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Development of a Risk Assessment Decision Support System for Optimal Control of Water Supply Systems

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Abstract

This paper describes a decision support system (DSS) for optimal control of water supply systems during periods of drought. By combining the capabilities of database technology and mathematical modeling, the aim is to improve the quality of decision making when evaluating water supply alternatives from a multi-sources water supply system. The methodology applied incorporates the genetic algorithm procedure to derive some optimal daily release policies in order to minimize long-term drought damages and water shortage threats. An application of the DSS to the operation of the water supply system of Fukuoka City, Japan, reached very promising results.

1. Introduction

Operation of water supply systems involves a diversity of problems. In addition to the complexity of the water system itself, i.e., the number of reservoirs and demand targets, the multi-dimensionality of the optimal control problem results from conflicting objectives among users, uncertainties in the evaluation of environmental and physical phenomena involved, and most of all sustainability requirements. Recently, decision support systems (DSS) are receiving a growing interest among water managers to effectively address some of these issues in the operation of complex water supply systems (Jamieson and Fedra,1996; Siminovic and Bender, 1996; Reitsma,1996). This paper describes the conceptual design of a DSS developed to assist decision-makers in deriving the optimal release policy from a multi-sources system of reservoirs and water heads, during periods of drought. In complex water supply systems, the performance of the system may exhibit strong sensitivity to changes in the release distribution among a group of linked sources supplying a common demand target. Thus, a non-optimal release policy from at least one of the sources will lead to performance retrogression of the entire system (Darko and Bogardi, 1997). Despite the multipurpose objectives of most complex real-world water supply systems, the release policy investigated in this study considers only the domestic water demand during drought. To achieve this goal, the present DSS components include a hydrologic model, a domestic water demand prediction model, and a risk based reservoir operation model.

The DSS is applied to the drought management of the water supply system of Fukuoka City, Western Japan. The region suffered its most extreme drought on record during 1994. Severe and continuing water use restrictions, lasting for 295 days, were required to limit the impact of drought on municipal water supplies, particularly in the surrounding towns.

2. System development

In the present DSS the essence of database technology and mathematical modeling procedures are combined into a comprehensive environment to improve the quality of decision making in evaluating daily water supply alternatives under drought conditions. The DSS is developed under the Windows 95/NT platform. An advantage of the Windows platform, in addition to the wide spread use of IBM systems, is the possibility to bring data from existing database software tools such as ACCESS and EXCEL into the system (Dunn et al 1996). The actual system requires a minimum of 8 MB RAM, 18 MB of free disk space, 16 bit color graphics and 1280x1024 screen resolution. The graphical user interface (GUI) of the DSS, shown in Figure 1, is mouse driven and user-friendly to facilitate operation by the non-specialist. The main menu and buttons across the top of the screen give access to the various components of the system. Menu-trees and options in each section allow the user to perform either model generation or input-output display operations.

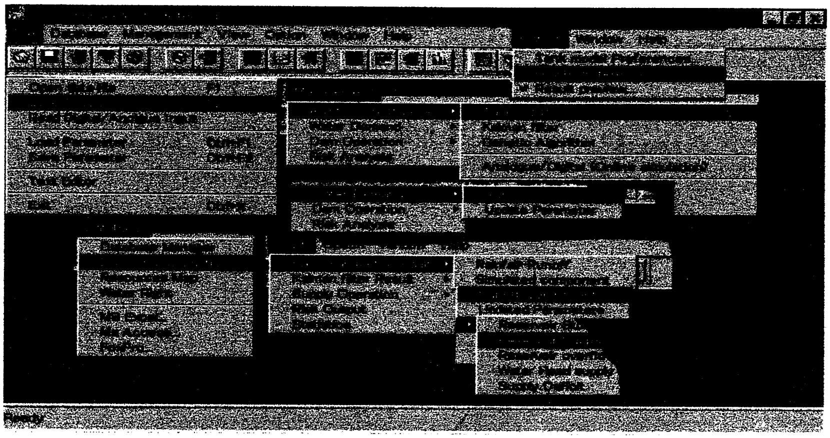


Figure 1. DSS graphical user interface.

The present DSS consists of two main elements as shown in Figure 2: the database manager and the mathematical modeling modules.

As required in the management of complex water supply systems, the database manager integrates a substantial quantity of different data types. Thus, in addition to the database on the water supply system functionality and structure, three types of data sets are provided to each of the integrated mathematical models. These include hydrological data sets, water demand data sets, and reservoirs and water heads data sets (Merabtene et al 1997a).

