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Development and application of water allocation model based on ET-control

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Abstract Traditionally, water allocation is to distribute water to different regions and sectors, without enough consideration on the amount of water consumed after water distribution. Water allocation based on ET (evaporation and transpiration) control changes this idea and emphasizes the absolute amount of evaporation and transpiration in a specific area. With this ideology, the amount of ET involved in the water allocation includes not only water consumed from the sectors, but also the natural ET. Therefore, the water allocation consists of two steps, the first step is to estimate reasonable ET quantum in regions, then allocate water to more detailed regions and various sectors with the ET quantum according to the operational rules. To make qualified ET distribution and water allocation in various regions, a framework is put forward in this paper, in which two models are applied to analyse the different scenarios with predefined economic growth and ecological objective. The first model figures out rational ET objective with multi-objective analysis for compromised solution in economic growth and ecological maintenance. Food security and environmental protection are also taken as constraints in the optimization in the first model. The second one provides hydraulic simulation and water balance to allocate the ET objective to corresponding regions under operational rules. These two models are combined into an integrated ET-control water allocation. Scenario analysis through the ET-control model could discover the relation between economy and ecology, and to give suggestions on measures to control water use with conditions of changing socio-economic growth and ecological objectives. To confirm the methodology, Haihe River is taken as a study case. Rational water allocation is an important branch of decision making in water planning and management in Haihe River Basin, since water scarcity and deteriorating environment fights for water in this basin, and reasonable water allocation between economy and ecology is a focus. Considering water scarcity conditions in Haihe River Basin, the ET quota is taken as an objective for water allocation in provinces to realise the requirement of water inflow into the Bohai Sea. Scenario analysis provides the results of water evaporation from the natural water cycle and artificial use. A trade-off curve based on fulfilment of ecological and economic objectives in different scenarios discovers the competitive relation between human activities and nature.

Key words water allocation; ET management; Haihe River Basin; multi-objective analysis

INTRODUCTION

Haihe River Basin is well-known as the most serious water shortage area in China, with a per capita quantity of water resources of 293 m^3. But the social and economic water demand ranks top in the country, with a rate of water shortage >20% in a normal year, and much more in dry year. Long-term water overuse and sewage discharge cause severe environmental and ecological problems. Subject to increasing pressure from social and economic water demand, water users in Haihe River Basin have excessively developed the water resources and discharged a huge quantity of wastewater, thus causing serious ecological and environmental problems.

To solve the water-related problems in Haihe River Basin, the integrated water resources and environmental management (IWEM) is promoted to realize rational allocation of water resources. The purpose is to promote the efficiency and benefits of water resources utilization, restore the ecology and environment, effectively alleviate water shortage, reduce continental source pollution to the Bohai Sea and truly improve the water environmental quality of the Haihe River Basin. The eligible model is needed to analyse the compromised solution for multi-dimensional decision-making. In recent years, water shortage and accompanying issues under deteriorating water conditions press for more research on water allocation. In the Yellow River Basin, near to Haihe Basin with similar water issues, water allocation with a flexible water-use limit against water shortage is applied to provide a practical measure for actual decisions in the water-short area (Shao *et al.*, 2009).

Some models have been developed to probe the multi-objective analysis on water allocation. During the earlier stage, some software packages were developed with simulation technology to analyse the outcome from a variety of water allocation policies during times of water shortage

(Burton, 1994). To make better decisions on water use among multiple sectors, the interactive Integrated Water Allocation Model (IWAM) is put forward in optimal allocation of limited water from a storage reservoir to different user sectors, considering socio-economic, environmental and technical aspects with three computational modules on reservoir operation, economic analysis and water allocation (Babel *et al.*, 2005). Practical demand under complex water issues increasingly shows multi-objective decision-making is an important direction for research on water planning and management. Therefore, a stochastic nonlinear programming model is used for a multi-period water allocation with multiple objectives.

