Study on Decision Support System for Management of Water Supply Systems Using Risk Analysis

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Abstract

This study presents the development of a decision support system (DSS) for management of water supply system during periods of drought. The objective is to derive the best water supply alternatives that minimize the long-term drought damages and threat of water shortage from a multi-reservoir system,. The DSS integrates a database manager and simulation models for runoff analysis, water demand forecast and reservoir operation. The reservoir operation is based on the application of risk analysis using the concept of reliability, resiliency, and vulnerability. An application of the DSS to the existing water supply system in Fukuoka City, Japan, is presented. The DSS was found efficient tool for risk analysis in the operation of water supply systems.

Keywords: Decision support system, Risk analysis, Runoff analysis, Water demand, Reservoir operation

1. Introduction

In recent years, drought management to maintain reliable water supply under various climatic and hydrological conditions has received increasing attention. Several methodologies have been proposed to assess the long-term adequacy of water supply systems to minimize the damages due to water deficit during periods of drought. Therefore, the concept of risk management has become widely accepted and applied in several studies. Recently, using so-called decision support system (DSS) is considered the best, if not the only, way to deal with the increasing complexity of water supply systems.

In the present paper, a risk based management DSS is presented. The objective is to develop a comprehensive DSS for simulating daily operational plans and assessing the performance of the water supply system for selected supply-demand alternatives. The DSS is applied to derive water take policies, among a group of supply sources, that satisfy an acceptable "risk level" introduced to minimize the drought damages and threat of water shortage. The difficulties of such operation in general are due to the serious uncertainties involved. These uncertainties are particularly associated with the river discharge forecast, the prediction and forecast of daily water demands, the system dimensionality, and the multi-objective and multi-institutional character of water supply systems. To respond to those problems, the present DSS is designed to integrate a data base manager, modeling frameworks, simulation and optimization procedures. To overcome the problem of imperfect streamflow forecast, the DSS includes the tank model (Sugawara, 1974) combined with the Kalman filtering technique to optimize the runoff model parameters in adaptive mode. To predict the daily water demand, a one-dimensional regression model is applied (Zongxue et al., 1998). The study area is a fast-growing economic center in the western Japan, where governmental agencies give a high priority to the safety and sustainability of water resources management.

2. Decision support system

The DSS introduced in this study is an expanding model which attempts to comprise several aspects of water resources, water quality, and groundwater management. In this paper, the components of the DSS related to the first topic, water resources management, are presented. The user interface is written in Microsoft Visual Basic and consists of tools and menus for database management and mathematical modeling.

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2.1 Graphical user interface

The user-interface represents the communication window between the user, i.e., decision-maker in water resources management, and the DSS components. The design of the user-interface in term of interactivity and graphical features has a great impact on the user's ability to assimilate information from the DSS and optimize the use of available functions (Simonovic and Bender, 1996). Interactivity is used to describe the ability of the interface to allow the user to invoke, update and communicate with all the DSS components as well as the external environment. The graphical features govern the ability of the DSS to present the integrated module's components and corresponding results in a clear and comprehensible format for interpretation and decision making. The graphical user interface of the present DSS is shown in **Fig. 1**.

As shown in the figure the user may evoke from the main menu all components of the DSS. The menu is mouse driven and short cuts to the sub-menus are in the term of toolbars, so called short-cut buttons. The DSS environment was developed on a DOS\V computer using the Windows 95 operating system. There are many reasons for selecting the Windows platform, one important being the wide and growing use of personnel DOS\V computers. The software requires 13 MB of free hard-disk space, 8 MB of RAM memory, and a 256 colors screen display. For higher performance and execution speed, a Pentium series and higher quality DOS\V machine is strongly recommended. The present version of the software was updated for a Pentium II 400 MHz, 64 MB of memory, and a 16 high color screen. The graphical user interface is written in Microsoft Visual Basic with some modules in Microsoft FORTAN. The use of multi-language programming gives more flexibility to the system in terms of execution time and disk space use. The FORTRAN language was used particularly to write the Kalman filter version of the tank model and some statistical routines such as exceeding probability whereas the language offers a higher flexibility to manage complicated mathematical formulations.

