Simulation based water resources allocation decision support system for Beijing

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Abstract

Sufficient quantity and quality of water resources are preconditions for the development of big cities. Water scarcity is especially a main restricting factor for cities in semi-arid or arid climate zones. An example for such a city is Beijing. The capital of P.R. China takes up the challenge of water shortage, the outstanding conflict between water supply and demand.

Sustainable utilization of water resources through modern technologies has become an important research subject. In this paper the approach of an decision support system (DSS) for the joint optimal operation of different water sources such as surface water, ground water, recycled water and transferred water is presented. It will be developed in the frame of the joint Chinese - German project "Toward Water-Scarcity Megalopolis's Sustainable Water Management System". The project is of significance for the sustainable development of economics and society in Beijing and the success of the Olympic Games in 2008. An indispensable requirement for such a DSS is a simulation model of the water resources and the water supply system.

Keywords: water resources management, water scarcity, decision support system, optimised water allocation, simulation system

INTRODUCTION

Beijing is a fast growing city. For several years the total population has increased steadily as well as the economy has grown very fast. The trend will continue in the future. An increasing demand of several resources, especially water, follows from this development. In connection with the semi-arid climate, these are the causes for the scarcity of the resource water in Beijing. Without consideration of sustainable resources use, the very positive development of the region is endangered.

Central management of all usable water resources for the city is urgently needed. That is why the Beijing Water Authority (BWA) is developing a "Capital Water Resources Allocation Decision Supporting System" to assist in the management of all the water resources of the capital of the People's Republic of China.

The general objectives of the joint Chinese - German project "Toward Water-Scarcity Megalopolis's Sustainable Water Management System" are as follows:

- To build rainfall - runoff models for the catchment areas of the most important reservoirs in the Beijing region with the aim to improve precision of runoff forecast.
- To establish water demand prediction models for a large city to solve the problem of water demand prediction under different circumstances.
- To built the joint operation model of multi water resources including surface water, groundwater, recycled water and water diversion as well as to primarily solve the allocation problem of Beijing water resources.
- To primarily establish operation-orientated Beijing water resources integrated allocation decision supporting system (DSS) and provide techniques for water resources management and decision-making.

The project is under the charge of BWA, German Fraunhofer Institute for Information and Data Processing and Fraunhofer Center for Applied Systems Technology. The project will be completed until 2008.

The DSS will realize an optimal allocation of existing water resources such as surface water, ground water, recycled water and transferred water. That means an multiple optimization problem has to be solved (Rauschenbach (2001)). Therefore, a goal function and a simulation model of the water resources as well as of the water supply system are necessary. In the first phase of the project the simulation model of the Beijing water supply system will be developed. Starting point for this development is a rough model for the simulation of the surface and groundwater resources. This model meets the demands for a decision support system with respect to accuracy and simulation speed. The model takes account of

- the Miyun, Guanting, Huairou and Baihebao reservoirs and their catchment areas,
- the groundwater storage,
- the rivers and channels linking the reservoirs to the city and
- the pattern of consumption in households, industry and agriculture.

This paper presents the simulation model and the first experiences with this model as well as a first definition for a goal function for use in the DSS.

STRUCTURE OF DECISION SUPPORT SYSTEM

The objective of the project is to establish an integrated intelligent water resources allocation decision support system based on GIS. It uses advanced computer and net work technology and it implements a man-machine-interface between decision makers and the system. Fig. 1 shows the logical structure of the DSS which will be developed.

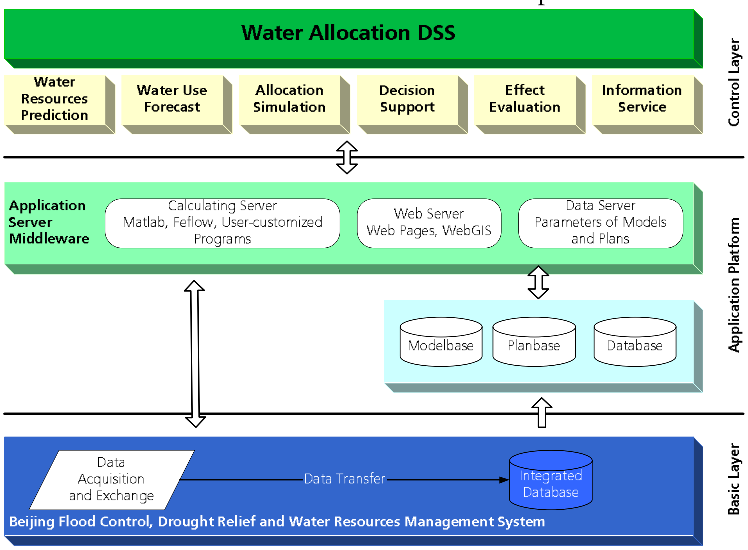

Fig. 1 The logical structure of the "Capital Water Resources Allocation Decision Supporting System"

The DSS is designed as a distributed system, which consists of three layers. These are the basic layer, the application layer (application platform) and the control layer. In the basic layer, the functions for data management and data storage are concentrated. The simulation models and the optimization strategies for decision-making are located in the application layer. Man-machine-interface is provided by the control layer. From here, the locally distributed users can access data and simulation results as well as optimization results. Therefore different rights of access can be assigned to the users.

