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Advance on conjunctive operation of surface water and groundwater

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ABSTRACT

The implementation of conjunctive operation of surface water and groundwater is an efficient way to make good use of water resource, strengthen the management of groundwater resource, and solve the problem of water resource shortage in China. This research firstly summarizes the sort of conjunctive operation system of surface water and groundwater, and the principles to conduct conjunctive operation, introduces the mathematical mode category of conjunctive operation of surface water and groundwater, analyzes the present research situation of the optimal methods of it at home and aboard, makes clear the problems existing in this field, and then prospects the research tendency of this field. By the way, it puts forward an idea that the cross and fusion of hydrology, meteorology, ecology, soil science, and computer science will be the future research tendency of conjunctive operation of surface water and groundwater; so it supplies reference for further study of this field.

Keywords: Groundwater management; Surface water; Groundwater; Conjunctive operation; Advance

1. Introduction

In China, water resource distribution is seriously unbalanced, and the south of China is rich, while the north is short of it. So over exploitation of groundwater is very severe in some areas of the north, a large-scaled cone of depression of groundwater exists in these areas as a result, and some areas face the threat of exhaustion of groundwater resource. Meanwhile, due to poor knowledge of groundwater resource, imperfect measure of management for water resource, lack of unified planning and unreasonable allocation, water resource is severely wasted. In order to make good use of water resource, solve the problem of the shortage of water resource in some areas and meet the need of the development of industry and agriculture, in addition to saving water and increasing water resource, strengthening combined exploitation of multiple water resource is the efficient way in China, especially the implementation of conjunctive operation of surface water and groundwater.

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2. An outline of conjuctive operation of surface water and groundwater

The so-called conjunctive operation of surface water and groundwater is a kind of mode of water exploitation and utilization, which is based on the consideration of the respective hydrological law of surface water and groundwater and their mutual effects, to conduct a manual adjustment of surface water and groundwater regarding them as a whole to achieve optimal allocation and sustainable utilization of water resources in some area. The thought of conjunctive operation is to make use of the feature of which peak period of the groundwater runoff comes later than that of stream runoff [1]. That is to say, in low-flow season of surface water, groundwater can be properly overexploited to meet the need of water, meanwhile, to vacate underground storage, while in ample flow season, surface water abandoned is used to recharge groundwater that is overexploited in low-flow season. The implementation of conjunctive operation of surface water and groundwater can achieve reasonable spatiotemporal allocation of water resource to improve utilization ratio of water resources and water-supply guaranteed rate and realize comprehensive treatment of drought, water logging and alkali.

2.1. The sort of conjunctive operation system

According to the existing form of surface water source and the complex degree, conjunctive operation of surface water and groundwater can be divided into 3 sorts.

(1) Conjunctive operation of surface reservoir and underground water layer

This sort is special for that surface supply water system is reservoir with the capacity of regulation and storage, which reservoir can be a single one, parallel ones or several in series, while underground water layer can be divided into several different unites according to their hydrologic geology condition, natural geographical condition, economic condition, and administrative division.

(2) Conjunctive operation of river diversion project and underground water layer

Corresponding to the first sort, the surface supply water system of this sort has not the capacity of regulation and storage, which relies on the natural runoff water supply, so it varies greatly with the change of rainfall in plentiful and low water period, so irrigation guarantee rate is relatively low. This sort of system gives priority to utilizing stream flow and conducts artificial recharge of groundwater in rainfall of plentiful period, while in the low water period, the groundwater is exploited to improve the water-supply guaranteed rate, so artificial recharge of groundwater in this system appears very important.

(3) Conjunctive operation of multiple surface water sources and groundwater

As for a area or a basin, surface water supply system can be not only reservoirs but also rivers; in this sort of conjunctive operation, the amount of surface water supply projects, groundwater supply projects and customers of water using is large, and the relations of these subsystems are complex, so it is characterized by huge scale, complex structure and multiple objectives.