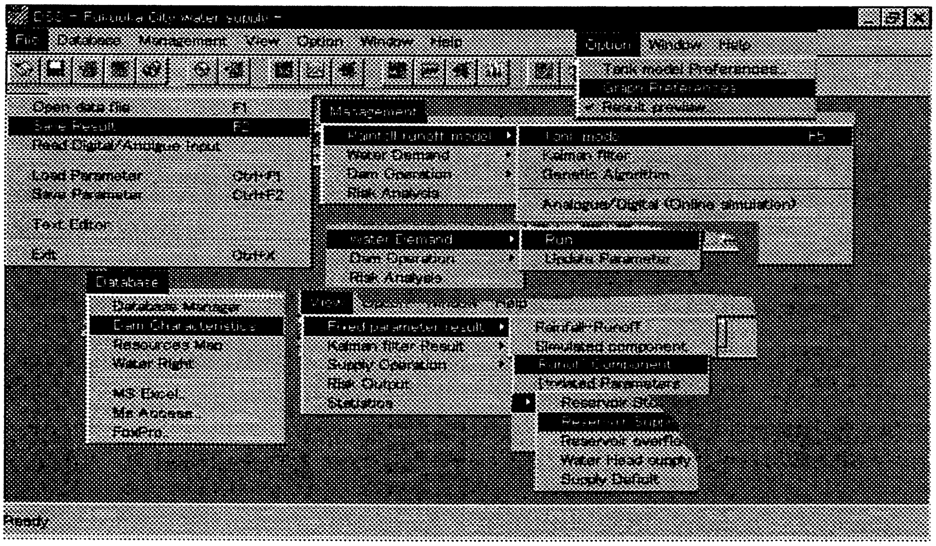

Fig. 1. DSS graphical user interface.

2.2 Database manager

Data quality and data handling are fundamental in all successful applications of any mathematical model, particularly in the calibration and validation stage preceding the actual application. This calibration stage and the associated manipulation of suitable data require much time and experience that may not be available during emergency actions. Therefore, the database manager is designed to be interactively integrated with the rest of the DSS components, and plays the role of a data communication network. Through the database manager the user may perform routine statistical analysis, aggregate the data for different time increments, select data corresponding to a certain event or season, plot and tabulate them, etc. All spatial data can be plotted as two-dimensional maps. Summary statistics for any location and functional component (reservoir, river basin, and water purification station) can be viewed by clicking on the appropriate location on the map. Moreover, the database manager permits data exchange (input/output) with software operating within a Microsoft Windows environment, such as Microsoft Excel and Microsoft Access, for subsequent data processing.

2.3 Mathematical models

(1) Rainfall-runoff model

The rainfall-runoff model is based on the application of the tank model (Sugawara, 1974, Merabtene et al., 1997). In order to alleviate the problems associated with imperfect streamflow prediction the developed model integrates Kalman filtering technique to optimize the model parameters in adaptive mode.
Fig. 2 displays the four-stage tank model graphical user-interface. The interface shows the selected structure of the model such as tanks, side outlets in each tank, and infiltration outlets. For each tank a number of buttons and text boxes are supplied to input initial values of the model parameters, such as water storage levels, and model parameters *A*, *B*, and *C*. A knowledge-based help for calibrating the tank model parameters by trial-and-error and choosing the initial value is available by clicking on the appropriate parameter button.

