flexible (Wu et al. 2014). The model's parameter-setting UI is shown in Fig. 5.

Validation of the Water Economic Model Result

The closure of the WEM sets the endogenous variables and exogenous variables, and mathematically, it means to explain "the necessity of providing the model with the same number of equalities and endogenous variables." Generally, an equation set is closed in order to resolve this set (Fig. 6). However, as for a multidimensional economic theory model, the closure rules are more complicated. Thus, closure rules should be correctly set to produce more appropriate results. The four closure rules in the CGE models include neoclassical closure, Keynes's closure, Kaldor's closure, and Johnson's closure, one of which is selected by the WEM according to the simulated scenario.

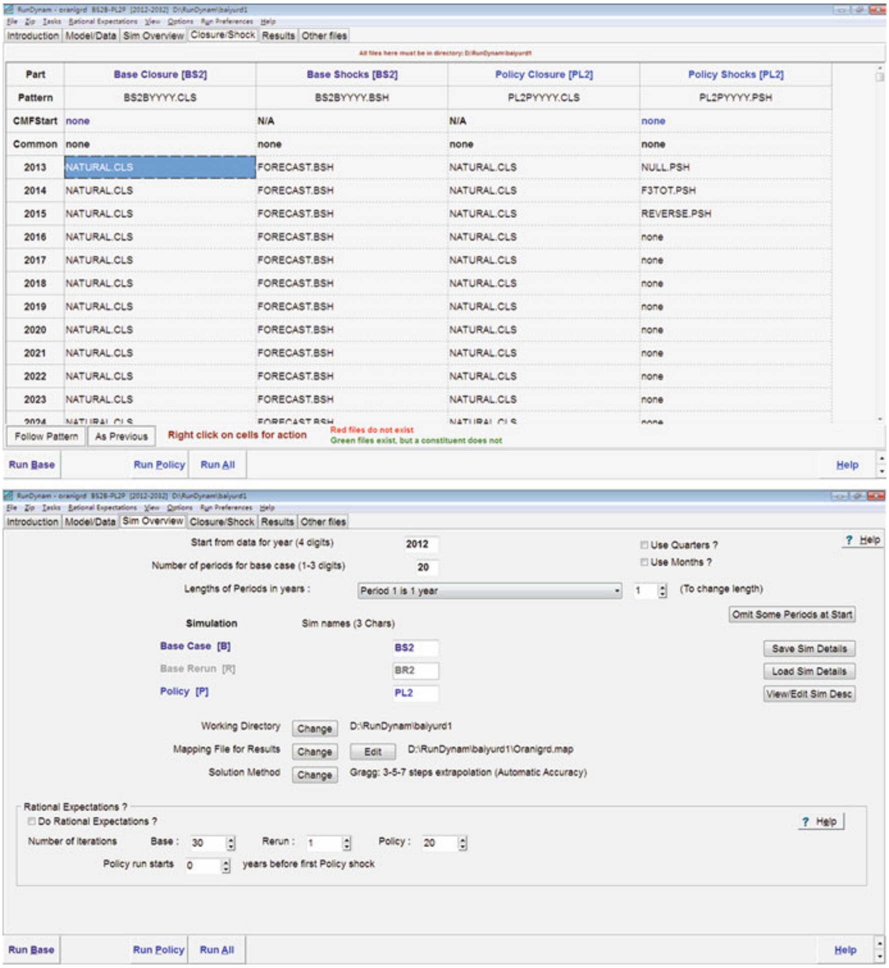

Fig. 5 Parameter-setting user interface (UI) of the computable general equilibrium (CGE) model

Neoclassical closure is long term, while Keynes's and Johnson's closures are short term, so the four closure rules are not contradictory. The appropriate closure rule should be selected according to the objective of the modeling. Admittedly, the operation result is determined by the use of the specific macroscopic closure rules. Moreover, for either neoclassical closure or Johnson's closure, the output is fully determined by the production function. Since the elements are appointed and completely used, the real wage rate and wage yield are identified by the marginal labor productivity and income surplus. As for Keynes's closure, the output, employment, and relative price are obtained jointly by the demand and supply. Kaldor's closure is relatively simple, as it considers full employment (Wu et al. 2017).

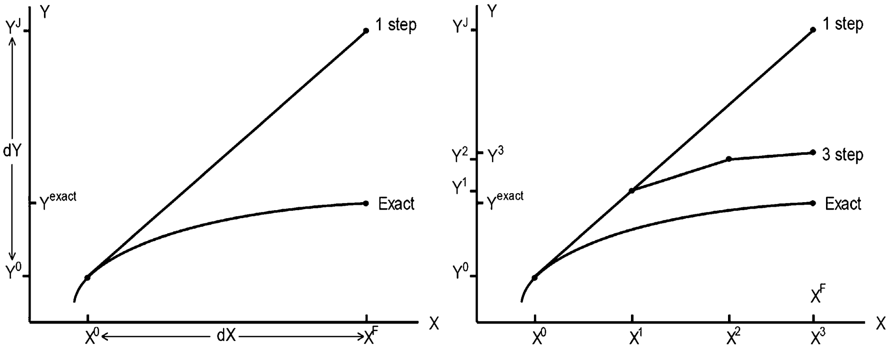

Fig. 6 Water Economic Model (WEM) methods for solving linear model error (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Application of IAGWR-DSS

Case Study Area

The Heihe River Basin is located in an arid/semiarid region (90–102°E, 37°50’–42°40’N), which includes part of Qilian County in Qinghai Province, some counties and cities in Gansu Province, and part of Ejina Banner in the Alxa League of Inner Mongolia (Li et al. 2001; Deng et al. 2015). The total basin area is 0.24 million km^2, and the average altitude of the basin is over 1200 m. The major river of the basin is the Heihe River, with a total length of 821 km, composed of three major reaches: upstream, middle, and downstream. Our study area includes the upstream and middle reaches of the river (Fig. 7). The upstream reach, which is the water source area, is located in the southern Qilian Mountains. This region is characterized by remarkable vertical zonality; the elevation ranges from 5290 m in the high-mountain zone to 2000 m in the low-mountain or hill zone. This results in a steep gradient in mean annual precipitation, which decreases from about 500 mm to 250 mm as the elevation decreases. The middle reach is located between the Qilian Mountains and the deserts. The elevation in this part of the basin ranges from 2000 m to 1340 m, and the mean annual precipitation decreases from 250 mm to $<$100 mm, respectively. Water scarcity is therefore mainly created by the topographic characteristics of the Heihe River Basin.

