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Water resources planning and management based on system dynamics: a case study of Yulin city

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Abstract Water security is an integral aspect of the socio-economic development in China. Nevertheless, water resources are under persistent pressures because of the growing population, heavy irrigation, climate change effects and short-term policies. Traditional management approaches narrowly focus on increasing supply and reducing demand without considering the complex interactions and feedback loops that govern water resource behaviour. Whereas these approaches may provide quick fix solutions, they often lead to unanticipated, sometimes catastrophic, delayed outcomes. Therefore, water management needs to take a holistic approach that caters to the interdependent physical

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(e.g. water inflows, outflows) and behavioural (e.g. decision rules, perceptions) processes in the system. Unlike reductionist approaches, System Dynamics (SD) takes a system-level view for modelling and analysing the complex structure (cause–effect relationships, feedback loops, delays) that generates the systemic behaviour. Simulating the SD model allows assessing long-term system-wide impacts, exploring leverage points and communicating results to decision makers. In this paper, we follow an SD modelling approach to examine the future of water security in Yulin City. First, we present a conceptual model for integrating water supply and demand. Based on this, we build an SD model to simulate and analyse the dynamics of water resource over time. The model output is tested to ensure that it satisfactorily replicates the historical behaviour of the system. The model is used to quantitatively assess the effectiveness of various supply/demand management options. Three scenarios are designed and examined: business-as-usual, supply management, and demand management. Results show that current management regime cannot effectively meet the future water demand. Whereas supply acquisition provides short-term benefits, it cannot cope with the growing population. A combination of conservation measures and demand-management instruments is regarded the most effective strategy for balancing supply and demand.

Keywords System dynamics · Water resources · Water demand management · Water conservation · Yulin city

1 Introduction

Water is inextricably linked with every aspect of life, including food security, human health, economic development and ecological balance. Water shortage is regarded as one of the most challenging environmental problem in the twenty-first century (Brown and Flavin 1999). This threatens food security, economic development and ecological balance.

During the twentieth century, the ultimate objective of water management was to satisfy the growing requirements of the fast development pace. For this, command-and-control approaches were used to increase the capacity to access water supplies (Holling and Meffe 1996). This included massive infrastructure projects, such as building additional dams and drilling deeper for water.

Whereas infrastructure projects provided solutions for chronic water crises, they could not cope with the persistent pressures of population growth, climate change effects, water-intensive agriculture and more. In addition, they have come at expensive, irreversible socio-ecological costs (Brierley and Fryirs 2008). For example, the shrinking of the Aral Sea, formerly the world's fourth largest lake, illustrates the catastrophic outcomes of short-term water planning policies (Glantz 1999). As a result, there has been almost consensus that command-and-control approaches are no longer adequate to deal with the complexity and uncertainty inherent in contemporary water management (Born and Sonzogni 1995); (Hjorth and Bagheri 2006).

Recently, there has been a shift towards integrated management that takes a holistic view of the interdependent hydrological, ecological and socio-economic processes that influence water resource (Jakeman et al. 2005). The objective is to design policies that compromise goals relevant to the triple pillars of sustainability: ecology, society and economy. The concepts of integrated management have been widely used. Examples include (Stephenson 1999; Butler and Memon 2006; Gumbo 2004; Wheida and Verhoeven 2007).

Integrated water-management policies need to be guided by an informed understanding of the system, its processes and responses to various changes. Nevertheless, water management arises in the context of complex and interdependent ecological, social and economic systems whose behaviour is governed by numerous feedback interactions and delays that are characterized by non-linear and counter-intuitive behaviour. Failure to consider such dynamic complexity often leads to unanticipated, policy resistant and, sometimes, catastrophic situations.

System Dynamics (SD) provides a feedback-oriented modelling framework for learning and communicating about the inherent complexity of water management. SD is designed for modelling and analysing complex socio-economic systems. It has been widely applied in many environmental problems, including water management (Winz et al. 2009).

This paper presents a dynamic simulation model of a water system in Yulin City and analyses the effectiveness of various supply and demand policies in meeting socio-economic and ecological requirements. Three scenarios are examined and reported: business-as-usual, capacity acquisition, and price-control. Results suggest that demand management represents the leverage point for achieving long-term sustainability outcomes.

The paper is organized as follows: Section 2 introduces SD modelling. The case study is introduced in Sect. 3. The followed methodology is described in Sect. 4. Simulation results are reported and discussed in Sect. 5. Finally, we wrap up with the conclusion.

2 System dynamics modelling

System Dynamics (SD) is a rigorous methodology for thinking, visualising and communicating about the future evolution of complex systems by creating qualitative and quantitative causal models which captures the interrelationships of the physical (e.g. water inflows, outflows) and behavioural (e.g. decision rules, perceptions) processes in the system (Wolstenholme 1990). Based on Systems Thinking, SD takes a system-level view for analysing complex problems by modelling the causal structure deriving the problematic behaviour (e.g. cause–effect interrelationships, feedback loops, delays, non-linearity) (Sterman 2000). Simulating the SD model shows the delayed and systemic impacts of alternative policies in a time-compressed manner (Sterman 1994).

Usually, an SDM project consists of the following phases: problem definition, system conceptualization, model formulation, model evaluation/testing, policy analysis and implementation (Karavezyris et al. 2002; Xu et al. 2002; Ahmad and Simonovic 2004; Elmahdi et al. 2007; Zhang et al. 2008). It is important to determine the positive and negative relationships between variables, feedback loops, system archetypes and delays. Then with the initial conditions for the first time step, the SD model can take certain steps along the time axis in the simulation process. All system dynamics model consists of the following basic elements, which are shown in Fig. 1.

Software tools like Stella, Dynamo, Vensim and Powersim use the principles of object-oriented programming for the development of system dynamics simulation programs. They provide a set of graphical objects with their mathematical functions for easy representation of the system structure and the development of computer code. Simulation models can be easily and quickly developed using these software tools (Guo et al. 2001; Sun et al. 2002; Xu et al. 2002; Ahmad and Simonovic 2004; Elmahdi et al. 2007; Zhang et al. 2008). The following equations show the basic mathematical form of the Vensim modelling language.

