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A SIMULATION-OPTIMIZATION-BASED DECISION SUPPORT SYSTEM FOR WATER ALLOCATION

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ABSTRACT

Water is critical, but often overlooked element in sustainable development. The paradigm encapsulated in the "Beijing water allocation decision support system" (BjDSS) explicitly challenges conventional, fractional water development and management systems and places emphasis on integrated approach with more coordinated decision making across sectors and scales. Recognizing that exclusively top-down, supply-led, technically-based and sectoral approaches to water management are imposing unsustainably high economic, social and ecological costs on human and on the natural environment. BjDSS utilize optimization techniques to facilitate optimal decision making in the planning and management of especially large scale water resources systems. A water system involves several stakeholders with different, often conflicting objectives, and thus the proper framework for the statement of the decisional problem under consideration should be that of multi-objective decision analysis. Therefore, BjDSS couples a simulation model based on the RiverMod-Library with numerical search methods IPOPT/HQP for optimizing relevant decision variables. The concept is tested and now in application on the large scale Beijing water supply system, where all challenges of water resources management come together.

***Index Terms*—** Decision supports system, water resources management, optimization, sustainable development

1. INTRODUCTION

Beijing is located in Northeastern China. This semi-arid region sits on the downstream portion of the Haihe Basin in northern apex of the Great North China Plain. It is bordered by the Mongolian Plateau to the north, Yanshan Mountains to the northeast. The Municipal Region of Beijing consists of 16,800 km2. Beijing is in a temperate zone with a semi-humid monsoon climate. There are four distinct seasons in this region: a cold and dry winter, a windy and dry spring, a hot and rainy summer, a cool and humid autumn. Average annual precipitation in the region 560 mm with total annual water supply resources available in the region are approximately 6.91 billion m3 in a normal year and 4.83 billion m3 in a dry year. Rainfall varies geographically, seasonally and yearly. Eighty-five percent of rainfall falls between July and September. At times, 40-70% of rainfall falls within 3 days. Precipitation is also extremely varied from year to year, typically in a cycle of several consecutive wet years followed by several consecutive dry years. Variable rainfall makes Beijing prone to both floods and droughts. Since the 1980s, the region has faced increasingly difficult drought problems.

Groundwater is the most important source of water for the Beijing region. Beijing draws 50-70% of its water from groundwater. The quality of groundwater in the Beijing area is generally acceptable. Almost all available groundwater resources are already developed. Beijing has suffered from over exploitation of this source. In the late 1970s and early 1980s, drought forced farmers to turn to groundwater, which had previously only been used by industry and households. As a result of over-pumping, the water table experienced fell throughout the 1980s with a citywide subsidence rate of 0.5m/year with up to 1m/year in some places. Groundwater levels in some areas have fallen by as much as 40 m since the late 1970s, with some spots pumped down to the bedrock. Surface water supply in the Beijing region depend mainly on upstream inflows. The major river systems affecting this region include the Chaobai, North Grand Canal, Yongding. Almost all of these river systems stem from the mountainous areas in neighboring provinces. Aside from problems such as excessive withdrawal and water quality deterioration of surface waters, the lack of regional coordination leads to issues such as uncoordinated withdrawals (e.g. upstream withdrawals affecting downstream cities negatively) and upstream water contamination.

Beijing's total population has topped 17.4 million, including just over 12 million official residents in the

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Thanks to BMBF for funding.

household register and 5.4 million in the floating population. With population growth and expansion of the economy, water demand has increased dramatically over the past two decades. Total water demand for the Beijing municipal region was estimated at 4.1 billion m^3 in 1987, 4.3 billion m^3 in 2000, and 4.9 billion m^3 in 2010. Agriculture accounted for about 65% of this water use, while domestic and industrial uses made up the rest Although proportionally, use of water in Beijing for irrigation purposes has reduced, agriculture still remains the largest water user in this region. Some efforts have been made to reduce agricultural use of water, mainly through the application of water saving technologies. Domestic water use in Beijing is probably rising at the quickest rate. Additionally, domestic household consumption per capital has risen from 28 l/day per person in 1949 to 240 l/day/person in 2000 and 300l/day/person 2010.

