Available online at www.sciencedirect.com

ScienceDirect

Procedia Environmental Sciences 2 (2010) 1451–1460

Procedia Environmental Sciences

International Society for Environmental Information Sciences 2010 Annual Conference (ISEIS)

Simulation-based optimization method for water resources management in Tarim River Basin, China

Y. Huang[a,c], Y.P. Li[b]*, X. Chen[a], A.M. Bao[a], M. Zhou[c]

[a] *Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*
[b] *S-C Research Academy of Energy and Environmental Studies, North China Electric Power University, Beijing 102206, China*
[c] *College of Urban and Environmental Sciences, Peking University, Beijing 100871, China*

Abstract

In this study, a simulation-based optimization method (SOM) is developed for supporting water resources planning and management under uncertainty in Tarim River Basin, China. The modeling system couples a lumped rainfall runoff model and an inexact multistage stochastic programming (IMSP) into the general framework. The SOM extends upon the existing multistage stochastic programming method by allowing uncertainties expressed as probability density functions and discrete intervals to be effectively incorporated within the optimization framework. Its random parameter is provided by the statistical analysis of simulation outcomes of the rainfall runoff model. Moreover, it can also reflect dynamic features of the system conditions through transactions at discrete points in time over the planning horizon. The results indicate that reasonable solutions have been generated. The results are helpful for water resources managers in not only making decisions of water allocation but also gaining insight into the tradeoffs between environmental and economic objectives.

© 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: optimization; simulation, multistage stochastic; uncertainty; water resources management.

1. Introduction

Over the past decades, controversial and conflict-laden water resources allocation issue has challenged decision makers [11]. The growing population and shrinking water availability have exacerbated such competitions, leading to complexities in generating desired decisions, particularly under varying natural conditions and deteriorating quality of water resources. Consequently, the constantly increasing demand for water in terms of both sufficient quantity and satisfied quality, has forced planners to contemplate and propose ever more comprehensive, complex,

* Corresponding author Tel.: +86-010-51971215; fax: +86-010-51971255.
E-mail address: yongping.li01@gmail.com.

1878-0296 © 2010 Published by Elsevier Open access under CC BY-NC-ND license.
doi:10.1016/j.proenv.2010.10.158

and ambitious plans for water resources systems [8, 12]. Moreover, spatial and temporal variations can exist in system components such as stream flows and water-allocation targets, and fluctuations can be associated with the net system benefits that are functions of many stochastic factors. These complexities could become further compounded by not only interactions among the uncertain parameters but also their economic implications. As a result, the inherent complexity and stochastic uncertainty that exist in the real-world water resources systems have essentially placed them beyond the conventional deterministic optimization methods.

Two-stage stochastic programming (TSP) is an effective method for problems in which an examination of policy scenarios is desired and the system data is characterized by probability distribution [2, 4, 8, 9, 10, 15, 17]. However, the TSP has difficulties in reflecting the dynamic variation of system components, especially for large-scale problems with sequential structure. To deal with such a dynamic feature, multistage stochastic programming (MSP) methods were developed as extensions of dynamic stochastic optimization methods.

The MSP improved upon the TSP by permitting revised decisions in each time stage based on the uncertainty realized so far. In the past decades, a number of researchers made efforts to propose MSP methods for planning water resources systems [7, 8]. For example, Watkins et al. [18] proposed a scenario-based multistage stochastic programming model for planning water supplies from highland lakes, where dynamics and uncertainties of water availability (and thus water allocation) could be taken into account through generation of multiple representative scenarios. Ahmed et al. [1] addressed a multistage capacity expansion problem with uncertainties in demands and cost parameters as well as economies of scale in expansion costs. Li et al. [11] developed a multistage scenario-based interval-stochastic programming method for water-resources allocation under uncertainty, which improved upon the existing multistage optimization methods with advantages in uncertainty reflection, dynamics facilitation, and risk analysis.