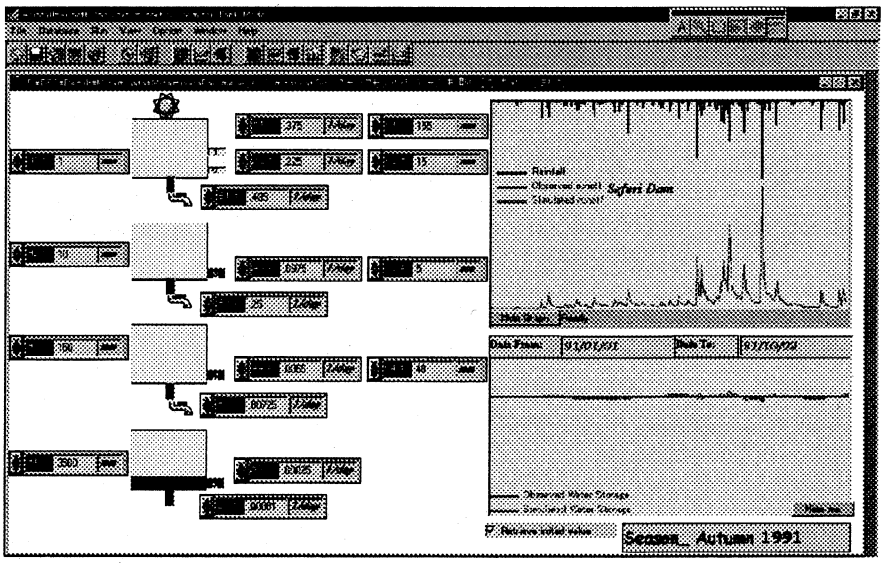

Fig. 2. Tank model main interface: the four-stage tank model.

(2) Water demand model

The water demand model considers only the forecasting of the daily domestic demand. The industrial and irrigation demands are assumed to be given for the operation period and retrieved to the system through the database manager. The domestic daily water demand is expressed by a straightforward linear regression model expressing weekly and yearly cycles superimposed on an overall trend (Zongxue al., 1998):

$$Wd(t) = trend * t + MDD * Mcoef * Dcoef \qquad (1)$$

where *Wd(t)* is the domestic daily water demand in (m^3/day) at time step *t*, *trend* is the gradient of the trend in (m^3/day/day), *MDD* average water demand in (m^3/day), and *Mcoef* and *Dcoef* are monthly and daily dimensionless coefficients, respectively. For model calibration, the user may manually update the model parameters from the water demand interface.

(3) Risk assessment model

In this study, the performance of a multi-sources system under drought conditions is evaluated by means of four indices: reliability, resiliency, vulnerability, and drought risk index (Hashimoto et al., 1982; Jinno et al., 1995).

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 time interval (*T*) of the operational period. It is expressed as:

$$Rel = \frac{1}{T}\sum_{t=1}^{T} SS_t \tag{2}$$

where SS_t is the state variable of the water supply system. SS_t equals 1 if no deficit occurs in the day *t*, and 0 if deficit occurs.

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

$$Res = \frac{1}{\frac{1}{NF}\sum_{i=1}^{NF} FS_i} \tag{3}$$

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

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

$$Vul = \sum_{t=1}^{T} \frac{Wd_t - WDS_t}{Wd_t} \tag{4}$$

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

The three risk indices (risk of failure (1-Rel), risk of non-recovery from failure (1-Res), and vulnerability) may be summarized in the drought risk index (DRI) defined by the linearly weighted function:

$$DRI = w_1\,(1\text{-}Rel) + w_2(1\text{-}Res) + w_3\,Vul \tag{5}$$

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

In Eq.(5), w_1, w_2, and w_3 specify the relative weights of the respective risk criteria. As the simplest situations, as used in this study, all weights are assumed to be equal, i.e., $w_1 = w_2 = w_3 = 1/3$.

The four risk indices (*Rel*, *Res*, *Vul*, and *DRI*) are used by the reservoir operation model to evaluate the performance of the water supply system and assess the simulated water supply scenarios. Thus, in order to determine whether derived water take scenarios is acceptable from the point of drought damages, a maximum acceptable "risk levels" is defined as shown in **Fig. 3**. The drought risk index threshold may be then formulated as:

$$DRI_{max} = w_1\,(1\text{-}Rel)_{max} + w_2(1\text{-}Res)_{max} + w_3\,Vul_{max} \tag{6}$$

where $(1\text{-}Rel)_{max},$ $(1\text{-}Res)_{max},$ Vul_{max} are the acceptable risk thresholds.