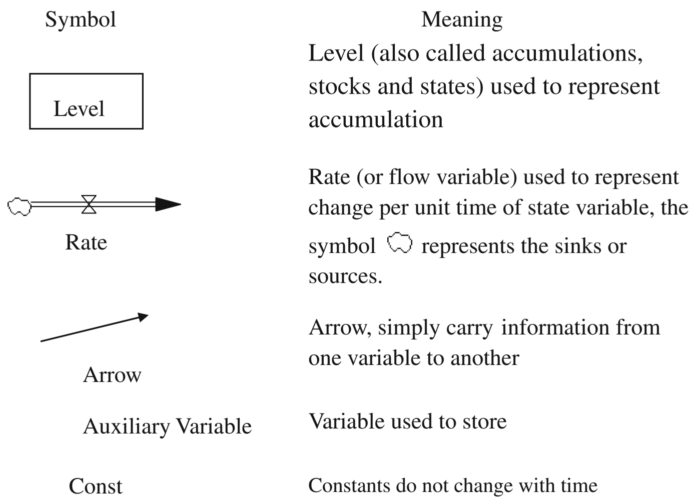

Fig. 1 Basic element for system dynamics model

$$\text{Levels}_t = \int_0^T \text{Rates}_t \mathrm{d}t \quad \text{or} \quad \frac{\mathrm{d}}{\mathrm{d}x}\text{Levels}_t = \text{Rates}_t \tag{1}$$

$$\text{Rates}_t = f(\text{Levels}_t, \text{Aux}_t, \text{Data}_t, \text{Const}) \tag{2}$$

$$\text{Aux}_t = g(\text{Levels}_t, \text{Aux}_t, \text{Data}_t, \text{Const}) \tag{3}$$

$$\text{Data}_t = h(\text{Levels}_t, \text{Aux}_t, \text{Data}_t, \text{Const}) \tag{4}$$

In these equations f, g and h are arbitrary, non-linear, potentially time varying and vector-valued functions. Equation 1 represents the evolution of the system over time, Eq. 2 the computation of the rates determining that evolution, Eq. 3 the intermediate results necessary to compute the rates and Eq. 4 the initialization of the system. Equation 1 above is written using both integral and differential notation. The format that vensim uses for expressing equations matches more closely the first, but the two equations have the same meaning (http://www.vensim.com).

3 Case study area

Yulin locates at latitude 36°57′–39°35′N and longitude 107°28′–111°15′E; encompassed within the administrative boundaries are 12 counties at a combined territory of 43,578 km^2, which are shown in Fig. 2. The annual rainfall is about 400 mm, 75% of which is concentrated in June, July and August, the mean annual runoff is 22.9×10^8 m^3, equivalent to the mean runoff depth of 52 mm, the groundwater resources of the whole city is 24.78×10^8 m^3, as the duplicative amount is 15.6×10^8 m^3, the gross mean annual potential of water resources is estimated at 32.01×10^8 m^3. The water resource per capita in Yulin is 910 m^3/p in 2005, and the scarcity of water resources had handicapped the development of city in the past years.

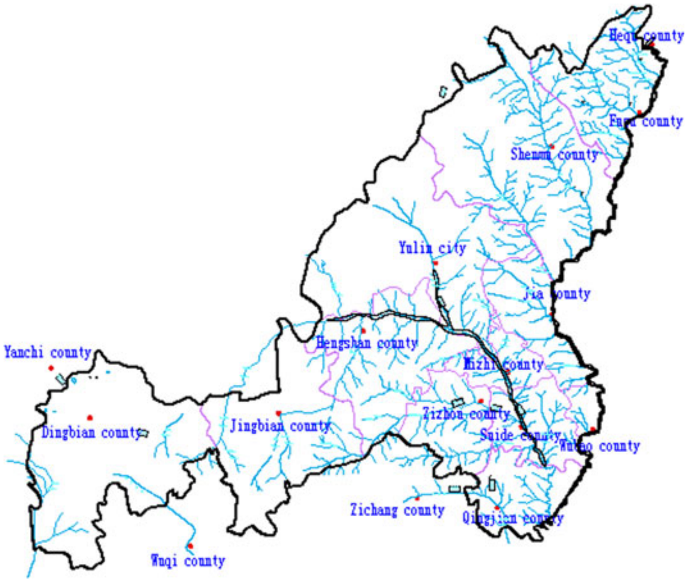

Fig. 2 Sketch map of the study area

4 Methodology

In this paper, we follow an SD modelling approach to analyse the dynamics of supply and demand and develop a model that can be used to simulate the changes in water balance over time.

4.1 Problem articulation

To articulate the problem, we start by defining the main issues that are relevant to water resource management in Yulin. Figure 3 presents a conceptual framework of these issues, categorized into supply, demand and price adjustment.

4.2 System interaction

4.2.1 Water demand

According to the water resources planning technical specifications in China, total water demand includes production water demand, domestic water demand and ecological water demand (Zhang 2005). They can be estimated by the following equations.

$$W_p^t = LW_i^t + PW_j^t + EW_k^t \tag{5}$$

In which,

$$LW_i^t = LuW_i^t + LrW_i^t = Pu_i^t \cdot LQu_i^t \cdot 365/1000 + \mathop{Pr}\limits_i^t \cdot LQr_i^t \cdot 365/1000 \tag{6}$$

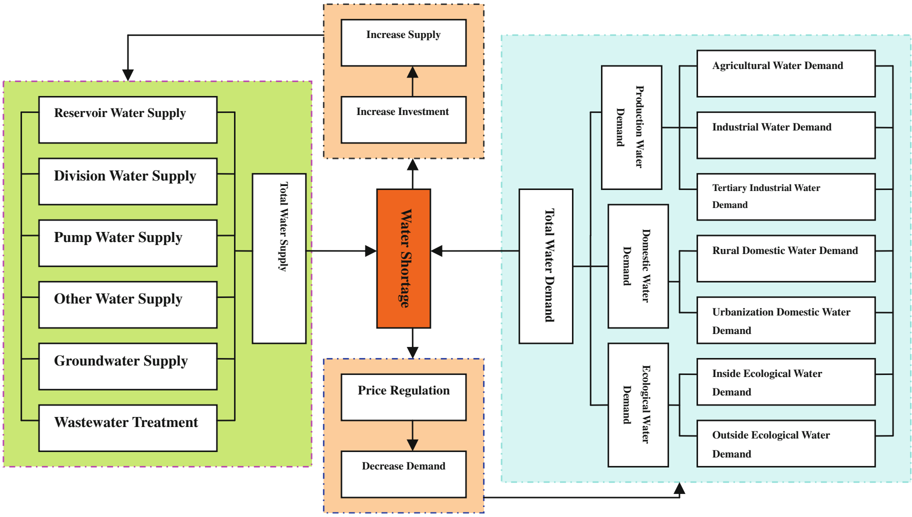

Fig. 3 Overall conceptual diagrams for Water resources planning and management

$$PW_j^t = AW_i^t + IW_j^t + TW_k^t = \sum_{j=1}^{3}\left(S_j^t \cdot AQ_n\right) + Sn_i \cdot m_i + Mr \cdot A + \sum_{i=1}^{n}\left(X_i^t \cdot IQ_i^t\right) \quad (7)$$

$$EW_k^t = E_{\text{in}} W_k^t + E_{\text{out}} W_k^t \quad (8)$$

Where i, j, k is different department for water demand, t is time, W_p^t is the total water demand (10^4 m^3).