STRUCTURE OF THE WATER SUPPLY SYSTEM

The structure of the system is shown in Fig. 2. All essential parts of the Beijing water supply system will be considered in the model (BWA (2003)). First, there are the four reservoirs Miyun, Huairou, Baihebao and Guanting. The catchments area models are integrated in this system in order to take into account the precipitation and the evapotranspiration. Further sources are groundwater storages. Secondly there are the water transportation systems such as channels and rivers. Miyun reservoir and Huairou reservoir are connected with Beijing-Miyun water diversion. After that, the water flows in this channel in direction Beijing. The arrows show the directions of water flows. In the simulation model, these arrows describe hydraulic behavior of water flow. Baihebao and Guanting reservoir are connected with tunnel and river Guishui. From Guanting water runs inside the Yongding river water diversion system to Beijing. Existing retention areas for flood control will be considered later in the simulation model.

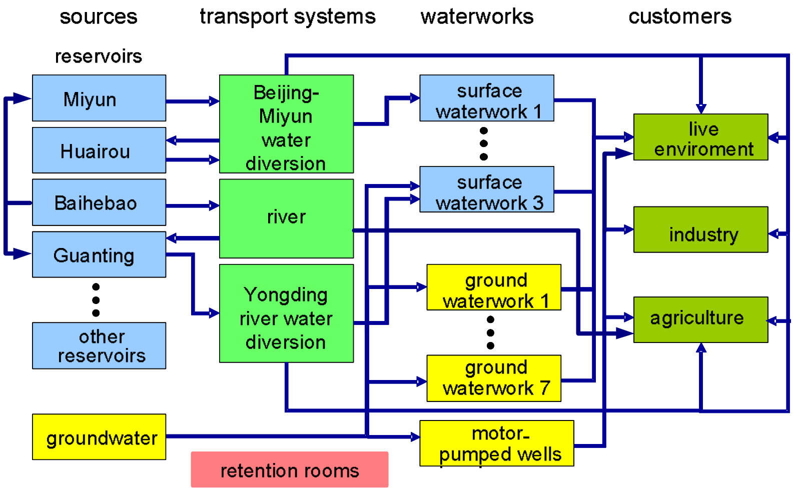

Fig. 2 Structure of the Beijing water supply system

The surface water from channels and rivers is delivered to the customers in two ways. Either water is delivered directly from the channels to the customers or the surface waterworks distributing the water. Ground waterworks as well as motor-pumped wells distribute groundwater to the customers. These waterworks are the third part of the Beijing water supply system. The several customers are the fourth part of this system.

ELEMENTS OF THE SIMULATION MODEL FOR THE WATER SUPPLY SYSTEM

This section describes the subsystems of the Beijing water supply systems, which are essential to the creation of a model. The Library "ILM-RIVER" is used for simulation (Pfuetzenreuter & Rauschenbach (2005)). In this library the following modules are available:

- *Catchment area:* The catchment area model serves to assist in long-term forecasting or simulation of water flow at the output of the catchment area. The input values are the measured precipitation and the potential evapotranspiration (ETP). There are three submodels in the overall system. Submodel 1 calculates the net rainwater from the measured rainfall data and the ETP. Submodel 2 computes transportation of surface water (surface runoff), and submodel 3 the drainage of water into the water table (groundwater flow). The model for storage of surface water has non-linear behaviour.
- *Surface water reservoir:* The height and volume of the stored water, taken as a measurement of the storage effect, are the significant parameters for the state of a reservoir. There is usually a non-linear relationship between the two values, which can be represented with a characteristic curve for the volume of a particular reservoir. From the start volume, inflow to the reservoir causes an increase in volume. The system is thus effectively an integrator. If there is simultaneous outflow from the reservoir, the difference between the in- and outflows will cause an alteration to the volume stored. The change in the height of the dammed water can be determined by means of the characteristic curve for the volume.
- *Groundwater reservoir:* A similar model to that applied for the surface water reservoirs is used to simulate the groundwater reservoir. However, there is one difference from the way the surface reservoirs are to be seen. Groundwater storage does not take place in one single homogeneous body of water, but in hollow spaces in the soil. This makes it necessary when creating the model to have regard to a po-

rosity factor for the earth. In the case of the model for groundwater storage, if the same quantity of water enters the same absolute volume for storage as in the surface storage model, there will be a greater rise in the water level. The model reflects this.