Therefore, as an extension of previous research efforts, this study aims to develop a simulation-based optimization method (SOM) for planning water resources management systems. The SOM will incorporate runoff simulation and interval multistage stochastic programming (IMSP) within a general framework. It can not only deal with uncertainties expressed as not only probability density functions (PDFs) and interval values, but also reflect the dynamics of system uncertainties and decision processes under a complete set of scenarios. Moreover, penalties are exercised with recourse against any infeasibility, which permits in-depth analyses of various policy scenarios [13]. The developed SOM will be applied to planning water resources allocation in the Tarim River Basin. The results will be useful for water resources managers in making decisions of water allocation, and gaining insight into the tradeoffs between the system benefit and the constraint-violation risk.

2. Methodology

2.1. Definitions of the interval parameter

Let x denote a closed and bounded set of real numbers. An interval-parameter number $x^{\pm}$ is defined as an interval with known upper and lower bounds but unknown distribution information for x [7]:

$$x^{\pm} = [x^{-}, x^{+}] = \{t \in x \mid x^{-} \le t \le x^{+}\} \qquad (1)$$

where x^{-} and x^{+} are the lower and upper bounds of $x^{\pm}$, respectively. When $x^{-} = x^{+}$, $x^{\pm}$ becomes a deterministic number.

For $x^{\pm}$, we define $\text{Sign}\,(x^{\pm})$ as follows:

$$\text{Sign}\,(x^{\pm}) = \begin{cases} 1, & \text{if } x^{\pm} \ge 0 \\ -1, & \text{if } x^{\pm} < 0 \end{cases} \qquad (2)$$

Its absolute value $|x|^{\pm}$ is defined as follows:

$$|x|^{\pm} = \begin{cases} x^{\pm}, \ if \ x^{\pm} \geq 0 \\ -x^{\pm}, \ if \ x^{\pm} < 0 \end{cases} \tag{3a}$$

Thus we have

$$|x|^{-} = \begin{cases} x^{-}, \ if \ x^{\pm} \geq 0 \\ -x^{+}, \ if \ x^{\pm} < 0 \end{cases} \tag{3b}$$

$$|x|^{+} = \begin{cases} x^{+}, \ if \ x^{\pm} \geq 0 \\ -x^{-}, \ if \ x^{\pm} < 0 \end{cases} \tag{3c}$$

2.2. Simulation-based optimization method

Consider a problem in which a water resources manager is responsible for allocating water to multiple users over a multi-period planning horizon. Assuming that water demands from different users are deterministic, the formulation of the T-stage water resources management model can be written as a multistage stochastic programming (MSP) [7]:

$$\text{Max } f = \sum_{i=1}^{I}\sum_{t=1}^{T} B_{it}W_{it} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{k=1}^{K_t} p_{tk}C_{it}S_{itk} \tag{4a}$$

subject to

$$\sum_{i=1}^{I}(W_{it} - S_{itk}) \leq q_{th} + \varepsilon_{(t-1)k} \quad \forall h, k = 1, 2, \ldots, K_t; \quad t = 1, 2, \ldots, T \tag{4b}$$

$$\varepsilon_{(t-1)k} = q_{(t-1)h} - \sum_{i=1}^{I}(W_{i(t-1)} - S_{i(t-1)k}) + \varepsilon_{(t-2)k} \quad \forall h, k = 1, 2, \ldots, K_t \tag{4c}$$

$$W_{i\max} \geq W_i \geq S_{itk} \geq 0, \quad \forall i, t, k \tag{4d}$$

where f is the net system benefit over the planning horizon; i is the water user, i = 1, 2, . . ., I; t is the planning time period, t = 1, 2, . . ., T; k is the flow level available ($k = 1, 2, \ldots, K_t$) with k = 1 representing the low flow, k = 2 representing the medium flow and k = 3 representing the high flow; B_{it} is the net benefits to user i per unit of water allocated during period t; W_{it} is the fixed allocation target for water that is promised to user i during period t; is the probability of occurrence for scenario k in period t, with $p_{tk} > 0$ and $\sum_{K=1}^{K_i} p_{tk} = 1$; C_{it} is the reduction of net benefit to user i per unit of water not delivered during period t ($C_{it} > B_{it}$); S_{itk} is the amounts by which the respective water-allocation targets (W_{it}) are not met when the seasonal flows are q_{th} with probabilities p_{tk} in period t; is the water availability with probability levels of p_{tk} for K_t scenarios at each time stage (t); $\varepsilon_{(t-1)k}$ is the surplus water in the reservoir when water is delivered in period $t-1$ under scenario k ($k = 1, 2, \ldots, K_t$); $W_{it\max}$ is the maximum allowable allocation amount for user i during period t.