However, whatever the conjunctive operation is, when the scale of irrigation area is comparatively large or the situation of it is complex, it is necessary to divide the area researched into several subareas to study [2]. According to topography and geomorphology, hydrogeology condition and the character of surface water supply, the conjunctive operation in these subareas may vary greatly in their methods. Considering their main elements, these subareas can be divided into 3 sorts: (1) well canal irrigation area (2) canal irrigation area (3) well irrigation area.

2.2. Conjunctive operation principles

The principles as below should be abided, while conjunctive utilization of surface water and groundwater is conducted [3]:

(1) Focusing on long-term plan, adapting to local condition

When conjunctive utilization of surface water and groundwater is conducted, it is necessary to make an overall arrangement with the principle of making full use of surface water and putting groundwater to rational exploitation, taking the need of water of local industry and agriculture in recent and forward days, the distributive feature of surface water and groundwater in planning area into consideration.

(2) Comprehensive governance and unified planning

The project of conjunctive operation of surface water and groundwater should take the comprehensive governance of natural disaster of drought, water logging and salinity into consideration, in this way, the problem of drought can be solved, and so can the measure to prevent water logging and land Stalinization be put forward, for which comprehensive governance and unified planning can be achieved. Especially groundwater utilization not only can supply water resource to farmland irrigation, but also can prevent salinity and water logging through exploiting groundwater to lower groundwater level. Besides, due to the groundwater exploiting before flood season, the underground storage vacated becomes available in flood season to be recharged, as a result, the groundwater level would not rise beyond the highest water logging level, for which a beneficial condition to prevent drought and water logging can be achieved.

3. Research status at home and abroad

In recent 40 years, with the development of computer technology, researches at home and abroad usually take the way of system analysis to study the complex system of conjunctive operation of surface water and groundwater with multiple water resource and multiple users to put forward various mathematical models and optimization methods.

3.1. The mathematical model of conjunctive operation of surface water and groundwater

Mathematical model is an abstract of real system; it uses a set of organic combination of mathematical equation to express research problem or system. As for the specific research problem of conjunctive operation of surface water and groundwater, researchers at home and at abroad put forward various mathematical models according to "problem orientation" or "method orientation." No matter what is complex model or simple one, mathematical model of conjunctive operation of surface water and groundwater always includes three submodels as below [4].

3.1.1. Physical submodel

Physical submodel is a mathematical model to describe the physical characters of water resource system, while common hydrological model is one of the physical models. According to distribution status of parameters, physical models can be divided into lumped parameter model and distributed parameter model.

(1) Distributed parameter model

So-called distributed parameter model refers to the system parameters closely relating to temporal and spatial variation, it subdivides the research area into some kinds of subareas according to a certain rule, which subareas take respectively different values. Especially, the distributed parameter of groundwater model can obtain the groundwater status of every spatial point in different period. Because distributed parameter model describes dynamic changing process in a comparatively subtle way, it can be used in the research of large-scaled, heterogeneous and complex conjunctive operation of underground water layer system and surface water system and also can be used in the research of long-term planning problem and short-term conducting problem. The shortcoming of the model is its high requirement of data and it needs clearly understanding local hydrogeology situation and with the model, it is difficult to describe hydraulic connection between surface water and groundwater.

(2) Lumped parameter model

When real problem is unclear or the variation of parameter with time-space coordinate need not knowing, and the only way is from the macro-angle to hold the changing law of the whole system status with the change of time, lumped parameter model is mainly used to deal with the system problem. That is to say, the system is treated as black box without concerning the inner mechanism of the system, while just concerning the relation between input value and output value. As for conjunctive operation of surface water and groundwater, water balance equation is taken to describe surface water, groundwater and their hydraulic connection. Lumped parameter model needs little data and can easily be used to describe hydraulic connection between surface water and groundwater. However, state variable is represented by mean water level of aquifer system, so it can just be used in homogeneous aquifer of a small area or planning problem.