The integrated mathematical models perform analytical rainfall-runoff analysis, water demand prediction, and risk based multi-reservoirs operation. In this study the rainfall-runoff model is based on the tank model introduced by Sugawara (1974). The present version of the tank model is designed for both catchment characterization and real-time streamflow forecasting. The best sets of fixed parameters, i.e., that minimize a given objective function, may be obtained by a genetic algorithm procedure and further adjusted by trial and error. In real-time inflow forecasting the model uses Kalman filtering. The Kalman filtering technique provides online updated parameters and runoff components, i.e., surface, intermediate, and groundwater runoff (Merabtene et al. 1997b).

The applied water demand model considers only the daily domestic water demand. The DSS uses a simple linear regression model as defined in Xu et al. (1998). The industrial and irrigation water demands are retrieved to the DSS through the database manager.

The reservoir operation model is a risk based assessment approach. The model utilizes the concepts of reliability, resiliency, and vulnerability to derive some water take allocation patterns from a group of sources. The methodology applied is based on genetic algorithm theory as described in the following sections.

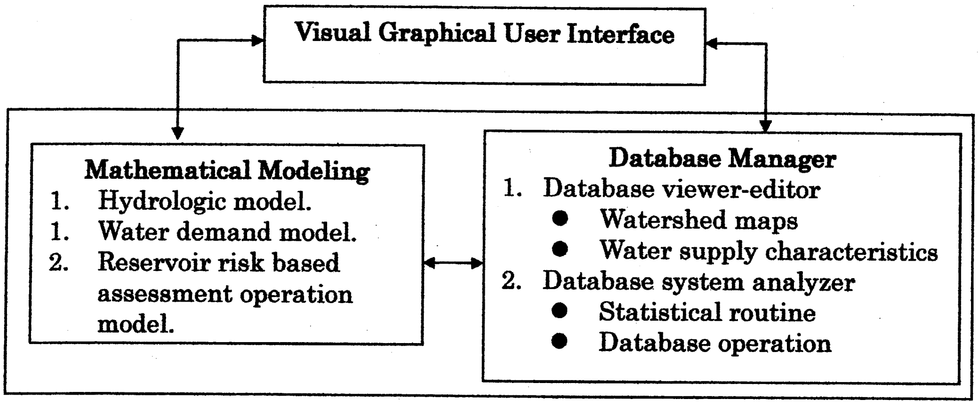


Figure 2. Decision support system flowchart.

3. Performance evaluation

The primary aim of the application of the present DSS is to derive optimal water supply alternatives that minimize the long-term drought damages. The performance criteria used in this study are based on the concepts of reliability, resiliency, and vulnerability (Hashimoto et al. 1982).

Reliability (Rel) is defined as the probability that a system remains in a satisfactory state. It is estimated as the ratio of the number of satisfactory state intervals to the total operation interval *T*. It is expressed as:

$$Rel = \frac{1}{T}\sum_{t=1}^{T} SS_t \qquad (1)$$

where SS_t is the state variable of the water supply system. SS_t equals one if no deficit occurs on day t, and zero if deficit occurs.

Resiliency (Res) is used to describe the ability of the system to recover from failure to an acceptable state. It is measured as the inverse of the average period of water deficit:

$$Res = \frac{1}{\frac{1}{NF}\sum_{i=1}^{NF} FS_i} \qquad (2)$$

where NF is the number of times the water system enters a failure state during the operation period, and FS_i the ith failure day.

Vulnerability (Vul) quantifies the severity of occurring failures. In the present study vulnerability is used as a measure of the average deficit divided by the average water demand during the whole water supply period:

$$Vul = \sum_{1}^{T} \frac{Wd_t - WDS_t}{Wd_t} \qquad (3)$$

where Wd_t is the daily water demand at time t, and WDS_t the daily water supply at time t.

Each of the risk indices bears its own specific importance in the assessment of a water supply system operation. For instance the reliability provides an estimate of the long-run efficiency of the water supply alternatives. On the other hand, the resiliency reflects the sensitivity of the devised strategy to changes in the hydrological conditions. Finally, the vulnerability reflects the most severe shortage events that may be encountered if a particular strategy is followed. Therefore, one performance measure can not be singled out as more relevant than the others (Milutini and Bogardi 1997).

