Water Resources Management **16:** 239–261, 2002.

Sustainability Analysis for Yellow River Water Resources Using the System Dynamics Approach

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(Received: 9 October 2001; accepted: 17 May 2002)

Abstract. The water resource issue is one of the most significant problems that the Yellow River basin will face this century, and one which has received much attention by public and government for several years. Water authorities will face great challenges in meeting the in-stream flow requirements and providing more water for growing populations, industry and agriculture. In order to evaluate the sustainability of the water resource system in the study area, an object-oriented system dynamics approach has been used to develop a model for the water resources system in the Yellow River basin, which is referred to as the Water Resources System Dynamics (WRSD) model. It has been developed for simulating a water resource system and capturing the dynamic character of the main elements affecting water demand and supply in the study area. For the business-as-usual (BaU) scenario, the water demands in the Yellow River basin are estimated 50.9, 56.5, and 59.5 billion m^3 for 2010, 2020, and 2030. The existing and potential water supplies from surface water, aquifers and treated waste-water are estimated, and potential water demands for domestic, industrial and agricultural uses are projected. Various water supply and demand scenarios have then been explored by changing variables and parameters, and the sustainability index of the water supply system is estimated for different sub-regions over various periods.

Key words: groundwater, industrial water, irrigation water, system analysis, surface waters, waste-water re-use, water demand, water supply

1. Introduction

During the past decade, sustainable development has received much attention everywhere in the world. Sustainable water supply should include non-excessive use of surface water, non-depletive groundwater abstraction, and efficient re-use of treated wastewater, etc. (Downs *et al.*, 2000; Shiklomanov, 2000; Vörösmarty *et al.*, 2000). Meeting the objective of sustainable water supply is also one of the greatest challenges for China, particularly in the north of the country. Located at the centre of North China, the Yellow River basin is facing the dilemma of increasing municipal and industrial water demand, whilst at the same time maintaining enough in-stream flow for scouring sediment and environmental requirements. Urbanization and economic growth in the study area has been remarkable during the past two decades and will continue to be so for the foreseeable future. The considerable hydrological and climate uncertainties further increase the vulnerability of water supply in the study area. Water authorities must always try to manage the balance between the needs of consumers with those of the environmental and ecological systems. During low-flow seasons, these targets become more difficult to reach. Streamflow cessation and water curtailments, which have occurred during the past decades, demonstrate the vulnerability of the water supplies. Possible scenarios, including integrated water resources management, transfer of water rights and more efficient use of water resources, need to be investigated and evaluated to achieve a sustainable water supply for the Yellow River basin.

In a complex water resource system such as this case study, the problems usually include many kinds of subjective variables (Danielson, 1979). Difficulties mainly arise from the integration of social perspectives with the technical elements. Although the application of optimisation techniques has been a major field of research in water resource planning for many years, their adaptation to practical applications are still not fully satisfactory, partly due to the fact that most deal with over-simplified systems (Yeh, 1986; Ahmad and Simonovic, 2000). Therefore, there is a need to explore new tools for representing the complex relationships found in water resource systems. One of those promising options is the system dynamics (SD) technique, a feedback-based, object-oriented simulation approach.

The object-oriented system dynamics approach is an appropriate technique for integrated water resources analysis. The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex water resource systems with subjective variables and parameters. The flexibility allows the application of hierarchical decomposition in the model development and the transparency raises the possibility of practitioners' involvement in the model development, increasing their confidence on model operation and its outputs (Simonovic, 2000). Compared with the conventional simulation or optimisation models, the system dynamics approach is more beneficial for indicating how different changes of basic elements affect the dynamics of the system in the future. It is therefore particularly useful for representing complex systems with strong influences from social or economic elements. Recent applications of the SD approach in the field of water resources, although still quite few, include river-basin planning (Palmer *et al.*, 1999), long-term water resource planning and policy analysis (Simonov and Fahmy, 1999), reservoir operation (Ahmad and Simonovic, 2000), etc.

A system dynamics model for water resources planning is proposed for this study to analyse the sustainability of water resources in the Yellow River basin to future climate change, population growth, and industrial development. The so-called Water Resources System Dynamics (WRSD) model of the Yellow River basin was developed to explore a wide variety of water-supply scenarios for the study area. The WRSD is an interactive, computer-based tool, allowing users to explore how various water-supply objectives can be met for future scenarios. The model has been developed using STELLA Research 6.0 (High Performance, 1999), and can be used to identify preferred solutions to meet a variety of requirements relating to regional development, environmental concerns and ecological needs of the river basin. By estimating future water demands and supplies, users can assess how various assumptions actually affect the performance of the water resource system during a predetermined planning period. The questions addressed in this study include how much water will the study area need in the future and how sustainable will the water-supply be in different sub-regions? The model was formulated with the aim of determining how these questions can be answered. The water resource system and the model formulation will be outlined in the following section. Model structure and application will be presented in the third section, and the conclusion will be summarized in the last section.

2. Yellow River Water Resources System

Yellow River is the second largest river in China. It loops north, bends south, and flows east for 5,464 km within a basin area of 752,443 km^2. The river runs through semi-arid and arid mountainous regions for 3,472 km from its origin to Hekouzhen in Inner Mongolia Province. With a sharp turn to the south near Hekouzhen, the river flows south between Shaanxi and Shanxi provinces to Huayuankou in Henan Province. The geology of the middle reaches mainly comprises thick loess deposits whose erosion by precipitation accounts for over 90 percent of the sediment in the main channel downstream. After traversing 1,206 km from Hekouzhen to Huayuankou, the river emerges from narrow mountainous valley onto a flat alluvial plain, with a sharp turn to the east. In the lower reaches from Huayuankou to the Gulf of Bohai, a distance of 786 km, the river is confined to a levee-lined course as it flows across the North China Plain.

In past centuries, excessive sediment deposits have raised the riverbed several metres above the surrounding lands, with a maximum of 10 m above the ground level near Kaifeng City in Henan Province. The most challenging aspect for the Yellow River is without doubt, the control of the high sediment load that the river carries into its lower reaches. However, both water supply and water pollution issues are also becoming increasingly important in recent years. The main channel of the river receives on average, an annual total of 58.0 billion m^3 of surface water from its tributaries. Of that amount, 40.6 billion m^3 were diverted for irrigation and other uses in 1993 and this is increasing at the rate of 1.5% year by year (Zhang, 1999). Currently, the river is also required to supply an additional 8.98 billion m^3 of water to several cities such as Tianjin and Qingdao outside the Yellow River basin (He, 2000).