LW_{pi}^t is the domestic water demand (10^4 m^3), which 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. It can be estimated by multiplying the projected population (10^4 p) with the projected per capita water consumption (l/p.d), and the methods are distinct for urban and rural area. As for urban population, urban water demand LuW_i^t is estimated by multiplying the urban population Pu_i^t (10^4 p) with the per capita water consumption for urban LQu_i^t (l/p.d), and for rural water demand LrW_i^t, it is estimated by multiplying the rural population Pr_i^t (10^4 p) with the per capita water consumption for rural LQr_i^t (l/p.d) (Zhang 2005).

PW_j^t is the production water demand (10^4 m^3), which includes different departments for water demand of the national economy. Usually, we classify them into agricultural water demand AW_i^t, industrial water demand IW_j^t and tertiary industrial water demand TW_k^t. Agricultural water demand generally accounts for more than 70% of the total demand and normally includes irrigation water demand, fisheries water demand and animal husbandry water demand. In this paper, irrigation water demand is estimated by the total irrigation area multiplied by the quotas. Fisheries water demand can also be estimated by multiplying fishery area (10^4 p) with the quotas of fishery. Methods for animal husbandry water demand is the same with domestic water demand, it is estimated by multiplying the number of livestock Pr_i^t (10^4 p) with the quotas of animal husbandry LQr_i^t (l/p.d). And for industrial water demand IW_j^t and tertiary industrial water demand TW_k^t, they can be estimated as the product of the industrial production with the corresponding water-demand per unit of industrial production (Zhang 2005).

EW_k^t is the ecological water demand (10^4 m^3), which includes water demand for environment protection and ecological system. In this paper, water demand for environment protection is studied, and it is assumed by multiplying urbanization population Pr_i^t (10^4 p) with the quota for urbanization ecology LQr_i^t (l/p.d) (Zhang 2005).

4.2.2 Water supply

Typically, the main potential sources of water supply include surface water (dams and water harvesting techniques), groundwater (wells and boreholes) and other sources including reuse of water and purification of effluent (Zhang 2005). In this paper, we estimated water supply by the following formula:

$$SW^t = SW_s^t + SW_g^t + SW_o^t \tag{9}$$

where SW^t is total water supply, SW_s^t is surface water supply, which includes reservoir, diversion water supply and pump water supply, SW_g^t is groundwater supply, SW_o^t is other kinds of water supply, mainly include wastewater reuse and collection of rainwater. But something should mention, water supply obey to physical capacity and environmental constraints.

4.2.3 Demand-management instrument

Water price is widely considered by economists as a key instrument in assisting the implementation of an efficient allocation of limited water resources by providing appropriate signals and incentives. As we know, price and supply act as a balancing loop; as price increases, desired supply raises and causes the supply to increase (Stephenson 1999; Savenije and van der Zaag 2002; Rogers et al. 2002; Butler and Memon 2006). An increase in supply decreases price.

Economics calculate the elasticity as:

$$\varepsilon = \frac{dQ/Q}{dp/p} \tag{10}$$

where ε is elasticity, Q is quantity and p is price. Elasticity is a negative number, since demand expected to decrease as price increases. If assume ε is constant, then

$$\int \frac{dQ}{Q} = \varepsilon \int \frac{dp}{p} \tag{11}$$

$$Q = kp^{\varepsilon} \tag{12}$$

where k is a constant.

Then can get

$$Q_2 = Q_1 \left(\frac{p_2}{p_1}\right)^{\varepsilon} \tag{13}$$

where p_1 and p_2 are water price before and after adjustment, Q_1 and Q_2 are quantities before and after adjustment. So, adjustment of the water price of is one of most effective economic levers for water supply and demand. But one thing should mentioned, that is how to set a reasonable price, many of the research papers also studied this problem in the past years. As in this paper, we calculate water price as:

$$P = P_1 + P_2 + P_3 \tag{14}$$

where P_1, P_2 and P_3 is resource Price, engineering Price and environment Price, respectively.

4.3 Model conceptualization

Based on the described conceptual framework, we use Causal Loop Diagram (CLD) to capture the interactions between economic development, population growth, water investment, irrigation water demand, industrial water demand, tertiary industrial water demand, surface water supply, groundwater supply, water price as well as water pollution in Yulin city. The feedback structure is further developed, as to represent the influence factors for co-operation in more detail, which is shown in Fig. 4. In which, each arrow indicates an influence of one element on another. This influence is considered as positive (+) if an initial change is amplified in the same direction as all components are traced through the loop, or negative (−) if an increase in one element causes a decrease in another (Karavezyris et al. 2002; Xu et al. 2002; Yu et al. 2003; Ahmad and Simonovic 2004; Zhang 2005; Elmahdi et al. 2007; Zhang et al. 2008). The hypotheses about these influences are based on literature studies as well as works previously carried out at our research unit.