3.1.2. Management submodel

Management submodel is a model to describe reaching the management goal under the situation of meeting the requirement of various society, economy, resource, and environment. With the developing of management theory and method of water resource, management submodel of conjunctive operation of surface water and groundwater has developed from a single goal at beginning into a multiple-goal planning management model including resource, society, environment and economy.

3.1.3. Coupling model between the two

Coupling method of physical submodel and management submodel includes simulation method, embedding method and response-function method. Simulation method makes use of the physical model to set up a group of nonlinear equations for response function of different decision variable to get iterative solution. Coupling method based on the concept of embedding method is to take the whole physical mode (surface water salinity, soil water and salt, Simulation of groundwater salinity) as equality constraints to be directly added to optimization model or as state transition equation to dynamic planning of time-related decision. Due to the fact that the equation to describe physical system is simple, it can be embedded in optimization model in the constraint form to become a physical feasible constraint, common lumped parameter model is a coupling method which is used more, while distributed parameter model is used less for its large-scaled algebraic equations and its enlarging with the increasing in period. Moreover, response-function mainly takes advantage of superposition and times of linear system or quasilinear system, and uses pulse response-function and the concept of convolution integral to express the response of physical system for different management decision, so that physical system and optimization model can be connected.

Among these three couple methods, embedding method is the most convenient and visual and can directly take physical feasibility constraint into consideration in optimization. But because this method can result in enlarging the scale of optimization, its requirements of algorithm and computer memory are high. Response-function method is an indirect way, which firstly need obtain system response of unit pulse by conducting physical model and then expresses the response relationship of decision and system by convolution integral in optimization model. Its physical meaning is clear; the discrete form of it can change physical constraint into linear constrain, so that the planning problem becomes easier, for which this method is the most vital one. But as for the conjunctive utilization system with complex hydraulic connection or nonlinear system, the calculation of response function is not easy.

3.2. Optimization method of conjunctive operation of surface water and groundwater

With the developing of system engineering theory and optimization technology, there are five kinds of usual methods about optimization method of conjunctive operation of surface water and groundwater: linear planning method, nonlinear planning method, dynamic planning method, large system decomposition-coordination method and simulation technology.

3.2.1. Linear planning method

Objective function and constraint condition of linear planning method are linear, due to the fact that linear planning can use simplex method, a general algorithm to solve; linear planning has been widely applied to conjunctive utilization system. This research had been conducted in 1960s abroad; Castle et al. [5] is the first person to introduce linear planning to conjunctive utilization system of surface water and groundwater between two agricultural customers. Willis et al. [6] used linear planning method to solve a complex conjunctive utilization problem of a surface reservoir and four underground water units. Khare et al. [7] set up linear planning model of conjunctive utilization system of surface water and groundwater, in which objective function achieves the greatest economic benefit through optimizing structures of crop planting and analyzed economic benefits of planting structures under six projects.

In China, until the early 1980s, application research of linear planning method to conjunctive utilization system of surface water and groundwater is conducted. Li et al. [8] made use of irrigation model of Smith from Harvard University, modified this model according to the real condition of irrigation area of China and drafted deterministic model of linear planning of the conjunctive utilization of surface water resource and underground water resource. Liu et al. [9] took groundwater depth as main environmental control variable, decided the optimal water using project of groundwater, surface water and diversion water with linear planning method. Shao et al. [10] took the water supply in the urban area of Bao Tou city as an example, applied response matrix method to couple groundwater numerical model into linear objective planning, which takes maximum industrial output value, the minimum water supply expenses, controlling the groundwater to the best level and furthest meeting the need of agricultural water consumption as its goal to build multiobjective linear planning management model, which obtains the optimal distribution project of groundwater in each area and each customer by the solution of linear objective planning. Wang et al. [11] took urban domestic water consumption, rural domestic water consumption, industrial water, farmland irrigation water, eco-environmental water consumption and salt washing water into consideration to calculate distribution proportion of ground water and surface water in different level years and different units to prevent soil salinization. Liu et al. [12] took the method of linear planning to set up a model of conjunctive operation of surface water and groundwater in the basin of Huang Shui River, whose object is the maximum amounts of water supply, this model coupled the balance equation of reservoir water with the numerical simulation model of distributed groundwater through leaching losses between surface water and groundwater. Lu et al. [13] applied the method of fuzzy linear planning of nonaccurate rough interval to conjunctive operation project of water resource of agricultural irrigation system and comparatively analyzed the results of fuzzy linear planning of same interval value of settlement results.