During the past decade, water shortage in the Yellow River basin has resulted in extensive economic losses to industry, domestic life, and agriculture. With the aim of understanding this aspect of the Yellow River basin, the objective of this study has been to develop the WRSD model to provide a practical tool for evaluating different management options for operation of the water resource system. A basin map showing the study area and its location in China is given in Figure 1. The

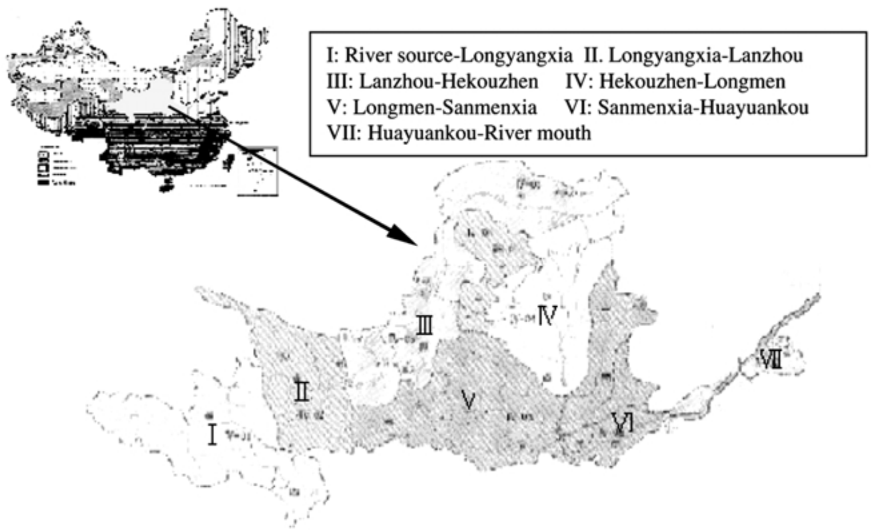

Figure 1. Yellow River basin map showing the seven sub-regions.

population in the Yellow River basin has grown rapidly from approximately 45.0 in 1949 to 99.2 million in 1993, with a corresponding increase of 7.4 to 40.6 billion m^3 in the demand for water (Zhang, 1999). As a result, the per capita water in the study area is under the water poverty threshold. Irrigation consumes 84.4% of the total water supplied and domestic supply is less than 10.0% of the total water demand (Chen *et al*., 1997). Looking to the future, sustainable supply and efficient use of water will be the main objectives of both central government and local water authorities.

The previous water resource development scenarios in the study area were generally formulated assuming ample fresh surface water supply from the Yellow River, in which financial and technological elements were the main constraints. Recently, satisfying the increased demand for water has become the major objective of water resources management. To that end, water authorities have to satisfy the increased industrial, domestic, and agricultural demand, as well as the requirements for environmental protection and ecological improvement. Re-allocation of water among different users and sub-regions, together with the reuse of treated wastewater, have become attractive scenarios that are now usually considered. The approach proposed in this study presents a systematic technique to analyse various water-demand scenarios and their effects on long-term water supply. Over the 30 years planning period, the time increment assumed for simulation is taken as 1 yr. On the spatial scale, the study area has been divided into 7 sub-regions with the combinations of different climate and water resource characteristics, as given in Table I.

Table I. Seven subregions in Yellow River basin

No.	Subregions	Area (km^2)
I	River source – Longyangxia	131,420
II	Longyangxia – Lanzhou	91,131
III	Lanzhou – Hekouzhen	163,415
IV	Hekouzhen – Longmen	111,595
V	Longmen – Sanmenxia	190,860
VI	Sanmenxia – Huayuankou	41,615
VII	Huayuankou – River mouth	22,407
Total	Yellow River basin	752,443

2.1. WATER DEMAND ESTIMATION

The following equation shows the nine components considered in the model. Water demand for each of the 7 sub-regions is forecasted initially. The total demand is then estimated by summing the nine demands.

$$D = D_{C,Ind} + D_{T,Ind} + D_{R,Ind} + D_{C,Dom} + T_{C,Dom} + \\ + D_{R,Dom} + D_{Agr} + D_{Env} \pm D_{Tran} \quad (1)$$

in which D is the total water demand in billion m^3, $D_{C,Ind}$ the city industrial water demand, $D_{T,Ind}$ the town industrial water demand, $D_{R,Ind}$ the rural industrial water demand, $D_{C,Dom}$ the city domestic water demand, $D_{T,Dom}$ the town domestic water demand, $D_{R,Dom}$ the water demand in rural areas, D_{Agr} the agricultural water demand, D_{Env} the environmental and ecological water demand, and D_{Tran} the inter-basin water transfer. In this study, both industrial and domestic water-demand sectors were further divided into three subsectors: city, town, and rural, because the per capita water demand for domestic use and water-use for unit industrial production are quite different for city, town and rural area. Cities usually represent advanced industrial technology and high living standards with less water-use for unit industrial production and much per capita water for domestic use. Towns are placed in the middle between cities and rural areas. Rural areas consume little water for domestic use, but use much water for the backward industry, as given in the following sections.

2.1.1. *Domestic Water Demand*

Domestic water demand includes those quantities of water consumed in a given period for all residential purposes such as in-house water use for kitchen, laundry and bath, as well as outside uses in gardens, etc. It is estimated by multiplying the projected population with the projected per capita demand. Future population and per capita demand are projected by using the system dynamics technique. Based on historical data, the population in each sub-region is characterized by the initial population and the growth rate specified for each year, i.e., the total population for *i*th year in the future is estimated as follows

$$POP_i = POP_0(1 + rp_1)(1 + rp_2)...(1 + rp_i) \tag{2}$$

in which POP_0 is the initial population, rp_i the growth rate of population in *i*th year, which can take different values for each year, and include any changes in future population policy.

Unit domestic demand is measured in litres per capita per day. In the Yellow River basin, this parameter has been found empirically to change among cities with different scales. On the basis of this fact and with the combination of the data condition, the domestic water demand is further divided into three subsectors: city (with population more than 0.5 million), town (with population less than 0.5 million), and rural subsectors. In 1989, the daily per-capita demand in the 7 sub-regions ranged from 21 L in the rural subsector to 180 L in the city subsector (Xi *et al.*, 1996). Livestock water-demand in rural areas is estimated as the rural domestic water multiplied by the ratio of livestock demand to domestic demand in the rural areas. The per capita demand for *i*th year is then estimated as follows,

$$WP_i = WP_0(1 + rwp_1)(1 + rwp_2)...(1 + rwp_i) \tag{3}$$

in which WP_0 is the initial per capita water demand, rwp_i the growth rate of per capita demand in *i*th year, that takes different values for each year to account for any improvement in standards of living. The domestic water demand for *i*th year is then estimated as

$$D_{Dom,i} = WP_i \cdot POP_i \tag{4}$$

The inputs in this sector include existing population, population growth rate, per capita water use, and growth rate of per capita demand due to improvement of living standard in the future, etc.