From Fig. 3, the fundamental feedback structure for the YulinSD that embodies six feedback loops could be obtained. These are referred to as:

R1: Economic Development → +Domestic Water Demand → +Total Water Demand → +Water Shortage Rate → −Economic Development
R2: Economic Development → +Production Water Demand → +Total Water Demand → +Water Shortage Rate → −Economic Development
R3: Economic Development → +Ecology Water Demand → +Total Water Demand → +Water Shortage Rate → −Economic Development
R4: Economic Development → +Domestic Water Demand → +Total Water Demand → +Water Shortage Rate → −Water Supply → +Water Price → −Total Water Demand → −Water Shortage Rate → +Economic Development

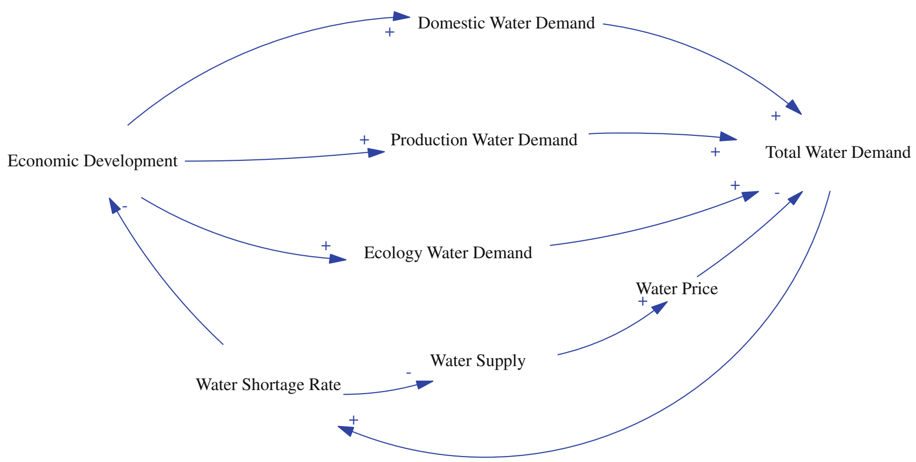

Fig. 4 Causal loop diagram of the basic model for YulinSD

R5: Economic Development → +Production Water Demand → +Total Water Demand → +Water Shortage Rate → −Water Supply → +Water Price → −Total Water Demand → −Water Shortage Rate → +Economic Development
R6: Economic Development → +Ecology Water Demand → +Total Water Demand → +Water Shortage Rate → −Water Supply → +Water Price → −Total Water Demand → −Water Shortage Rate → +Economic Development

4.4 Model formulation

As the key elements defined, these have to be quantified as variables and their influences have to be formulated mathematically. The WMM is definitively determined when the parameters and the start values for the state variables (stocks) have been specified. The YulinSD model in this study has been developed within Vensim Personal Learning Edition (PLE), and the boundary of the model is the total administrative area of Yulin city. The strategic planning period ranges from 1980 to 2030. The model includes 139 parameters and three major subsystems; the flow diagram for Yulin city is shown in Fig. 5. Vensim PLE makes it possible to develop a complex water resources model with less programming

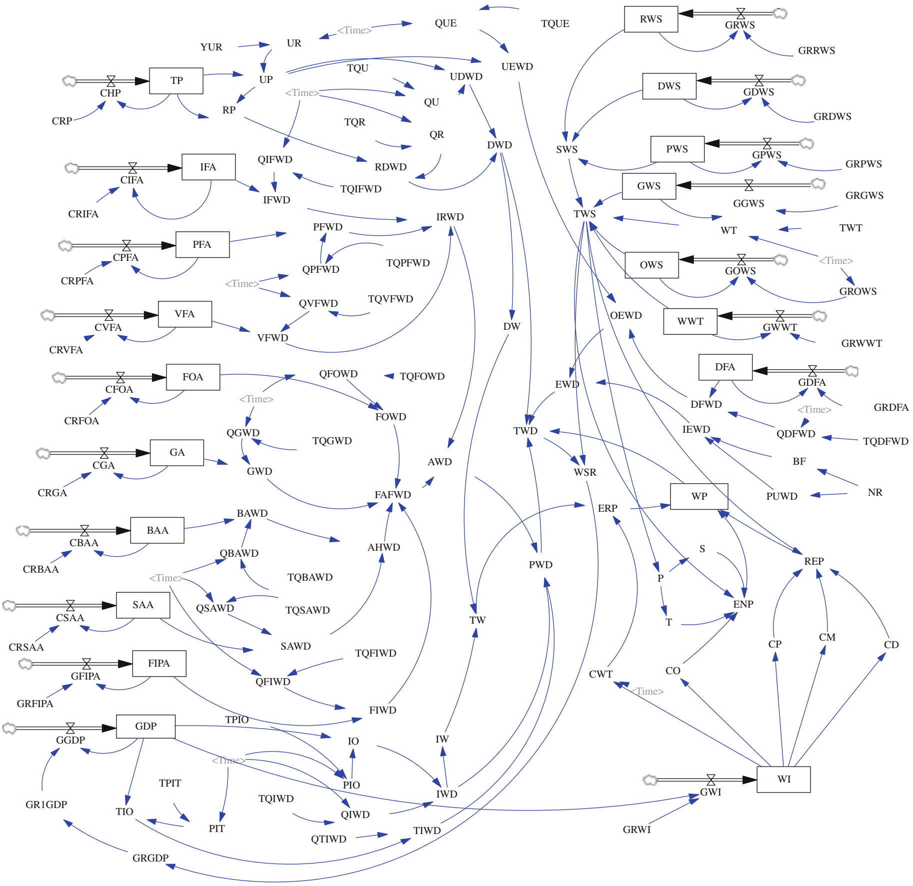

Fig. 5 Flow diagrams for water resources planning and management in Yulin city

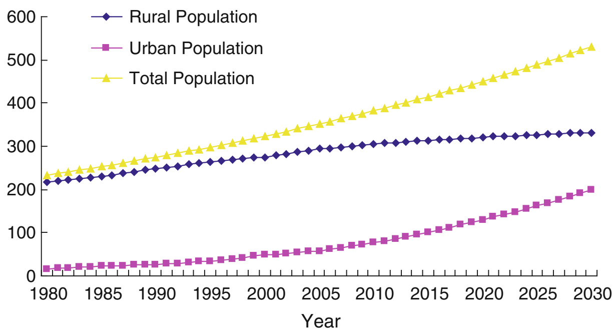

Fig. 6 Population growth of the base run

Table 1 Compared result of simulated values and actual value of the main variables

Variables	2000			2005		
	Actual value	Simulated value	Relative error	Actual value	Simulated value	Relative error
Total population (10^4 people)	317.80	323.99	1.95	351.63	351.79	0.05
Urbanization Population (10^4 people)	47.28	48.59	2.77	58.89	58.04	−1.44
Vegetable field area (10^3ha)	12.5	13.05	4.40	18.58	21.02	13.13
Agricultural water Demand (10^4m^3)	52854	49895	−5.60	49779	46922	−5.74

effort than using traditional computer languages and makes it easy for model expansion. And most of the core elements contained in this model are presented in "Appendices".