However, model 4 can only reflect uncertainties in water availability (i.e. q_{th}) presented as random variables when the left-hand side and cost coefficients are deterministic. An extended consideration is for more uncertainties in the other parameters such as, W_{it} C_{it} and B_{it}. For example, it may often be difficult for a planner to promise a deterministic water-allocation target (W_{it}) to users when the available water flows are uncertain; the water demands from the users may be uncertain; also, the economic data of benefit and cost (i.e., C_{it} and B_{it}) may not be available as deterministic values. Moreover, in many practical problems, the quality of information that can be obtained is often not good enough to be presented as probabilistic distributions [7]. Based on the above considerations, interval parameters are introduced into the multistage programming framework to communicate uncertainties in W_{it}, C_{it} and B_{it} into the optimization process. This leads to a hybrid inexact MSP model as follows:

$$\text{Max } f^{\pm} = \sum_{i=1}^{I}\sum_{t=1}^{T} B_{it}^{\pm} W_{it}^{\pm} - \sum_{i=1}^{I}\sum_{t=1}^{T}\sum_{k=1}^{K_t} p_{tk} C_{it}^{\pm} S_{itk}^{\pm} \tag{5a}$$

subject to

$$\sum_{i=1}^{I}(W_{it}^{\pm} - S_{itk}^{\pm}) \le q_{th}^{\pm} + \varepsilon_{(t-1)k}^{\pm} \quad \forall h, k = 1, 2, \ldots, K_t; \quad t = 1, 2, \ldots, T \tag{5b}$$

$$\varepsilon_{(t-1)k}^{\pm} = q_{(t-1)h}^{\pm} - \sum_{i=1}^{I}(W_{i(t-1)}^{\pm} - S_{i(t-1)k}^{\pm}) + \varepsilon_{(t-2)k}^{\pm} \quad \forall h, k = 1, 2, \ldots, K_{t-1} \tag{5c}$$

$$W_{it\max}^{\pm} \ge W_{it}^{\pm} \ge S_{itk}^{\pm} \ge 0, \quad \forall i, t, k \tag{5d}$$

where $W_{it}^{\pm}$, $B_{it}^{\pm}$, $C_{it}^{\pm}$, $S_{itk}^{\pm}$ and $W_{it\max}^{\pm}$ are interval variables. An interval is defined as a number with known upper and lower bounds but unknown distribution information [4, 7]. Letting W_{it}^{-} and W_{it}^{+} be lower and upper bounds of $W_{it}^{\pm}$, we have [W_{it}^{-}, W_{it}^{+}]. When W_{it}^{-} = W_{it}^{+}, $W_{it}^{\pm}$ becomes a deterministic number.

A simulation-based optimization method (SOM) is developed by coupling the simulation results of the lumped rainfall runoff model with the inexact multistage stochastic programming (IMSP).

3. Case study

Kaidu-kongque watershed is located in the middle reach of the Tarim River, and has an area of approximately 31.4×10^3 km^2. Peck flows at the Dashankou (DSK) station in the upstream of the watershed reach around 400 - 700 m^3/s in August and September, and drop to almost zero during the end of the dry season [5]. The Kaidu-kongque River supplies water to the region's municipality, industry, stockbreeding, forestry and agricultural sectors; it is also the most important source for ecosystem recovering of the lower reaches of the Tarim River.

