Water resource allocation for the Songhua River Region, China, under the uncertainty of water supply

SUXIA LIU & YAOWEI ZHANG

Key Laboratory of Water Cycle & Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

liusx@igsnrr.ac.cn

Abstract Water resources allocation (WRA) is a useful and yet complicated topic in water resources management. The solution of WRA may be uncertain due to the uncertainty of the input, the structure itself, and the parameters of the models. So far, very few studies deal with the topic about how much these uncertainties influence the solution and how to adapt the situation. By using Dependent-Chance Goal Programming (DCGP), this paper built a WRA under the uncertainty of water supply for the Songhua River Region (SHRR) located in the northeast of China, one of China's most important commercial grain bases. Two sets of WRA results were obtained under the two ranges of uncertainty relative to bad (S1) and good (S2) water supply situations. Situation S1 takes a higher water shortage rate and S2 takes a lower water shortage rate than the routine WRA results by the SHRR Commission's comprehensive plan, but all keeping the rate of water resources exploitation approaching or lower than the international standards. The result helps SHRR to make a more resilient decision to the change of water supply condition in meeting the national needs of Newly Increasing Yield of 10×10^{11} Jin.

Key words water resources allocation; uncertainty; dependent-chance global programming

INTRODUCTION

Water resources allocation (WRA) plays an important role in integrated water resources management. There are always two ways to do WRA, optimization and simulation. Simulation is like the comparison between the schemes, which is simpler mathematically than the optimization method. However, the final result of the simulation greatly depends on the schemes chosen for comparison. The optimization method can achieve an exact result in mathematics, but needs huge computation efforts to get an exact solution when the water resource system is complicated. With the development of computer technology, many matured optimization methods, such as Multi-Objective Analysis, Goal Programming model, Interval-parameter Fuzzy Two-stage Stochastic programming, Rule-based model and Robust Interval-based Minimax-regret Analysis, have found successful applications in WRA (Du *et al.*, 2005; Imran *et al.*, 2005; Gao *et al.*, 2008; Li *et al.*, 2009; Zhu *et al.*, 2009).

A very recent achievement in this field is the application of Dependent-Chance Goal Programming (DCGP), a class of stochastic programming model based on fuzzy programming, proposed by Liu in 1997. It considers the uncertainty of the input of the optimization system and is related to maximizing some chance functions of events defined by stochastic sets in a complex uncertain decision system (Liu, 1997). The water resource system in the real world is a random system, which makes the uncertainty in WRA. Also, the priority levels of water user are different, which makes WRA even more complicated. DCGP is a good tool to describe the uncertainty and intricacy of WRA. Since the establishment of DCGP, several applications have been found in WRA in China (e.g. Lv *et al.*, 2010). However, the study was only focused on the city scale. So far there have been no research cases using DCGP in a large catchment region.

The great SongHua River Region (SHRR) is one of the most important main and commercial grain bases in China. With the plan of Newly Increasing Yield (NIY) of 10×10^{11} Jin (1 kg = 2 Jin) grain from 2009 to 2020 initiated in 2009, SHRR was chosen as one of five regions to realize this national plan. One of the immediate questions asked for this is: if the water is enough to support the required yield increase by the Chinese government and if not, how to carry out WRA. Songhua River Water Conservancy Committee made a WRA plan – version 2009, called here SHPv2009, in February 2009 by adopting the routine WRA method (Wang *et al.*, 2003), in which a single and determinant value of water supply is used to carry out WRA for each case.

This paper applies DCGP in SHRR to carry out WRA, with special consideration of the uncertainty in water supply. A hybrid intelligent algorithm is used to find the solution. The aim is to see how the water will be allocated if we consider the uncertainty of water supply.