4.5 Model testing

The developed YulinSD model was verified with the data of 2000–2005, because there are 139 variables in the model and it is difficult to examine, so we chose total population (TP), urbanization population (UP), vegetable field area (VFA), and agricultural water demand (AWD) for examination. With this model, results of total population can be obtained, which are shown in Fig. 6. Table 1 shows the Predictions results for population, vegetable field area and agricultural water demand; most of the variables have low relative errors, which show that the model is reasonable for the actual situation.

5 Simulation results

Besides the base run, two additional decision alternatives were examined and compared with the base scenario. They were water supply pattern and the price-control pattern, and both of them were provided by the local authorities based on the previous planning study and other materials. And the simulative alternatives can be attained through adjusting variables and parameters.

With the development of economy, the government pays more attention to water supply, even taking into consideration of the South-to-North Water Diversion in Yulin. According to the previous planning study, there will be four water transfer projects in the future; there are Longkou, Qikou, Daliushu and Tianqiao, all of them have to transfer water from Yellow River. But the situation is that Yellow River has been running out in recent years for several times, besides, each of them has a high cost, the marginal cost of additional water is higher and higher. While the perception of water saving is not changed, with more and more supply, they will be more and more useless, and the demand is higher and higher. Moreover, environmental impact is also a serious problem. These economic and environmental reasons eventually make it difficult to achieve sustainable development. Through systematic analysis and simulation, we can get the results of future water demand and water supply pattern as shown in Fig. 7.

With increasing awareness of water-saving in price control program, water market gradually matures, and price as a fundamental economic tool to influence demand, the function is more and more apparent and will finally turn water-supply management to water-demand management to achieve balance between water supply and demand eventually. Figure 8 shows relationships between water demands under different price, and the higher the price is, the smaller is the water demand. With the public awareness growth and water crisis, prices will become an important way to water management, and future water price in Yulin is as shown in Fig. 9.

With the analysis and simulation of the YulinSD, it could be found that the supply-sided approach treats fresh water as a virtually limitless resource, rarely taking fully account of environmental and economic impacts, and continuing to expand infrastructure and develop new water sources has become increasingly expensive. And it is ultimately unsustainable both economically and environmentally (Butler and Memon 2006; Wheida and Verhoeven

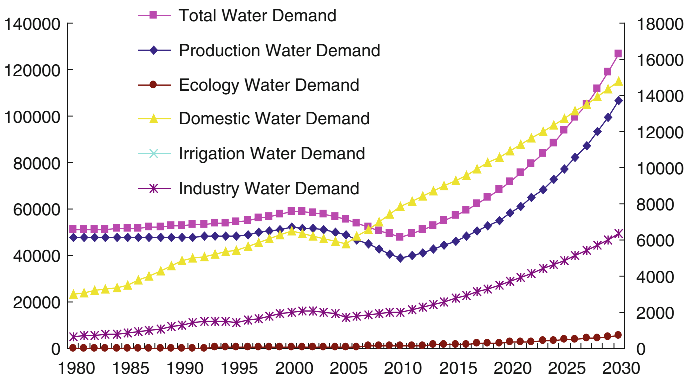

Fig. 7 Water demand of the supply pattern in the future

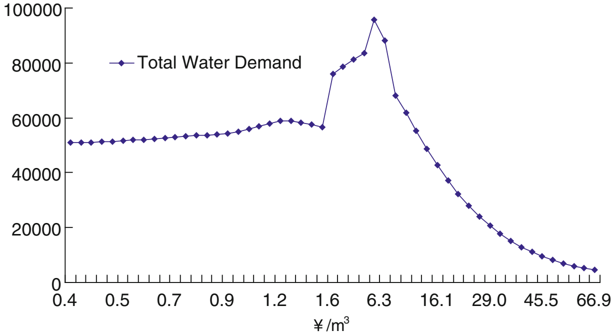

Fig. 8 Relationships between water demand and price of the price control pattern

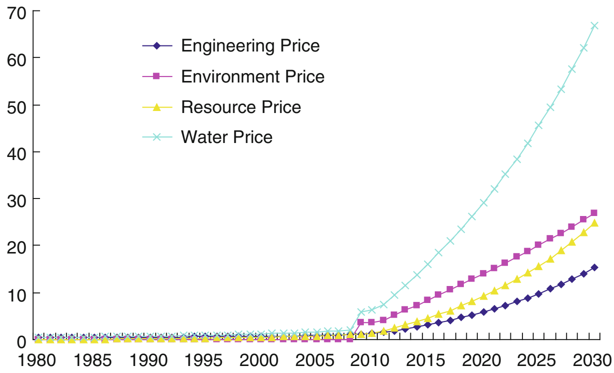

Fig. 9 Different kind of water price in the future of the price control pattern

2007). But in the price control pattern, it is useful to solve the water scarcity by efficient and effective utilization of water supply resources, the efficiency and environmental integrity both take into consideration with it, this is known as water-demand management, and considered to be the best potential solution to meet future needs. It has been widely implemented in many areas around world, such as South Africa, Middle East, Canada, et al., and demonstrated that predominant benefits of WDM include both lower costs and environmental protection (Stephenson 1999; Butler and Memon 2006; Gumbo 2004; Wheida and Verhoeven 2007).

With the development of chemical energy industry, economy of Yulin has been developing quickly in recent years. GDP has risen 22 times from 1980 to 2005, and per capita GDP has risen 15 times, but water resources has become a seriously problem than ever before. Data showed that per capita water consumption was 213 m^3/p in 1980, but 180 m^3/p in 2005, only four-fifth of 1980. In order to deal with water shortage, many infrastructures have been built in the past years; however, water demand is also increasing, additional with climate change. With more stress on water supply systems, the gap between supply and demand is still apparent, which accelerates the degradation of ecological environment. So it is necessary to carry out WDM in Yulin city to solve the problem.

(1) WDM in Yulin city expects a deep understanding of the basic rules of local water resources system. To achieve the objectives of WDM programme, it should be based on some instruments. All of these instruments applied or not depend on local conditions. So it is necessary to some basic laws of local water system, such as water resources and water environment carrying capacity, the state of water supply systems, water demand characteristics and its impact factors. WDM cases have to be founded on local needs and conditions.
(2) The basis of WDM is government regulations and policies; this means WDM should be implemented with political acceptability.
(3) The aim of WDM is to improve water-use efficiency and finally achieve human–water harmony. As to Yulin city, the main objectives are: in short term (2005–2010), by means of necessary economic measures (water rights, water market, price, et al.) to promote efficient use of water resources in order to achieve the maximization of economic benefits from minimize water resource; in long-term (2010–2020), WDM programme will focus on quality requirements, which becomes the main target. Through optimization between economic and ecology, it will realize a balance between the competing needs and desires of human social and economic systems and the integrity of aquatic ecosystems, and finally achieve the human–water harmony in Yulin city.