In **Fig. 3** the total feasible space ($0 \leq 1\text{-}Rel \leq 1$, $0 \leq 1\text{-}Res \leq 1$, and $0 \leq Vul \leq 1$) includes all feasible solutions. In term of risk management, the qualified scenarios are all solutions with risk values smaller than or equal to the risk thresholds defined by $(1\text{-}Rel)_{max},$ $(1\text{-}Res)_{max},$ and Vul_{max} as shown by the dotted line in Figure 4. On the other hand, solutions with the risk values falling within the shaded space are likely to lead to long-tem drought damages. In practice, the acceptable risk levels, Eq. 6, should not only include the criteria and preferences of the water officials (i.e., decision-makers) but also those of the public (i.e., consumers) in the planning and assessment of the water supply system reliability. Although it is clear that the public has limited experience with drought damages and water shortage 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 may then be converted into an admissible risk level.

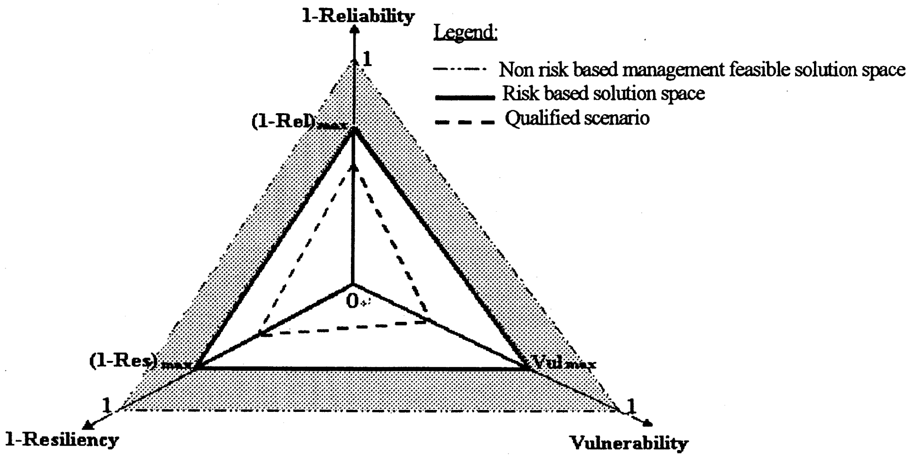

Fig. 3. Non risk management feasible space, acceptable risk space and qualified scenario.

(4) Reservoir operation model

The reservoir operation model is derived from the continuity equation:

$$S_t = S_{t-1} + I_t - R_t - L_t \qquad t = 1,\ldots,T \tag{7}$$

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

In Eq. (7) the release operation is subjected to the constraints on storage capacity and maximum water right for domestic water take. 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 forecast information (inflow and water demand) are updated and the water take allocation pattern among the sources, reservoirs and water heads, is performed. The simulation procedure is as follows: (1) perform the real-time inflow forecasts to each basin by tank model using Kalman filter, (2) estimate actual water demand, (3) Simulate water supply alternative, (4) evaluate the risk level for each alternative, (5) modify the operation accordingly.

3. Case study

In order to demonstrate the planning and management aiding capability of the developed DSS, the daily operation of the water resources in Fukuoka City is presented. Fukuoka City water supply provides direct service to 1,295,832 residents. The region is characterized by only a limited groundwater supply (1% of the daily supply) due to shallow aquifers, salt intrusion, and groundwater pollution caused by chlorinated hydrocarbons. Thus, the primary supply is from surface water (99%). As shown in **Fig. 4**, in addition to the water take from the Chikugo barrage, the water supply system of Fukuoka City consists of seven dams, six water intakes for the small surrounding rivers, and six purification plants with a total supply capacity of 704,800 m^3/day. Noteworthy is the Chikugo River from which Fukuoka City receives a third of its average daily water supply of 410,000 m^3/day. During severe droughts, a significant reduction in yield from the Chikugo river is expected because of water sharing conflicts among users, streamflow depletion, and water quality deterioration. Moreover, despite the large capacity of the dam reservoirs, they are very vulnerable to drought due to their slow recovery (small catchment area and steep surface slopes). For successful operation, the reservoir storage levels must recover to near the full capacity after the rainy season. The average precipitation during the rainy season (Jun to July) is about 950 mm. Thus, the system also depends on the typhoon season (September to October) to partially refill its capacity. Unusual climatic events, such as the droughts that occurred in 1978 and 1994, the worst on record, cause the system storage to decline to levels that require water use restriction.