The meteorological data including air temperatures, pan evaporation and daily rainfall are collected from 1960 to 2005. The definition of initial condition parameters in the rainfall runoff model are according to the DHI reference [3] and related publications. Values of $W_{it\max}$, $W_{it}^{\pm}$, $B_{it}^{\pm}$ and $C_{it}^{\pm}$ are estimated based on the statistical yearbook of Xinjiang Uygur Autonomous Region in 2009 and presented in Tables 1 and 2.

Table 1. Water allocation targets for users (unit: 10^6 m^3)

An example of a column heading	Time period		
	t=1	t=2	t=3
Water allocation target ($W_{it}^{\pm}$)			
Municipality	[69, 191]	[80, 200]	[90, 220]
Industry	[469, 803]	[550, 900]	[420, 800]
Stockbreeding	[41, 155]	[45, 170]	[50, 175]
Forestry	[407, 527]	[460, 588]	[480, 600]
Agriculture	[2335, 3113]	[2420, 3200]	[2480, 3350]
Ecology	[445, 1051]	[500, 1100]	[500, 1100]

To get the optimal water allocation schemes for the study watershed, values of $q_{th}^{\pm}$ should be obtained first. This value can be conducted through statistical analyses with simulation results of annual stream flow of the Kaidu-kongque River which supply water to the watershed. In this study, the time span for statistical analysis was set from year 1960 to 2005 (46 years). As shown in Figure 1, the simulated daily discharges are compared with observed data, the Nash-Sutcliffe coefficient R2 (Nash and Sutcliffe, 1970) would be 0.72. We then used the verified hydrological model to estimate the time series of daily stream flow from 1960 to 2005 for the DSK station.

Table 2. Net benefits and penalties (unit: $\$/10^3\ m^3$)

An example of a column heading	Time period		
	t=1	t=2	t=3
Net benefit when water demand is satisfied ($B_{it}^{\pm}$)			
Municipality	[7857, 10000]	[6907, 9903]	7220, 10003]
Industry	[1820, 6414]	[1900, 6300]	[1968, 7001]
Stockbreeding	[3900, 6485]	[3900, 6279]	[3830, 6000]
Forestry	[257, 371]	[288, 407]	[269, 392]
Agriculture	[341, 455]	[367, 480]	[390, 555]
Ecology	[157, 429]	[170, 520]	[191, 529]
Reduction of net benefit when demand is not delivered ($C_{it}^{\pm}$)			
Municipality	[14285, 18571]	[13084, 18998]	[14430, 19300]
Industry	[3600, 11442]	[3500, 12000]	[3687, 13200]
Stockbreeding	[7857, 12857]	[7500, 11355]	[7600, 11938]
Forestry	[515, 742]	[530, 800]	[520, 780]
Agriculture	[642, 1000]	[720, 1100]	[780, 1100]
Ecology	[285, 643]	[305, 1002]	[325, 956]

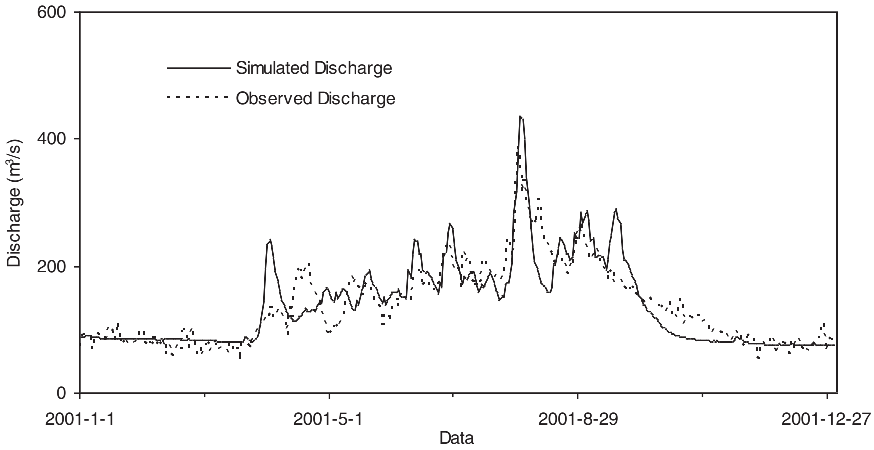

Fig. 1 Verification of the lumped rainfall runoff model (2001)

The interval values of q_{th} under different probability levels can then be calculated with the fitted gamma distribution. As a result, we have F (q_{th}) = [0.85 q_{th} , 1.15 q_{th}]. Table 3 presents the probability levels correspond to different interval values of the stream flow. By inputting the interval values of stream flow and economic data, the model 5 can be solved.

