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Integrated Decision Support System for Drought Risk Management of Water Supply System

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ABSTRACT

This paper describes how risk models are integrated within a decision support system (DSS) and used to support the risk management in a practical water supply system during drought. An application is made in which the performance of the existing water supply system of Fukuoka City is analyzed and the potential of water deficits and corresponding risk for different drought scenarios is discussed.

Keywords: Decision Support System, Risk Management, Reservoir Operation.

INTRODUCTION

Fukuoka City, Western Japan, as well as the surrounding small communities are facing a threat of water rationing due to lack of water resources and water demand growth. In Fukuoka City the construction of new reservoirs, water desalinization using the reverse osmosis membrane and the further recycle of treated water are planned. However, the failure of the water supply system is unavoidable due to the delay on water resources development and particularly to extreme severe droughts with long-term return period. This study highlight, that the robustness of the water supply system in Fukuoka City may not be enhanced unless a fundamental strategy for the water resources planning and operation based on the concept of risk management for drought is considered.

The current DSS consists of two main modules, a data base manager and simulation models. The data base manager is integrated to provide information on the water supply components (i.e., reservoirs, water heads and purification stations) and some fundamental operation on time series analysis. The simulation models are the mathematical base of the DSS incorporating a rainfall-runoff model based on the application of the tank model by Kalman filter, a domestic water demand forecast model and a water balance model based on multireservoir decision making by risk assessment.

STUDY AREA

Fukuoka City is located in the northern part of Kyushu island, western Japan. The region has mild weather, and no severe earthquake or flood has ever been recorded. The hydrologic feature is characterized by a high seasonal variability with an annual precipitation of 1600 mm/year with little snow. Because of seasonal winds, there are both an early rainy season (June to July) and a typhoon season (September to October) (Kawamura A, and Jinno K., 1996). In order to satisfy the increasing water demand, due to economic development and population increase, Fukuoka City, in addition to the water received from the Chikugo river, withdraw water from seven dams, five water heads and groundwater. The maximum water right for domestic water supply from all sources is 685,100 m^3/day. The corresponding maximum water right ratio from each source is given in Table 1. The total effective water storage for all reservoirs is 42,778,000 m^3. Furthermore, the water supply system includes six water purification stations with a total capacity of 704,800 m^3/day. The water supply components and their link are depicted in Figure 1.

Table 1

Maximum water right ratio of Fukuoka City sources

Dam	Egawa	Kubaru	Magari-buchi	Minamihata and Sefuri	Nagatani[1]	Zuibaiji
Water right (%)	11.72	1.65	6.71	20.86	4.60	2.19
Water head	Koishihara[2]	Bantaku	Tatara	Muromi[3]	Osae[4]	
Water right (%)		20.29	3.46	4.61	2.92	
Other Sources	Chikugo River basin		Ground water			
Water right (%)	20.41		0.58			

[1] Nagatani dam operational since October 23rd, 1993.

[2] Koishihara water head is located on the remaining catchment of Egawa dam and chare.

[3] 4.61% for the period from June 21st to October 10th.

[4] Osae water head operational from June 1st, to October 10th.