2.1.2. *Industrial Water Demand*

As with the domestic water demand, the historical data also show that the industrial amount of water used per unit of production changes with the scale of production. For example, the amount of water used by township industry is quite different to that of urban industry with its advanced technologies. Therefore, the industrial demand sector has also been divided into three subsectors: city, town, and rural (including township) industry. In the city and town subsectors, each one is further divided into ten subdivisions: (1) mining, (2) food and beverage, breweries, (3) textile, (4) paper and printing, (5) chemicals, petrochemicals and plastics, (6) building material, (7) metals and smelting, (8) electricity, (9) machinery, and (10) other industries. The industrial water demand for each subdivision equals the product of industrial production with the corresponding water-demand per unit of production for that industrial subdivision. Due to data limitations, the rural industrial water demand has been estimated as the product of the industrial production with the corresponding water-demand per unit of rural industrial production. The industrial water demand in *i*th year is estimated as follows,

$$D_{IND,i} = INP_i \cdot WI_0(1 - \alpha i_i) \tag{5}$$

in which WI_0 is the initial water demand per unit industrial production, αi_i is the reduction rate of water demand per unit of production in *i*th year due to improved water-use efficiency, and INP_i is the industrial production in *i*th year, estimated as follows:

$$INP_i = INP_0 \cdot (1 + rin_1)(1 + rin_2)...(1 + rin_i) \tag{6}$$

where *rin* is the growth rate of industrial production.

The inputs in this sector include existing industrial production, industrial growth rate, water demand per unit of production and the possible decrease in the rate of water demand per unit of industrial production due to improved water-use efficiency, etc.

2.1.3. *Agricultural Water Demand*

Agricultural water demand, generally accounts for more than 70% of the total demand, and would normally include irrigation, fisheries and livestock (Al-Weshah, 2000). In this study, water for livestock is included in the rural domestic demand due to data limitation. Irrigation water is estimated as the total irrigated land area multiplied by the water demand per hectare. Due to the lack of the data on crops and the crop-dependent water demand, an average annual irrigation demand per hectare for each sub-region has been adopted. With the advances in irrigation techniques, the water demand per hectare is expected to decrease with time and it is thereby assumed to be a time-dependent function. In addition, the irrigated land area will also change with urbanization and the development of new crop fields (Casterad and Herrero, 1998). Therefore, both water demand per hectare and irrigated land area have been treated as variables instead of constants in this study, which is one of the main features of system dynamics models. Irrigation water is estimated by using the following equations,

$$D_{Agr,i} = IRD \cdot \alpha A_i \cdot A_{Irr,i} \tag{7}$$

$$A_{Irr,i} = A_{Irr,0}(1 + rA_1)(1 + rA_2)...(1 + rA) \tag{8}$$

in which IRD is the water demand per hectare, A_{Irr} the irrigated land area, αA_i the decreased rate of irrigation demand per unit area in *i*th year, and rA_i the growth rate of irrigation area in *i*th year.

In this sector, input data includes the irrigated area, the irrigated areas growth rate, water use per unit area and reduction rate due to the improvement of irrigation techniques, etc.

2.1.4. *Environmental Water Demand*

The water demand for environment protection and ecological system are assumed constant at the present stage of the study. For example, the annual water demand for sediment scouring has been taken to be 21.0 billion m^3 at Huayuankou.

2.1.5. *Inter-Basin Water Transfer*

The external water demand supported by the Yellow River is mainly abstracted from the middle and downstream reaches of the river and used for water supply in the Hai River and Huai River basins. This is estimated to be approximately 8.98 billion m^3 annually (He, 2000).

2.2. AVAILABLE WATER-SUPPLY ESTIMATION

Equation (9) is a mass balance equation for the total available water-supply:

$$S = S_S + S_G + S_R \tag{9}$$

In which S is the total available water-supply, S_S the available surface water-supply, S_G the available groundwater supply, and S_R the re-used treated waste water-supply. Equation (9) means that all existing and potential surface water, groundwater, and wastewater should be considered for integrated water resources management.

2.2.1. *Surface-Water Resources Characteristics*

The average annual precipitation in the study area is estimated to be 449.9 mm, ranging from 1500 mm in the southern humid region to 200 mm or less in the northern arid region of the Yellow River basin. As a potential resource, rainfall provides an annual volume of more than 300.0 billion m^3 of water, of which only 58.0 billion m^3 materialises as runoff. Approximately 21.0 billion m^3 of this runoff has to be used for scouring sediment and environment protection, leaving only a portion of the remainder for supply purposes. Therefore, in business-as-usual (BaU) scenario, only about 37.0 billion m^3 of water are available for surface-water supply.

Besides the runoff in rivers, surface-water resources also include the return flow from agriculture, as well as treated industrial and domestic effluent. The potential resources in each sub-region are estimated from historical streamflow data, expressed as the annual streamflow volumes. Return flow, which is expressed as a percentage of the wastewater or irrigated water, is directly estimated on the basis of the ratio derived from the most recent annual water balance data for different types of water users. In order to estimate wastewater flows available for recycling in different sub-regions, the wastewater yields from domestic and industrial sources were estimated using historical data and a variable reclamation efficiency to account for the progress of technologies.

2.2.2. *Groundwater Resources Characteristics*

In the Yellow River basin, 26.3% of the water consumption is provided by groundwater, of which 20.4% is used for industrial demand, 63.3% for irrigation, and 16.3% for domestic demand and livestock (Chen *et al.*, 1997). The estimated recharge in the basin is between 30.0 and 40.0 billion m^3 (Zhu and Zhang, 1999). Over-exploitation of groundwater in some sub-regions in the basin has destroyed the use of groundwater as a renewable resource, which will seriously restrict groundwater abstraction rates elsewhere. Over-pumping of groundwater has also reduced the hydraulic head in the aquifers, which has resulted in ground subsidence. For example, a zone with an area of larger than 30 km^2 in Xi'an city has suffered an average 1.0 m of subsidence over the past few decades (Qin *et al.*, 1998).

2.3. WATER RESOURCES SYSTEM EVALUATION

There are many criteria to evaluate the performance of water resource systems such as reliability, vulnerability and resiliency (Jinno *et al.*, 1995; Xu *et al.*, 1998). In this study, a new index, named sustainability index (SI) is introduced. It is defined as the ratio of aggregated possible water deficit relative to the corresponding supply in the same region, and is given as follows:

$$SI = \begin{cases} (S - D)/S, & S > D \\ 0 & S \leq D \end{cases} \quad (10)$$

where D is the water demand, and S is the available water-supply. SI values greater than 0.2 correspond to low or no stress of water supply, which implies that water demand is less than or equal to 80% of the potential water supply, whereas those smaller than 0.2 reflect vulnerable conditions, i.e., water demand is greater than 80% of the potential water supply. Values of zero indicate an unsustainable water supply, i.e., water demand already equals or exceeds all available local water resources.