(4) The main tools used to achieve WDM objectives in Yilin city include legislation, institutional arrangements, flow metering, leakages reduction to improve efficiency of water use, wastewater recycle, water allocation between multiple sectors, water price, public education to improve awareness of water saving, etc. And the achieved through collaboration between water planners, water service providers and end-users.

6 Conclusion

In this paper, we present an SD modelling framework for understanding and analysing the complex dynamics of supply and demand in Yulin City. The model is used to assess the impacts of various supply and demand management measures. Simulation results show that the current management regime cannot maintain the socio-economic and ecological sustainability in the region. Although additional infrastructure can cover the water deficit in the short period, it cannot cope with the increasing irrigation and domestic requirements. In addition, the costs for operating and maintaining infrastructure are increasing to a level that may not be politically and socially acceptable. Instead, results indicate that a portfolio of demand management instruments and conservation measures is the most sustainable strategy for maintaining the economic and ecological status of the region.

Two considerations are noteworthy. First, the model should be regarded as a policy analysis tool that enables decision makers to learn about the system dynamics, explore and assess alternatives, rather than a predictive tool that generates accurate predictions of the resource future. Second, the reported scenarios still represent an optimistic view of the water future in Yulin as they not consider the plausible impacts of climate change on supply and demand. Adding climate change to the picture will require changes in the dynamic hypothesis, and consequently, the model results. We propose this as an interesting point for future research.

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Appendices

Appendix 1

See Table 2.

Table 2 Abbreviations of variables and parameters in the YulinSD model

Number	Abbreviation	Name	Unit
1	TP	Total population	10^4 people
2	CHP	Change of population	10^4 people/year
3	CRP	Change rate of population	%
4	UP	Urbanization population	10^4 people
5	UR	Urbanization rate	%
6	TUR	Table function of urbanization rate	%

Table 2 continued

Number	Abbreviation	Name	Unit
7	RP	Rural population	10^4 people
8	TQU	Table function of quota for urbanization	l/p.d
9	QU	Quota for urbanization	l/p.d
10	UDWD	Urbanization domestic water demand	10^4 m^3
11	TQUE	Table function of quota for urbanization ecology	l/p.d
12	QUE	Quota for urbanization ecology	l/p.d
13	UEWD	Urbanization ecology water demand	10^4 m^3
14	TQR	Table function of quota for rural	l/p.d
15	QR	Quota for rural	l/p.d
16	RDWD	Rural domestic water demand	10^4 m^3
17	DWD	Domestic water demand	10^4 m^3
18	NR	Natural runoff	mm
19	BF	Base flow	mm
20	PUWD	Purification water demand	mm
21	IEWD	Inside ecological water demand	10^4 m^3
22	GRDFA	Growth rate of defending forestry area	%
23	GDFA	Growth of defending forestry area	10^3 ha/year
24	DFADFWD	Defending forestry area	10^3 ha
25	TQDFWD	Table function of quota for defending forestry water Demand	10^4 m^3/ha
26	QDFWD	Quota for defending forestry water demand	10^4 m^3/ha
27	DFWD	Defending forestry water demand	10^4 m^3
28	OEWD	Outside ecological water demand	10^4 m^3
29	EWD	Ecological water demand	10^4 m^3
30	FOA	Forestry area	10^3 ha
31	CFOA	Change of forestry area	10^3 ha/year
32	CRFOA	Change rate of forestry area	%
33	TQFOWD	Table function of quota for forestry water demand	10^4 m^3/ha
34	QFOWD	Quota for forestry water demand	10^4 m^3/ha
35	FOWD	Forestry water demand	10^4 m^3
36	GA	Grass area	10^3 ha
37	CGA	Change of grass area	10^3 ha/year
38	CRGA	Change rate of grass area	%
39	TQGWD	Table function of quota for grass water demand	10^4 m^3/ha
40	QGWD	Quota for grass water demand	10^4 m^3/ha
41	GWD	Grass water demand	10^4 m^3
42	IFA	Irrigated farmland area	10^3 ha
43	CIFA	Change of irrigated farmland area	10^3 ha/year
44	CRIFA	Change rate of irrigated farmland area	%
45	TQIFWD	Table function of quota for irrigated farmland water Demand	10^4 m^3/ha
46	QIFWD	Quota for irrigated farmland water demand	10^4 m^3/ha
47	IFWD	Irrigated farmland water demand	10^4 m^3
48	VFA	Vegetable field area	10^3 ha
49	CVFA	Change of vegetable field area	10^3 ha/year

Table 2 continued

Number	Abbreviation	Name	Unit
50	CRVFA	Change rate of vegetable field area	%
51	TQVFWD	Table function of quota for vegetable field water Demand	10^4 m^3/ha
52	QVFWD	Quota for vegetable field water demand	10^4 m^3/ha
53	VFWD	Vegetable field water demand	10^4 m^3
54	PFA	Paddy field area	10^3 ha
55	CPFA	Change of paddy field area	10^3 ha/year
56	CRPFA	Change rate of paddy field area	%
57	TQPFWD	Table function of quota for paddy field water demand	10^4 m^3/ha
58	QPFWD	Quota for paddy field water demand	10^4 m^3/ha
59	PFWD	Paddy field water demand	10^4 m^3
60	IRWD	Irrigation water demand	10^4 m^3
61	SAA	Small animal amount	10^4 p
62	CRSAA	Change rate of small animal amount	%
63	CSAA	Change of small animal amount	10^4 p/year
64	TQSAWD	Table function of quota for small animal water demand	l/p.d
65	QSAWD	Quota for small animal water demand	l/p.d
66	SAWD	Small animal water demand	10^4 m^3
67	BAA	Big animal amount	10^4 p
68	CRBAA	Change rate of big animal amount	%
69	CBAA	Change of big animal amount	10^4 p/year
70	TQBAWD	Table function of quota for big animal water demand	l/p.d
71	QBAWD	Quota for big animal water demand	l/p.d
72	BAWD	Big animal water demand	10^4 m^3
73	AHWD	Animal husbandry water demand	10^4 m^3
74	FIPA	Fishery pound area	10^3 ha
75	CFIPA	Change of fishery pound area	10^3 ha/year
76	CRFIPA	Change rate of fishery pound area	%
77	TQFIWD	Table function of quota for fishery water demand	10^4 m^3/ha
78	QFIWD	Quota for fishery water demand	10^4 m^3/ha
79	FIWD	Fishery water demand	10^4 m^3
80	FAFWD	Forestry, animal husbandry and fishery water demand	10^4 m^3
81	AWD	Agricultural water demand	10^4 m^3
82	TWD	Total water demand	10^4 m^3
83	WSR	Water shortage rate	%
84	GRRWS	Growth rate of reservoir water supply	%
85	GRWS	Growth of reservoir water supply	10^4 m^3/year
86	RWS	Reservoir water supply	10^4 m^3
87	GRDWS	Growth rate of division water supply	%
88	GDWS	Growth of division water supply	10^4 m^3/year
89	DWS	Division water supply	10^4 m^3
90	GRPWS	Growth rate of pump water supply	%
91	GPWS	Growth of pump water supply	10^4 m^3/year