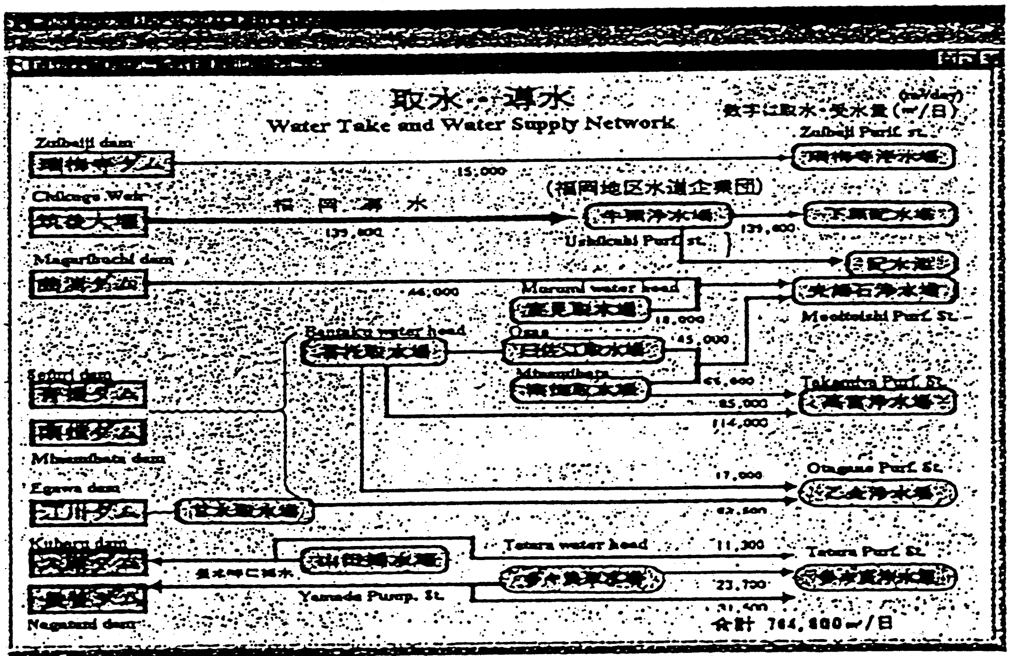

Figure 1 Fukuoka City water supply network

DECISION SUPPORT SYSTEM

The present DSS is an interactive menu designed as an advisory for the risk management of water supply system. The user interface is written in Microsoft Visual Basic and consists of tools and menus for data base management and mathematical models. The framework of the developed system is given in Figure 2. The process begins with the selection of a period, a rainfall pattern, input of acceptable risk (i.e., risk threshold), initial storage of reservoirs, initial water takes ratio and water takes priority from the sources. Then the prediction model of water demand is retrieved from the main menu, followed by evaluating the runoff to each catchment. The water deficit in the period is then calculated next. Finally, the system calculates the risk for different water supply scenarios, corresponding to different water transfer ratios and different water take priority. The simulation process continues until the risk thresholds are satisfied. For each alternative the total storage of all dams, the storage of each dam, the water supply from each source, the loss from each dam, the water deficit, and the risk assessment result are displayed.