Table 3. Stream flows in the three periods (unit: 10^6 m^3)

Flow level	Probability t = 1	Stream flow	Probability t = 2	Stream flow	Probability t = 3	Stream flow
Low (L)	0.304	[2459, 2989]	0.37	[2399, 3003]	0.174	[2602, 2901]
Medium (M)	0.455	[3002, 3721]	0.502	[3062, 3847]	0.49	[2917, 3626]
High (H)	0.261	[3752, 5708]	0.128	[4068, 5676]	0.336	[3700, 5500]

4. Results analysis

By inputting the interval numbers of simulated stream flow and the economic data, the optimal water allocation targets, plans, system benefits and penalties were obtained through the SOM model. Figures 2 show the solution of the optimal allocation targets during periods 1 to 3. The results indicate that, during periods 1 to 3, the optimal water allocation targets would be (1) for the municipality sector: 191.0×10^6, 200.0×10^6 and 220.0×10^6 m^3, respectively; (2) for the industry sector: 803.0×10^6, 900.0×10^6, and 800×10^6 m^3, respectively; (3) for the stockbreeding sector: 155.0×10^6, 175.0×10^6 and 175.0×10^6 m^3, respectively; (4) for the forestry sector: 407.0×10^6, 460.0×10^6 and 480.0×10^6 m^3, respectively; (5) for the agriculture sector: 2335.0×10^6, 2420.0×10^6 and 3350.0×10^6 m^3, respectively; (6) for the ecology sector: 1051.0×10^6, 1100.0×10^6 and 1100.0×10^6 m^3, respectively.

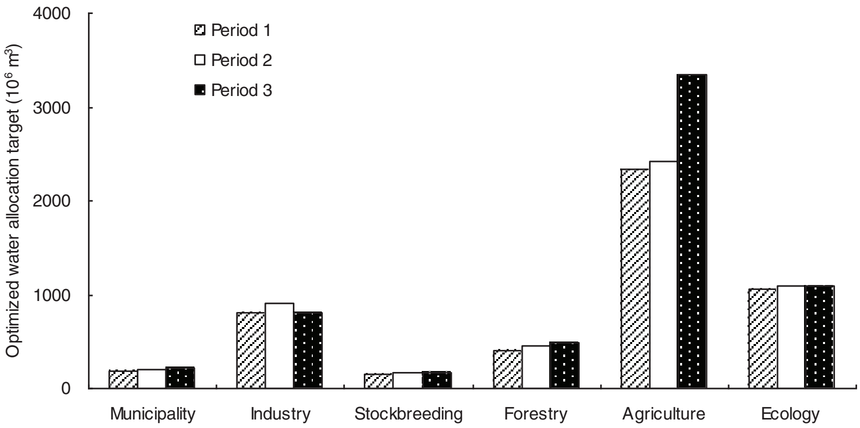

Fig. 2 Optimized water allocation targets during periods 1 to 3

In period 1, the solutions for water shortage (i.e. $S_{itk}^{\pm}$) under the given targets reflect potential system condition variations caused by uncertain inputs. For example, the solutions of $S_{411opt}^{\pm}$ = 407.0 × 10^6, $S_{412opt}^{\pm}$ = 407.0 × 10^6 and $S_{413opt}^{\pm}$ = [0, 407.0] × 10^6 m^3 means that, for user 4 (i.e., forestry), there would be zero water allocation would definitely occur when the seasonal flow are low (probability = 0.304) and medium (probability = 0.455), Similarly, when the flow is high (probability = 0.241), the shortage may be relatively low under advantageous conditions, and would be raised under demanding conditions. The solutions of $S_{511opt}^{\pm}$ = [495.0, 1026.0] × 10^6, $S_{512opt}^{\pm}$ = [0, 1323.0] × 10^6 and $S_{413opt}^{\pm}$ = [0, 1798.0] × 10^6 m^3 imply that, for user 5 (i.e., agriculture), there would be water shortage when the seasonal flows are low to high. For the ecology sector, the water shortage under low to high flows would be 1051.0 × 10^6 m^3.