STUDY AREA

The study area SHRR is located in the northeast of China, covering an area of 934 800 km^2, with 178 000 km^2 of cultivated fields. The total population is 62.93 million. The averaged annual precipitation is from 300 to 1000 mm, decreasing from east to west. Annual evapotranspiration (E601 pan) is from 500 to 1200 mm, decreasing from southwest to northeast (from SHPv2009 report). In order to do WRA for this big area effectively, it is divided into eight sub-regions according to the eight major rivers in the region, namely, Heilong River sub-region (HL), Argun River sub-region (AG), Nenjiang sub-region (NJ), Songhua River sub-region (SH), Di'ersonghua River sub-region (ES), Wusuli River sub-region (WS), Suifeng River sub-region (SF) and Tumen River sub-region (TM) (Fig. 1).

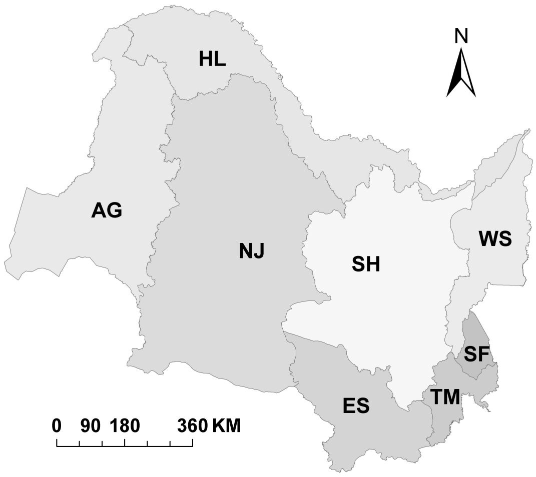


Fig. 1 SongHua River region and its eight sub-regions.

METHOD

The DCGP

The DCGP is a class of stochastic programming which is used to solve those management decisions that are made in an uncertain environment (Liu, 1997). Not as deterministic models as well as expected value models, the feasible set is essentially assumed to be deterministic after the real problem is modelled and an optimal solution is always given, regardless of whether or not it can be performed in practice. The DCGP model never assumes that the feasible set is deterministic. Although a deterministic solution is given by the DCGP, this solution is only requested to be performed as much as possible. In this way, DCGP can be considered as an extension of goal programming in a complex stochastic decision system.

The hybrid intelligent algorithm was designed to solve the DCGP. The algorithm is produced by integrated simulations, Neural Network (NN) and Genetic Algorithm (GA). The procedure is as follows (Liu *et al.*, 2003):

Step 1. Generate training input–output data for uncertain functions by simulations.

Step 2. Train a neural network to approximate the uncertain functions according to the generated training data.

Step 3. Initialize population size chromosomes for genetic algorithm.
Step 4. Update the chromosomes by crossover and mutation operations.
Step 5. Calculate the objective values for all chromosomes by the trained neural network.
Step 6. Compute the fitness of each chromosome according to the objective values.
Step 7. Select the chromosomes by spinning the roulette wheel.
Step 8. Repeat the fourth to seventh steps for a given number of cycles.
Step 9. Report the best chromosome as the optimal solution.

Quantifying the uncertainty of water supply and the priority of water demand

The water resources system of the study area is complex. In each sub region there are three major water supply sources (surface water, groundwater and other water resources, including treated wastewater, rain water collection, etc.). Different water supply sources have their own features and users. They are also different in cost and benefit of exploitation, causing different influences on society and the environment. The randomness and the incomplete knowledge of the water system cause the uncertainty in the WRA. The surface water resources are relatively more susceptible to the change of climate than groundwater. Furthermore, there are many surface water supply projects in planning. So the quantity of the surface water resources that can be used may change in a large range in the future. The change of groundwater resources is not so obviously reacting to the climate changes, but groundwater is hard to renew after exploitation, so the quantity of the groundwater that can be used must be used with caution. The quantity of other water supply resources in the study area is small. So its effect on water use is tiny. Considering that the system is uncertain, we regard them all as stochastic variables and of uniform distribution in a given range.

The major water users in each sub area are domestic (D), agricultural (A), industrial (I) and environment (E) water users. Agricultural water use demands most of the water in the region, which changes with season. Domestic water use and industrial water use are relatively stable for a whole year. According to the SHPv2009, in the study area, domestic water demand must be satisfied first. As mentioned in the Introduction, the study area has a prior task of NIY in the near future, so agricultural water use should be of secondary importance. In this way, the priority of each water user is given as follows: domestic water use, agricultural water use, industrial water use and environment water use, with priority levels of 0.95, 0.9, 0.85 and 0.85, respectively.