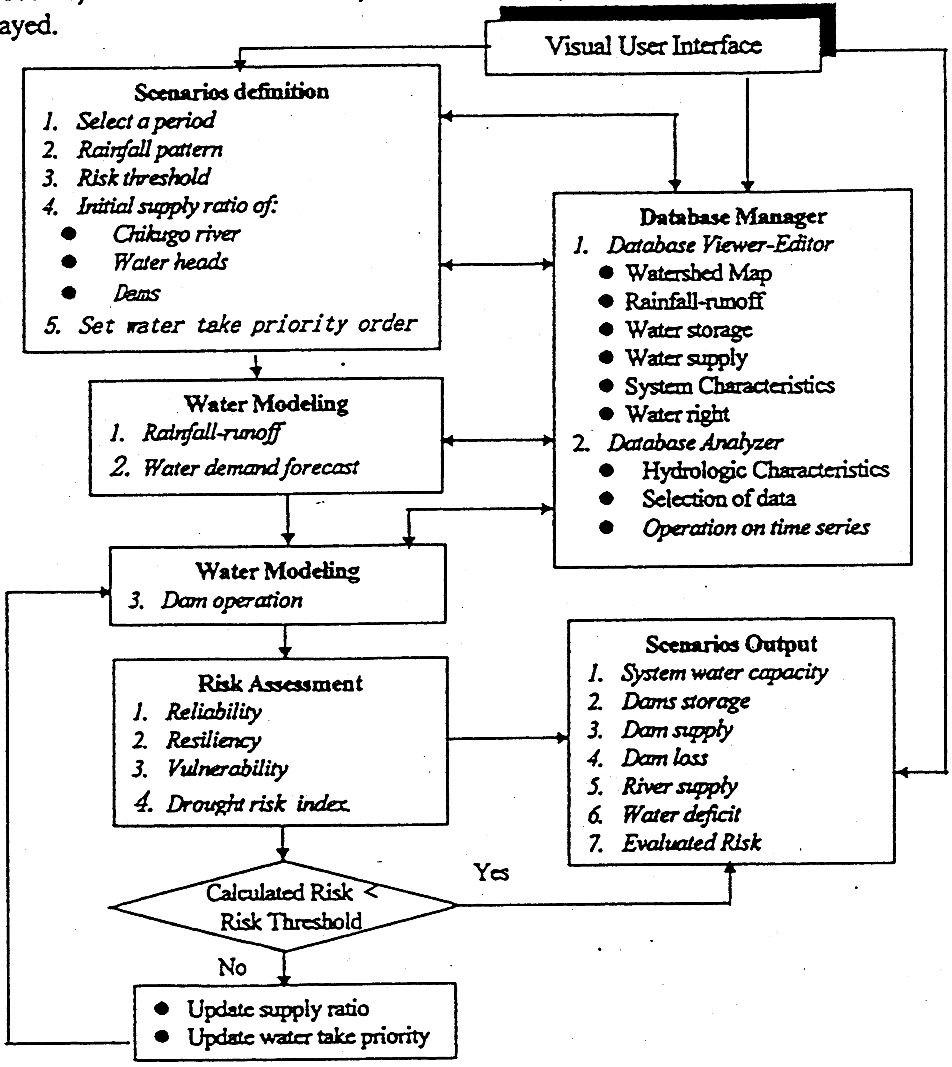

Figure 2 *Decision support system framework*

Data base manager

The data base manager plays the role of data communication network including some fundamental operation on time series analysis (i.e., probability analysis and test criterion) (Merabtene et al., 1997a). It provides information on the water supply system structure and functionality as shown in Figure 2. Each related source database can separately be viewed, updated and sorted (i.e., by season, by return period, etc.) (see Merabtene et al., 1997b).

Simulation models

The integrated mathematical models are the most important component of the present DSS. Each module can be invoked for model parameterization and initial data input. These models concern a rainfall-runoff analysis, domestic water demand, and a reservoir operation model.

Rainfall-runoff model

In the present study a four-stage tank model (Sugawara M., 1961, 1974) combined with a Kalman filtering technique is used as forecasting algorithm. The model provides 1 day ahead inflow forecast and a forecast error criteria reflecting the reliability of the forecast (see Merabtene et al. (1997a). Furthermore, The rainfall-runoff model combined with a preliminary expert system is used for catchment parameters characterization. An application of the tank model to rainfall-runoff analysis of Egawa catchment in given in Figure 4.

Water demand model

The integrated water demand model in our developed DSS considers only the domestic demand forecasting. The industrial and irrigation demand are considered as known for each time period and used as input for the operation model. The domestic water demand is expressed by a straightforward equation (Tajiri et al., 1997) which does not include climatic and hydrologic conditions.