The upstream and midstream are divided according to differences in water production and use, and cover areas of 11,200 and 25,600 km^2, respectively. The natural conditions and economic characteristics are spatially differentiated in regular ways. The population, economy, and industry are mostly concentrated around the midstream oases. The midstream covers the Gansu Corridor irrigation agriculture belt, with widely distributed oases, and provides the majority of commodity grains and vegetables for Northwest China. The major water consumers in the industry sectors are electric power, food production, and mineral mining. The water demand for economic development has been an annual

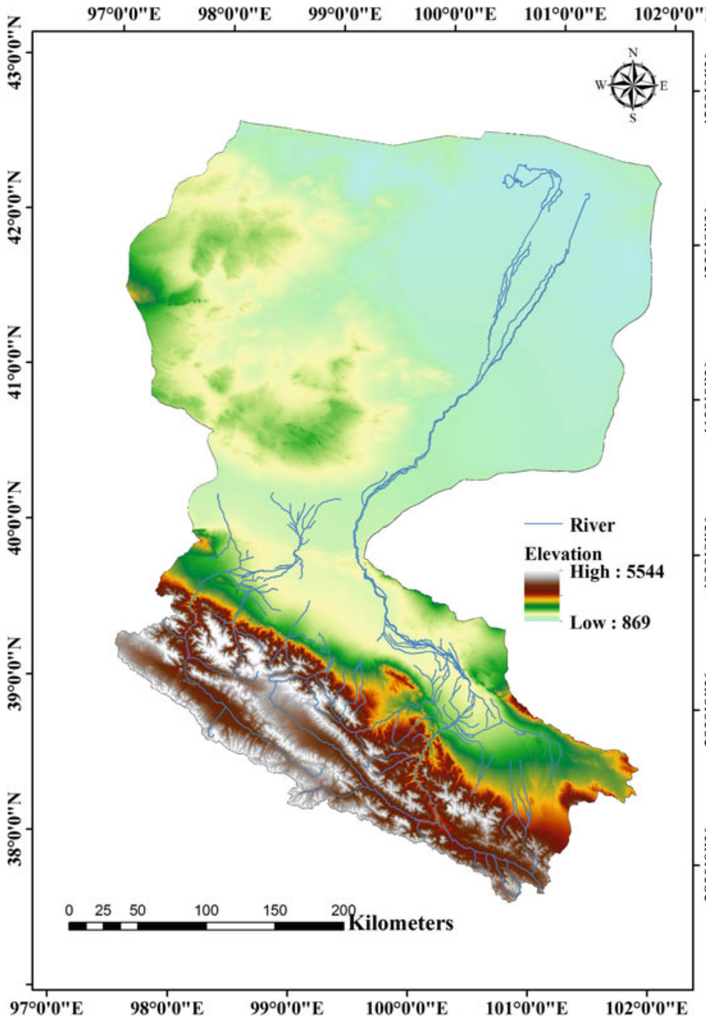

Fig. 7 Location of the study area

average water volume of 2.4 billion m^3 in recent years: 1.9 billion m^3 for agriculture and 0.5 billion m^3 for daily life, industrial use, and ecological use. The water use efficiency values are 400 and 90 m^3/CNY 10,000 in agricultural added value and industrial added value, respectively. During eco-city construction, about 5000 m^3 water was transferred through the transformation from agricultural to nonagricultural status, so as to maintain wetland construction and ecological tourism. The tourism production value in the basin was CNY 6 billion, which greatly improved water productivity in the service industry (Wu et al. 2017).

Data Used

The corresponding data are the social and economic indicator data on the city (county) scale; those used in the models are provided by the Cold and Arid Regions Sciences Data Center in Lanzhou (http://westdc.westgis.ac.cn).

The core data of the WEM is in the input–output table. We first complied an extended multiregional input–output table in 2012, with land and water in the basin and one unit outside the basin (Table 1). The multiregional input–output table was worked out on the basis of single-region input–output tables and can provide basic input parameters for the WEM (Okadera et al. 2006; Jonathan 2011; Zhang and

Table 1 Parameter descriptions

Parameter	Description
XP_i	Total output of department i
$acom_{c,\, i}$	Share of intermediate input products C in the manufacturing process of department i
$aprim_i$	Share of primary factors in the manufacturing process of department i
$aoct_i$	Share of other inputs in the manufacturing process of department i
$COM_{c,\, i}$	Total number of intermediate input products C in the manufacturing process of department i
$PRIM_i$	All primary factors in the manufacturing process of department i
OCT_i	All other inputs in the manufacturing process of department i
PX_i	Price of total output in department i
$PCOM_{c,\, i}$	Price of intermediate input products C in department i
$PPRIM_i$	Price of primary factor combinations in department i
$POCT_i$	Price of other input combinations in department i
$PDCOM_{c,\, i}$	Price of domestic commodities C of intermediate input in department i
$PICOM_{c,\, i}$	Price of imported commodities C of intermediate input in department i
$DCOM_{c,\, i}$	Number of domestic commodities C of intermediate input in department i
$ICOM_{c,\, i}$	Number of imported commodities C of intermediate input in department i
$sdc_{c,\, i}$	Share parameters of domestic commodities C of intermediate input in department i
$sic_{c,\, i}$	Share parameters of imported commodities C of intermediate input in department i
σcom_c	Elasticity of substitution of domestic commodities of intermediate input in department i
$\sigma prim_i$	Elasticity of substitution of primary factor combinations in department i
$PLND_i$	Price of land resource input in department i
$PLAB_i$	Price of labor input in department i
$PCAP_{\mathrm{i}}$	Price of capital input in department i
$slnd_i$	Share parameters of land resources in department i
$slab_i$	Share parameters of labor force in department i
$scap_i$	Share parameters of capital in department i
σlab_i	Elasticity of substitution of different labor types in department i
$slabo_{o,\, i}$	Share parameters of labor type o in department i
$PLABO_{\mathrm{i}}$	Price of labor type o in department i