Making of the DCGP

Excessive groundwater exploitation will cause many eco-environmental problems. Groundwater is hard to renew, so to use groundwater to serve the city-green (environmental water) is restricted. It is also assumed that the other water resources just serve industrial and environmental users. These assumptions are subjective. However, they make the solving processes of DCGP simple. As the quantity of this source is relatively small, this assumption would not significantly affect the result.

Based on these assumptions, the decision variables of DCGP are set as follows. Quantities x_{i1}, x_{i3}, x_{i5}, x_{i8} are water resources that domestic water users, agricultural water user, industrial water user and environmental water user, respectively, in the *i*th sub-region taken from the surface water resources. Quantity of x_{i2}, x_{i4} and x_{i6} are the water resources that domestic water user, agricultural water user and industrial water user, respectively, in the *i*th sub region take from the groundwater resources. Quantity of x_{i7} and x_{i9} are water resources that industrial water user and environmental water user in the *i*th sub region take from other water resources. C_{i1}, C_{i2}, C_{i3} and C_{i4} are the demands from domestic water user, agricultural water user, industrial water user and environmental water user in the *i*th sub region, respectively. B_{i1}, B_{i2} and B_{i3} are surface water resource, groundwater resources and the other water resources in the *i*th sub region that can be supplied. They are all stochastic variables.

The structure of the multi-objective optimization DCGP model for the SHRR WRA based on the typical formulation of DCGP (Liu & Kakuzo, 1997) is as follows:

$$\begin{cases} \min\{d^-_1, d_2^-, d_3^-, d^-_4\} \\ s.t. \\ P_r\{x_{i1}+x_{i2}=C_{i1}\}-d^-_1+d^+_1=0.95 \\ P_r\{x_{i3}+x_{i4}=C_{i2}\}-d^-_2+d^+_2=0.90 \\ P_r\{x_{i5}+x_{i6}+x_{i7}=C_{i3}\}-d^-_3+d^+_3=0.85 \\ P_r\{x_{i8}+x_{i9}=C_{i4}\}-d^-_4+d^+_4=0.85 \\ x_{i1}+x_{i3}+x_{i5}+x_{i8}\le B_{i1} \\ x_{i2}+x_{i4}+x_{i6}\le B_{i2} \\ x_{i7}+x_{i9}\le B_{i3} \\ x_{ij}\ge 0 \qquad j=1,2,\ldots 9 \\ d^-_k, d^+_k \ge 0 \qquad k=1,2,3,4 \end{cases} \tag{1}$$

where d_k^+ and d_k^- are positive and negative deviation from the *k*th target; P_r denotes the probability of the event in {}. Chromosome codes:

$$x_{i1}=v_{i1}, x_{i3}=v_{i2}, x_{i5}=v_{i3}, x_{i6}=v_{i4,} x_{i8}=v_{i5}$$
$$x_{i2}=C_{i1}-v_{i1}, x_{i7}=C_{i3}-v_{i3}-v_{i4}$$
$$x_{i9}=C_{i4}-v_{i5}, x_{i4}=C_{i2}-v_{i2}$$

produce a set of input–output data for the uncertainty function:

$$U:(v_{i1}, v_{i2}, v_{i3}, v_{i4}, v_{i5}) \rightarrow (f_1(x), f_2(x), f_3(x), f_4(x))$$

by a simulation. According to the generated data, a feed-forward NN is trained to approximate the uncertainty function, *U*. Then the trained NN and GA are integrated to produce a hybrid intelligent algorithm. Running the hybrid intelligent algorithm (5000 cycles in simulation, 1000 data in NN, 100 generations in GA) produces the optimal solution.

Implementation of the model

The input of water demand in DCGP is the water demand in the planning years of 2020 and 2030 with reference to SHPv2009. With investigation in the local departments and communication with stakeholders and managers in the study area, a slightly lower value of water demand is adopted accordingly for S1 and S2.