3.2.2. Nonlinear planning method

Among the real problems, most mathematical planning models belong to the problem of nonlinear planning. According to specific problem, nonlinear planning model usually puts forward specific pattern of mathematical models to find out concrete solution because it has no general solving method. Matsukawa et al. [14] made use of general reduced gradient method of nonlinear planning to solve distributed parameter of reservoir, river, and groundwater system in conjunctive utilization, by the way to take power, water supply and environment, multiple objectives into consideration. Bharati et al. [15] set up conjunctive operation model of surface water and groundwater in Volta Basin through dynamic coupling economic model and hydrological model, in which economic model applies the nonlinear optimization engine of GAMS to the solution.

As for conjunctive utilization of multiple water resources: groundwater, local runoff, lake waters, interbasin water transfer and return water, Li et al. [16] combined with the practical operation of gate, station, cascade river net of irrigation and drainage canal to set up a nonlinear planning irrigation model, which takes the fact that crop's water requirement changes with the change of output, and the nonlinear relationship between expense and water supply into consideration. Finally, optimal distributive proportions of various water resources and crops planting patterns are solved under the condition of maximizing annual net benefit in different four years. Huang et al. [17] used Jensen forecast model to reflect the relationship between water requirement and output in each stage of the whole-growth period and then set up nonlinear forecast mathematical model with a parabolic formula which can approximately solve crop output in different irrigation treatments to realize optimal operation of three water resources: pumping station pumping, artesian water, and well water. Cheng et al. [18] applied experimental optimization method to the solution of the nonlinear model of conjunctive operation of groundwater and surface water, which supplies a new way for the optimization of a complex large-scaled conjunctive operation system of surface water and groundwater. Li et al. [19] applied nonlinear planning techniques to setting up conjunctive operation model of surface water and groundwater with the object to achieve the maximum economic benefits of irrigation districts, and the constraint condition of balance equation of water supply and water needed, available water supply and groundwater level.

3.2.3. Dynamic planning method

The dynamic planning method with its methods improved (including the state increment dynamic planning method, the discrete differential dynamic planning, etc.) is one of the basic mathematical methods widely used in optimal technology. It can be used to analyze the process of multistage decision to obtain the optimal project of a whole system. For the problem of conjunctive management of surface water and groundwater, as the reservoir problem has a seasonal, periodic and multi-stage character in terms of time, the dynamic planning model is adopted and is widely applied to conjunctive management of surface water and groundwater.

Buras et al. [20] first introduced the dynamic planning method into the conjunctive utilization system of surface water and groundwater and set up a model for conjunctive utilization of surface water and groundwater. In order to overcome the dimensional problem of conjunctive utilization of multiwater sources, Noel [21] transferred the conjunctive utilization problem into a discrete time linear quadratic control problem and solved it by dynamic optimal system control theory. Karamouz et al. [22] took the way of dynamic planning to set up conjunctive use of water resource of city area in Teheran and made use of relative data to set up mathematical model of water level change of stimulating aquifer to calculate the response function of aquifer.