Anadon 2014). As there is no published county-level input–output table from statistical departments in the Heihe River Basin, we first complied the county-level input–output table embedding land and water in 2012. The table comprises 48 sectors, including 42 sectors in accordance with the national input–output table and seven subsectors disaggregated from the agricultural sector. During the compiling of the county-level table, we added accounts for water and land resources and calculated their values. For agricultural land, we used the sowing area from the county-level statistical yearbook (2012) as land use data and average land use rent of CNY 7500/ha as the price. For nonagricultural land, we calculated land use area by interpreting remote sensing images into 41 nonagricultural sectors and used the local remise price of land as the price. We also used a water consumption coefficient and sowing area to evaluate the agricultural water demand, and collected the enterprises' information from the water resources survey to evaluate the water use in industry sectors. With regard to water prices, surface water was CNY 0.01/m^3, while groundwater was CNY 0.15/m^3. We accounted for the values of water and land in different sectors and embedded them into the input–output table. On the basis of the county-level input–output table, we compiled the multiregional input–output table in the Heihe River Basin. We collected the sector-level trade flow data based on the surveys from statistical departments reporting the inflow and outflow of each county separately. Then we constructed an interregional trade flow matrix with both sector and county dimensions, using the best-known gravity model of Leontief et al. (1963), which had achieved popularity and success in calibrating trade flows because of its mathematical simplicity, its intuitive nature, and the reliability of its empirical results (Meng et al. 2013; Zhang et al. 2013). For calibration of the augmented gravity model, each sector needed a known trade matrix of dominant/representative commodities. For sectors such as the service sector, we had no qualified sample data on dominant/representative commodities. We adopted the simple data pooling method of Hulu and Hewings (1993) to get the initial trade flow matrix. Considering the equilibrium relationships between counties, we applied the RAS technique to ensure agreement with sum constraints, as well to minimize the number of necessary changes for getting the respective values of row and column sums (Lenzen et al. 2012; Guo et al. 2014). The multiregional input–output table could be created after linking and calibrating the input–output tables in the Heihe River Basin (Tables 2 and 3).

Scenario Designs for Impacts of Industrial Transformation on Water Consumption

The main water source for Zhangye is the Heihe River, and water consumption is closely related to the category and development of industries. In Zhangye, the output values for all industries, except for other agriculture, continued to increase during 2003–2008 (Table 4). The output values for secondary industry increased significantly by 39.78% during 2003–2005 and by 88.43% during 2005–2008, followed by those for tertiary industry, which increased by 24.59% and 39.07%, respectively,

Table 2 Parameter descriptions

Parameter	Description
SWT_i	Surface water capacity of primary factors in department i
UWT_i	Underground water capacity of primary factors in department i
OWT_i	Other water capacity of primary factors in department i
$PRWT_i$	Water price of primary factors in department i
σrwt_i	Elasticity of substitution of different water resource inputs in department i
$sswt_i$	Ratio of surface water to total water input of primary factors in department i
$suwt_i$	Ratio of underground water to total water input of primary factors in department i
$sowt_i$	Ratio of other water to total water input of primary factors in department i
$PLWT_i$	Price of water–land combination in department i
$arwt_i$	Ratio of water in water–land combination in department i
$alnd_i$	Ratio of land in water–land combination in department i
LWT_i	Number of water–land combinations in department i

Table 3 Variable descriptions

Variable	Description
KGRj,t	Growth rate of capital stock in the current period
Kj,t	Current capital of industry sector j
Dt	Current allowance for depreciation
It	Current investment
E	Expected rate of return
R	Bank rate
INFt	Current inflation rate
Rt + 1	PK/PI
Wt	Current real wage
T	Employment trend
Lt	Actual employment

during the same periods. However, the output values for animal husbandry and the construction industry increased by 30% and 35%, respectively, during 2003–2005, whereas their growth rates during 2005–2008 were only 7% and 10%, respectively. Water consumption increases with output growth, especially in the planting industry. The increases in the rates of water consumption were 30% during 2003–2005 and 7% during 2005–2008. At the same time, the marginal revenue of water in tertiary industry rose from 1.22 during 2003–2005 to 5.43 during 2005–2008. The abrupt decreased growth rate of water consumption between the two periods, even as the irrigation water supply from precipitation held stable in Zhangye, can be explained by two factors. First, in pursuit of rapid economic development, higher output of crops at a lower level of water consumption may occur. Second, improvement in water use technology led to lower water consumption (Wu et al. 2014).

In this model, water is the primary factor in the agricultural sectors and the intermediate input in the industrial sectors; therefore, water is embedded in the economic flow. The assumption that the data are obtained from an economy in

Table 4 Changes in output, water consumption, and marginal water revenue from 2003 to 2008

Sector	2003		2003–2005			2005–2008		
	I: output (CNY billion)[a]	II: water consumption ($\times 10^8$ m^3)	III: output change (CNY billion)[a]	IV: water consumption change ($\times 10^8$ m^3)	V: marginal water revenue (CNY/m^3)[a]	VI: output change (CNY billion)[a]	VII: water consumption change ($\times 10^8$ m^3)	VIII: marginal water revenue (CNY/m^3)[a]
Planting	22.4	15.49	0.13	0.3	0.43	0.22	0.07	3.14
Animal husbandry	7.76	0.23	0.3	−0.25	−1.20	0.07	0.13	0.54
Other agriculture	1.17	2	−0.24	−0.27	0.89	0.08	0.23	0.35
Industry	17.44	0.39	0.4	0.22	1.82	0.88	−0.1	−8.80
Construction	9.08	0.05	0.35	0.11	3.18	0.1	0.12	0.83
Services	31.06	0.34	0.22	0.18	1.22	0.38	0.07	5.43

[a] In 2008 values

some type of equilibrium is the primary condition for all CGE models. In the baseline simulation, the model operates in a reverse fashion with gross domestic product (GDP), production, consumption, and international trade being exogenous, and the corresponding technical and preference change variables being endogenous. In the baseline simulation, the model operates according to changes in GDP, consumption, investment, and other observed variables during a historical period, and then it calculates the necessary changes in technology and preferences. Calibration is the procedure commonly used for parameter specification, which was carried out with the data from 2003 to 2008 based on the input–output table in 2002; the model is completed when the parameters have been calibrated and we are ready to evaluate the effects of three scenarios of water consumption. We followed the static calibration procedure to compute the baseline after determining the parameter values, applying the CGE model until all parameter values were correctly specified.

In this study, we designed three scenarios to analyze the impacts of industrial transformation on water consumption with a modified CGE model, which provides a scientific basis for water resource management. In the three scenarios, we separately assumed that the output value for secondary industry increased by 5% during 2003–2008 (scenario 1), the output value of the planting industry decreased by 5% in 2003–2008 (scenario 2), and the output value of the tertiary industry increased by 5% in 2003–2008 (scenario 3). The three scenarios represent industrial transformation, and the simulation results can show the influence of industrial transformation on water consumption, which can provide a scientific basis for water resource management.