In the present study, the three risk indices, risk of failure (defined as 1-Rel), risk of non-recovery from failure (1-Res) and vulnerability (Vul), are summarized in the drought risk index (DRI) expressed as a linearly weighted function (Jinno et al 1995):

$$DRI = w_1\,(1\text{-}Rel) + w_2\,(1\text{-}Res) + w_3\,Vul \tag{4}$$

where $\sum_{i=1}^{3} w_i = 1$

In eq. (4), w_1, w_2, and w_3 specify the relative weights of the respective risk criteria. In the simplest case, all weights may be assumed to be equal.

The four risk indices (1-Rel, 1-Res, Vul, and DRI) are used by the reservoir operation model to evaluate the performance of the water supply system and assess simulated water supply scenarios. Thus, "risk level" is defined in order to assess the derived water take scenarios from the existing sources, and minimize drought damages. The risk level is represented by the feasible space defined by the risk indices thresholds as shown in Figure 3:

$$1\text{-}Rel <= (1\text{-}Rel)_{max} \tag{5}$$

$$1\text{-}Res <= (1\text{-}Res)_{max} \tag{6}$$

$$Vul <= Vul_{max} \tag{7}$$

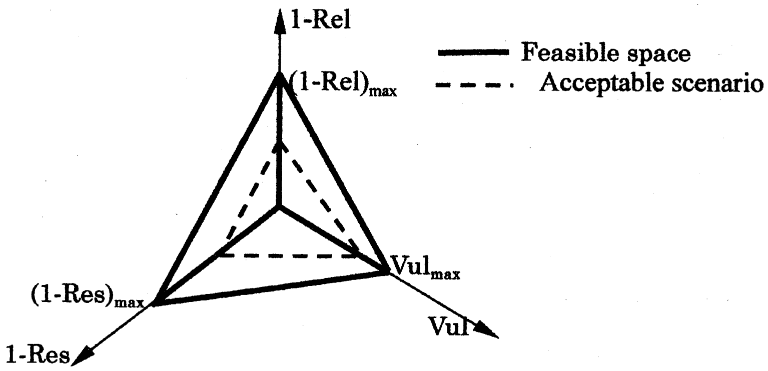


Figure 3. Desired performance feasible space and acceptable scenario.

The drought risk index threshold may be then formulated as:

$$DRI_{max} = w_1\,(1\text{-}Rel)_{max} + w_2\,(1\text{-}Res)_{max} + w_3\,Vul_{max} \tag{8}$$

where $(1\text{-}Rel)_{max}$ specifies the maximum number of acceptable failing days, $(1\text{-}Res)_{max}$ the maximum acceptable length of a failure, and Vul_{max} the maximum acceptable water restriction.

In practice, the risk levels, Eqs. 5 to 8, expresse limits of acceptable drought damages that will not harm the consumers health and comply with the social, economical, and political requirements. Thus, in the assessment of water supply system reliability, the evaluation of the acceptable risk should not only include the criteria (i.e., preference) of the water agents (i.e., decision-makers) but also those of the wide type of consumers. Although it is clear that the consumers have limited experience with drought damages and water shortage (Howe and Smith 1993), studies should be conducted to extract the necessary information on the risk accepted by the society, particularly in areas where water shortage has been severe. Thus, an investigation among consumers may be undertaken to define the acceptable water shortage magnitude (severity and duration) which is then converted into an admissible risk level.

4. Genetic algorithm model

The use of genetic algorithms (GA) as search procedures in optimization and machine learning problems was first proposed by Holland (1975). A basic goal of GAs is to develop systems that possess self-organization and adaptation to the environment, that is, systems that learn to adapt to changes. The GA is an iterative procedure maintaining a population of structures, i.e., daily water take from each source in our application, termed "chromosomes" or "strings", that are candidate solutions to specific domain changes. During each temporal increment, i.e., "generation" or set of water take solutions in our study, the structures in the current population are rated for their fitness as domain solutions. Based on this evaluation, a new population of candidate solutions is formed using specific genetic operators such as reproduction, crossover, and mutation. Through this reproduction, GAs produce new generations of improved solutions by selecting "parents" with higher fitness ratings or by giving parents greater probability to be contributors.

Recombination of strings in the population of a new generation is affected by crossover. In the present GA procedure, so-called two points crossover is performed on the entire population (Grefenstette, 1990). This involves a pair of strings exchanging corresponding parts of their gene sequence defined by randomly chosen points. All strings have the chance of undergoing crossover, but not all will participate in the process during a single generation. This is because the probability of crossover occurrence, which must be specified by the user, is usually less than unity.