The input of water supply in DCGP is the water supply at two situations chosen for analysis. S1 is a bad situation, where the adopted range of water supply is from the quantity of water supply in the current status to the predicted water supply quantity in the planning years based on the current water supply projects. S2 is a good situation, where the adopted range of water supply is from the predicted water supply quantity in the planning years based on the current water supply projects to the predicted water supply quantity in the planning years, considering more exploitation projects.

The output of DCGP is shown in Table 1, taking NJ sub-region as an example.

RESULTS

The results of the DCGP model

Table 1 shows the result of DCGP for sub-region NJ for years 2020 and 2030. It is shown that with consideration for the uncertainty of water supply in the WRA, we still get a unique solution (S1O and S2O) relative to bad and good water supply situation, as the typical WRA did. However, this unique solution corresponds to a range of possible water supply conditions. This means that for 2020 and situation S1, as long as the water supply projects can provide surface water, groundwater and other water totally from 89.37 to 155.92 × 10^8 m^3, our suggestion to allocate domestic, agricultural, industrial and environmental water will be 6.32, 113.21, 24.22 and 4.04 × 10^8 m^3 for situation S2, if the total water supply is from 153.19 to 174.77 × 10^8 m^3, our suggestion will be 6.59, 133.31, 29.76

and 4.66 × 10^8 m^3, respectively. They are all allocated to satisfy the relative water demand of 6.59, 133.6, 30.05 and 9.02 × 10^8 m^3, respectively. The allocated water demand is larger in 2030 than that in 2020. With the increase of water supply capability, the allocated water will also be increased. This is true for all the other sub-regions (Fig. 2). These results give decision makers a more resilient suggestion to adapt the change of water resources system.

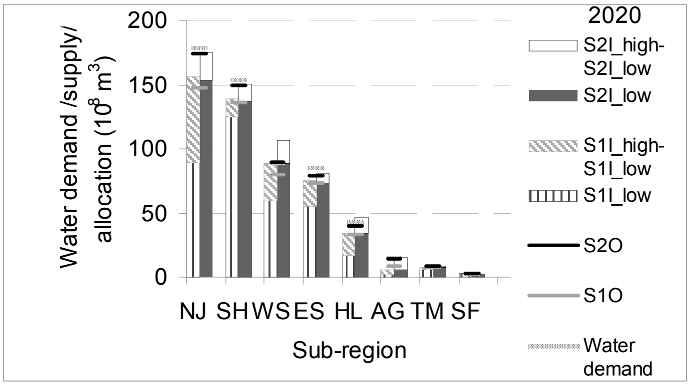
The water shortage rate for S1, S2 and SHPv2009

Any decisions will involve risks. Figure 3 shows the total water shortage rate ((water demand – water supply)/water demand) for S1, S2 and P. It is seen that bad water supply situation (S1) faces a high risk of water shortage. Good water supply situation (S2) faces lower risk of water shortage. S1 takes a higher water shortage than SHPv2009 for all the sub regions. S2 takes a lower rate than SHPv2009 for most of the eight sub regions. To adapt to the water shortage, countermeasures of water-saving, water transfer between sub-regions or from outside of the region, and the adjustment of priority levels are the possible options.

Table 1 The input and the result of DCGP for NJ for year 2020 and 2030（units: 10^8 m^3）.