Results Analysis

Water Balance of the Water–Economy–Society Integrated System

Water use in the water–economy–society integrated system of the Heihe River Basin in 2012 is shown in Fig. 8. The results reveal that the total water use in the economic system in 2012 was about 4505 million m^3, including direct production water use of 4460 million m^3 and direct domestic water use of 45 million m^3. According to the consumption of real water and virtual water, the economic system consumed 5520 million m^3, while the social system consumed 4460 million m^3, including surface water of almost 2973 million m^3 and groundwater of 1532 million m^3.

According to the relevant literature and the regional development plans, we clarified the predictions for population, investments, consumption, and economic growth by 2030 in the midstream (Table 2). We simulated the trend of economic development, built the baseline scenario (with no adoption of any economic water-saving policy/measure or economic sector development policy), and analyzed the water demand from the economic systems in this baseline scenario. The long-term closure dominated by employment growth was set on the basis of the dynamic WEM according to the future economic development prediction indicators.

According to the parameters in Table 5 and in the baseline scenario, we first adjusted the forecast parameters so as to make the simulated results in 2013 and 2014

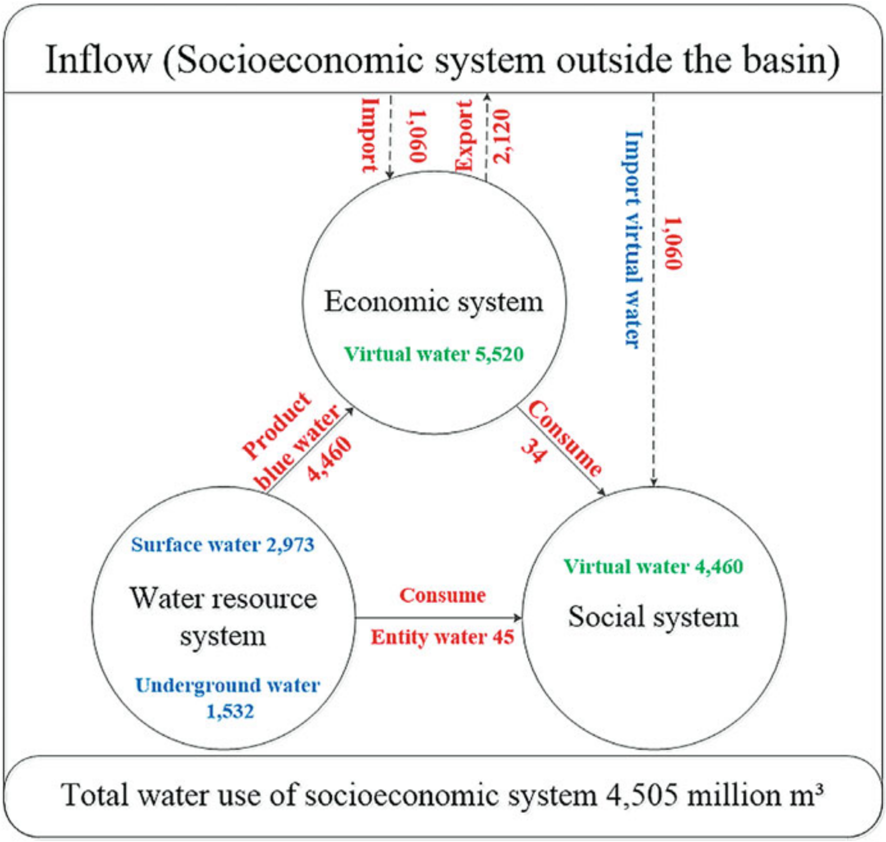

Fig. 8 Water balance of the water–economy–society integrated system in 2012 (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Table 5 Predictions of economic development (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Parameter	Accession rate (%)	Technology progress (%)	Average resident consumption growth rate (%)	Average investment growth rate (%)
2000–2012	0.23	6.8	12	28.33
Predicted value	0.30	4	5.8	18

consistent with the corresponding statistics. After that, the baseline forecast was expanded to 2030. The growth rate of GDP would gradually smooth down and decline from 5.4% in 2014 to 2.1% in 2030, so the GDP in 2030 was predicted to be CNY 75 billion.

With regard to the water demand in the economic system, it was assumed that the phenomenon of water consumption exceeding the available water resource amount would occur in 2017. The total water demand in the economic system would rise from 21.9×10^8 m^3 in 2012 to 39.15×10^8 m^3 in 2030, and the water demand would exceed the available water resource quantity in the midstream (26.5×10^8 m^3) as early as 2017. Thus, in order to maintain the appropriate agricultural scale and to guarantee rapid economic growth by actively developing the secondary and tertiary sectors, the midstream would have to cope with the very severe stress of a water shortage. According to the current economic laws and water use efficiency, the demand for the water resource would nearly double by 2030, which would be unachievable. It was predicted that the economic water consumption in the midstream would be maximized to 39.88×10^8 m^3 by 2029. Along with the inflection in the uptrend of industrial structure growth, the changing trend of economic total water consumption would also inflect. The total water consumption by the economic systems would start to decline by 2029 (Fig. 9). Thus, as for the simulated rules alone, the industrial structures would significantly affect the total water consumption in the economic systems. From the point of industrial output growth, the output growth in the primary sector would be very high until 2020, while the output growth from the secondary sector would be maximized, whereas the output growth in the tertiary sector would become the largest by 2026. The output growth rates gradually separated the secondary and tertiary sectors (Fig. 9). Before 2025, the midstream would still enjoy rapid growth; the output growth rates of different sectors would grow at a rate of above 5% per year. The simulated results further validated the conclusion about the necessity of industrial transformation in the midstream, aimed at sustainable economic development. The development objectives of novel urbanization would bring the driving force and opportunity into the renewal of sector transformation during the economic development in the future.