4. DSS application

To derive a water take policy from different sources using the present DSS, the user starts by selecting the operation period using the database manager. For forecast operation, the user is requested to input the starting and ending dates of the forecast period. The hydrological characteristics of each catchment in the water resources system are then evaluated. The rainfall used in this evaluation is either the recorded rainfall in each catchment during the operation period, or any other rainfall event period selected from the database manager. Next, the water demand is estimated by updating the appropriate parameters for each time step. The decision-maker is then requested to input the management and planning preference, e.g., the risk thresholds defining the acceptable risk level, initial water take proprieties from sources, (i.e., initial water take order among sources), and maximum number of trials. Simulations continue until the number of trials is reached. The output of the system is the state of the water take sources and system performance for all qualified scenarios, i.e., scenarios that satisfy the acceptable risk level within the maximum number of trials.

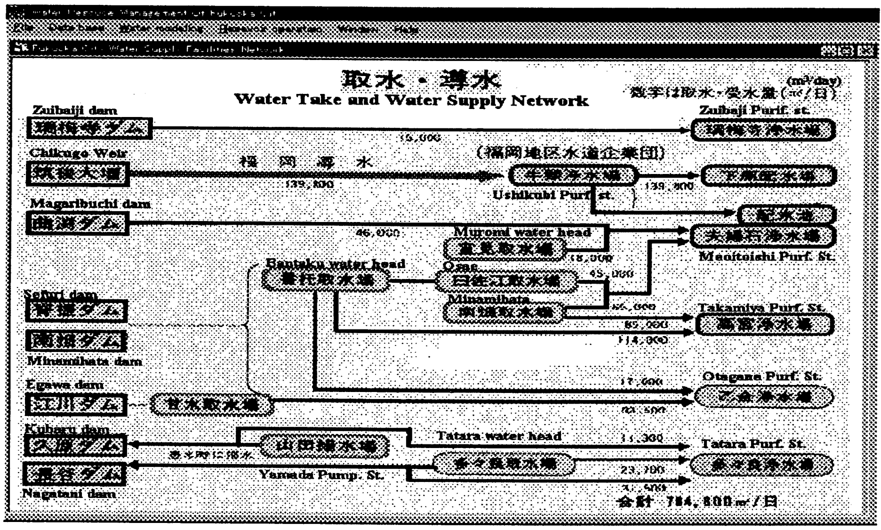

Fig. 4. Fukuoka City water supply network.

In the following results, the susceptibility of the water supply system when subjected to water supply restrictions from the Chikugo River subsystem under different weather conditions was simulated. Two sets of climatological conditions were considered. The first was that of 1992, particularly characterized by drought in the Chikugo river basin, but not in Fukuoka City, and the second set of conditions is that of the 1994 drought. The drought risks for 1992 and 1994 were evaluated for the same water take allocation pattern from the local subsystem in Fukuoka City. Moreover, unlike the actual water supply state during the two periods, in the analysis assumed that the full water right from surrounding rivers could be supplied.

Fig.5 shows the variation of the performance of the entire water supply system for different percentages of maximum yield from the Chikugo River basin. As shown in **Fig. 5**, under normal weather conditions in Fukuoka City (as in 1992 with 1435 mm/year of precipitation), 20% of the maximum water right allocated to Fukuoka City from the Chikugo River is sufficient to satisfy the domestic water supply without need for water rationing. The result shows that if no water was supplied from the Chikugo River during the 1992 operation period the risk of non-recovery of the system (*1-Res*) is 0.22 for a vulnerability (*Vul*) approximately equal to 0.01. In other words, the system may remain in a failure state for about 2 days each time a failure occurs. The expected water shortage during the failing days is about 1% of the water demand. The frequency of failure is still very low for this particular case since the risk of failure *1-Rel* is 0.05, which means that there is 5% chance that the system fails during the operation period. By increasing the water supply from the Chikugo River, the total risk defined by the drought risk index (*DRI*) gradually decreases from 0.1, if no water for the Chikugo River is supplied, to 0 for 20% yield of the maximum water right allocated to Fukuoka City.