Industrial water demand has also risen in absolute volumes. In the last fifteen years, water demand by industry has increased 57.5%. However, water demand per industry is decreasing due to efforts to reuse water. While water demand has increase 57.5%, total industrial output has increased by 650%. This implies that either industries are becoming more water-efficient or that they are shifting towards sectors with lower-water requirements. In Beijing there is evidence that both phenomenon occur. Industrial wastewater reuse rates have increased from 45.3% of total water volume in the early 1980s, to 91.4% in 1996. There has also been a movement away from heavy industry in this region, as governments promote high-tech and tertiary sectors.

1.1. Objectives of the decision support system

The objective of the project is to establish an integrated intelligent water resources allocation decision support system to

(1) provide decision support for comprehensive water management: Surface water and groundwater resources, (2) Support water management through comprehensive water models for SIMULATION and model-based OPTIMIZATION and (3) Support water management through SCENARIOS.

2. THE DECISION SUPPORT SYSTEM

The Beijing water DSS uses advanced computer and network technology and implements a man machine interface between decision makers and the system. Fig. 1 shows the logical structure of the DSS which was developed.

The DSS is designed as a distributed system, which consists of three layers. These are the basic layer, the application layer and the control layer. The functions for data management and data storage are implemented in the basic layer. The simulation models and the optimization strategies for decision making reside 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.

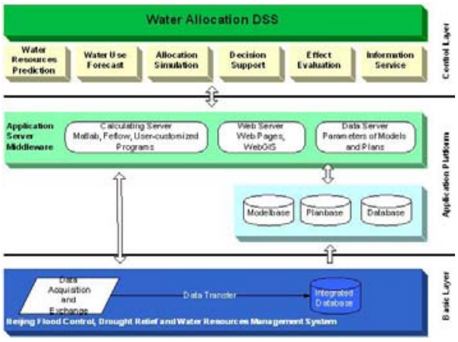


Fig. 1. Logical structure of DSS

3. THE WATER SUPPLY SYTEM

The structure of the Beijing water supply system is shown in Fig. 2 and all essential parts of the system are considered in the simulation model[1]. 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 and Huairou reservoirs 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 by tunnel and river Guishui. From Guanting water runs into the Yongding river water diversion system to Beijing. Existing retention areas for flood control are also considered in the simulation model.

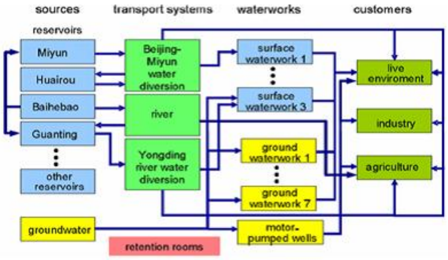


Fig. 2. Structure of the Beijing water supply system

The surface water from channels and rivers is delivered to the customers in two ways, either directly from the channels to the customers or through the surface waterworks. Groundwater is distributed to the customers through ground waterworks as well as motor-pumped wells. Therefore, the waterworks build the third part of the Beijing water supply system and the several customers are the fourth part of this system.

3.1. Elements of the simulation model

This section describes the essential subsystems of the Beijing water supply systems. The Library "ILMRIVER" is used for simulation (Pfuetzenreuter & Rauschenbach (2005)). The following modules are integrated in the Library:

1. *Catchment area:* The catchment area model serves to assist in long-term forecast or simulation of water flow at the output of the catchment area. The required inputs 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 nonlinear behaviour.

2. *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 nonlinear relationship between the two values, which can be represented by 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 stored volume. The change in the height of the dammed water can be determined by means of the characteristic curve for the reservior.

3. *Groundwater reservoir:* A similar model as the surface water reservoir model is used to simulate the groundwater reservoir. However, there is one difference from the way the surface reservoirs behave. Groundwater storage is not a homogeneous body of water, but water appears in hollow spaces in the soil. In regard to this a porosity factor is included in the model. 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.

4. *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 the available water sources. It is necessary to take into account the supply limits for a waterworks, which are determined by the design of the works.

5. *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.

6. *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. The hydrodynamic behaviour of a conduit will be depicted by resolution of higher order partial differential equation systems such as the Saint-Venant equations.

7. *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.

8. *Water demand:* Water use/demand is a complex function of socio-economic characteristics, climatic factors and public water policies and strategies. This study therefore develops a models for industrial, agricultural and domestic water demand based on the multivariate econometric approach which considers these parameters to forecast and manage the water use/demand. The model applies statistical tools to select suitable demand function and most relevant explanatory variables that have strong relationship with water use/demand.