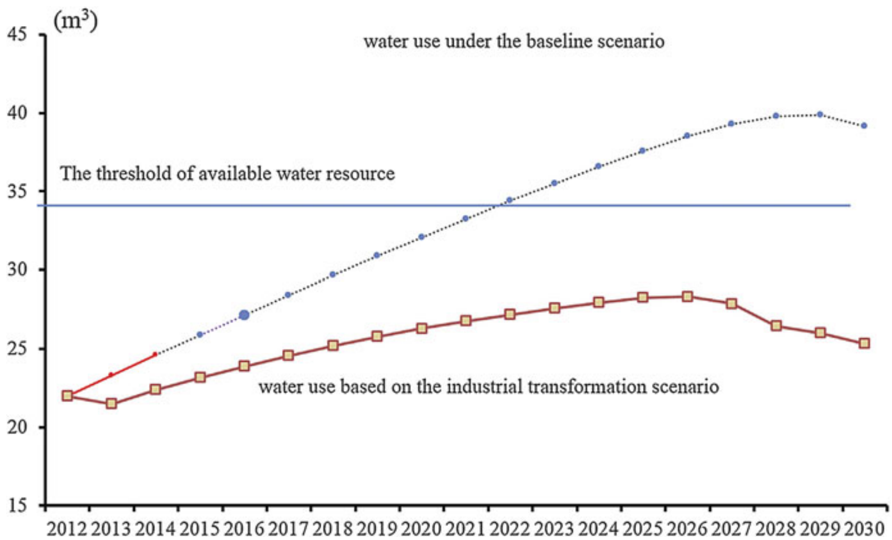

Fig. 9 Water demand of the economic system in the baseline and industrial transformation scenarios (Reprinted from Wu et al. (2017) with permission of Physics and Chemistry of the Earth, Parts A/B/C)

Urbanization has enlarged the runoff volumes in the main streams of the Heihe River and reduced the recharge of groundwater in the urbanized areas, though the trend was not significant. According to the urbanization plans in Gansu Province, the focus area is the Gansu Corridor in the midstream of the Heihe River Basin. Urbanization would increase the runoff entering from ground surfaces in the midstream, but also the demand for water. Simulation in the WEM showed that the change in resident consumption propensity caused by urbanization would affect the production and consumption in the economic system, and the allocation of water–land resource elements in this sector. On the basis of the static WEM, we simulated the effects of urbanization (rising from 36% to 60%) on the water demand of the economic systems (Wu et al. 2015). The results showed that exportation declined by 0.12%, while importation increased by 0.22%. Calculations with the income approach showed that the contribution rates of the labor force and direct tax increased by 0.05% and 0.04%, respectively. However, among all elements, only the contribution rate of the labor force increased, by 0.07%. The reasons were that the rise of urbanization rate leaded to the general enhancement of worker quality, so did the marginal labor productivity and the income efficiency. Moreover, the rise in the urbanization rate led to general enhancements of worker quality, marginal labor productivity, and income efficiency. From the aspect of the sectors, the increase in the urbanization rate led to an improvement in the capacity for agricultural consumption, so the product consumption amount in the agricultural sectors increased by over 7.10%. The increase in the urbanization rate also promoted demand in the energy and resource sectors. For instance, the demands for coal mining and for oil and natural gas exploitation increased by 7.10%. Meanwhile, the product demands supplied by water, electricity, and natural gas increased by over 2.7%. The supply demands for the service sectors such as architecture, wholesale and retail, and restaurants were promoted. Conversely, the product demand from the nonresident consumption sectors declined. Moreover, the increments in the residential consumption level and the consumer price index promoted the elevation of land rents. In particular, it had an effect on the sectors of water conservancy, the environment, and public facility management of to 9.83%, followed by the sector of water production and supply (3.45%) (Table 6). Finally, with regard to the water resource depletion driven by household-consumed products, the water resource depletions rose in most sectors but also declined slightly in some sectors. The percentages of water resource depletions were very little, but the concrete figures were large, so the pressure on the water resource demand was still very large. With regard to the agriculture sector alone, although the percentage of water resource consumption could not exceed 0.50%, the concrete amount was very large. It was indicated that the resulting variation in the water resource was very severe. Thus, the demand for the water resource caused by the urbanization-driven consumption demand from the entire agricultural sector increased by 3.88×10^6 m^3. The comprehensive analysis indicated that the demand for domestic water and industrial water increased by 1.57×10^7 m^3 because of urbanization.

Table 6 Simulation results for household consumption and resource consumption with urbanization

Product	Household consumption	Land rent	Water consumption
Wheat	7.11	0.21	0.09
Maize	7.11	0.29	0.12
Oil plants	7.11	0.56	0.31
Cotton	7.1	0.15	0.06
Fruit	7.11	0.44	0.19
Vegetables	7.11	0.89	0.38
Other farming	7.11	0.75	0.43
Coal mining and dressing	7.12	0.76	0.31
Petroleum and natural gas extraction	7.1	0	0.14
Metal mining	4.69	0.1	0.05
Nonmetallic minerals and other mining	−1.4	0.19	0.11
Food manufacturing and tobacco processing	−1.78	0.21	0.06
Textile products	−1.39	0	0.04
Textile, leather, and feather products	−2.52	0	−0.24
Timber processing and furniture manufacturing	−1.38	0.51	0.07
Printing, paper stationery, and sporting goods manufacturing	−1.38	0.27	0.12
Petroleum processing, coking, and nuclear fuel processing	−1.39	0.01	0.12
Chemical products	−1.39	0.04	0.11
Nonmetallic mineral products	−5.65	−0.28	0
Metal smelting, rolling, and processing	−5.75	0.4	0.08
Metal products	−1.38	0.2	0.06
General and special equipment manufacturing	2.86	0.13	0.09
Transportation equipment manufacturing	−3.77	0	0.06
Electrical machinery and equipment manufacturing	−4.01	0	0.1
Communication, computer, and other electronic equipment manufacturing	−5.74	0	−0.82
Instrumentation and office machinery manufacturing	−5.74	0	−0.08
Handicrafts and other manufacturing	−5.7	0	−0.63
Scrap waste	−5.75	0	0.11
Electricity and heat production and supply	2.75	1.45	0.2
Gas production and supply	2.83	0	0.52
Water production and supply	2.76	3.45	0.15
Construction	2.82	0.12	0.1
Transportation and warehousing (including postal services)	−1.4	0.22	0.08
Main business	1.83	0.08	0.1
Information transmission, computer services, and software	2.64	1.37	0.22

(*continued*)

Table 6 (continued)