- *Waterworks:* There are waterworks for both groundwater and surface water in the Beijing water supply area. The same model is used to simulate both types. The task of the waterworks is to satisfy customers' demand for water from an available reservoir or water flow. It is necessary to take into account the supply limits for a waterworks, which are determined by the design of the works.
- *Pumping stations:* The pumping stations are modelled in the same way as the waterworks, because, for the purposes of this simulation model, it can be said that a pumping station works as a waterworks does.
- *Rivers and channels:* The flow characteristics are represented in this rough simulation model by simple lag elements of the first order combined with dead-time elements. In the detailed models to come, the hydrodynamic behaviour of a conduit will be depicted by resolution of higher order partial differential equation systems such as the Saint-Venant equations. Using the solution at present selected, the runtime of the water in the river or channel can be described as well as can be described the alteration in energy/shape of a surge of water as it proceeds through a section of conduit.
- *Data generator:* As there are certain input time series, which are not known, the simulation system has to be provided with assumed values for them. Instances of this will be the time series for precipitation or for consumption. The sample time is one hour.

5 SAMPLE SIMULATION

To prove that the simulation model works, a rough approximation of the Beijing situation was taken as a sample for simulation. A time series for a year's precipitation divided into hourly steps was generated for the purpose, as was a similar set of evapotranspiration values. Parameters based on experience were entered into the catchment area model. The various characteristics for reservoirs were also created, though in this case all that was known was the storage capacity. The geometry of the reservoirs was based on assumptions. An annual figure for the water surface evaporation which was matched to the actual conditions was assumed (and divided into the relevant series of values). The dead-times and delay-times for the rivers and the channels (both above and below ground) were approximated and taken over. Consumption characteristics were generated as a series for the year with a figure for every hour, and the relevant consumer demand linked to the appropriate waterworks, pumping stations and storage facilities (reservoirs and groundwater). Fig. 3 shows time series of precipitation and evapotranspiration for the year at hourly intervals. The sum of precipitation for the year is 578 mm.

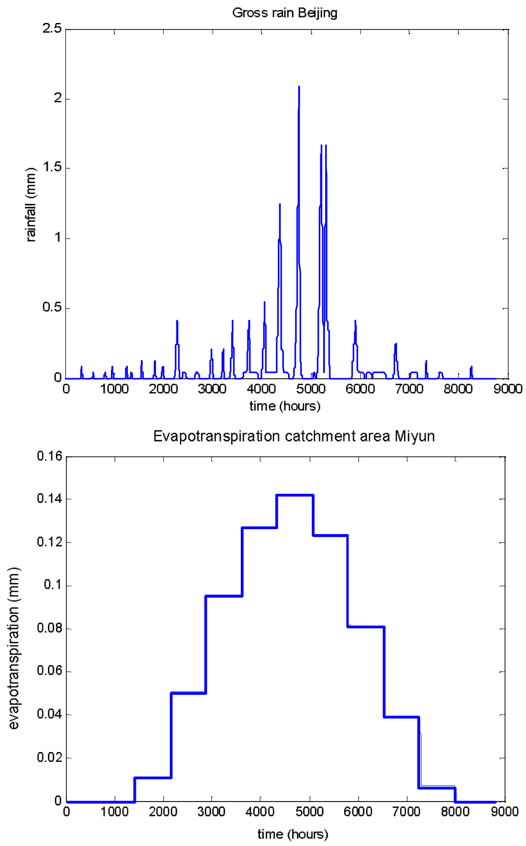

Fig. 3 Assumed annual rainfall and evapotranspiration for the Beijing area

Only the one year total consumption of water of the individual customer groups was known. Assumptions were therefore made for the time series of the water demand.

Some simulation results shall be shown now. The water flowing from the Beijing catchment area in the form of groundwater flow as well as the water level in the groundwater storage are represented in Fig. 4. The maximum of the catchment output is postponed by approximately 1000 hours from the time of maximum precipitation and considerably smoothed. At the beginning of the year the water level is still 20 m. At the end it is 19.38 m and so has dropped by 62 cm a year. Changes to the water table are positive under the influence of additions from the catchment area and from channels and the river network, and negative under the influence of outflow to waterworks and pumping stations.