Besides crossover, after a new population has been generated, mutation is applied to each string in the new population assuming a low mutation rate, i.e., probability. This allows reintroducing genetic diversity to avoid getting trapped in local optima and avoid disruption of proper solutions. Unlike general optimization algorithms, the GA does not rely on any mathematical properties of the objective functions, such as, differentiability and continuity. This leads to a robust search less likely to get trapped in regions of local optima.

5. Reservoir operation model

The reservoir operation procedure developed here intends to straight-forwardly simulate the usual decision making process in domestic water supply management. In the present approach, the focus is on drought management, therefore control actions are derived to minimize drought damages and consequently reduce the shortage threats during the operation horizon. At each time interval the reservoir and forecast information (inflow and water demand) are updated and a new evaluation of the water take allocation pattern among the sources, reservoirs and water heads, is performed. The optimization process for the water take alternatives is carried out at each time period as follows: (1) perform the real-time inflow forecasts to each basin by Kalman filtering integrated in the Tank Model, (2) estimate the actual water demand, (3) derive optimal water take alternatives by GA, (4) evaluate the risk level for each alternative, (5) modify the operation accordingly.

In the GA scheme two distinct features are introduced: (1) the combined risk objective function (DRI eq. 8), and (2) the qualification of selected strings, i.e., water take solutions, as parents for the next generation.

In each generation the drought risk index (DRI) is evaluated for each GA solution, i.e., water take allocation. The strings qualified as parents for the next generation are those being in the feasible operation space, defined by the risk thresholds expressed by Eqs. 5 to 8. There are two reasons for selecting only the chromosomes, i.e., water take solutions, from the acceptable risk operation feasible space: (1) speed-up of the convergence process which is particularly important in real-time operation, (2) generation of future chromosomes which cluster within the defined acceptable risk level leading to appropriate practical decisions. In order to maintain the breeding of contributing chromosomes, random strings are selected from outside the acceptable risk feasible space if necessary.

The reservoir operation is based on the conservation equation defined by:

$$S_t = S_{t-1} + I_t - R_t - L_t \qquad t = 1,\dots,T \tag{9}$$

where T is the operation period. At each the time step t, S_t denotes the water storage, I_t the reservoir inflow, R_t the total release, and L_t the reservoir losses.

In eq. (9) the release decision is subjected to the following constraints on storage capacity and maximum water right for domestic water take:

$$\begin{cases} R_t = WI_t + WDD_t & \text{if} \quad S_t \le S_{\max} \\ R_t = WI_t + WDD_t + Ov_t & \text{if} \quad S_t > S_{\max} \end{cases} \tag{10}$$

$$S_{\min} \le R_t \le S_{\max} \tag{11}$$

$$WDD_t \le WP_t \tag{12}$$

$$WDD_t \le WR_t \tag{13}$$

where $S_{\min}$ and $S_{\max}$ are the minimum and maximum reservoir storage, respectively. At each time step t, WI_t denotes the industrial and irrigation water demand, WDD_t the domestic water supply from the reservoir, Ov_t the reservoir overflow, WP_t the available daily storage for domestic water take, and WR_t the daily water right of the considered source.

Besides these constraints on reservoirs operation, we add constraints on water heads and linked sources operation:

$$WDR_t \le WR_t \tag{14}$$

$$\sum WDD_t + \sum WDR_t \le P_m \tag{15}$$

where WDR_t is the domestic water take from water head at time t, and P_m the maximum water treatment capacity of purification station m. The summation in Eq. (15) is done for all reservoirs and water heads linked to the same purification station m.

6. Case study

As illustrated in Figure 4, the water supply system of Fukuoka City, western Japan, is comprised of 4 major components including: (1) six purification stations with a maximum supply capacity of about 704,800 m^3/day, (2) direct water right from the Chikugo river basin yielding a maximum of 118,000 m^3/day, (3) water heads including five pumping stations implemented on the surrounding small rivers, and (4) seven dams with a total effective capacity of 45 million m^3. The capacity directed to the municipal water supply is about 25 million m^3. Despite the large capacity of the dams reservoirs, they are very vulnerable to drought due to their slow recovery. For successful operation the reservoir storage must recover up to near the capacity after the rainy season (May to July).

The devised DSS was applied to derive the water release allocation alternatives for domestic water consumption regardless of the multi-purpose character of the actual water supply system. Moreover, in the following results the water take from water heads are excluded from the decision variables, because of insufficient knowledge on the actual river operations and lack of hydrological data. Thus, the water take from water heads used in this analysis are those observed during the selected operation period extending from January 1, 1994, to May 30, 1995.