Product	Household consumption	Land rent	Water consumption
Wholesale and retail trade	2.82	0.01	0.1
Hotel and catering services	2.82	1.61	0.76
Finance	−2.23	−1.91	−0.47
Realty business	−0.47	−6.22	−0.28
Leasing and business services	−2.44	−0.31	−0.03
Research and experimental development	−2.54	0.3	0.16
Integrated technological services	−2.54	0.64	0.34
Water conservancy and environmental and public facilities management	−2.54	9.83	0.38
Services to households and other services	−2.34	−1.78	−0.63
Education	−5.51	−3.41	−1.11
Health, social security, and social welfare	−5.57	−4.92	−1.96
Culture, sports, and entertainment	−5.42	−2.87	−0.93
Public management and social organization	−5.75	0.03	0.13

Impacts of Industrial Transformation on Water Consumption

It is challenging but necessary to boost economic development through the efficient use of water resources. The simulation results show that the output value of all sectors increased in scenario 1 when the output value of secondary industry increased by 5% (Fig. 10a). However, the proportion of water consumption in secondary industry increased, while those of farming, animal husbandry, and the service sector decreased, and that of other agriculture remained stable (Fig. 10b). The analysis suggests that the output value of other sectors was driven by the industrial technical change. The food industry is the major secondary industry in Zhangye; therefore, development of secondary industry may advance primary and tertiary industries by raising prices. Specifically, GDP increased by 2.6% and total water consumption was reduced by 0.13%, indicating that the farming industry is the largest water-consuming sector in the region. In the second scenario, the outputs of almost every industry sector decreased, but the change in water consumption was different. The change in water consumption in secondary industry was contrary to that of the output value. In the last scenario, the development of tertiary industry would promote secondary industry, but the effect on agriculture was not significant. However, the water consumption of the planting industry decreased by 2.5%; therefore, it would be beneficial to promote the expansion of secondary industry and tertiary industry with lower water use intensity while advancing the development of the planting industry and other agricultural sectors.

A reduction in water consumption per unit of GDP can be achieved through promotion of technical change in the three scenarios. The industrial transformation of planting plays a key role in improving water use efficiency to achieve the goal of reducing water consumption. In scenario 1, when the output value of secondary industry increased by 5%, the annual GDP increased by 0.80%, while the water

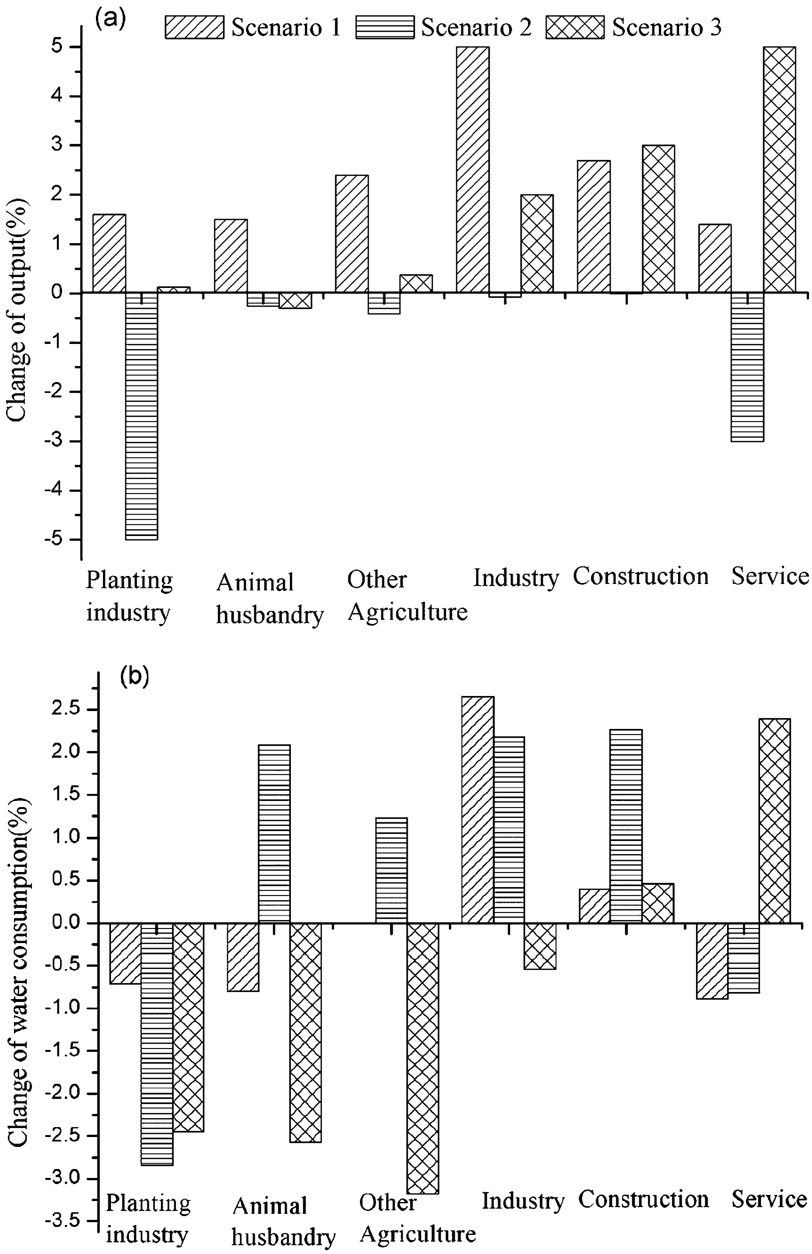

Fig. 10 Effects of industrial transformation on (**a**) output values and (**b**) water consumption in different scenarios (Reprinted from Wu et al. (2014) with permission of Sustainability)

consumption per unit of GDP decreased from 80 m^3/CNY 10,000 in the baseline scenario to 65 m^3/CNY 10,000 in scenario 1. In scenario 3, the water consumption per unit of GDP decreased by 25% as the annual GDP increased by 0.50% (Table 6). This indicates that secondary industries play an essential role in pushing economic development, while development of tertiary industries can greatly raise water use efficiency in Zhangye. The food industry in the secondary industries can push the development of primary industry, which is also closely related to the development of tertiary industry. Therefore, the development of tertiary industries can drive the complete industrial chain in Zhangye's economic system. The proportion of industries with high water consumption in Zhangye is very large, which can cause serious environmental issues, so the development of these industries goes against the goal of sustainable development. Therefore, the municipal government and relevant institutions in this environmentally fragile region should cooperate to promote coordinated development of both economic and ecological systems. For example, high-water-consuming industries with a high direct water use coefficient should be limited to some extent in the future. Overall, according to the simulation results in the three scenarios, we suggested that the third scenario should be adopted for water resource management reform (Table 7).