3. System Dynamics Model Development

The WRSD model in this study has been developed within STELLA, an object-oriented simulation environment (High Performance Systems, 1999). STELLA makes it possible to develop a complex water resources model with less programming effort than using traditional computer languages and makes it easy for model expansion. For example, with further studies on social, economic and other sectors that directly affect water balance, the WRSD model presented in this paper will be easily expanded. It has a user-friendly, graphical interface, which indicates the functional relationships among different objects (Ahmad and Simonovic, 2000). The process of model development is analogous to drawing a flow chart of the system to be simulated.

The SD tools used in this study include stock, flow, converter, and connector. Stock, representing conditions ‘how things are’ and accumulations serving as resources, is used to represent the increased population, per capita water use, irrigated land area, etc. Flow, representing actions ‘how things are going’, is used to represent components whose values are measured as rates. A converter is used to transform input in the form of algebraic relationships and graphs into output. A connector, representing the relationship between stocks and converters, conveys information from one variable to another in the form of a quantity, an algebraic relationship, or a graphical connection (Simonovic, 2002). The relationship between structure and behaviour in system dynamics is based on the concept of information, feedback and control.

3.1. MODEL DEVELOPMENT

Prior to model development, the spatial and temporal scales of the model have to be predetermined, which mainly depend on the nature of the problem and the objective of the model development. In this study, the main objective was to simulate various water resources scenarios, with a view to satisfy long-term socio-economic plans on the basin scale. The time horizon of most socio-economic plans is 25 to 30 yr (Simonovic and Fahmy, 2000), and therefore, the planning period for this study has been taken as 30 yr, with a time increment of 1 yr. On the basis of the geographical homogeneity, the study area was divided into 7 geographic units. Whilst this greatly reduced the temporal and spatial variability, it is still a complex task to simulate large socio-economic sectors and link them together (Simonovic and Fahmy, 1999). To that end, the hierarchical decomposition technique was used, with each complex sector being disaggregated into different sub-sectors, e.g., the industrial water sector was divided into three subsectors: city, town and rural, due to the significant difference of the characteristics with respect to industrial pattern, unit water rate, growth rate, etc.

The objective of the WRSD model was to simulate various water resources scenarios using the SD technique with a view to identify viable options. It may also serve as a tool for investigating impacts of changing water-supply allocation and temporal distribution. The model was formulated graphically on screen by using the basic building blocks of STELLA. Difference equations are used to describe the complex relationships in the dynamic systems, such as non-linear increase of the domestic water-demand, and are solved by Euler’s method. STELLA is also convenient in developing the interactive user-interfaces. In this study, the user interface was formulated so that navigation through the various models was intuitive.

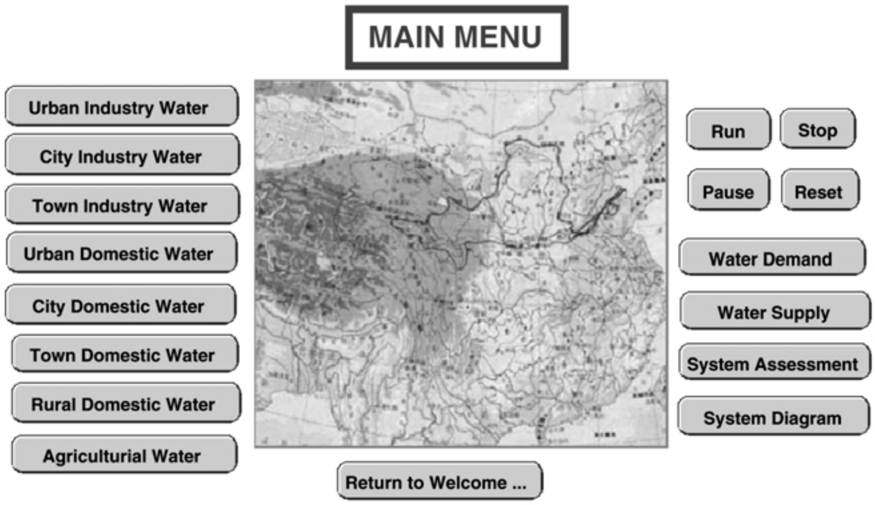

Figure 2. Main menu of the WRSD model showing the structure of the system.

These primary types of interface screens include: (1) scenario screens that allow the user to select a scenario; (2) input screens that present raw data which can be revised by users; and (3) output screens that provide the interpretation of results. The WRSD has the basic functions inherited from STELLA. The main menu of the user interface for WRSD is given in Figure 2. In addition, the model may import/export data from/to Microsoft Excel spreadsheets. Whilst STELLA component is involved in the water resource simulation over a specified period using historical streamflow data and projected water demands, the Excel spreadsheets show demand-related data and selected output. Figure 3 gives one of the simplest examples of the 14 sector models for agricultural water prediction and shows the mechanism by which the WRSD model is operated on the basis of stocks, flows, converters, and connectors.

The structure of the model and a schematic diagram of the water resource system with its main sectors are shown in Figure 4. In total, the model has over 50 variables such as those given in the following sections. Every effort has been made to make the model as simple as possible and to provide the user with an effective interface to manipulate the model.

3.2. MODEL APPLICATION AND RESULT ANALYSIS

The WRSD model developed in this study has been used to evaluate different water resource options for the Yellow River basin. In doing so, various scenarios for different socio-economic sectors: industrial, agricultural, and domestic demands, as well as the water-supply constraint have been related. Scenarios involved in different sectors include a large number of variables and inputs. Satisfying any one

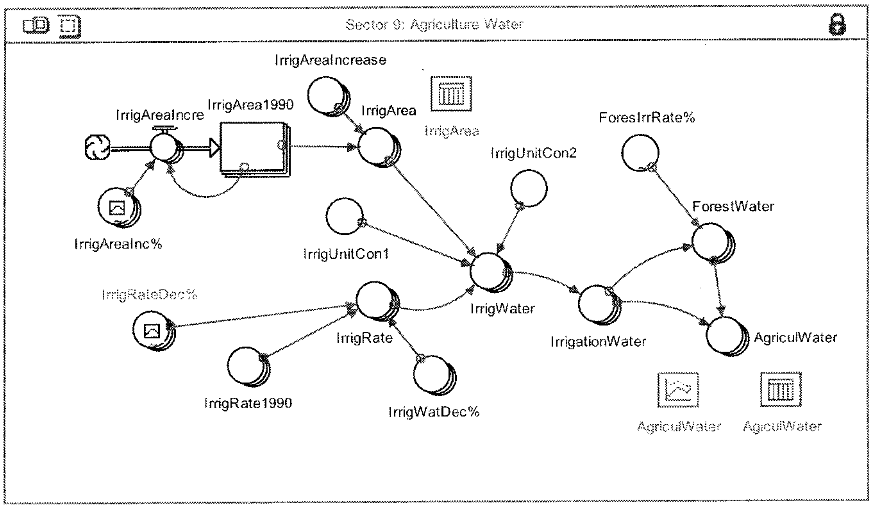

Figure 3. Model components in agricultural water sector.