The result for the 1994 drought conditions shows that if no water is supplied from the Chikugo River, the system exhibit a high risk of non-recovery with *1-Res* exceeding 0.7 with about 12% of water shortage (*Vul*=0.12) compared to 1% for the 1992 conditions. For this particular scenario (i.e., no water supply from the Chikugo River) the risk of failure of the system is about 31% (*1-Rel*=0.31). In other words, even under the circumstance that 100% of the water right from the surrounding rivers could be supplied during the 1994 drought, the entire system exhibits a strong dependency on the water supply from the Chikugo River subsystem. This conclusion is also justified by comparing the results of the total risk between the two hydrologic periods. As can be seen from **Fig. 5**, the drought risk index for the 1994 drought scenarios is 4 times higher (*DRI* = 0.4) compared to the 1992 drought scenarios (*DRI*=0.1).

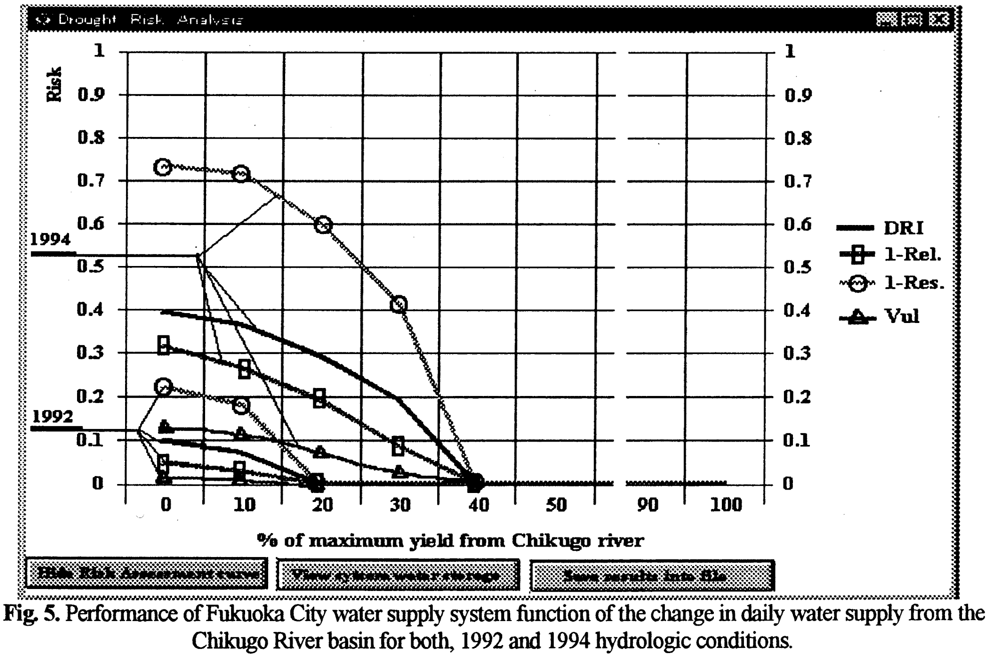

Fig. 5. Performance of Fukuoka City water supply system function of the change in daily water supply from the Chikugo River basin for both, 1992 and 1994 hydrologic conditions.