Discussion and Conclusions

This study demonstrates the design and development of IAGWR-DSS, a decision support system prototype for integrated river basin water resource management. IAGWR-DSS provides a reference solution for integrating the models, data, knowledge, and experts into one system and one database. IAGWR-DSS took the Heihe River Basin as an example; integrated the CGE and DLS models; collected socioeconomic data, fundamental geographic information data, natural geographic data, and ecological environmental data; and outputted some results of scenario simulation under the constraint of the water resource management redline.

This study constructed a decision-making tool for water resource supply-and-demand scenario regulation and analysis, which serves the selection of a water resource–adaptive approach to the watershed socioeconomic system. In addition, this study also analyzed the relation of the mutual feed between the watershed water

Table 7 Comparison of different scenarios' effects on economic development and water consumption (Reprinted from Wu et al. (2014) with permission of Sustainability)

	Annual GDP growth rate during 2003–2008 (%)	Water consumption per unit of GDP (m^3/CNY 10,000)
Baseline	14.40	80
Scenario 1	13.80	72
Scenario 2	15.20	65
Scenario 3	14.90	60

GDP gross domestic product

resource and the socioeconomic system, gave some examples to explain that how the ecological -hydrological processes affect the socioeconomic system.

We investigated the patterns and routes of eco-hydrological processes affecting the water demand of the economic systems in the midstream of the Heihe River Basin, and explored the potential route of the economic systems' response to eco-hydrological change in the midstream. The key parameters for the model integration simulation were obtained, and thereby the WEM was developed on the basis of an extended multiregional input–output table with land and water resources. We revealed the coupling mechanisms between natural water cycles and economic water cycles in the midstream and upstream of the Heihe River Basin. On the basis of the WEM, we simulated the water demand of the economic system in the scenario where the urbanization rate would increase to 60% by 2030. We found that the midstream urbanization scenario entailed a 12% increase in the economic water demand, which highlighted the water supply-and-demand contradiction in the midstream area.

To resolve the conflicts between water supply and demand in the midstream and to guarantee economic stability and sustainable development, we hope the decision makers of Heihe River Basin can reconfiguration the water resources of midstream and downstream, thereby balancing the water demand of the economic system in the midstream. Moreover, new water resource reallocation methods should be found to improve the single-unit water productivity and promote stable and healthy economic growth, which are critical to guarantee sustainable regional development.

We found that the direct water consumption coefficients of the planting sector and other agricultural divisions are much higher than those of other sectors, and changes in the corresponding output values have significant effects on the total water consumption. However, the marginal revenue of water use in the tertiary sector is the highest among all sectors. Then we evaluated the changes in water consumption caused by industrial transformation, using the CGE model in three scenarios designed with industries' technical changes in mind. The simulation results indicated that the water-saving benefit from industrial structure transformation is significant when the output value of secondary industry and tertiary industry increases but the percentage of the planting sector in the total output value decreases. Enhancing water use efficiency through industrial transformation will be an effective way to meet water needs in the face of severe water scarcity in this typically arid region of Northwest China. The simulation suggested that encouraging the development of tertiary industry is a sustainable trade-off scheme for raising water use efficiency, and moderating the development of the planting sector is also an important way to improve water use efficiency in the whole river basin.

The decision support system implements integration, query, analysis, and sharing of data. It can offer a scientific basis, support data, and analysis results for decision makers but cannot help decision makers make decisions. IAGWR-DSS is a prototype and still under development. Some functions are under development to enable interaction with data and comparison of scenarios. A simple Android version of IAGWR-DSS will be provided in the future, which will be very convenient for use by decision makers.

References

A. Abramson, N. Lazarovitch, S. Massoth, E. Adar, Decision support system for economic assessment of water improvements in remote, low-resource settings. Environ. Model. Softw. **62**, 197–209 (2014)

J. Anderson, R. Iyaduri, Integrated urban water planning: big picture planning is good for the wallet and the environment. Water Sci. Technol. **47**, 19–23 (2003)

N.Y. Aydin, D. Zeckzer, H. Hagen, T. Schmitt, A decision support system for the technical sustainability assessment of water distribution systems. Environ. Model. Softw. **67**, 31–42 (2015)

A. Calzadilla, K. Rehdanz, R.S.J. Tol, H. Hoff, M. Falkenmark, D. Gerten, L. Gordon, L. Karlberg, J. Rockström, The economic impact of more sustainable water use in agriculture: a computable general equilibrium analysis. General Inform. **384**, 292–305 (2008)

A. Calzadilla, K. Rehdanz, R. Tol, *The GTAP-W Model: Accounting for Water Use in Agriculture*, Kiel Working Papers (Institute for the World Economy, Kiel, 2011)

D. Chen, S. Shams, C. Carmona-Moreno, A. Leone, Assessment of open source GIS software for water resources management in developing countries. J. Hydro Environ. Res. **4**, 253–264 (2010)

Y. Çirpici, The effects of agricultural liberalization on sectoral water use: a CGE model for Turkey. METU Stud. Dev. **38**, 125–146 (2009)

D.C. Cliburn, J.J. Feddema, J.R. Miller, T.A. Slocum, Design and evaluation of a decision support system in a water balance application. Comput. Graph. **26**, 931–949 (2002)

X. Deng, R. Singh, J. Liu, B. Güneralp, Water use efficiency and integrated water resource management for river basin. Phys. Chem. Earth, Parts A/B/C **89**, 1–2 (2015)

X. Deng, J. Gibson, P. Wang. Management of trade-offs between cultivated land conversions and land productivity in Shandong Province. J Cleaner Prod. **142**, 767–774 (2017)

A. Droubi, M. Al-Sibai, A. Abdallah, S. Zahra, M. Obeissi, J. Wolfer, M. Huber, V. Hennings, K. Schelkes, in A Decision Support System (DSS) for water resources management – design and results from a Pilot Study in Syria, ed. by F. Zereini, H. Hötzl. *Climatic Changes and Water Resources in the Middle East and North Africa* (Springer, Berlin/Heidelberg, 2008), pp. 199–225

N.V. Fedoroff, D.S. Battisti, R.N. Beachy, P.J.M. Cooper, D.A. Fischhoff, C.N. Hodges, V.C. Knauf, D. Lobell, B.J. Mazur, D. Molden, M.P. Reynolds, P.C. Ronald, M.W. Rosegrant, P.A. Sanchez, A. Vonshak, J.-K. Zhu, Radically rethinking agriculture for the 21st century. Science **327**, 833–834 (2010)