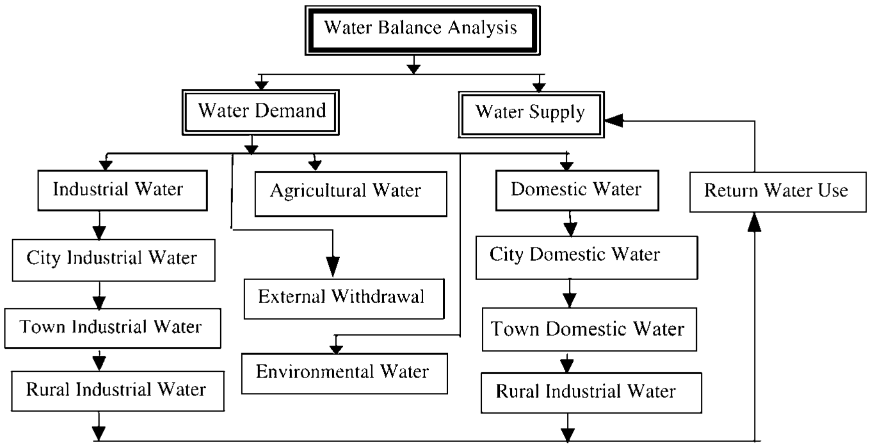

Figure 4. Mechanism of the main sectors showing the model structure.

of these scenarios in one sector pertains to another set of variables in other sectors. The input data includes precipitation, streamflow, in-stream flow requirements and a great deal of variables related to water demand projections such as the industrial growth rate, per capita water use, population growth rate, etc. In the present study, 10 water-supply scenarios, as given in Table II, have been evaluated, corresponding to the possible water-supply options from the present to 2030. For comparability purposes, local groundwater abstractions assume the current over-exploitation of water in scenarios A to C and F to I, whilst scenarios D, E, and J correspond to 10 or 20% of groundwater reduction in sub-regions V and VII, where the over-exploitation of groundwater has already resulted in ground subsidence. Scenario

Table II. Scenarios proposed and evaluated in the study

Scenario	Category	Description
A	BaU	Business-as-Usual Scenario
B	Climate change	Runoff decreases by 10%
C	Climate change	Runoff decreases by 20%
D	Groundwater constraint	Groundwater decreases by 10% in regions V and VII
E	Groundwater constraint	Groundwater decreases by 20% in regions V and VII
F	Irrigation improvement	Demand per unit of area for irrigation decreases 20% in region III
G	Irrigation improvement	Demand per unit of area for irrigation decreases 30% in region III
H	Irrigation area increases	Irrigation area increases 20% in region V
I	Recycling water increases	Recycling water increases 10% in region IV and 20% in regions II, III, V, VI, and VII
J	Integrated scenario	A composite of scenarios B, D, G, H, and I

A is the BaU scenario. Scenarios B and C are based on reduced runoff due to climate change but assume the same magnitude/spatial distribution of population and economics as that in the BaU scenario. Scenarios D and E mainly relate to the constraint on the over-exploitation of groundwater in sub-regions V and VII due to ground subsidence. Scenarios F, G and H use the projected irrigation water demands in sub-regions III and V, assuming the water supply based on the present climate. Scenario I investigates the impact of using recycled wastewater and J is a composite scenario to evaluate the effect of integrating scenarios B, D, G, H, and I.

3.2.1. *Business-as-Usual Scenario*

SD model is especially suitable for problems with uncertain elements such as water resource simulation. It is also convenient for exploring how changes in one variable affect others. A major advantage of the model is in providing quantitative information with which various scenarios can be analysed and the optimum solution can be selected. This objective is usually attained in two stages. In the first stage, the BaU scenario is identified and assorted input variables such as industrial growth rate, irrigated area, etc. are incorporated. This work provides the basis for further studies. In the second stage, various scenarios can be further evaluated or ranked relative to specific criteria such as adequacy of supply, groundwater exploitation, environmental impacts and water-supply reliability. The parameters in the BaU scenario are mainly from the long-term trend analysis of economic growth in China (Zhang, 1999), as given in Table III. Due to the lack of industrial quotas and water

Table III. Main parameters in BaU scenario

Period	2000–2010	2010–2020	2020–2030
Population increase (%)	1.0–0.75	0.75–0.5	0.5–0.25
Per capita water demand: City	147–180	180–260	260–280
Rural	68–90	90–130	130–150
Industrial increase (%)	12.0–10.0	10.0–8.0	8.0–6.0
Irrigation water per unit area (m^3 ha^{-1})	7000–8000	6000–7000	5000–6000

Table IV. Total water demand (million m^3) for the ten industrial sectors

Sectors	Cities	Towns
Metals and smelting	303	955
Machinery	204	643
Electricity	3170	1260
Building material	569	174
Mining industry	1050	1070
Chemicals, Petrochemicals, and plastics	3470	972
Textile industry	1780	362
Paper and printing	776	368
Food and beverage, breweries	739	383
Other industries	3520	520
Total	20100	6700

requirements per unit of production for each of the 10 industrial sectors, data relating to the total water demand for each of the 10 industrial sectors have been used in this study (Xi *et al.*, 1996), as given in Table IV.

3.2.2. *Population and Water Demand Forecasts*

One of the advantages for system dynamics is its ability to directly display the simulation result in the formats of both tables and figures, as given in Figure 5, which shows the predicted domestic water demand in town sector from Longmen to the mouth of the Yellow River. This feature makes it quite easy for model calibration and parameter identification.