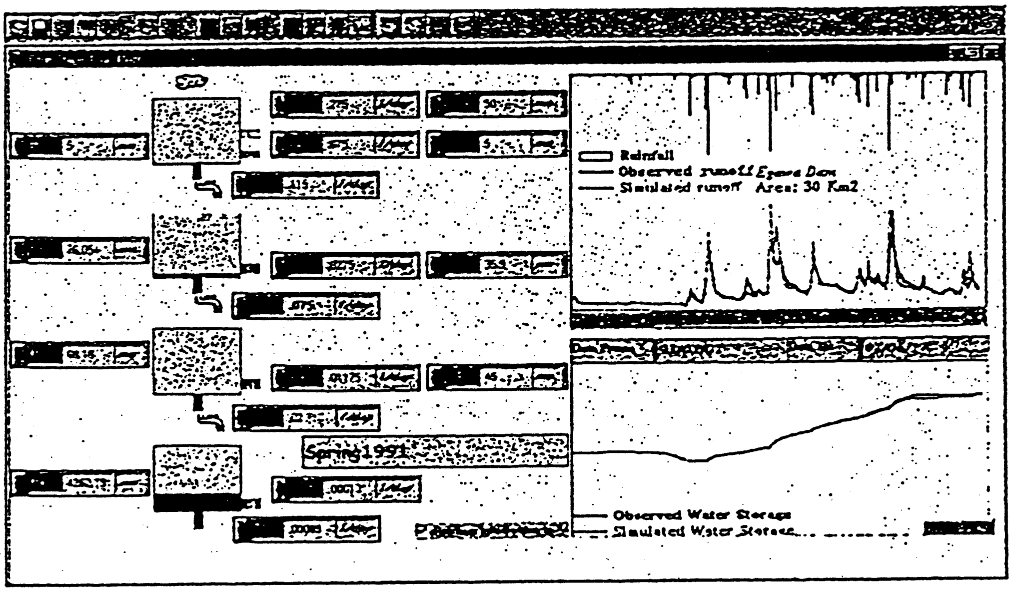

Figure 4 *Tank model interface, rainfall-runoff analysis of Egawa dam.*

The domestic water demand is given by:

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

Where Wd is the domestic daily water demand in (m^3/day), $trend$ is the gradient of the trend in (m^3/day/day) (it expresses a general tendency of the variation of the daily water demand), MDD is the intercept of linear trend at the beginning of the period in (m^3/day), $Mcoef$ are the monthly coefficients and $Dcoef$ are the daily coefficients (i.e., week days and holidays), dimensionless

The result of the model applied for the period extending from January 1st, 1991 to January 1st, 1996 is depicted in Figure 5. During the 1994/5 drought the result shows the amount of water deficit from the daily demand target due to the execution of water rationing.

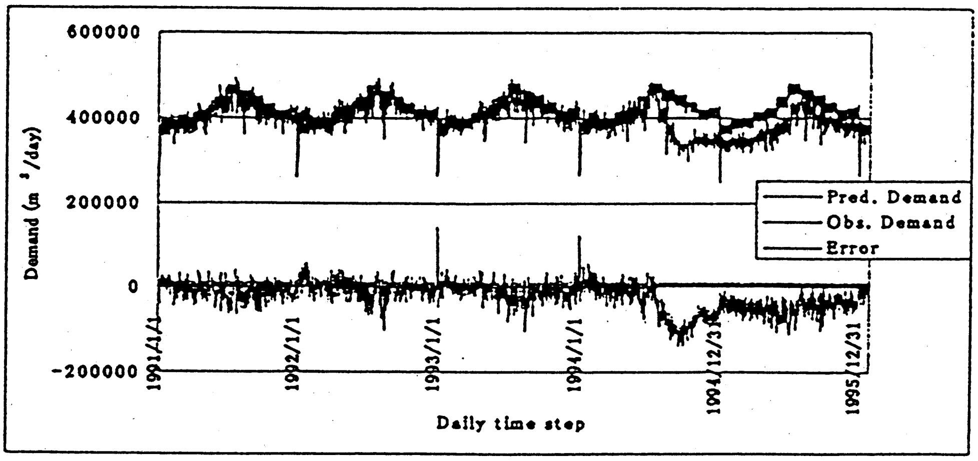

Figure 5 *Variation of the domestic daily water demand*

Reservoir operation model

The objective of the reservoir operation model is to define the best water take policy from each source that minimizes the risk of water deficit during drought. Eqs. 2-6 define a mathematical model for single reservoir daily operation problem based on available stream forecast information. The mathematical program has been presented in a standard form with all known quantities on the right-hand-side of the constraints. A similar system equation is written for each of the 7 reservoirs. The system is subject to the water right constraints (Eq. 7) and the constraints on the maximum purification treatment capacities (Eq. 8) of the linked group of sources (see Figure 1).

The multipurpose-multireservoir operation model is derived from consideration of the continuity equation:

$$S_t = S_{t-1} + I_t - R_t - L_t \quad t=1,2,\ldots,T \qquad (2)$$

$$\text{with} \quad \begin{cases} R_t = WI_t + WDD_t & \text{if} \quad S_t \le S_{max} \\ R_t = WI_t + WDD_t + Ov & \text{if} \quad S_t > S_{max} \end{cases} \qquad (3)$$

Where T is the time period, S_{max} is the maximum water storage, t is the time step, S_t is the water storage, I_t is the inflow to the reservoir, R_t the total release, L_t is the losses from the reservoir, WI_t is the industrial and irrigation demand, WDD_t is the domestic water supply from dam and Ov_t is the overflow.