Cai et al. [23] took the People's Victory Canal irrigation district as the research example, considered the randomness of seasonal rainfall amount, chose the seasonal rainfall amount and water storage amount in aquifer as the state variables, established a stochastic dynamic planning model for conjunctive utilization of surface water and groundwater and calculated the optimal amount of water pumped and diverted in each season as well as the probability distribution of initial groundwater table and the amount of pumped water. Tang [24] studied a certain irrigation district in the middle reaches of the Yellow River, set up a multiobjective optimization model for water resources allocation in large river basin and proposed the solution of hierarchical dynamic planning for large scale system. Dai et al. [25] took the minimum cost of water supply as the objective function and the water storage amount in the supply points of the groundwater and surface water as the state variables, then selected the typical hydrological years and finally constructed a dynamic planning model for conjunctive regulation of groundwater and surface water. Yang et al. [26] set up multiobjective conjunctive use model of surface water and groundwater, in which dynamic planning method is applied to the conjunctive operation of surface reservoir groups, groundwater exploitation is solved by numerical simulation method, in this way dynamic planning and numerical simulation program are embedded in multiobject genetic algorithm to calculate.

3.2.4. Large-scale system decomposition–coordination method

With the development of control theory and large-scale system theory, the large-scale system decomposition–coordination method became the most prospective approach for the planning and management of complex water resources system. The actual groundwater and surface water system is undoubtedly an open complex giant system, and thus, its optimization problem could be solved by the large-scale system decomposition– coordination method.

The work of Haimes [27] is the representative for the application of large-scale system decomposition–coordination method to the conjunctive management problem, which takes each constraint and the social economical objectives into consideration and describes the groundwater system by distributed parameter model. But it has too many factors and is too complicated to be applied to practical situation. Matsukawa [28] applied this theory to Mad basin in California to solve the problem of conjunctive use of river and groundwater system. In order to conduct optimum water resources allocation, Cosgrove et al. [29] set up conjunctive operation model of surface water and groundwater with the method of large-scale system decomposition–coordination, linear planning and dynamic planning.

Ru [30] applied large system optimization to the expansion and reconstruction planning of the well-canal combined irrigation areas, who constructed a three-level large system optimization–coordination model which was decomposed by time and regions and used this model in Shijin irrigation area to get the optimal results of water allocation of surface water and groundwater, the irrigation area and the scale of seepage control project in subareas. Liu [31] adopted hierarchical analysis of large system method to establish a hierarchical large system model for the water resources of Beijing-Tianjin-Tangshan area, and proposed the combination of simulation technology and optimal method as the solution. Qi et al. [32] constructed a hierarchical large system management model for the conjunctive regulation of diverted water from the Yellow River and the groundwater and determined the optimal water allocation amount of diverted water and groundwater in each sector and the optimal planting area for the crops by large-scale system decomposition–coordination method. Zhang [33] took the maximum net benefit of irrigation as the objective function, established a large-scale system decomposition–coordination model for conjunctive regulation of surface water and groundwater in the irrigation district, which includes simulation and optimization of irrigation schedule, optimization of water allocation among crops and optimization of diverted water allocation in sub–areas. The research determined the optimal allocation of the diverted water from the Yellow River among the subareas of Penglou irrigation district and the optimal allocation of surface water and groundwater in each growth period for the major crops of the irrigation district. With the example of Cha Ha Yang irrigation district, Xu et al. [34] applied the theory of large-scale system decomposition–coordination to setting up optimum water resources allocation of irrigation districts with two-layer structure, in which the operation of surface water and groundwater is taken into overall consideration.

3.2.5. Simulation technology

The simulation technology is one of the effective tools to realize the optimal decision for complex water resources system, especially in the conjunctive regulation of surface water and groundwater, its application is relatively broad. The simulation model as the mathematical planning consists objective function and constraints, but it also includes system operation rules. The system operation rules for the conjunctive regulation of surface water and groundwater include the reservoir operation rule, river water diversion rule, groundwater management rule and the conjunctive regulation rule. Moreover, the simulation model generally needs a relatively accurate mathematical model, and its solution approach is different from the mathematical planning. Before the simulation appearing, the simulation technology must assign values to the decision variables and make the decision according to the operation rules.