Once parameters are identified, the simulation will be easily performed. Figure 6 shows the forecasted population in the Yellow River basin from 2000 through 2030. In order to compare the results obtained in this study with previous projections, the populations predicted by Zhang *et al.* (1999) and Xi *et al.* (1996)

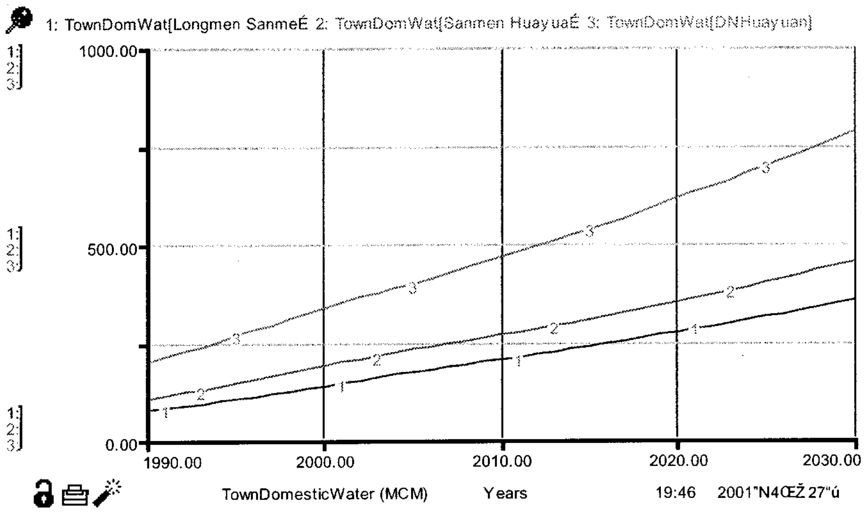

Figure 5. Town domestic water demand forecasting.

are also shown in the same graph. The results show a good agreement with two previous studies. For the purposes of parameter estimation, the calibration period from 1990 through 2000 is also included in the graph, as with the other graphs. Figure 7 shows predicted population and domestic water demand in the study area. The population and domestic water demand in 2010, 2020, and 2030 in the study area are 115.6, 122.2 and 128.0 million and 5.83, 7.53, and 9.38 billion m^3, respectively. The results obtained by Zhang *et al.* (1999) are also given in this graph. For example, the population for 2000 and 2010 predicted in the present study are 107.0 and 115.6 million, which are nearly same with the results obtained by Zhang *et al.* (1999) as 108.0 and 118.0 million. Similarly, the domestic water demands for the same two years: 4.28 and 5.83 billion m^3, are not quite different to those estimated by Zhang *et al.* (1999) as 4.35 and 5.62 billion m^3. Figure 8 shows the water demand forecasts for the different sectors. The proportional split amongst industrial, domestic, and agricultural water demands is 20.9, 11.5, and 67.7% for 2010, 24.3, 13.3, and 62.4% for 2020, and 25.5, 15.7, and 58.8% for 2030, as given in Figure 9. Obviously, with the development of industry and the progress of urbanization, the percentage of water demand for industrial and domestic use will increase gradually, whilst demand for agricultural water will continue to decrease as a result of advances in irrigation technology, although the irrigated land area also continues to increase in the foreseeable future. This illustrates that the amount of water-demand for the increased irrigated land is less than the amount of water decreased due to the improved irrigation technologies.

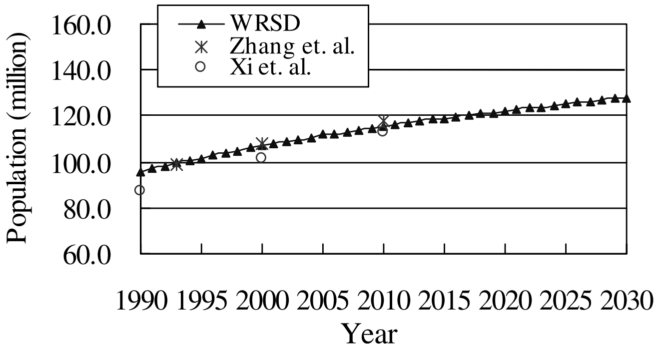

Figure 6. Population forecast from 2000 through 2030.

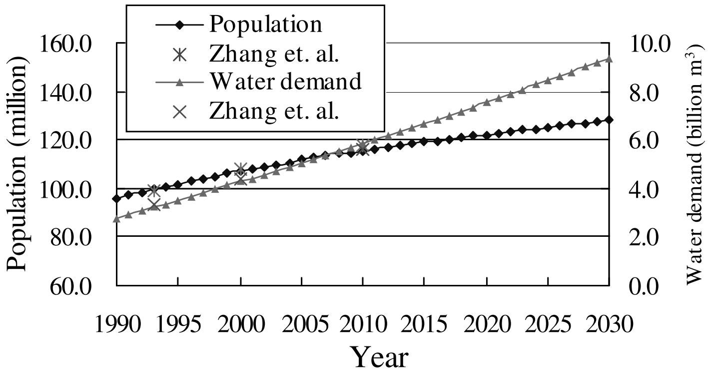

Figure 7. Comparison between forecast population and domestic water demand.

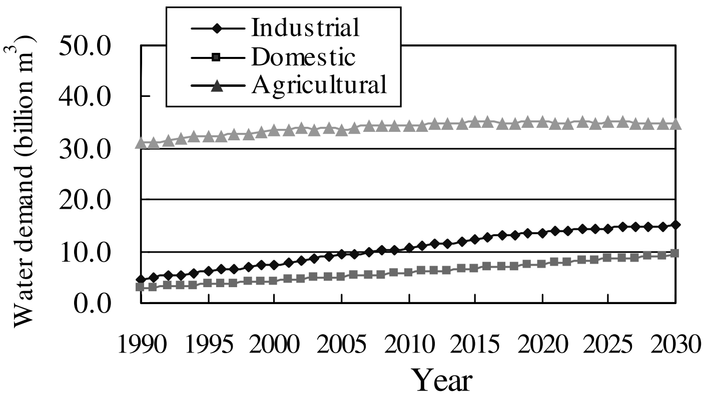

Figure 8. Forecast water demand for different sectors.

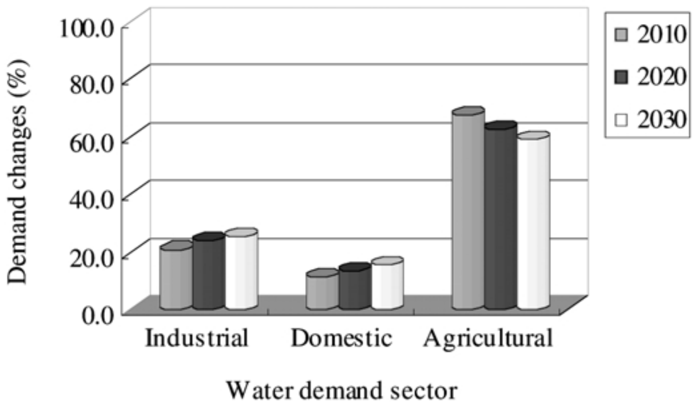

Figure 9. The splits among industrial, domestic, and agricultural water demand.

3.2.3. *Water Shortage Forecasts*

Water shortage for the year 2010 in the Yellow River basin was estimated as 3.1 billion m^3 (4.3%) by Xi *et al*. (1996) and 2.08 billion m^3 (4.1%) by Zhang *et al*. (1999), respectively. Based on the water demands estimated in this study, the water shortage will be 2.29 billion m^3 (4.5%) by 2010. Unless alternative sources are developed, the shortages in 2020 and 2030 will be 6.24 (11.1%) and 6.62 billion m^3 (11.2%), respectively, due in part to the uncertainty of the local groundwater supply. This shortage will be much more serious in sub-regions III, V and VII.