Table 2 continued

Number	Abbreviation	Name	Unit
92	PWS	Pump water supply	10^4 m^3
93	GROWS	Growth rate of other water supply	%
94	GOWS	Growth of other water supply	10^4 m^3/year
95	OWS	Other water supply	10^4 m^3
96	SWS	Surface water supply	10^4 m^3
97	GRGOWS	Growth rate of groundwater water supply	%
98	GGWS	Growth of groundwater water supply	10^4 m^3/year
99	GWS	Groundwater water supply	10^4 m^3
100	TWT	Table function of water transfer	10^4 m^3
101	WT	Water transfer	10^4 m^3
102	WWT	Wastewater treatment	10^4 m^3
103	GWWT	Growth of wastewater treatment	%
104	GRWWT	Growth rate of wastewater treatment	10^4 m^3/year
105	TWS	Total water supply	10^4 m^3
106	GR1GDP	Growth rate 1 of gross domestic product	%
107	GRGDP	Growth rate of gross domestic product	%
108	GGDP	Growth of gross domestic product	10^4 ¥/year
109	GDP	Gross domestic product	10^4 ¥
110	IO	Industrial output	10^4 ¥
111	PIO	Percentage of industrial output	%
112	TPIO	Table function of percentage of industrial output	%
113	TQIWD	Table function of quota for industrial water demand	$m^3/10^4$ ¥
114	QIWD	Quota for industrial water demand	$m^3/10^4$ ¥
115	IWD	Industrial water demand	10^4 m^3
116	IW	Industrial wastewater	10^4 m^3
117	DW	Domestic wastewater	10^4 m^3
118	TW	Total wastewater	10^4 m^3
119	TIO	Tertiary industrial output	10^4 ¥
120	PIT	Percentage between industrial and tertiary industrial	%
121	TPIT	Table function of percentage between industrial and Tertiary Industrial	%
122	QTIWD	Quota for tertiary industrial water demand	$m^3/10^4$ ¥
123	TIWD	Tertiary industrial water demand	10^4 m^3
124	PWD	Production water demand	10^4 m^3
125	GRWI	Growth rate of water investment	%
126	GWI	Growth of water investment	10^4 ¥/year
127	WI	Water investment	10^4 ¥
128	CD	Cost for design	10^4 ¥
129	CM	Cost for management	10^4 ¥
130	CP	Cost for planning	10^4 ¥
131	CO	Cost for operation	10^4 ¥

Table 2 continued

Number	Abbreviation	Name	Unit
132	CWT	Cost for wastewater treatment	10^4 ¥
133	REP	Resource price	¥
134	ENP	Engineering price	¥
135	ERP	Environment price	¥
136	WP	Water price	¥
137	P	Profit	10^4 ¥
138	T	Taxes	10^4 ¥
139	S	Subsidies	10^4 ¥

Appendix 2: Main equations of the YulinSD model

(1) GRGDP = (0.09 + RAMP(−0.05, 10, 20) · (1 − WSR · 5))
(2) GR1GDP = MAX(GRGDP, 0.08)
(3) GGDP = GDP · GR1GDP
(4) GDP = INTEG(GGDP, 72879)
(5) TIO = GDP · PIT
(6) TPIT([(1980, 0) − (2050, 1)] , (1980, 0.17), (1985, 0.2), (1990, 0.3), (1995, 0.35), (2000, 0.31), (2005, 0.28), (2010, 0.35), (2020, 0.38), (2030, 0.4))
(7) PIT = TPIT(Time)
(8) TPIO([(1980, 0) − (2050, 1)], (1980, 0.195), (1985, 0.193), (1990, 0.21), (1995, 0.36), (2000, 0.5), (2005, 0.67), (2010, 0.6), (2020, 0.55), (2030, 0.5))
(9) PIO = TPIO(Time)
(10) IO = GDP · PIO
(11) TQIWD([(1980, 0) − (2050, 500)] , (1980, 468), (1985, 411), (1990, 389), (1995, 170), (2000, 118), (2005, 52), (2010, 46), (2020, 43), (2030, 37))
(12) QIWD = TQIWD(Time)
(13) QTIWD = 13
(14) CRP = 0.0166
(15) CHP = TP · CRP
(16) TP = INTEG(CHP, 233.1)
(17) TUR([(1980, 0) − (2050, 1)] , (1980, 0.07), (1985, 0.092), (1990, 0.096), (1995, 0.115), (2000 , 0.15), (2005, 0.165), (2010, 0.201), (2020, 0.288), (2030, 0.375))
(18) UR = TUR(Time)
(19) UP = UR · TP
(20) RP = TP − UP
(21) TQU([(1980, 60) − (2050, 150)], (1980, 67.6), (1985, 74.8), (1990, 83.3), (1995, 88.7), (2000, 98.6), (2005, 101), (2010, 97), (2020, 105), (2030, 110))
(22) QU = TQU(Time)
(23) TQUE([(1980, 0) − (2050, 30)] , (1980, 5), (1985, 6), (1990, 7), (1995, 6), (2000, 7), (2005, 8), (2010, 10), (2020, 13), (2030, 15))
(24) QUE = TQUE(Time)
(25) TQR([(1980, 30) − (2050, 60)], (1980, 33), (1985, 34), (1990, 45), (1995, 45), (2000, 47), (2005, 34), (2010, 46), (2020, 51), (2030, 56))