4. OPTIMIZATION MODEL

The 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

4.1. Formulation of the allocation problem

The water resources allocation problem is formulated as a discrete-time optimal control problem:

$$\min_{u^k,\ \mathrm{k=1,\ldots,K}} \left\{ F\left(x^K\right) \ + \ \textstyle\sum_{k=0}^{K-1} f_0^k\left(x^k, u^k, z^k\right) \ \right\}$$

subject to

$$x^0 = x\left(t_0\right) x^0 = x\left(t_0\right)$$

$$x^{k+1} = f^k\left(x^k, u^k, z^k\right) x^{k+1} = f^k\left(x^k, u^k, z^k\right)$$

$$h^k\left(x^k, u^k, z^k\right) = 0 h^k\left(x^k, u^k, z^k\right) = 0$$

$g^k\left(x^k,u^k,z^k\right)\leq 0 g^k\left(x^k,u^k,z^k\right)\leq 0$

The equality and inequality constraints of the full discrete-time optimal control problem are composed of the constraints of the individual elements (nodes and connections) of the network. The overall objective function is the sum of all objectives of the network elements.

4.2. Solution of the allocation problem

The discrete-time optimal control problem is first transformed to a nonlinear programming problem:

$$\min_{y}\ \left\{J\left(y\right)\ \mid h\left(y\right)=0\,;g\left(y\right)\leq 0\right\}$$

Depending on the purposes of water management planning, objective functions can be formulated in various forms and should incorporate measures such as efficiency (i.e., maximizing current and future discounted welfare), survivability (i.e. assuring future welfare exceeds minimum subsistence levels), and sustainability (i.e. maximizing cumulative improvement over time)". The criteria are economic, social and environmental issues. Some common types of objectives include: (1) maximizing the flow to downstream nodes, (2) maximizing the economic production, (3) minimizing the differences in water deficits among all demand sites, or (4) minimizing the pollutant concentrations at some locations, (5) maximize groundwater head at final time, (6) maximize reservoir level at final time.

There exist two possible approaches for this conversion process:(1)Formulation in the space of the control variables and (2) Formulation in the space of the state and control variables.

The first approach requires the elimination of the state variables und leads to an unstructured nonlinear programming problem of dimension (Km) (K- number of time steps, m- number of control variables), which can be solved numerically with about O $\left((Km)^3\right)$ basic arithmetic operations. Simple bounds of the state variables turn to general constraints of the control variables:

$$x_i^k\leq x_{i,\max}^k\Rightarrow g\left(u^0,u^1,\ldots,u^{k-1}\right)\leq x_{i,\max}^k$$

The Hessian matrix as well as the Jacobian matrices of the equality and inequality constraints is in general full.

Using the second approach the vector of optimization variables y contains the state and control variables of all stages:

$$y=\left[\left(x^0\right)^{\mathrm{T}}\ \ \left(u^0\right)^{\mathrm{T}}\ \ \ldots\left(x^K\right)^T\right]^T$$

The process equations of the discrete-time optimal control problem are directly included in the nonlinear programming problem. While the problem dimension resulting from this formulation $(K\,(n+m)+n)$ is higher (n- number of state variables), the advantage is the special sparsity structure with a block-diagonal Hessian-matrix and block-banded Jacobian matrices. The numerical solution effort is about O $\left(K\,(n+m)^3\right)$ basic arithmetic operations. From simple considerations about the structure of the water resources allocation system at hand follow, that the second approach for transformation can lead to a significant lower computational cost. The IPOPT solver is the currently most efficient, freely available optimization solver, which is suitable for large-scale, highly-structured problems [2].

Another optimization solver, which is specially suited for structured problems due to discrete-time optimal control problems and is also freely available, is HQP (Omuses). One important advantage of this solver is the special tailored problem interface, which allows for very efficient problem formulation process. Furthermore HQP uses the automatic differentiation software Adol-c to compute numerically exact derivatives of the objective function and the equality and inequality constraints with respect to the optimization variables, which are necessary for gradient-based optimization algorithms.