Year	Item	Water demand (use) or allocated water D ($x_{Xi1}+x_{i2}$)	A ($x_{Xi3}+x_{i4}$)	I ($x_{Xi5}+x_{i6}+x_{i7}$)	E ($x_{Xi8}+x_{i9}$)	Total	Water supply Surface ($x_{Xi1}+x_{i3}+x_{i5}+x_{i8}$)	Ground ($x_{Xi2}+x_{i4}+x_{i6}$)	Other ($xX_{i7}+x_{i9}$)	Total
2020	PI	7.59	144.6	32.05	10.22	194.46	126.87	45.17	2.73	174.77
	S1I	6.59	133.6	30.05	9.22	179.46	[53.38, 109.14]	[35.99, 44.05]	[0, 2.73]	[89.37, 155.92]
	S2I						[109.14, 126.87]	[44.05, 45.17]	[0, 2.73]	[153.19, 174.77]
	PO	7.59	131.8	32.05	10.22	181.66	——	——	——	——
	S1O	6.32	113.21	24.22	4.04	147.79	104.37	42.39	1.03	147.79
	S2O	6.59	133.31	29.76	4.66	174.32	126.88	44.89	2.55	174.32
2030	PI	8.35	154.58	33.78	10.41	207.13	138.12	47.14	2.91	188.17
	S1I	8.35	144.25	30.78	10.2	193.58	[53.38, 116.7]	[35.99, 44.05]	[2.73, 2.91]	[89.37, 163.48]
	S2I						[116.7, 138.12]	[44.05, 47.14]	[2.73, 2.91]	[163.48, 188.17]
	PO	8.35	141.04	33.79	10.41	193.59	——	——	——	——
	S1O	8.13	120.26	21.58	5.68	155.65	112.51	41.87	1.25	155.63
	S2O	8.35	142.13	28.74	8.94	188.16	139.27	47.11	1.79	188.17

Note: D, A, I and E are domestic, agricural, industrial and environmental water users, respectively; PI, S1I and S2I are the input of SHPv2009, S1 and S2, respectively; same as PO, S1O and S2O but for the output. Blanks in PO means there were no suggestions published on how much of water should be taken from surface water and groundwater in SHPv2009.



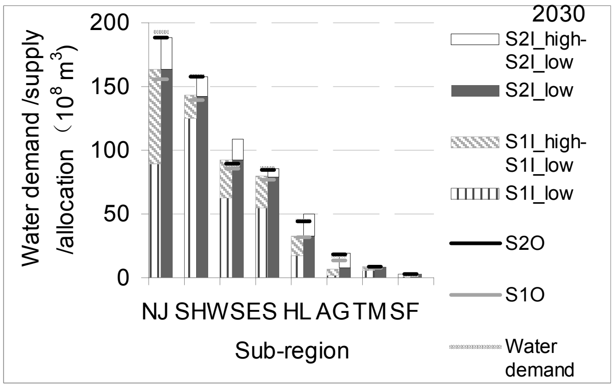


Fig. 2 The DCGP result for all the sub-regions.

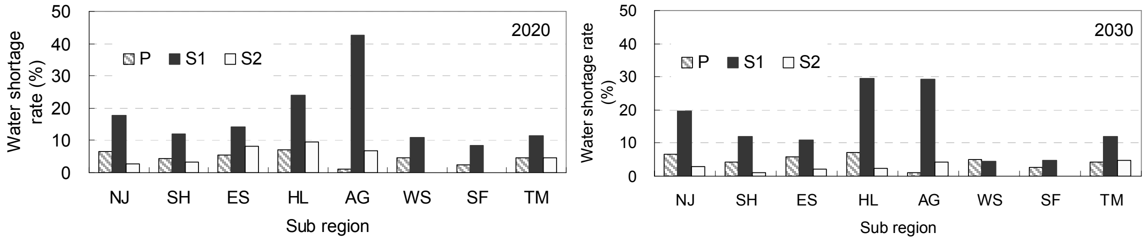


Fig. 3 Water shortage rate for each of eight sub-regions at S1, S2 and SHPv2009 for 2020 and 2030.

We also compare the shortage rate for domestic, agricultural, industrial and environmental water. It is seen that the water shortage rate is the highest for industrial and environmental water. This is mainly because we attributed a lower water use priority rate. It shows the merit of the WRA by DCGP model in that it is not necessary to satisfy every sub-goal 100% like the linear programming. Instead, it allows a certain degree of dissatisfaction. When the total water supply cannot satisfy the total water demand, the demand for each category of water uses are satisfied in turn according to the given priority.

The rate of exploitation

According to the international standards, the rate of exploitation (RE) of water resource should not be over 40% (Qian *et al.*, 2006). Based on historical data from SongLiao Water Resources Bulletin (2000–2007), it shows that RE (Fig. 4) rises slowly from 2007 to 2030 for surface water, with the velocity of ascendance decreasing progressively. RE for groundwater has a rising trend with fluctuation from 2000 to 2007, and then a descending trend from 2007 to 2030, tending towards being stable in 2030. In this way, we can say the water resource exploitation in the SHRR according to DCGP's result will basically remain sustainable.