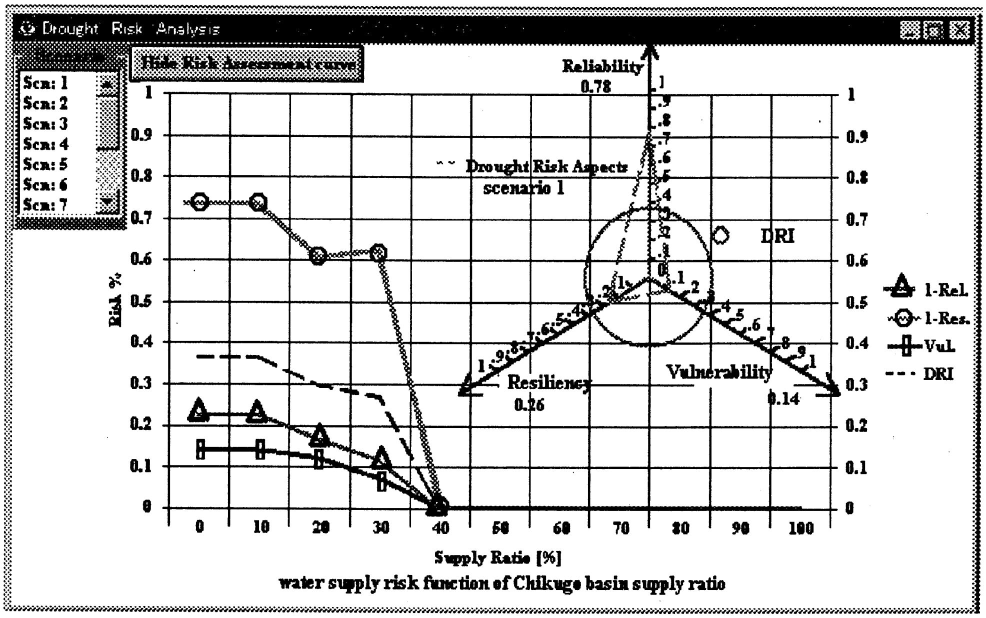

Fig. 6. Risk of water supply risk as a function of the water take from the Chikugo river using 1994 actual river supply as input.

The results of **Fig. 6** were obtained for the 1994 drought period extending from January 1st, 1994 to May 30th, 1995. For this simulation, the observed, i.e., actual, water supply from the surrounding rivers were used as input to the model. As can be seen from the figure *DRI* is equal 0.38 which is slightly lower than in the previous application (*DRI*=0.40). The main raisons are the difference in the operation period and the additional water transfer from the surrounding rivers, where some water designated for irrigation water right was added to support the domestic supply. The result shows that during periods of drought, as of 1994, the Fukuoka City water supply system may exhibit a high risk of non-recovery from failure (*1-Res*=0.73).

Moreover, unlike the first application (**Fig. 5**), the resiliency of the system may not increase regularly. As can be see from **Fig. 6**, despite increasing the water supply from the Chikugo River, for example from 0 to 10%, or from 20 to 30% of the total water yield allocated to Fukuoka City, the resiliency shows no improvement. However, it drastically decreases between 10 and 20% and particularly when increasing the water yield from 30 to 40%.

The variation of the total storage in all Fukuoka City's reservoirs for the risk scenarios of **Fig. 6** is depicted in **Fig.7**. The result shows that the difference in total water storage between scenario 0 (no supply from Chikugo River) and scenario 11 (100% of water supply from Chikugo River) is about 36% of the full storage accounted for about 50,000,000 m^3. While the difference in water storage between scenario 0 and scenario 5 (40% of water supply from the Chikugo River) is about 13% of total storage. The daily water deficit in term of quantity and period of sojourn, if failure occur for the scenario 0 of **Fig. 6** (no water supply from the Chikugo River) is depicted in **Fig. 8**.

In case of no water supply from the Chikugo River basin, It can be seen from the results of **Fig. 8** that the first major water deficits occurs during early July 1994. At that time the storage in Fukuoka City 's reservoirs was at its lower values (**Fig. 7**). Because of the precipitation in August 1994, the reservoirs storage recovered slightly and the problem decreased. Storage then decrease gradually, and the drought problems exacerbates after September.