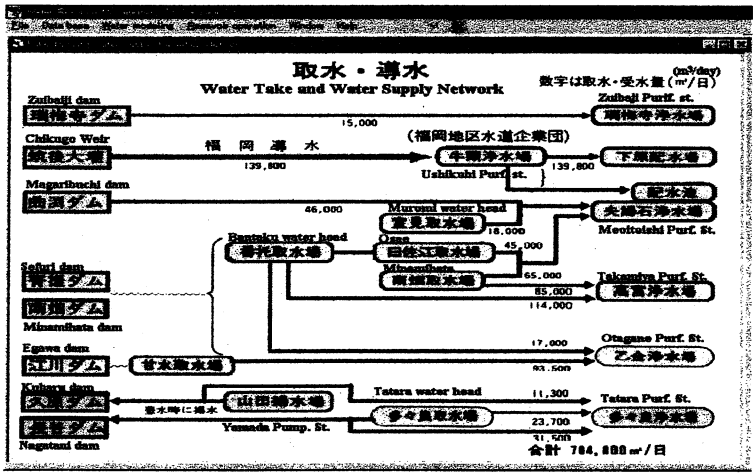
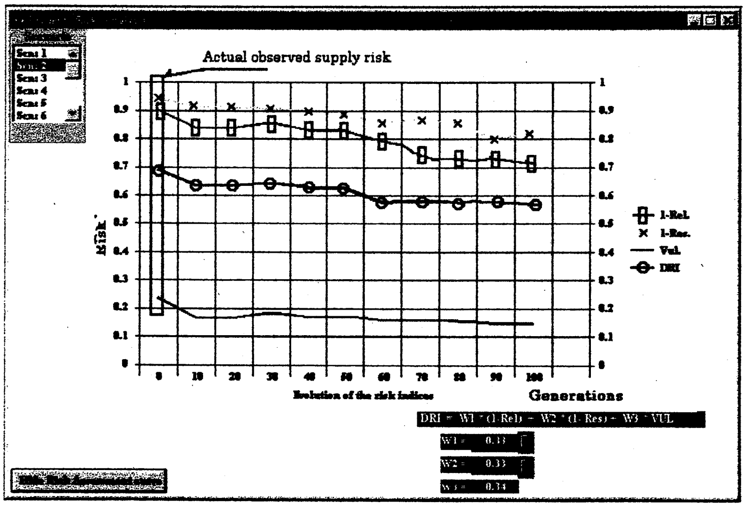


Figure 4. Fukuoka City water supply network.

In the GA application each decision variable, i.e., water take, was mapped on 10 bits long binary numbers resulting in 80-bit long strings to represent the eight unknown decision variables, namely the water take from each of the seven reservoirs and the water take from Chikugo river. The number of strings in each population was 30 and the maximum number of generation was 100. The crossover and mutation rate were set to 0.65 and 0.001, respectively.



DRI = W1 * (1-Rel) + W2 * (1-Res) + W3 * VUL

W1 = 0.33

W2 = 0.33

W3 = 0.34

Figure 5. Variation of the risk indices as a function of the number of generation

The result of Figure 5 shows the variation of the risk indices (1-Rel), (1-Res), Vul and DRI at the end of the selected operation period as a function of the number of generations. In Figure 5 the risk at generation 0 is the actual supply risk as observed in 1994. A careful interpretation of the results of Figure 5 shows that the fitness presents slight improvements as the number of generations increase. Moreover, the risk indices, risk of failure (1-Rel), risk of non-recovery (1-Res) and vulnerability (VUL) decrease considerably comparing to the actual observed risk. However, it is also observed, as shown in Figure 5, that the calculated risk indices do not show a strict decrease as the number of generations increase. This is generally due to the variability of the number of failure that occurs in each generation, the maximum sojourn on failure state, if failure occurs, and the random population generated to avoid the in-breeding of the chromosomes. It can nevertheless be concluded that clustering the chromosomes of the new generations inside the acceptable risk space leads to better fitness, i.e., DRI value, of the chromosomes, and thus a better overall performance of the water supply system.

7. Conclusions

In real-time management of water supply systems, advanced tools are required to deal with the persistent uncertainties and problems of hydrological and management issues. Fundamental tools are already available by the development of information technology. The present DSS was designed to facilitate the examination of sequences of scenarios faster and more accurately than traditional methods allow. It provides a complete database manager and a number of mathematical modeling frameworks involving tools for simulation and optimization. This study shows some of the potential of the risk based optimal operation that the DSS may offer to water resources analysts. The application of genetic algorithm theory to derive the water supply decision based on the concept of acceptable risk is very promising.

Acknowledgments

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