The risk assessment programming of multi-source operation for domestic water supply can be written as:

Minimize *the risk of water deficit (Equations 9 to 12)*

Subject to:

$$S_{min} \le R_t \le S_{max} \tag{4}$$

$$WDD_t \le WP_t \tag{5}$$

$$WDD_t \le WR_t \tag{6}$$

Beside these constraint on dam operation, we add the constraint on water head and linked sources operation:

$$WDR_t \le WR_t \tag{7}$$

$$\sum WDD_t + \sum WDR_t \le P_m \tag{8}$$

where S_{min} is the minimum reservoir water storage, WP_t the available volume for domestic water supply at time t, WR_t the maximum source water right at time t, WDR_t is the domestic water supply from water head at time t, P_m the maximum water treatment capacity of the purification station m. the summation in equation (8) is applied to all dams and water heads linked to the purification station m (See Figure 1).

Risk Assessment Model

The risk assessment model used in study includes the risk criteria (reliability (*Rel*), resiliency (*Res*) and vulnerability (*Vul*)) in similar manner as defined by Hashimoto et al. (1982) and the drought risk index (DRI) by Jinno et al. (1996). In the present DSS a successive assumptions and scenarios are simulated to minimize the risk of failure in respect to the maximum risk thresholds of the risk indices criteria (Rel_{max}, Res_{max}, Vul_{max}, DRI_{max}).

$$Rel \le Rel_{max} \tag{9}$$

$$Res \le Res_{max} \tag{10}$$

$$Vul \le Vul_{max} \tag{11}$$

$$DRI \le DRI_{max} \tag{12}$$

RESULT AND DISCUSSION

The developed decision support system is applied to evaluate the risk of failure to meet the daily water demand under some alternative drought scenarios. For the period extending from December 1st, 1993 to March 1st, 1995 three risk assessments are presented with 11 scenarios in each assumption (Figures 6 to 8). The result of Figure 6a-6b are calculated under the assumption that the maximum water ratio from the Chikugo river decrease from 100% to 0% of its maximum water right, and all other sources can satisfy their full water right in need (assumption 1). This assumption simulates the risk of failure when drought occurs in the Chikugo river basin during the period of interest, as the case in the 1992/93 drought. The result (Figure 6a) shows that risk can not be avoided unless 40% of the Chikugo river maximum water right can be taken, which represent 13.3 % of the average water demand for the studied period.

In the following assumption (Figure 7) we assume that 40% of the maximum water right from the Chikugo river basin is satisfied and we attempt to evaluate the risk