An integrated model is put forward to simulate the scenario of water cycle and water allocation for multi-objective decisions. The core part of the model is the module of DAMOS (multi-objective decision analysis) and ROWAS (Rule-based Objected-oriented Water Resources System Simulation Model) which are conjointly applied to analyse the water allocation under foreseen economic growth and economic protection, to formulate the control plan for both water quantity and quality at provincial borders. The significant border conditions of completion of the South to North Water Transfer Project (SNWTP) and control of groundwater pumping are jointly operated to provide the results of comprehensive water resources planning of the Haihe River Basin.

FRAMEWORKS AND METHODOLOGY

Ideology of ET based water allocation

Traditionally, water allocation is to distribute water to different regions and sectors, without enough consideration of the amount of water consumed after water distribution. Water allocation based on ET control changes this idea and emphasizes the absolute amount of evaporation and transpiration in a specific area. Actually, there are two parts of ET in the whole process of the water cycle. The amount of ET involved in the water allocation includes not only water consumed from the sectors, but the natural ET. One is the amount from the natural process, mainly the evaporation from unexploited land, natural vegetation and water cycle. The other is the part caused by human activities, including farming land, water use by industry and households. Among these two kinds of water evaporation, the ET caused by human water use is controllable; the natural kind could be influenced passively by human activities. Therefore, the meaning of ET control herein is mainly to control human water use and consumption. The natural part of the effect of human activities could be briefly analysed under the framework of the water cycle.

Therefore, with this ideology the water allocation consist of two steps: the first is to estimate reasonable ET quantities in regions, then allocate water to more detailed regions and various sectors with the ET quantities according to the operational rules. These two steps are completed by the DAMOS and ROWAS model.

Methodology of DAMOS

DAMOS is a multi-objective decision model with consideration of society, economy, environment, water resources and investment based on the macroscopic mechanism of their relations. The interplay between resources and capital is abstracted under the promotion mechanism of water to socio-economic development and water supply.

DAMOS is a macroscopic model to seek the rational socio-economic development through multiple trade-off of objectives and determine the schedule of large-scale hydraulic project construction. Structurally, DAMOS consists of a macro-economic module, a production module, the water balance module and water environment and ecology module blocks. In order to optimize and seek the compromised solution, it needs to estimate and forecast gross domestic product, the ratio between consumption and accumulation based on the current data. It continuously optimizes the structure of GDP and the structure of water use with full consideration of the guiding principles of water saving planning in the optimization process, combined with macro-economic models and population models, water demand forecasting model and investment in enlargement of water supply sewage treatment projects. Moreover, DAMOS adopts the green equivalent area as a measure of the ecological indicators, combines water resources, investment and environmental, ecological, economic and other objectives organically through continuous development of the economy and change of urban employment rates. The relations of different modules in DAMOS are illustrated in Fig. 1.