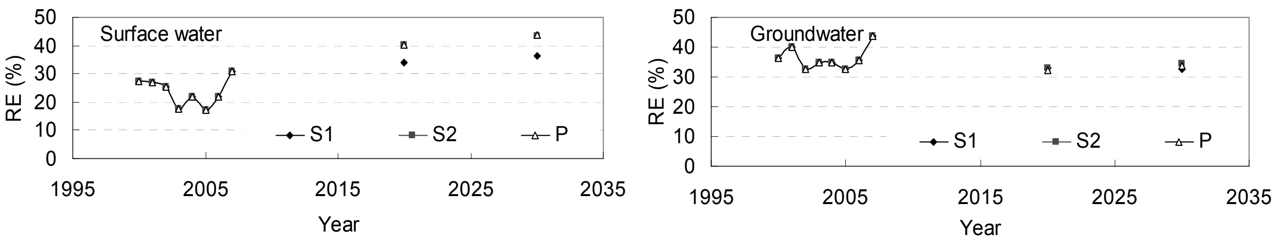


Fig. 4 Trend of RE for surface water (left) and groundwater (right) resources for S1, S2 and SHPv2009.

CONCLUSIONS

We built an optimal DCGP model to do WRA under the uncertainty of water supply for SHRR. Consideration of the uncertainty makes the result more resilient to the change of water supply, which makes the decisions based on it more reasonable and practical. Furthermore the results guarantee the rate of water resources exploitation is approaching or lower than the international standards, which is the basic requirement for SHRR to meet the national needs of NIY. This is the initial study result for WRA in SHRR. Other aspects, such as water quality, water transfer, benefit and cost of water use and more uncertainty factors in water resources systems will be studied further.

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REFERENCES

Du, C., Wei, Y., Liu, J. & Wang, W. (2005) A goal programming model for BaoJi available water resource. *J. Shanxi Inst. Edn*. **20**(2), 51–55 (in Chinese).

Gao, C., Cao, Y. & Liu, X. (2008) Water resources optimal allocation model based on sustainable development. *Yellow River* **30**(2), 35–36 (in Chinese).

Imran, M., Huang, H. & Julian, S. (2005) An interval-parameter fuzzy two-stage stochastic program for water resources management under uncertainty. *Europ. J. Operational Res*. **167**, 208–225.

Li, Y., Huang, G. & Nie, S. (2009) A robust interval-based minimax-regret analysis approach for the identification of optimal water-resources-allocation strategies under uncertainty. *Res. Conservation & Recycling*. **54**, 86–96.

Liu, B. (1997) Dependent-chance programming: a class of stochastic optimization. *Computers Math Application* **34**(12), 89–104.

Liu, B. & Kakuzo, I. (1997) Modeling stochastic decision systems using depent-chance programming. *European J. Operational Res*. **101**, 193–203.

Liu, B., Ruiqing, Z. & Wang, G. (2003) *Uncertain Programming with Applications*. Tsinghua University Press, Beijing, China. (in Chinese).

Lv, J. (2010) Optimal allocation and evaluation model of water resources based on uncertainty theory for BaoJi city. MSc Thesis, Xi'an University of Technology, Xi'an, China (in Chinese).

Qian, Z. Chen, J. & Feng, J. (2006) Harmonious development of human beings and rivers. *China Three Gorges Construction* **5**, 5–8 (in Chinese).

Wang, H., Qin, D., Wang, J. & Zhou, Z. (2003) State identification and multiple regulation of regional water resources shortage. *Resour. Sci*. **25**(6), 1–7 (in Chinese).

Zhu, Q., Gan, H., You, J., Gan, Z., Wang, L. & Fu, Y. (2009) Research on application of rules-based water resources allocation model. *Water Resour. Hydropower Engng* **40**(3), 1–7 (in Chinese).