Fig. 5 shows the water inflow into the Miyun reservoir and the appropriate water level. The peaks of the inflow can get up to practically 1000 m^3/s. The inflow from the groundwater was set at zero at the beginning and is characterised by a large delay-time and dead-time, groundwater flow is barely noticeable before 4000 hours have passed. At the end of the year it is still there, at 50 m^3/s. The figure taken for the beginning of the year was 24 m, the maximum level. At the end of the year the reservoir does still have a level of 22.5 m. The downward slope in the graph between 0 and 4300 hours is to be attributed to the effect of evaporation, of water diversion into the Beijing-Miyun channel at 50 m^3/s, and into the river Chaobai at 30 m^3/s, and of the demand from the No. 9 waterworks at approx. 10 m^3/s. The little additional groundwater coming from the catchment areas fails to compensate for these outflows. The start of the rainy season becomes apparent at 4300 hours. The inflows are then greater than the outflows. The water level rises until about at the 7000th hour. After that, the outflow again dominates and the level at the end of the year is 22.5 m. If the outflow regime selected is continued, a similar inflow figure over 5 years would mean that considerable restrictions must be set on consumption.

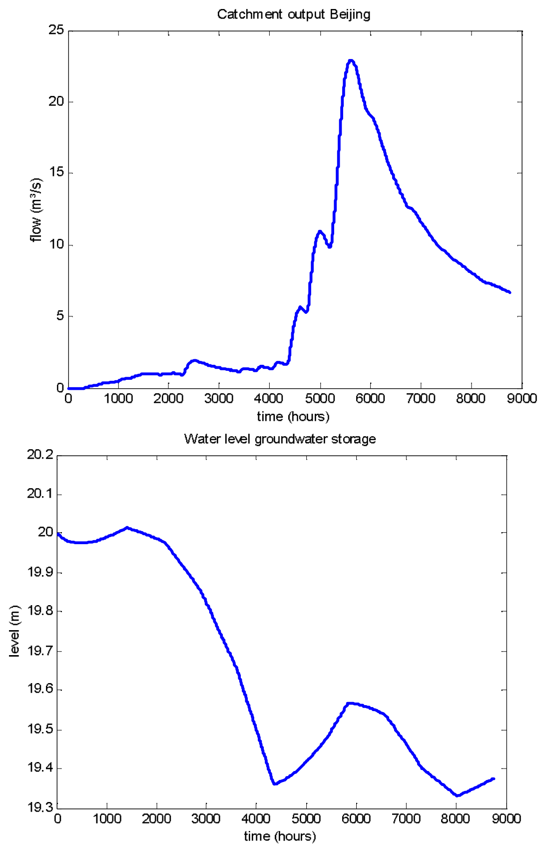

Fig. 4 Inflow of the city catchment area into the groundwater storage of the city region and the water level of this groundwater storage

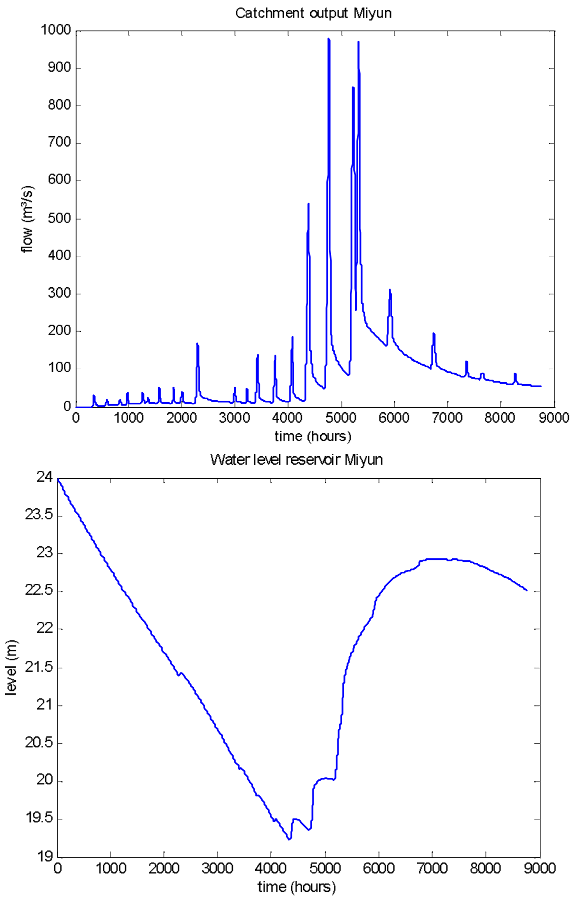

Fig. 5 Runoff from the catchment to Miyun reservoir and water level in the Miyun reservoir

GOAL FUNCTION FOR OPTIMIZATION

One can take the above-mentioned simulation results as a basis for characterizing the water supply situation in Beijing as follows (Rauschenbach & Gao. (2005)):

- The surface water and groundwater resources are decreasing.
- Main part of precipitation is concentrated on months July and August.