Y. Ge, X. Li, C. Huang, Z. Nan, A decision support system for irrigation water allocation along the middle reaches of the Heihe River Basin, Northwest China. Environ. Model. Softw. **47**, 182–192 (2013)

A. P. Georgakakos, Chapter 5 – Decision support systems for integrated water resources management with an application to the nile basin. Topics on System Analysis & Integrated Water Resources Management, 36(Fall), 99–116 (2007)

C. Giupponi, Decision support systems for implementing the European Water Framework Directive: the MULINO approach. Environ. Model. Softw. **22**, 248–258 (2007)

E. Giusti, S. Marsili-Libelli, A fuzzy decision support system for irrigation and water conservation in agriculture. Environ. Model. Softw. **63**, 73–86 (2015)

Z. Guo, X. Zhang, Y. Zheng, R. Rao, Exploring the impacts of a carbon tax on the Chinese economy using a CGE model with a detailed disaggregation of energy sectors. Energy Econ. **45**, 455–462 (2014)

M.A. Hanjra, M.E. Qureshi, Global water crisis and future food security in an era of climate change. Food Policy **35**, 365–377 (2010)

T. W. Hertel, *Global Trade Analysis: Modeling and Applications*. Gtap Books, (1998)

M. Horridge, G. Wittwer, A multi-regional CGE model of China. China Econ. Rev. **19**(4), 628–634 (2008)

E. Hulu, G.J.D. Hewings, The development and use of interregional input–output models for Indonesia under conditions of limited information. Rev. Urban Reg. Dev. Stud. **5**(2), 135–153 (1993)

G.D. Jenerette, L. Larsen, A global perspective on changing sustainable urban water supplies. Glob. Planet. Chang. **50**, 202–211 (2006)
L. Jiang, F. Wu, Y. Liu, X. Deng, Modeling the impacts of urbanization and industrial transformation on water resources in China: an integrated hydro-economic CGE analysis. Sustainability **6**, 7586 (2014)
L. Jonathan, Constructing an environmentally-extended multi-regional input–output table using the GTAP data. Econ. Syst. Res. **23**(2), 131–152 (2011)
S. Junier, E. Mostert, A decision support system for the implementation of the Water Framework Directive in the Netherlands: process, validity and useful information. Environ. Sci. Pol. **40**, 49–56 (2014)
P. Karimi, W.G.M. Bastiaanssen, D. Molden, Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements. Hydrol. Earth Syst. Sci. **17**, 2459–2472 (2013)
M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy. Environ. Sci. Technol. **46**(15), 8374 (2012)
S. Leontief, A. Strout, T. Barna, *Structural Interdependence and Economic Development Multi-Regional Input–Output Analysis* (St. Martin's Press, London, 1963), pp. 119–150
X. Li, L. Lu, G. Cheng, H. Xiao, Quantifying landscape structure of the Heihe River Basin, North-West China using FRAGSTATS. J. Arid Environ. **48**, 521–535 (2001)
H. Ling, B. Guo, H. Xu, J. Fu, Configuration of water resources for a typical river basin in an arid region of China based on the ecological water requirements (EWRs) of desert riparian vegetation. Glob. Planet. Chang. **122**, 292–304 (2014)
C. Lorz, C. Neumann, F. Bakker, K. Pietzsch, H. Weiß, F. Makeschin, A web-based planning support tool for sediment management in a meso-scale river basin in western Central Brazil. J. Environ. Manag. **127**, S15–S23 (2013)
B. Meng, Y.X. Zhang, S. Inomata, Compilation and applications of IDE-JETRO's international input–output tables. Econ. Syst. Res. **25**(1), 122–142 (2013)
D. Molden, *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture: Summary* (International Water Management Institute, 2007). http://www.eldis.org/document/A67920
T. Okadera, M. Watanabe, K. Xu, Analysis of water demand and water pollutant discharge using a regional input–output table: an application to the City of Chongqing, upstream of the Three Gorges Dam in China. Ecol. Econ. **58**(2), 221–237 (2006)
T. Oki, S. Kanae, Global hydrological cycles and world water resources. Science **313**, 1068–1072 (2006)
M. Lang, P. H. Gleick, A review of decision-making support tools in the water, sanitation, and hygiene sector. Pacific Institute (2008)
S. Pallottino, G.M. Sechi, P. Zuddas, A DSS for water resources management under uncertainty by scenario analysis. Environ. Model. Softw. **20**, 1031–1042 (2005)
O. Petit, C. Baron, Integrated water resources management: from general principles to its implementation by the state. The case of Burkina Faso. Nat. Res. Forum **33**, 49–59 (2009)
S. Pollard, D. du Toit, Integrated water resource management in complex systems: how the catchment management strategies seek to achieve sustainability and equity in water resources in South Africa. Water SA **34**, 671–679 (2008)
G.W.H. Simons, W.G.M. Bastiaanssen, W.W. Immerzeel, Water reuse in river basins with multiple users: a literature review. J. Hydrol. **522**, 558–571 (2015)
F. Wu, Y. Bai, Y. Zhang, et al., Evaluating impacts of industrial transformation on water consumption in the Heihe River Basin of Northwest China. Physics and Chemistry of the Earth, Parts A/B/C **101**, 178–184 (2017)
F. Wu, J. Zhan, Q. Zhang, et al., Evaluating impacts of industrial transformation on water consumption in the Heihe River Basin of Northwest China. Sustainability **6**, 8283–8296 (2014)
F. Wu, J. Zhan, İ. Güneralp, Present and future of urban water balance in the rapidly urbanizing Heihe River Basin, Northwest China. Ecol. Model. **318**, 254–264 (2015)

F. Wu, Y.P. Bai, Y.L. Zhang, Z.H. Li, Balancing water demand for the Heihe River Basin in Northwest China. Phys. Chem. Earth **101**, 178–184 (2017)

C. Zhang, L.D. Anadon, A multi-regional input–output analysis of domestic virtual water trade and provincial water footprint in China. Ecol. Econ. **100**(2), 159–172 (2014)

G.Z. Zhang, W.N. Zhao, H. Liu, A GIS-based decision support system for water trade management of river basin cities. Procedia Environ. Sci. **2**, 650–655 (2010)

B. Zhang, Z.M. Chen, X.H. Xia, X.Y. Xu, Y.B. Chen, The impact of domestic trade on China's regional energy uses: a multi-regional input–output modeling. Energy Policy **63**, 1169–1181 (2013)