(26) QR = TQR(Time)
(27) GRWI = 0.015
(28) GWI = GDP · GRWI
(29) WI = INTEG(GWI, 2550)
(30) CO = WI · 0.3
(31) CP = WI · 0.15
(32) CD = WI · 0.15
(33) CM = WI · 0.2
(34) CWT = IF THEN ELSE(Time > 2008, WI · 0.2, 0)
(35) ERP = CWT/TW
(36) P = TWS · 0.8
(37) S = P · 0.45
(38) T = P · 0.05
(39) ENP = (S + CO + T)/TWS
(40) REP = (CD + CM + CP)/TWS
(41) WP = ENP + ERP + REP
(42) CRPFA = 0.0131
(43) CPFA = PFA · CRPFA
(44) PFA = INTEG(CPFA, 98.39)
(45) TQPFWD([(1980, 0) − (2050, 400)], (1980, 390), (1985, 362), (1990, 322), (1995, 294), (2000, 273), (2005, 255), (2010, 140), (2020, 129), (2030, 122))
(46) QVPWD = TQVPWD(Time)
(47) PFWD = QPFWD · PFA
(48) CRIFA = −0.04
(49) CIFA = IFA · CRIFA
(50) IFA = INTEG(CIFA, 4.14)
(51) TQIFWD([(1980, 0) − (2050, 2000)], (1980, 1066), (1985, 1024), (1990, 972), (1995, 911), (2000, 809), (2005, 1187), (2010, 1057), (2020, 0), (2030, 0))
(52) QIFWD = TQIFWD(Time)
(53) IFWD = QIFWD · IFA
(54) PUWD = NR · 0.05
(55) IEWD = BF + PUWD
(56) UEWD = UP · QUE
(57) GRRWS = 0.015
(58) GRWS = RWS · GRRWS
(59) RWS = INTEG(GRWS, 155)
(60) GRDWS = −0.0008
(61) GDWS = DWS · GRDWS
(62) DWS = INTEG(GDWS, 26194)
(63) GRPWS = 0.0035
(64) GPWS = GRPWS · PWS
(65) PWS = INTEG (GPWS, 7601)
(66) SWS = DWS + PWS + RWS
(67) GROWS = IF THEN ELSE (Time > 2005, 0.03, 0.01)
(68) GOWS = GROWS · OWS
(69) OWS = INTEG (GOWS, 20)

(70) TWT([(1980, 0) − (2100, 100000)] , (1980, 0), (2019, 0), (2020, 4500), (2030, 92000))
(71) WT = TWT (Time)
(72) GRGWS = 0.0025
(73) GGWS = GWS · GRGWS
(74) GWS = INTEG(GGWS, 8882)
(75) TWS = OWS + GWS + SWS + WT
(76) GRDFA = 0.1
(77) GDFA = DFA · GRDFA
(78) DFA = INTEG(GDFA, 20)
(79) DFWD = DFA · QDFWD/10000
(80) OEWD = UEWD + DFWD
(81) EWD = IEWD + OEWD
(82) GRFIPA = 0.00041
(83) GFIPA = FIPA · GRFIPA
(84) FIPA = INTEG (GFIPA, 0.55)
(85) TQFIWD([(1980, 0) − (2050, 1500)] , (1980, 906), (1985, 1099), (1990, 1192), (1995, 890), (2000, 888), (2005, 1285), (2010, 1278), (2020, 1218), (2030, 1165))
(86) QFIWD = TQFIWD (Time)
(87) FIWD = QFIWD · FIPA
(88) CRVFA = 0.1
(89) CVFA = VFA · CRVFA
(90) VFA = INTEG(CVFA, 1.94)
(91) TQVFWD([(1980, 0) − (2050, 1000)], (1980, 989), (1985, 900), (1990, 874), (1995, 843), (2000, 808), (2005, 327), (2010, 318), (2020, 308), (2030, 300))
(92) QVFWD = TQVFWD(Time)
(93) VFWD = QVFWD · VFA
(94) IRWD = IFWD + PFWD +WWD
(95) CRGA = 0.024
(96) CGA = GA · CRGA
(97) GA = INTEG(CGA, 0.65)
(98) TQGWD([(1980, 0) − (2050, 400)], (1980, 382), (1985, 370), (1990, 352), (1995, 223), (2000, 217), (2005, 238), (2010, 205), (2020, 195), (2030, 187))
(99) QGWD = TQGWD(Time)
(100) GWD = QGWD · GA
(101) CRFOA = 0.06
(102) CFOA = FOA · CRFOA
(103) FOA = INTEG(CFOA, 1.32)
(104) TQFOWD([(1980, 0) − (2050, 400)] , (1980, 384), (1985, 379), (1990, 389), (1995, 240), (2000, 199), (2005, 193), (2010, 178), (2020, 168), (2030, 159))
(105) QFOWD = TQFOWD(Time)
(106) FOWD = QFOWD · FOA
(107) CRSAA = 0.00064
(108) CSAA = SAA·CRSAA
(109) SAA = INTEG(CSAA, 272.69)

(110) TQSAWD([(1980, 5) − (2050, 40)], (1980, 9), (1985, 10), (1990, 11), (1995, 11), (2000, 11), (2005, 12), (2010, 12), (2020, 14), (2030, 16))
(111) QSAWD = TQSAWD(Time)
(112) SAWD = SAA·QSAWD · 365/1000
(113) CRBAA = 0.00039
(114) CBAA = BAA · CRBAA
(115) BAA = INTEG(CBAA, 34.23)
(116) TQBAWD([(1980, 10) − (2050, 50)] , (1980, 19), (1985, 24), (1990, 26), (1995, 26), (2000, 28), (2005, 19), (2010, 30), (2020, 33), (2030, 36))
(117) QBAWD = TQBAWD(Time)
(118) BAWD = BAA · QBAWD · 365/1000
(119) AHWD = BAWD + SAWD
(120) FAFWD = FOWD + FIWD + AHWD + GWD
(121) AWD = IRWD + FAFWD
(122) IWD = IO · QIWD/10000
(123) IW = IWD · 0.3
(124) PWD = AWD + IWD + TIWD
(125) UDWD = UP · QU · 365/1000
(126) RDWD = RP · QR · 365/1000
(127) DWD = RDWD + UDWD
(128) TW = IW + DW
(129) DW = DWD · 0.8
(130) TWD = (3/WP)^(((63317 − (PWD + EWD + TDWD))/(1 − WP))·(WP/(PWD + EWD + TDWD)))·63317
(131) WSR = IF THEN ELSE(TWS − TWD < 0, (TWD − TWS)/TWD, 0)

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