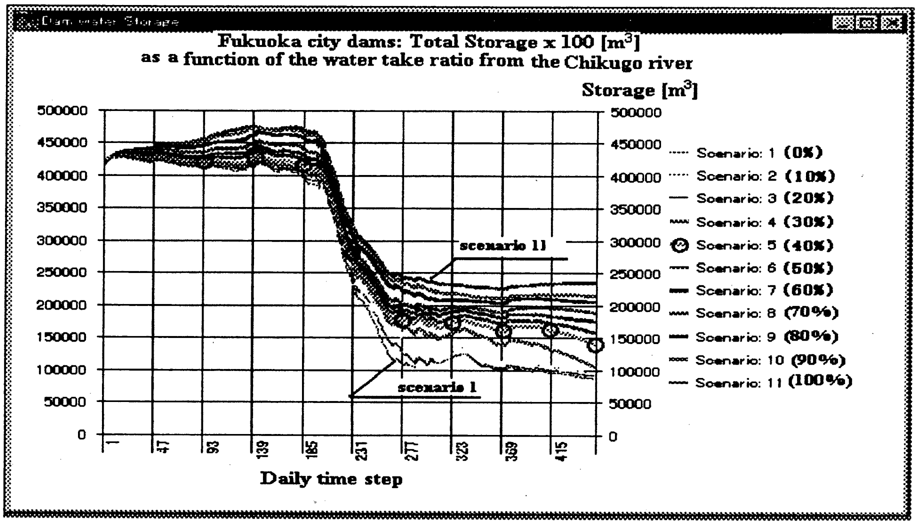

Fig. 7. Variation of the total water storage in all Fukuoka City's reservoirs as a function of the water take from the Chikugo River.

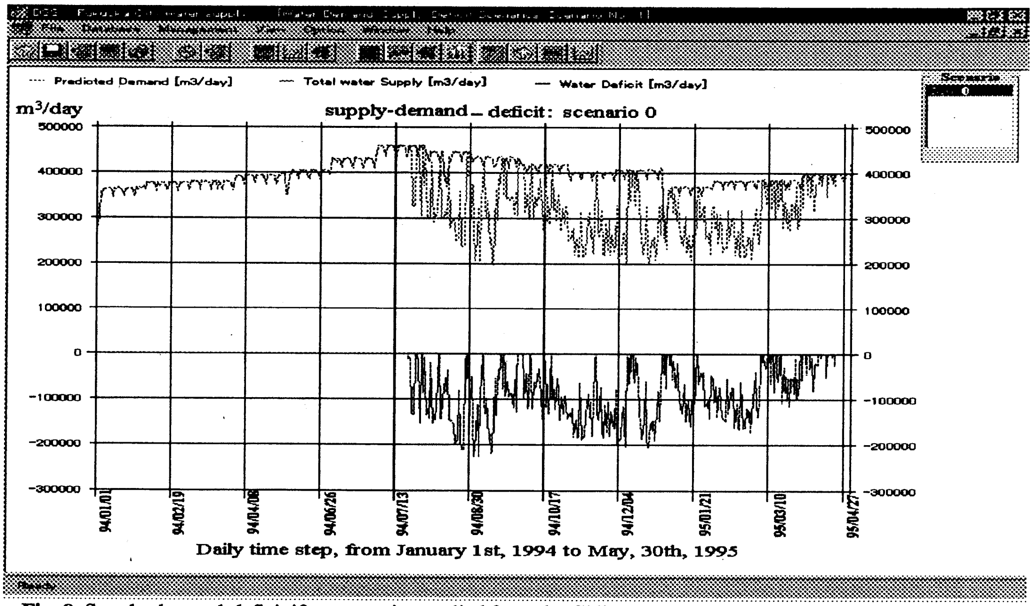

Fig. 8. Supply-demand-deficit if no water is supplied form the Chikugo River during the operation period extending form January, 1st, 1994, to May 30th, 1995.

4. Conclusions and future development

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. It is now clear that the decision support system (DSS) approach is the best, if not the only, way to close the existing gap between water resources management theories and the operation of real-world complex water supply systems.

The present DSS was designed to facilitate the examination of sequences of scenarios faster and more accurately than traditional methods allow. It provides a database manager and a number of mathematical modeling frameworks involving tools for simulation and optimization as well as expert system procedures. The graphical user interface of the model facilitates the evaluation of possible management actions as well as the interpretation of the results. The application to a complex real-world supply system was very encouraging. However, the DSS is intended to be further developed, and possible future developments include the following:

1/ To increase its objectivity, optimization routines may be developed to evaluate the optimal solution within the qualified scenarios. This will undoubtedly offer an improved performance of the DSS leading to better decision making.

2/ An expert system for incorporating experiences and judgement in the management of the water supply system during drought may be implemented.

3/ Water quality and groundwater management, although outside the scope of this paper, are of great concern for all water supplies.

4/ By law, the waterworks in each municipality in Japan have to be operated on a self-paying basis, so that each municipality has to set its own water rate to compensate the water development and management costs.

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