Wong et al. [35] conducted a simulation calculation for the conjunctive utilization of surface water and groundwater in Dashi River Basin of Beijing. He mainly considered the surface runoff formed by precipitation and the infiltration, selected three types of hydrologic model including the typical probability year method, field measurement time series method and artificial series statistical experiment method to make a simulation comparison. But its groundwater regulation only reckoned with the shallow groundwater without considering the deep groundwater. Yuan [36] put forward a mathematical model with only four parameters to simulate the movement and water equilibrium trend of the surface water and groundwater in a river basin or an irrigation district and to determine the optimal ratio between the canal irrigation and well irrigation and the scale of irrigation area. Yin et al. [37] conducted numerical simulations by MODFLOW for 4 well-canal irrigation projects of the study region and got a satisfactory result. Wang et al. [38] utilized FE-FLOW to construct a three-dimensional numerical simulation model for the groundwater flow and based on it to have studied the infiltration simulation of the river channels and the sandpits in the western suburb to provide two feasible projects for the conjunctive regulation of surface water and groundwater. Sarwar et al. [39] set up conjunctive operation model of surface water and groundwater with the stimulation technique and dynamically stimulated groundwater level under different projects with FEFLOW. Safavi et al. [40] applied trained artificial neural network to setting up prediction model of groundwater level, with which optimum model is combined to set up optimum-stimulation model of conjunctive use of surface water and groundwater, this model is calculated through genetic algorithm.

3.2.6. Other methods

In recent years, neural network, grey system, fuzzy theory, chaos theory, genetic algorithm, intelligent decision support system as well as the other methods were used more and more in the conjunctive regulation of surface water and groundwater. Furthermore, the model formed by the combination of multioptimal methods also gains a rapid development, such as the combination of dynamic planning and the simulation technology and the combination of optimal algorithm and grey system, fuzzy theory, etc. The co-use of these methods can not only solve more complicated problems but also improve the model fidelity.

4. Existing problems of the research

In conclusion, the research on the model of conjunctive regulation of the surface water and groundwater and on the optimal methods has achieved many valuable results. However, with the development of the study, problems in the conventional mathematical planning methods become more and more obvious, which is represented in the following three aspects:

First, theory does not integrate with practice. At present, many conjunctive regulation models of surface water and groundwater only stay in the theoretical discussion stage and the results cannot really be used in the production practice. Though more and more factors are considered in the conjunctive regulation model, there is still a difference between the model and the practical situation of the complex system. In reality, it is inevitable that the boundary conditions and the causality will be simplified, and after the simplifying, the model is unable to reflect the conditions of the conjunctive regulation system. So how to transfer the theoretical achievements of the conjunctive regulation of the surface water and groundwater to productive practice is one of the difficult problems faced by the researchers.

Second, as the conjunctive regulation of surface water and groundwater involves many factors like hydrology, ecology, soil, crops etc., these factors mutually affect and restrict each other and form a complex large system, which includes many problems with randomness and uncertainty. But the current stochastic planning is only capable to process quite limited stochastic factors such as the system input, and how to effectively deal with the complex uncertain problem still needs further research.

Third, presently, the meso-scale conjunctive regulation of surface water and groundwater in irrigation district has accomplished lots of results, but its large scale and micro-scale research is inadequate, and the research on parameter calibration for the conjunctive regulation model, sensitivity analysis and model verification is relatively insufficient.

5. Development trend

With the technology development, in future, it should combine the computer technology such as expert system, decision support system, 3S technology, artificial intelligent technology, etc. with the numerical simulation and system analysis, construct a meta-synthesis model for the conjunctive regulation of surface water and groundwater and realize the integration of different temporal and spatial scales and the calibration of uncertain parameters. On the basis of it, the development of the commercial software really can be used to guide the production practice is one of the main development directions.

The conjunctive regulation of surface water and groundwater involves dualistic water cycle in the river basin, water resource management and planning, eco-environmental protection, land use etc, and its research scope relates to hydrology, water resources, ecology, soil science, meteorology etc. Only by studying the interaction mechanism of the surface water and groundwater from a multi-subject angle and uncovering the law of conjunctive regulation from different aspects, can we make up the deficiency in present research, radically improve the agricultural water management level, and apply the research results of water resources system to productive practice. Thus, the multidisciplinary cross and fusion of hydrology, water resources, ecology, soil science, meteorology, computer science, etc. will be the inexorable trend for the future development.