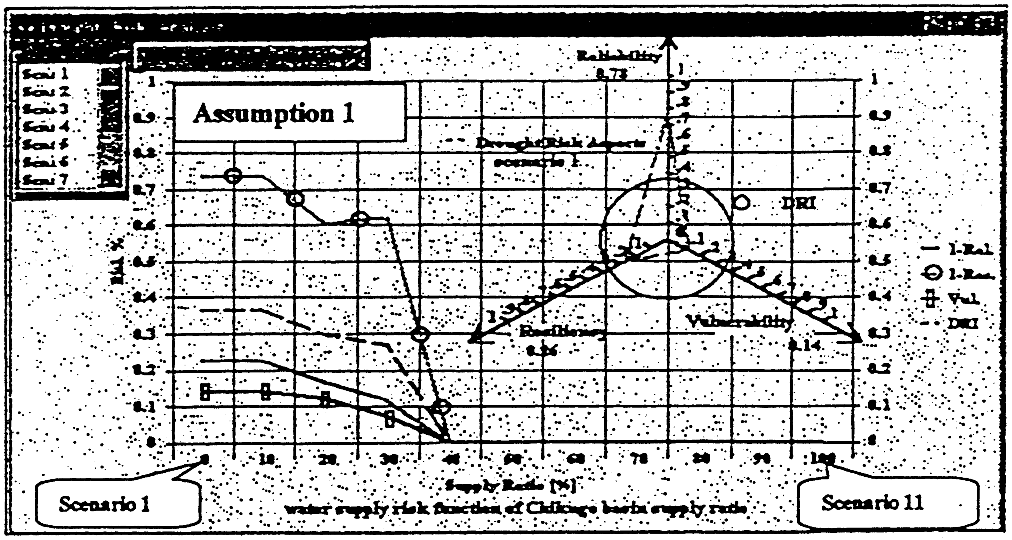

Figure 6(a) *Risk of water supply risk as a function of the water take from the Chikugo river.*

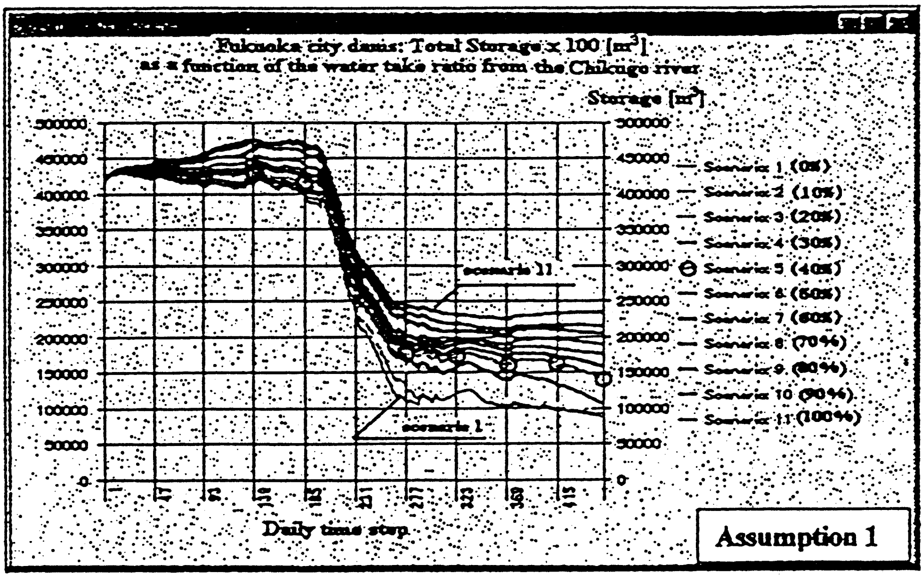

Figure 6(b) *Change in the total water storage of all dams of Fukuoka City As function of the water take from the Chikugo river.*

of failure when the maximum supply ratio from Egawa dam decrease. In this alternative Egawa dam has the top priority for the water take among the 7 dams, all other sources can fully supply their water right (Assumption 2). The result (Figure 7a) shows that if only 40% of the Chikugo river basin water right is taken, the risk of failure is unavoidable unless 60% of the water right Egawa dam is satisfied, which represents 6.6% of the average daily water demand for the period of interest. However, under this assumption when the water supply from Egawa increases Figure 7b (i.e., scenarios 6-11) shows that the water storage decreases until becomes empty before the end of the operation period.