In period 2, the results indicate that there would be no water shortage for the municipality, industry and stockbreeding sectors during the second period (following a high flow in period 1), whiles the corresponding water allocations would be 200.0 × 10^6, 900.0 × 10^6 and 170.0 × 10^6 m^3, respectively. For the forestry sector under low, medium and high seasonal-flow levels in period 2 (following a high flow in period 1), the water shortage would be [0, 460.0] × 10^6, [0, 460.0] × 10^6 and [0, 460.0] × 10^6 m^3 (with joint probability levels of 0.039, 0.058 and 0.031, respectively), whiles the corresponding water allocations would be [0, 460.0] × 10^6, [0, 460.0] × 10^6 and [0, 460.0] × 10^6 m^3. For the agriculture sector, the water shortage would be [0, 1249.0] × 10^6, [0, 1012.0] × 10^6 and [0, 334.0] × 10^6 m^3 respectively, whiles the corresponding water allocations would be [1171.0, 2420.0] × 10^6, [1408.0, 2420.0] × 10^6 and [2086.0, 2420.0] × 10^6 m^3, respectively. For ecology sector, the water shortage would be [937.0, 1100.0] × 10^6, [736.0, 1100.0] × 10^6 and [0, 1100.0] × 10^6 m^3 respectively, whiles the corresponding water allocations would be [0, 127.0] × 10^6, [0, 364.0] × 10^6 and [0, 1100.0] × 10^6 m^3, respectively.

In period 3, there would be zero shortage under low to high flow levels for municipality, industry and stockbreeding. The solutions of $S_{531opt}^{\pm}$ = [0, 845.0] × 10^6, $S_{532opt}^{\pm}$ = [0, 845.0] × 10^6 and $S_{533opt}^{\pm}$ = [0, 557.0] × 10^6 m^3 mean that, if the flows are high in period 1 and medium in period 2, then there would be [0, 845.0] × 10^6, [0, 845.0] × 10^6 and [0, 557.0] × 10^6 m^3 of water shortage under low, medium and high water-flow scenarios, respectively (joint probability = 0.051, 0.077 and 0.041), for agriculture sector during period 3; Thus, the corresponding water allocation patterns would be [2505, 3350] × 10^6, [2505, 3350] × 10^6 and [2793, 3350] × 10^6 m^3 under low, medium and high water-flow scenarios, respectively, for agriculture sector during period 3. If the flow is high in periods 1 and 2, then there would be [0, 368.0] × 10^6, [0, 368.0] × 10^6 and [0, 368.0] × 10^6 m^3 of water shortage under low, medium and high flow scenarios, respectively (joint probability = 0.013, 0.019 and 0.010), for user agriculture during period 3. The water shortage for the agriculture sector in period 3 would become less if there is some surplus in the water available due to the high-flow condition during period 2.

Solution of the objective function (i.e. $f_{opt}^{\pm}$ = \$[8.57, 29.96] × 10^9) provides two extreme expected values of the net system benefit over the planning horizon. As the actual value of each continuous variable varies within its lower and upper bounds, the expected system benefit would change correspondingly between f_{opt}^{-} and f_{opt}^{+} with a variety of reliability levels.