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References

[1] W. Su, N. Chen, Groundwater Resource Management Theories and Methods, Science and Technology Publishing House, Shanxi, 1999.
[2] Y. Guo, S. Li, Optimal Planning and Management of Irrigation and Drainage Engineering, Water Resources and Electric Power Press, Beijing, 1994.
[3] J. He, X. Li, Water Resources Planning and Management, China Agriculture Press, Beijing, 2006.
[4] Y. Shi, D. Zhu, Surface water and groundwater joint management model and optimization method research, Adv. Sci. Technol. Water Resour. 14(5) (1995) 16–21.
[5] E.N. Castle, K.H. Lindebory, Economics of Groundwater Allocation, Agri. Exp. Sta. Misc. Pap. 108, Oreg. State. Univ., Corvallis, OR, 1961.
[6] R. Willis, W.W-G. Yeh, Groundwater System Planning and Management, Prentice Hall, Upper Saddle River, NJ, pp. 21–23, 1987.
[7] D. Khare, M.K. Jat, Ediwahyunan, Assessment of conjunctive use planning options: A case study of Sapon irrigation command are of Indonesia, J. Hydrol. 328 (2006) 764–777.
[8] S. Li, R. Tang, Conjunctive use of ground and surface water in irrigation project, J. Hohai Univ. Natural Sci. 4 (1983) 1–1.
[9] C. Liu, W. Du, Optimal analysis on water conjunctive utilization considering environmental factors, J. Hydraulic Eng. 5 (1986) 38–44.
[10] J. Shao, Y. Cui, C. Li, Comprehensive multi-objective management model for conjunctive use of ground and surface water in Bao Tou City, China, Resour. Sci. 25(4) (2003) 49–55.
[11] W. Wang, J. Han, Y. Zhao, Optimal allocation of water resources in Yinchuan Plain, Resour. Sci. 26(2) (2004) 36–45.
[12] X. Liu, Z. Xu, J. Ding, Q. Liu, Research on the conjunctive dispatch model of surface water and ground water in the Huangshui River basin, Chin. Rural Water Hydropower 4 (2010) 12–16.
[13] H.W. Lu, G.H. Huang, L. He, An inexact rough-interval fuzzy 1inear programming method for generating conjunctive water-allocation strategies to agricultural irrigation systems, Appl. Math. Model. 35 (2011) 4330–4340.
[14] J. Matsukawa, Conjunctive use planning in Madriver Basin California, J.W.R. Plan & Manage. ASCE 120(2) (1994) 115–131.
[15] L. Bharati, C. Rodgers, T. Erdenbergere, M. Plotnikova, S. Shumilov, P. Vlek, N. Martin, Integration of economic and hydrologic models: exploring conjunctive irrigation water use strategies in the Volta Basin, Agric. Water Manage. 95(8) (2008) 925–936.
[16] S. Li, S. Peng, R. Tang, Non-linear programming model for studying the conjunctive use of water resources in irrigation project, J. Hydraulic Eng. 6 (1986) 11–19.
[17] B. Huang, J. Shen, Jensen model in the joint scheduling of the irrigation area "three waters", J. Irrigation Drainage 11(3) (1992) 39–43.
[18] J. Cheng, S. Liu, Z. Zhou, A solution of non linear model in conjunctive use of ground and surface water, J. Hydraulic Eng. 10 (1997) 53–57.
[19] Y. Li, X. Liu, X. Wei, W. Zhang, The study of optimal operation on surface water and groundwater resources in Baojixia irrigation area Yellow River, 31(3) (2009) 65–69.
[20] W.A. Hall, N. Buras, The dynamic programming approach to water-resources development, J. Geophys. Res. 66(2) (1961) 517–520.
[21] J.E. Noel, R.E. Howitt, Conjunctive multibasin management: An optimal control approach, W. R. R. 18(4) (1982) 753–763.
[22] M. Karamouz, R. Kerachian, B. Zahraie, Monthly water resources and irrigation planning: case study of conjunctive use of surface and groundwater resources, J. Irrigation Drainage Eng., ASCE, 130(5) (2004) 391–402.
[23] L. Cai, N.J. Buras, Dynamic management of surface water and groundwater in Yellow River irrigation area, J. Hydraulic Eng. 11 (1987) 37–44.
[24] S. Tang, Research on the model of optimization of multi-objective allocation of water resources in large valleys, J. Hohai Univ., Natural Sci. 20(6) (1992) 40–47.
[25] C. Dai, J. Liang, Application of dynamic programming for conjunct regulation of groundwater and surface water, Resour. Soil Water Conserv. 14(4) (2007) 143–145.
[26] C.C. Yang, L.C. Chang, C.S. Chen, Multi-objective planning for conjunctive use of surface and subsurface water using genetic algorithm and dynamics programming, Water Resour. Manage. 23 (2009) 417–437.
[27] Y.Y. Haimes, Hierarchical Analyses of Water Resources Systems, McGraw–Hall, New York, 1977.
[28] J.F. Matsukawa, Conjunctive use planning in Mad River Basin, California, J. Water Resour. Plan Manage. 118(2) (1992) 115–132.
[29] D.M. Cosgrove, G.S. Johnson, Transient response functions for conjunctive water management in the Snake River Plain, Idaho, J. Am. Water Resour. Assoc. 40(6) (2004) 1469–1482.