Since existing water resources cannot meet the demand even now, never mind 2030, new sources need to be explored and developed if the water-supply requirements of the Yellow River basin are to be met. Table V summarizes simulation results for 10 scenarios. Scenarios B and C involving climate change would bring about a serious shortage of water. Over-abstraction of irrigation water in sub-region III is one of the reasons that resulted in the decrease of streamflow in the Yellow River. If a reduction of more than 20% of the irrigation water used in this region is achieved, it would dramatically improve the water-supply situation, as shown in scenarios F and G. Although the increased use of recycled treated wastewater may reduce the effect of water shortage, it still cannot solve the problems of water deficit in part of the study area. As seen from scenarios D and E, any limitation on groundwater exploitation would increase the deficit of water. However, continued over-exploitation of the aquifer will make the water supply unsustainable. Although difficult, further studies are required to determine the ecological abstraction limits for both surface and groundwater. Table VI gives part of the results for sustainability index of water-supply relating to the 10 scenarios. Since none of these scenarios can provide a solution to the problem of water deficit in sub-regions III, V, and VII, the water-supply SI will always equal or be near to zero. Therefore, the values of SI for those sub-regions are not given in the Table. It also should be pointed out that the present study does not consider the transfer of water rights

Table V. Water demand/deficit (billion m^3) for various scenarios

Scenario	Water demand			Water deficit		
	2010	2020	2030	2010	2020	2030
A	50.88	56.49	59.52	2.29	6.24	6.62
B	50.88	56.49	59.52	6.41	10.48	11.08
C	50.88	56.49	59.52	10.50	14.73	15.56
D	50.88	56.49	59.52	3.11	7.09	7.50
E	50.88	56.49	59.52	3.92	7.94	8.40
F	48.34	53.84	56.82	0.00	3.59	3.92
G	47.06	52.52	55.46	0.00	2.27	2.56
H	52.19	57.80	60.83	4.33	7.56	7.92
I	50.88	56.49	59.52	0.64	4.25	4.26
J	48.37	53.83	56.77	3.23	6.84	7.05

Table VI. Water-supply SI estimates for various scenarios

Scenario	Longyangxia-Lanzhou			Hekouzhen-Longmen			Sanmenxia-Huayuankou		
	2010	2020	2030	2010	2020	2030	2010	2020	2030
A	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
B	0.64	0.60	0.59	0.59	0.51	0.46	0.22	0.10	0.03
C	0.59	0.55	0.54	0.56	0.47	0.42	0.14	0.01	0.00
D	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
E	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
F	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
G	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
H	0.67	0.64	0.63	0.62	0.55	0.51	0.29	0.18	0.11
I	0.68	0.65	0.64	0.63	0.55	0.51	0.30	0.20	0.15
J	0.64	0.61	0.60	0.60	0.52	0.47	0.24	0.18	0.07

amongst the different sub-regions. As a consequence, the increase or decrease of water supply in one sub-region only affects the water-supply sustainability in that sub-region and the river basin as a whole, as shown in Table VI. From these values, some of the conclusions obtained from Table V may be more clearly understood.

3.2.4. *Analysis for Water-Supply Sustainability*

Figures 10 and 11 show the sustainability indices of the water-supply system for the BaU scenario in all sub-regions, as defined in Equation (10). It shows that the water supplies in sub-regions III, V, and VII are unsustainable. This means that

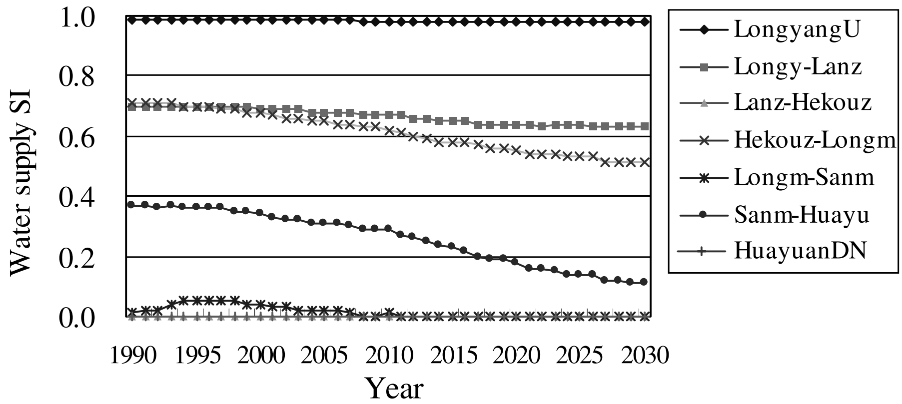

Figure 10. Dynamic changes of water supply SI for each sub-region.

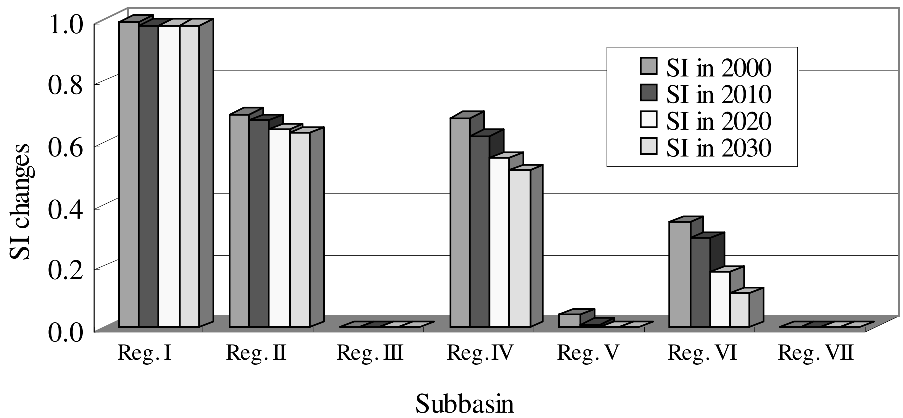

Figure 11. Comparisons among water supply SI for 2000, 2010, 2020, and 2030.

those three sub-regions will subject to a low reliability of water-supply. The runoff coefficient in sub-region III is very small and the available water is insufficient. Flooding irrigation is commonly used in this sub-region, the water consumed in one unit of the irrigated area is twice or more than that of other sub-regions. In practice, this sub-region has been consuming too much upstream runoff. Sub-region V has a deficit of water due to the very large irrigated area from Longmen to Sanmenxia as well as the large industrial base in this sub-region. The growth of the industry in this sub-region will dramatically increase the water deficit especially after 2010. Sub-region VII bears the brunt of supplying water for the Huai and Hai River basins and is typical of those sub-regions in deficit of water. Sub-region VI will also have a shortage of water if new sources can not be developed before 2010.