- The demand of drinking-water and industrial water will increase in next years.

Therefore, essential aims of the project are to prevent the water resources (especially groundwater) from decreasing and to guarantee the water supply of households, industry and agriculture. In order to achieve these goals a multiple criteria optimization problem has to be solved (Ehrgott (2005), Soncini-Sessa, R.. & others (2000)). A first approach for a goal function I(t) to be minimized is defined as follows:

$$I(t) = \alpha_1 \cdot I_1(t) + \alpha_2 \cdot I_2(t) + \alpha_3 \cdot I_3(t) + \alpha_4 \cdot I_4(t) \quad \text{with} \sum_{i=1}^{4} \alpha_i = 1.$$

In this equation the sub criteria have the following meaning:

1. The groundwater level change $\Delta H_G(t)$:

$$I_1(t) = \begin{cases} \min\left(-\Delta H_G(t)\right) & \text{for} \quad 5 \text{ to } 9 \text{ years} \left(\Delta H_G(t) \le 0\right) \\ \Delta H_G(t) & \text{for} \quad 10 \text{ to } 14 \text{ years} \left(\Delta H_G(t) \approx 0\right) \\ \max\left(\Delta H_G(t)\right) & \text{for} \quad \ge 15 \text{ years} \left(\Delta H_G(t) > 0\right) \end{cases}$$

2. The supply deficits of households $D_H(t)$, industry $D_I(t)$ and agriculture $D_A(t)$ in the following two possible forms:
   a. Mean deficit:

   $$I_{2,3,4}(t) = D_{H,I,A}(t) = \frac{1}{n} \sum_{i=1}^{n} \left(d_i - s_i\right)^+$$

   $$\text{with } \left(X\right)^+ = \begin{cases} X & \text{for} \quad X > 0 \\ 0 & \text{for} \quad X \le 0 \end{cases}$$

   with d_i demand per time unit and s_i supply per time unit.

   b. Days or months with deficit:

   $$I_{2,3,4}(t) = D_{H,I,A}(t) = \sum_{j=1}^{n} g^j$$

   $$\text{with } g^j = \begin{cases} 1 & \text{for} \quad s_i < d_i \\ 0 & \text{otherwise.} \end{cases}$$

In the next phase of the project, this goal function will be used for the optimization of water resources allocation in Beijing. That means the DSS delivers optimal trajectories (in the sense of the goal function) for the control of reservoirs, sluices pumping stations etc. An essential precondition for this way of proceeding is the simulation model above described.

SUMMARY

For the planned "Capital Water Resources Allocation Decision Supporting System" a simulation model of the water resources and the water supply system is indispensable. That is why in the first step of the joint Chinese - German project "Toward Water-Scarcity Megalopolis's Sustainable Water Management System" a rough simulation model has been developed. The advantages of this simulation model are that

- the main trajectories of the Beijing water supply system are simulated,
- the water levels in reservoirs and groundwater storage are simulated,
- the user of the model can modify its parameters with ease, thus adapting it to the supply system as found,
- it is also possible to adapt the structure of the simulation model (e.g., to take account of new building works),
- calculations on alternative scenarios can be carried out to answer questions of the "What will happen if ...?" type, including questions relating to best or next best means of operating the water reservoirs or how they are likely to be replenished in the near future according to forecasts of rain or snow,
- use of the model takes place through an easy to use human-to-machine interface (the software toolkit MATLAB/SIMULINK was used to program the simulation model).

Now the project partners are working on enhancement of the presented rough simulation model. A more detailed simulation model is in the process of development. The bases for this model are detailed information about the structure of the elements of the Beijing water supply system as well as extensive data sets of measured historical data.

In that process, the simulation tool will have to be adapted to fit the tasks required for the decision support system. Both are necessary: sufficient accuracy to meet the needs of the intended application, and sufficient simulation speed to enable swift and reliable weighing of alternative decisions (Rauschenbach & Wernstedt (1999)). And neither of these necessities is too much to expect of the model here presented.

Optimization methods are used for the decision making process. Thus, it is necessary to define a goal function for use in the optimization algorithm. A first possible goal function in form of a sum criterion was presented in this paper. This will be the starting point for the next phase of the project. The planned decision support system will be developed, will be tested and will be taken to use until 2008.

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