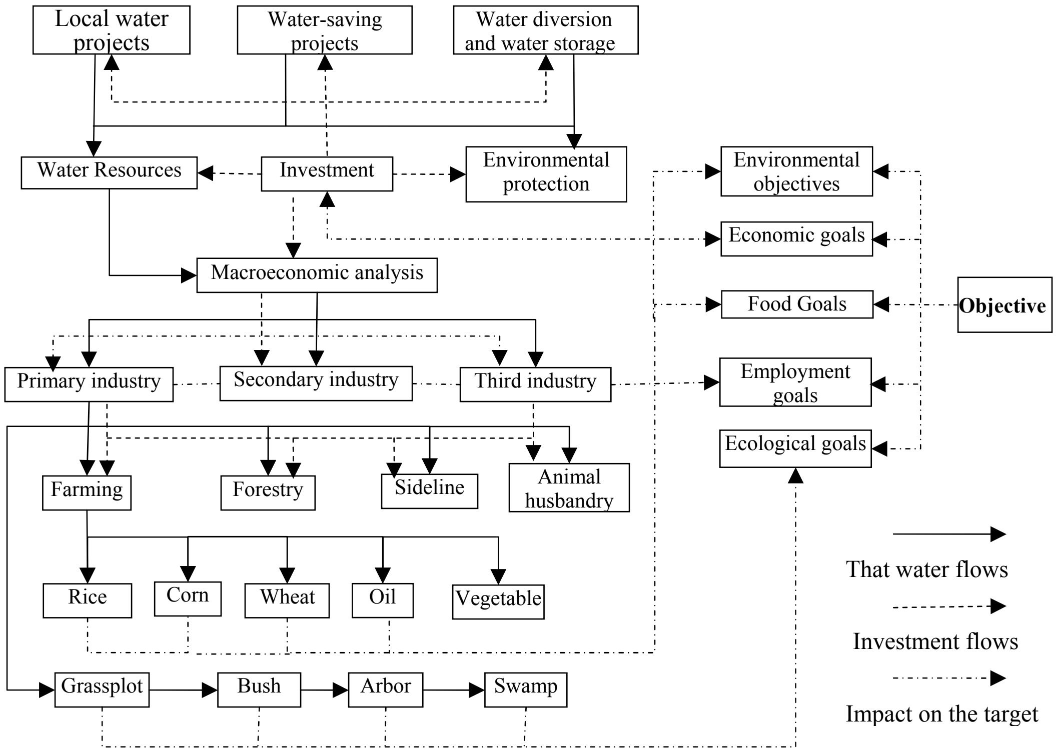

Fig. 1 the framework and inner relations of DAMOS model.

The Dynamic Input–Output module, which is used for analysis of the macro-economy development, illustrates the interrelationships among different national economic sectors. In addition to simulation of the economic activity, this paper focuses on the relationship between the economic development and water supply in water-scarcity areas. The main equation of the model can be written as follows:

$$\mathbf{BX}(t+1) = (\mathbf{I} - \mathbf{A} + \mathbf{B})\mathbf{X}(t) - \mathbf{V}(t) \tag{1}$$

where **B** is the matrix of capital; **X** is the total output vector; **A** is the matrix of direct consumption; **V** is the net products vector; and t is the time.

Considering the actual demand of Haihe River Basin, the highest GDP was treated as the economic development aim, grain yield approaching the central government's target was treated as the social stability index, groundwater overexploitation amount was treated as the sustainable water development goal, and chemical oxygen demand (COD) was treated as a health index of the environment. These four goals were interrelated, mutually-restrictive and incommensurable.

The objective equation of water allocation in the Haihe River Basin is:

$$Cobj = f\left[MaxGDP(t,d), MinCOD(t,d), MaxFOOD(t,d), MinOVEX(t,d)\right] \tag{2}$$

where the GDP represents objective of economic growth; COD is used to evaluate the quality of environment; FOOD means the minimal food production per capita to guarantee food security;

OVEX represents the amount of overused groundwater, which partially reflects the situation of regional ecology. The objectives "weights are set according to experts" experiences and different scenario setting. Besides the objectives, equations related to water balance, efficiency of water use and input–output table are taken as the constraints. The objectives and constraints are turned into linear programming and the software package of General Algebraic Modeling System (GAMS) is used to solve the optimization equation.

Methodology of ROWAS

ROWAS is a rule-based simulation model for water allocation, with a framework of general water resources system and its macroscopic realistic process, in which a river basin is modelled as different objects which represent the river basin physical entities or water users. In conceptualization of ROWAS, various elements are represented by abstracted conceptual objects which are described by different parameters.

In such a framework, the movement and conversion of various water sources are defined through these conceptual elements. The basic components involved in simulation are called calculating units. Calculating units are aggregates of water users, water treatment plants and combined information about small-scale water projects which are not listed separately in the network. Generally, the calculating unit is the overlapped area of a natural basin and administrative region. In this way, the natural hydrological characteristics are similar in calculation and it is convenient to collect data. The links are also divided into several kinds in terms of types of water flow. There are several links representing natural rivers, drainage of sewage, route of water supply and discharge from the separately listed water projects, respectively (Youjj *et al.*, 2005). There are 125 calculating units in total in Haihe River Basin (Fig. 2).