5. Conclusions

A simulation-based optimization method (SOM) has been developed for water resources planning and management. The developed SOM integrates the lumped rainfall runoff model into an inexact multistage stochastic programming (IMSP) framework. This method extends upon the existing multistage stochastic program by allowing uncertainties expressed as probability density functions and discrete intervals to be effectively incorporated within the optimization framework. Moreover, penalties are exercised with recourse against any infeasibility, which permits in-depth analyses of various policy scenarios that are associated with different levels of economic consequences when the promised water-allocation targets are violated. The developed SOM is applied to a real case of planning water resources management in Tarim River Basin, China. The results indicate that reasonable solutions have been generated, and will help generate desired policies for water resources management with maximized economic benefit and minimized system-failure risk.

Acknowledgements

This research was supported by the Natural Sciences Foundation of China (50979001 and 40730633) and China Postdoctoral Science Foundation (20100470123).

References

[1] Ahmed S, Tawarmalani M, Sahinidis NV. A finite branch-andbound algorithm for two-stage stochastic integer programs. *Math Program Ser A* 2004;100:355 – 77.

[2] Chen Z, Huang G H, and Chakma A. 2000. Risk assessment of a petroleum-contaminated site through a multi-phase and multi-component modeling approach, *Journal of Petroleum Science & Engineering* 26(1): 273-282.

[3] DHI. MIKE 11 user's and reference manual, *DHI Water & Environment, Horsholm, Denmark* 2007.

[4] Huang GH, Loucks DP. An inexact two-stage stochastic programming model for water resources management under uncertainty. *Civil Engineering Environment System* 2000; 17: 95-118.

[5] Huang Y, Chen X, Li YP, Willems P, Liu T. Integrated modeling system for water resources management of Tarim River Basin. *Environmental Engineering Science* 2010; 27(3): 255-269.

[6] Li JB, Huang GH, Zeng GM, Maqsood I, Huang YF. An integrated fuzzy-stochastic modeling approach for risk assessment of groundwater contamination. *Journal of Environmental Management* 2007; 82: 173-188.

[7] Li YP, Huang GH and Nie SL. An interval-parameter multistage stochastic programming model for water resources management under uncertainty. *Advances in Water Resources* 2006; 29: 776-789.

[8] Li YP, Huang GH. Inexact multistage stochastic quadratic programming method for planning water resources systems under uncertainty. *Environmental Engineering Science* 2007; 24: 1361-1377.

[9] Li YP, Huang GH, Yang ZF and Nie SL. Interval-fuzzy multistage programming for water resources management under uncertainty. Resources, *Conservation and Recycling* 2008a; 52: 800-812.

[10] Li YP, Huang GH, Nie SL, Liu L. Inexact multistage stochastic integer programming for water resources management under uncertainty. *Journal of Environmental Management* 2008b; 88: 93-107.

[11] Li YP, Huang GH, Wang GQ, Huang YF. FSWM: A hybrid fuzzy-stochastic water-management model for agricultural sustainability under uncertainty. *Agricultural Water Management* 2009; 96: 1807-1818.

[12] Loucks DP, Stedinger JR, Haith DA. *Water resource systems planning and analysis. Englewood Cliffs, NJ: Prentice-Hall;* 1981.

[13] Luo B, Li JB, Huang GH, Li HL. A simulation-based interval two-stage stochastic model for agricultural nonpoint source pollution control through land retirement. *Science of the Total Environment* 2006; 361: 38-56.

[14] Macuen RH, Snyder WM. Hydrologic modeling: statistical methods and applications. *Prentice-Hall* 1986.

[15] Maqsood I, Huang GH, Huang YF, Chen B. ITOM: an interval-parameter two-stage optimization model for stochastic planning of water resources systems. *Stochastic Environment Research Risk Assessment* 2005a; 19: 125-133.

[16] Nash JE, Sutcliffe JV. River flow forecasting through conceptual models part1 - a discussion of principles. *Journal of Hydrology* 1970; 10: 282-290.

[17] Wang D, Adams BJ. Optimization of real-time reservoir operations with Markov decision processes. *Water Resources Research* 1986; 22: 345-352.

[18] Watkins Jr DW, McKinney DC, Lasdon LS, Nielsen SS, Martin QW. A scenario-based stochastic programming model for water supplies from the highland lakes. *International Transition in Operation Research* 2000;7: 211–30.