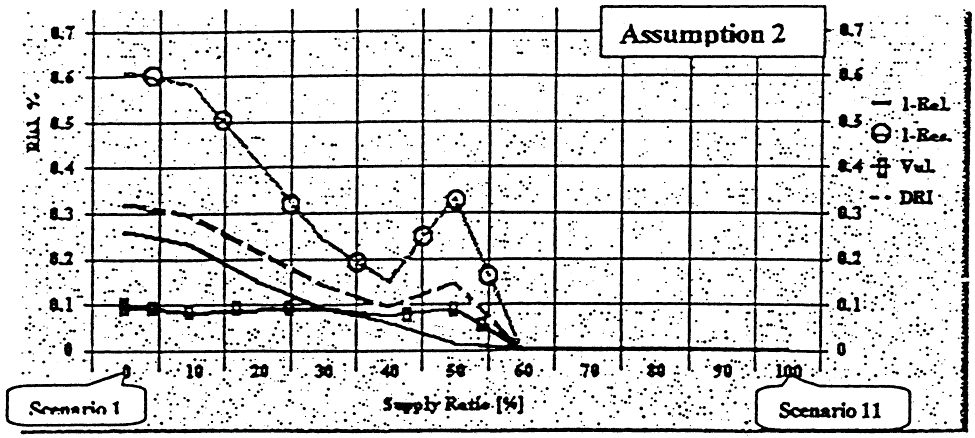

Figure 7(a) *risk of water supply as a function of the water take from the Egawa dam (top in dams water take priority order) when the water take from Chikugo river is 40%.*

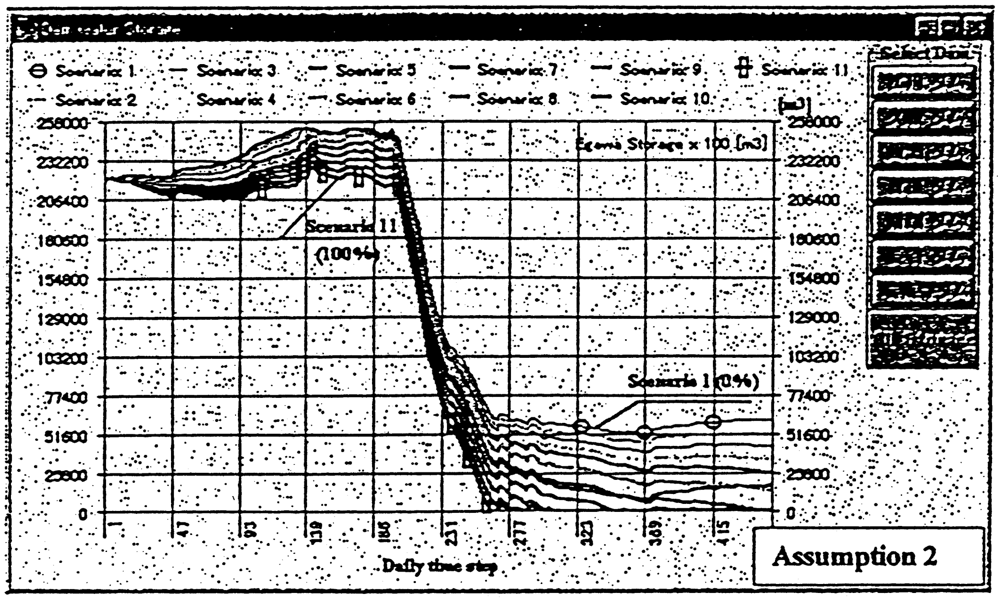

Figure 7(b) *Change in the water storage of Egawa dam when set top in the water take priority order*

The results of Figure 8 are obtained under the same assumption (water take from Chikugo river equal 40% of its maximum water right and the water take from Egawa dam decreasing from 100% to 0%), but Egawa dam is set 4th in the water take priority order among the 7 dams (assumption 3). As can be seen from Figure 8(a) the vulnerability (*Vul*) of the water deficit and the risk of failure (*1-Rel*) are smaller than those of Figure 7(a) but with a higher risk of non-recovery (*1-Res*). Moreover, despite the storage availability in Egawa dam (Figure 8(b)) the risk of failure under this assumption is unavoidable unless 70% of Egawa maximum water right is satisfied (compare to 60% in the assumption 2). The search of the solution that minimize the risk of failure, in respect of the risk threshold values, can be enhanced through an auto-successive run of the operation models.