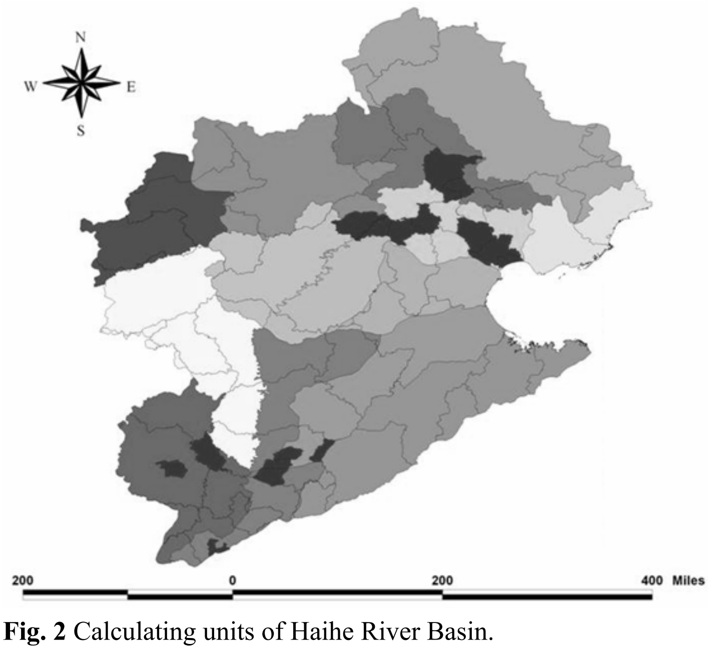

Fig. 2 Calculating units of Haihe River Basin.

To describe the major processes and relation among the objects in the framework, a set of rules are designed in the model. Through those rules, the movement and conversion in the system are conceptualized and described clearly. The rules are flexible and able to be modified or adjusted to adapt to different situations and requirements of users. The simulation model is created with those conceptual objects and corresponding rules. Table 1 show the basic elements used in ROWAS and the realistic objects they represent.

Table 1 Basic conceptual elements of ROWAS model.

Element	Type	Represented physical prototype
Node	Water source	Reservoir, pilot or diversion project
	Calculating unit	Congregation of water users, sewage-treatment and small-scale water projects in specific region
	Outlet	Terminal of flow (e.g. Ocean, lake, boundary of)
	Control cross section	Cross-section chosen according to demands
Line	River/canal	Directed segment representing line between two nodes, e.g. natural river, water supply canal, sewage canal

According to the purpose and the principle of ROWAS, it is applicable for river basin (regional) water resources and management. The water allocation in ROWAS model is classified in three layers under the model's framework. The first layer is to allocate water in time scale; the second layer is to allocate water in spatial scale, i.e. into different regions; the third layer is to distribute water in various sectors. Predefined rules and restraints are used in respective layers' water distribution. Figure 3 illustrates the framework of water allocation in ROWAS and the contraints.