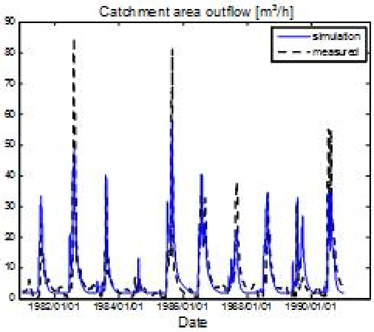
5. ORGANIZING MODULE

The DSS applies the scenario technique as a method for strategic planning, for preparation of decisions, determination of future developments and early detection of changes. To be able to make good decisions, relevant, typical, extreme, and trend scenarios should be analysed. The organizing-module simplifies the system configuration and scenario generation for the user and builds a communication interface between all components of the DSS. The DSS saves scenario data for further applications and controls the execution flow of the individual components of the DSS. For the scenario configuration the organizing module requires information about the factor-lists from the different models, data from the database and controls the information flow for all modules and models.

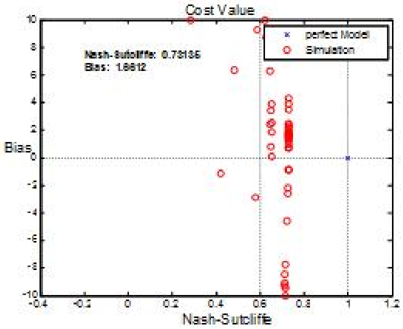
6. EXAMPLE RESULTS

6.1. Example results - Watershed modeling

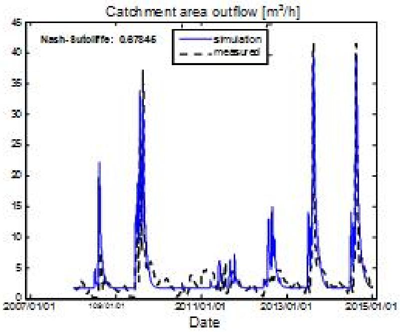
Fig. 3 a-c shows the results of modeling a selected catchment area as an example. The model was calibrated with data from 1981 to 1990 and validated with future data. The y-axis in the Nash-Sutcliffe-Bias-Diagram shows the Bias value of the simulated to the measured data and the x-axis shows the Nash-Sutcliffe value. A perfect model would have the Bias value of 0 and the Nash-Suttcliffe value of 1. In Fig. 3 b-c , the model shows good training and validation Nash-sutcliffe values of 0.73135 and 0.67845, respectively.



(a) Outflow from Miyun watershed (Training)



(b) Outflow from Miyun watershed (Training cost)

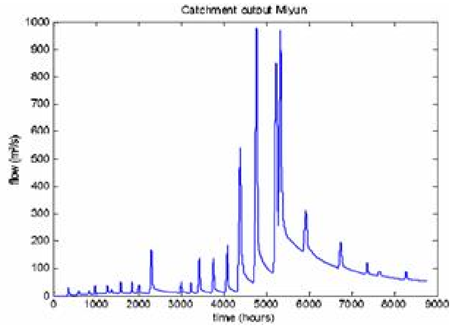


(c) Outflow from Miyun watershed (Validation)

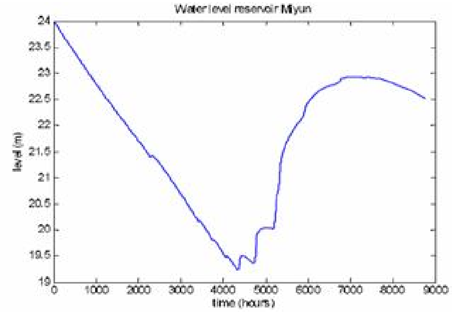
Fig. 3. Outflow from Miyun Catchment area

6.2. Example results - Reservoir modeling

Fig. 4 shows the water inflow into the Miyun reservoir and the corresponding water level. The peaks of the inflow can get up to practically 1000 m/s. The inflow from the groundwater was set at zero at the beginning and is characterized 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/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/s, and into the river Chaobai at 30 m/s, and of the demand from the No. 9 waterworks at approx. 10 m/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.