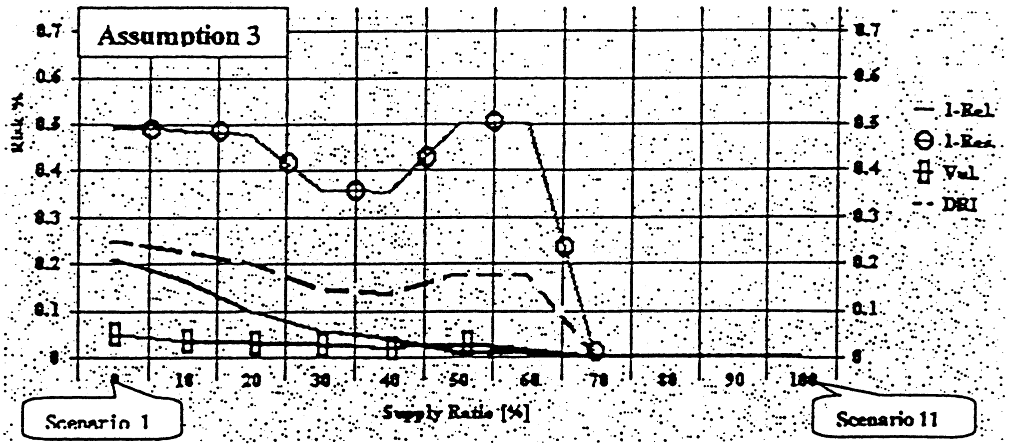

Figure 8(a) *Risk of water supply as a function of the water take from Egawa dam when its water take priority order is set 4th among the other dams*

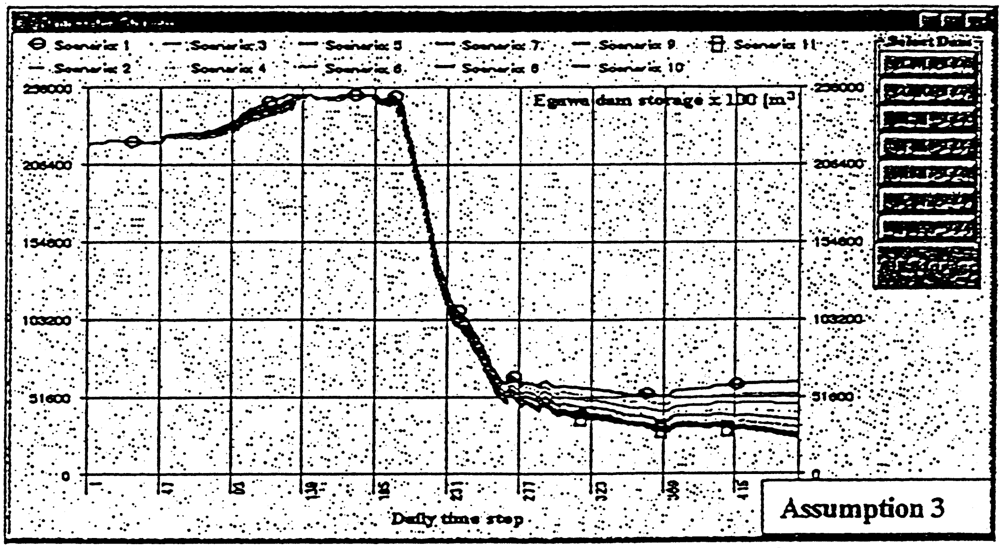

Figure 8(b) *Change in the water storage of Egawa dam when its water take priority order is set 4th among the other dams*

CONCLUSION

The integration of DSS technique and simulation models is an efficient way for risk management in the operation of water supply systems. DSS does not only facilitate the examination of series of scenarios quicker that would be impossible by using traditional methods, but it also provides a dynamic output display and simulation which could be modified by users at any time. This study demonstrates that the integration of DSS technique and risk analysis in the operation of complex water supply system is more significant and useful. Using the developed DSS several assumptions are conducted and some of the characteristics of Fukuoka City water supply system operation can be summarized as follows: (1) The water supply system of the region is vulnerable, and careful measures should be taken to decide not only on the ratio of water take from each sources during drought, but also in setting the water take order among sources, (2) under any hydrologic situation the water from the Chikugo river must be taken first, (3) despite the available water storage Egawa dam should be used first to minimize the risk of non-recovery and long period of water deficit, (4) the optimization of the existing system functionality and the development of new water sources with stable flow is of great urgent, (5) in order to increase the robustness and safety of the entire water supply system, the unified operation for different subsystems is necessary.

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