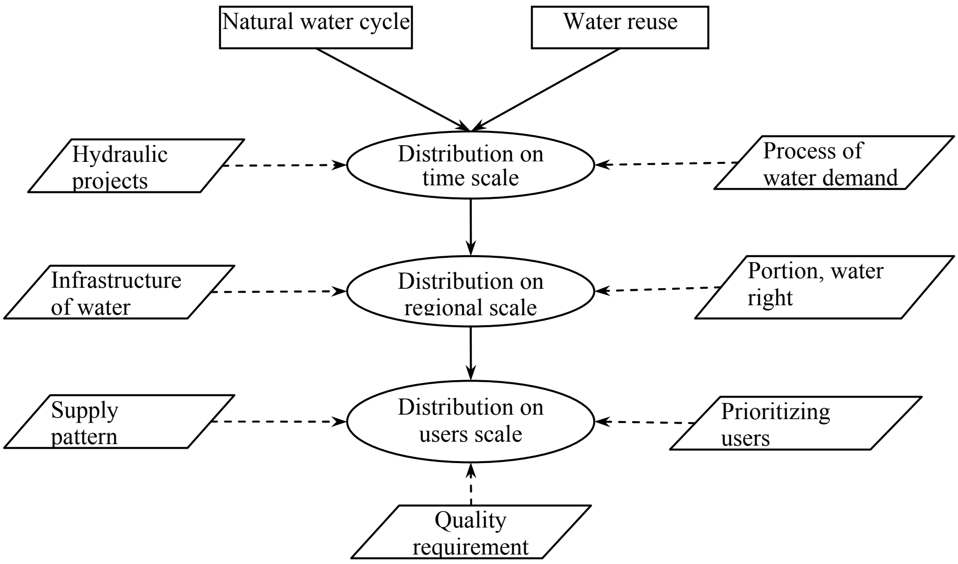

Fig. 3 Hierarchy and influencing factors of water resources allocation.

The input data of ROWAS model consist of two kinds of information, including basic information and control parameters. The basic information includes:

– Hydraulic relations: the relations to describe the water movement between different projects, water users and canals, discharge of sewage water.
– Information of water resources and hydrology: volume of total water resources, surface water, exploitable groundwater, available deep groundwater, natural inflow of reservoirs, irregular water resources.
– Information of large-scale reservoirs: total capacity, dead capacity, flood control volume, area–storage relation curve, regulation capacity, operation rules, natural inflow, principle of water allocation.
– Information of extraction and pilot projects: maxim capacity, range of water supply, inter-basin diversion project, time series of designed diversion process, regulation capacity.

Another kind of major input information is control parameter, which represents decision-making of specific scenario, including:

– Planning information: project planning, efficiency of canals, water consumption ratio, rate of sewage treatment and reclamation, capacity of canals, priority of water sources.
– Water demand: water use for economic activities, ecological and environmental demand.
– Information for model calibration: recent years' statistical data about water use, water supply, inflow into ocean and reservoirs.
– Information of water consumption: rate of consumed water (evaporated water) among total water use, infiltration of irrigation.

Model coupling

With above methodology, ET allocation can be realized from top layer basin level to lower layer smaller calculation units. The main process is as follows:

(1) First, comprehensively considering precipitation, groundwater overexploitation, transfer water amount and water into sea of the basin, the control target of ET was calculated by basin water balance analysis method. That is, the basin target ET was obtained.
(2) Second, based on the basin target ET, different kinds of ET targets of provincial administration units including natural ET and artificial ET can be calculated by the DAMOS model.
(3) Finally, under the restrictions of provincial level target ET and the control target of water withdrawal and drainage water, simulations of the artificial water cycle (ROWAS model) are carried out. Then, the target ET and total amount control indices in planning/management units and hydrological calculation units can be obtained.

Generally, target ET of hydrological calculation units and planning/management units can be achieved in the process with feedback to each other. The relation between the two models is illustrated in Fig. 4.