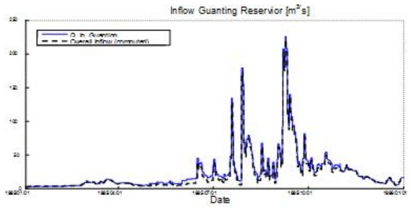
(a) Outflow from Miyun watershed



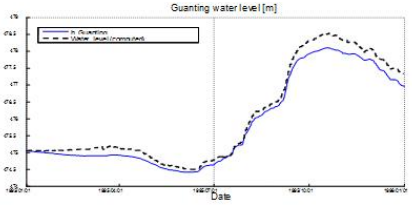
(b)Water level of Miyun

Fig. 4. Miyun reservoir inflow and water level

Results of the simulation of Guanting Reservior as an example are shown in Fig. 5.



(a) Inflow of Guanting Reservoir



(b) Water level of Guanting Reservoir

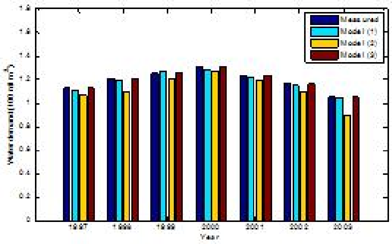
Fig. 5. Simulation results of Guanting Reservior

6.3. Example results - Water demand modeling

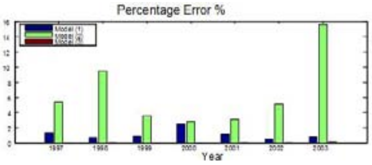
Fig. 6 shows the results of three water demand models for agriculture, namely neural networks (model 1), regression (model 2) and Kalman prediction (model 3). Raw data (water demand, population, gross domestic product) from 1990 to 2001 was applied for training and data from 2002 to 2003 were employed to examine the prediction efficiency of the three techniques. In this case, the results are satisfactory for all the model types as can be seen in the Figures. The comparison of the forecasting error among these are shown in Fig. 6 (b) , where the amount of error is calculated by

$$e_{\%} = \left(\left| D_k - \widehat{D}_k \right| / D_k \right) * 100$$

where e% is the percentage error, D_k is the actual water demand and $\widehat{D}_k$ is the forecasting water demand.



(a) Water demand forecasting using different methods

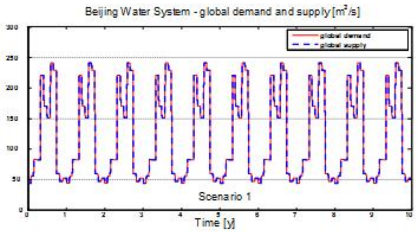


(b) % forecasting errors of the different methods

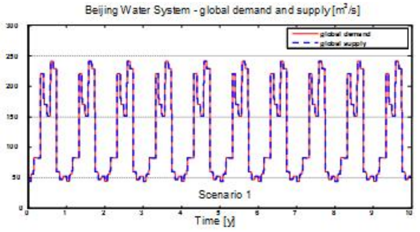
Fig. 6. Results of the water demand modeling

6.4. Example result - Optimization

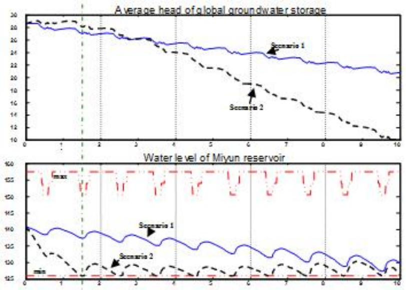
The proposed concept for optimal water management is evaluated for several sets of experiments. The first set of experiments, which will be given as an example in this paper compares two scenarios. In Scenario 1 of this experiment, we want to minimize demand deficit and keep demand constant for the next 10 years and in Scenario 2 we want to minimize demand deficit and increase demand 5% yearly for the next 10 years. The results of the two scenarios are illustrated in the Fig. 7 a-c. Scenario 1 shows that the demand can be fulfilled for the ten years, but without considering sustainability, the Miyun-Reservior and the Groundwater are overexploited. By increasing the demand yearly, then we can see that the demand won't be fulfilled anymore and within 1.5 years Miyun has already reached its minimum and at the end of the 10 years, the systems groundwater level has sunk rapidly.



(a) Total water supply /demand - Scenario 1



(b) Total water supply /demand - Scenario 2



(c) Groundwater head and water level in Miyun

Fig. 7. Scenario studies

7. CONCLUSIONS

A simulation model and a decision support system for the water supply system for Beijing was presented in this paper. The structure of the simulation model can be easily adapted (e.g., consider new channels, waterwork). Validation results of the simulation model and the decision support system show that the models are an effective tool for water resources management and planning.

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