[30] L. Ru, Large-scale system optimal mode of reconstruction and extension of irrigation district, J. Hydraulic Eng. 1 (1987) 43–51.
[31] J. Liu, S. Zhang, H. Liu, Hierarchical model of optimal planning and operation for water supply in JJT area water resources large-scale system, Adv. Water Sci. 2 (1993) 98–105.
[32] X. Qi, H. Zhao, J. Wang, A large-scale multi layer hierarchical model for high-efficiency agricultural water resources management in Shangqiu experimental area, Irrigation Drainage 18(4) (1999) 36–39.
[33] L. Zhang, Research for water resources optimal distribution and mode of operation and maintenance in Penglou irrigation area, Master's Thesis of North China University of Water Resources and Electric Power, Zhengzhou, 2004.
[34] X. Liu, Q.G. Fu, H. Cui, K. Wang, Q. Zhang, A Large system decomposition coordination model of optimal operation on water resources in Chahayang irrigation district, Chin. Rural Water Hydropower, 11 (2008) 15–18.
[35] W. Wong, R. Yao, S. Liao, S. Hui, Simulation of conjunctive utilization of surface water and groundwater in Dashi River Basin, J. Chin. Hydrol. 5 (1984) 19–27.
[36] H. Yuan, A mathematical model for conjunctive utilization of surface and groundwater-a case study of optimal operating policies for the People's Victory Canal in Henan, J. Wuhan Univ. Hydraulic Electric Eng. 4 (1984) 157–167.
[37] D. Yin, H. Hu, S. Hui, Simulation and analysis of well-canal combined irrigation patterns in Yinbei irrigation district, J. Irrigation Drainage 22(1) (2003) 53–57.
[38] X. Wang, M. Xu, X. Zhou, Model research of united dispatching of surface water and groundwater in western urban and outskirts of Beijing, Site Invest. Sci. Technol. 5 (2005) 16–19.
[39] A. Sarwar, H. Eggers, Development of a conjunctive use model to evaluate alternative management options for surface and groundwater resources, Hydrogeol. J. 14 (2006) 1676–1687.
[40] H.R. Safavi, F. Darzi, M.A. Marino, Simulation-optimization modeling of surface water and groundwater, Water Resour. Mange. 24 (2010) 1965–1988.