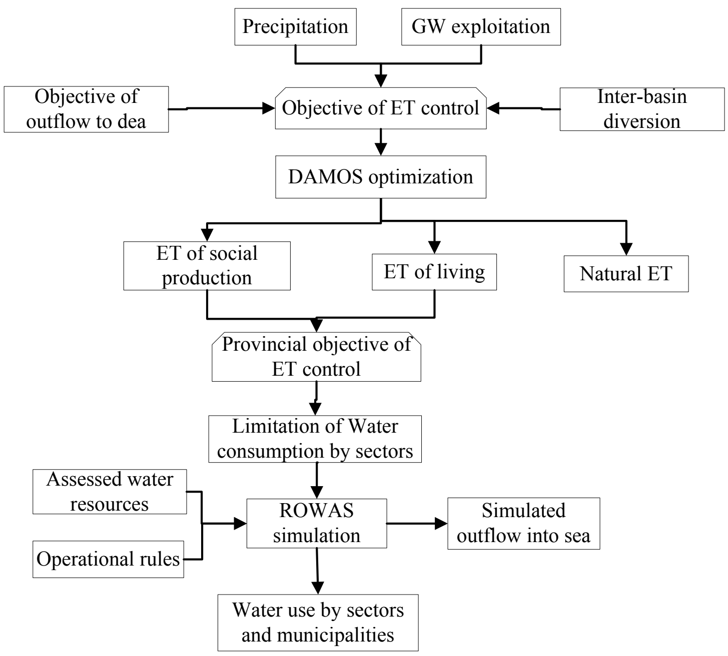

Fig. 4 Coupling of DAMOS and ROWAS.

OBJECTIVE SETTING OF ET CONTROL

Objective setting is a critical step for DAMOS application. Considering the general requirements of water resources planning and management, social development, economic growth, environmental protection and sustainability of water cycle are the major objective for decision-making.

The objective function for the DAMOS model is created based on equation (2). Besides the objectives setting, constraints are another important parameter setting for the DAMOS optimization. These constraints consist of different border conditions, mainly including maximal permitted groundwater exploitation, amount of inter-basin diversion, and minimal requirement of outflow to the sea. The inter-basin diversion includes three parts: the first two parts are diversion from the Middle Route and East Route of the South-to-North Water Transfer project, the third part is water diversion from the Yellow River.

According to above objectives and constraints, four scenarios are predefined to analyse different directions of water resources planning.

Table 2 Scenarios setting (units: 10^8 m^3).

Level year	Scenario name	Overpumping of groundwater	Water into sea	Inter-basin diversion		
				Middle route	East route	Yellow River
2020	S1	0	55	58.7	14.2	47
	S2	0	93	58.7	14.2	47
	S3	0	35	58.7	14.2	47
	S4	27	55	58.7	14.2	47

SCENARIOS ANALYSIS

According to the scenario settings, the results of predefined scenarios are optimized and simulated. The major results from the model are listed in Table 3. The results shows the simulated total ET of Haihe River Basin is higher than current situation since there will be more inter-basin diversion in future. Remarkably, total ET in S4 is higher than others since there is more groundwater exploitation. It indicates that the groundwater exploitation affects the ET dramatically. Simulation proved that natural ET is more stable than artificial ET. Water supply, therefore, is a decisive factor for objective realization of outflow to the sea. Higher water supply is accompanied with lower outflow to sea. Actually, ROWAS gives more detailed distribution of the total water supply to the municipalities and sub-basins.

Table 3 Major results of scenarios set (units: 10^8 m^3).

Item	2005 reality	S1	S2	S3	S14
Total ET	1571.0	1661.0	1623.0	1681.1	1703.4
GW overexploitation	78.0	0.0	0.0	0.0	21.7
Flow to the sea	24.86	58.6	95.3	35.8	71.1
Water supply	380.46	365.34	310.68	380.61	417.13

The results imply that the objectives of river basin management in Haihe River Basin are not consistent. The objectives of economic growth and ecological maintenance are incompatible. If more water supply is given to economic sectors, outflow to the sea might decline and reduce the environmental benefits. The conflicts could be compromised better with the analysis of DAMOS and implemented by ROWAS.

CONCLUSIONS

ET management, as an essential means for water management by control of regional water cycle, is an innovation. However, the methodology to realize this new concept is limited because of the difficulties in observation and control of ET. This paper put forward the framework to realize the

ET management by coupling two models. Based on the framework of water allocation, the objective of ET is classified into a natural part and an artificial part and allocated to different regions. The results prove that the framework is feasible, while more observation information is necessary to put into the model with refinement of model to make the scenarios analysis approach to reality.

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