The comparisons for different simulation results are made to evaluate the impacts each scenario has on water-supply reliability. When evaluating various alternatives, sub-regions I, II, and IV proved low vulnerability until 2030 demand projections. During the same period, sub-regions III, V and VII will experience

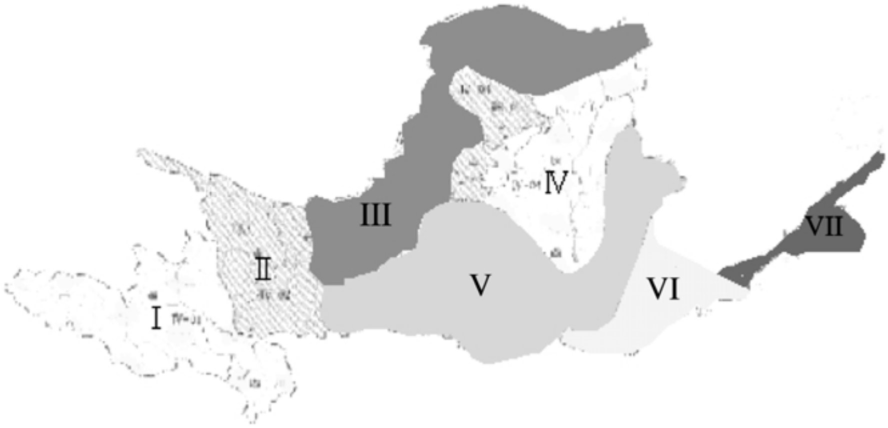

Figure 12. Spatial distribution of water supply SI in the study area.

failures in meeting increased demands after year 2000 and fail to achieve the desired supply reliability in the future. Sub-region VI may have a reliable water supply till 2010, but may become unsustainable in the future. This implies that the water supply in sub-regions III, V, and VII are presently unsustainable and sub-region VI will also join them if new water sources can not be exploited in the near future, as shown in Figure 12. In the figure, the sub-regions with low SI values are marked with shade. The thicker the shade in the area, the smaller the water-supply vulnerability is. In other words, the water-supply sustainability shows in order as: VII, III, V, and VI from low to high. The other sub-regions would have no problem on water-supply under normal conditions till 2030.

3.2.5. *Comparison with Previous Studies*

Comparing the results reported in this paper with previous studies could be difficult, since some different assumptions may have been made. For example, the level of effluent re-use and per capita water demands in previous studies are not entirely clear. Nevertheless, those results may provide a reference for this study. Xi *et al.* (1996) estimated that the total water demand for 2010 would be 72.3 billion m^3, of which the domestic demand in city and town, rural domestic/livestock, industrial, and agricultural demands were 2.73, 2.33, 18.9, and 48.4 billion m^3, respectively. Zhang *et al.* (1999) predicted that the total water demand for the same year would be from 50.8 to 51.1 billion m^3. In which the domestic demand for city and town would be 3.2, rural domestic and livestock demand 2.4, industrial water would be from 10.3 to 10.9, and the agricultural demand would be from 34.6 to 35.9 billion m^3. The results obtained in the present study are more similar to Zhang's estimation. Since the data used in Xi's study was out-dated, Zhang's predictions should be more suitable as a reference. Although some of the assumptions in this paper have been taken from both previous studies, it has been proved that the WRSD model developed in this study and the other related assumptions made in the model are reasonable. The results obtained in this study, therefore, are acceptable with some evidences.

4. Conclusions

Ten scenarios on future water-demand increases have been analysed to evaluate the sustainability of water supply in the Yellow River basin. Supplying the increased water for the study area will be a great challenge to water resources authorities, and they also have to meet more stringent water-quality standards, as well as environmental and ecological requirements. Presently, more than 30% of the domestic water supply is met by over-exploiting groundwater, but less wastewater is treated and reused. Although no panacea, recycling may help reduce the burden on the limited water resources. Inter-basin transfer supplying water to the Yellow River basin is regarded as an unavoidable measure even with recycling of wastewaters. Since importation of water from other basins, and re-use of wastewater is already being planned, scenario J should be used as the basis of the medium- to long-term plan, with the over-exploited groundwater being substituted by external sources and local recycling. The improvement of irrigation efficiency as a result of substituting the commonly-used flooding irrigation with new technologies such as spray and drip approaches should be further investigated and adopted as soon as possible.

Looking to the future, integrated water resource management practice must be extended to include protection of aquifer recharge areas and especially the control of deforestation. Development of regional options would allow all users to have access to safe and more reliable supplies, providing the entire region with a high degree of water supply reliability in the future. A permanent transfer of water rights, e.g., decreasing the irrigation water in sub-region III for ecological and in-stream requirements, also needs to be further examined so as to improve in-stream flow for the Yellow River basin.

The system dynamics technique has proved to be an efficient approach for the simulation of a complex water resource system. Its merits include the increased speed of model development, ease of model improvement, and the ability to perform sensitivity analysis. Modifications in both model structure and parameters can easily be made as new information becomes available. With the WRSD model, one can evaluate system performance for different surface-water operating rules, constraints on groundwater over-exploitation, various conservation options and changes to environmental and ecological water requirements. Scenarios, other than those investigated in this study, can be evaluated by using the existing framework. It should be pointed out that some of the present parameters in the WRSD model were assumed and some of input data used in this study were out-dated. With the involvement of local water resource authorities in the further development of the model, it is expected that the model would become a more practical tool for managing water resources of the Yellow River basin, or at least provide some useful references for this task. Moreover, in the on-going study, further effort should be made to improve the interface/structure of the WRSD model, so as to simulate the possible transfer of water amongst the different sub-regions and users. Sensitivity analysis for the WRSD model will be performed on the basis of the results presented in this paper, from which different kinds of uncertainties from model, parameter and input data may be estimated. It should be noted that the system dynamics approach is more beneficial for indicating the internal dynamics, rather than predicting the exact future system states. Another important role of this study, therefore, was to have provided the basis for analysing the internal dynamics of the water resources system in the Yellow River basin.

Acknowledgements

This study has been partly supported by the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Corporation (JST) under the project ‘Sustainable development and management for water resources in Yellow River basin’. Part of the data have been provided by several cooperators from China Institute of Water Resources and Hydropower Research, and Yellow River Conservancy Commission, Ministry of Water Resources, People’s Republic of China. The kind assistance from Prof. Simonovic, S. P. at the University of Western Ontario, Canada, on both model development and manuscript formulation, is greatly appreciated. The authors would like to thank the editor and two anonymous reviewers for their constructive comments and suggestions, which resulted in a significant improvement of the quality of the paper. The opinions expressed here are those of the authors and not those of other individuals or organizations.

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