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Drought Management of Water Supply Systems: A Decision Support System Approach

by

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Abstract

This study proposes a risk based decision support system (DSS) to promote the operation and management of municipal water supply systems under drought conditions. The objective is to develop a comprehensive DSS to improve the quality of decision making when simulating daily operational plans and evaluating alternative water resources management strategies. In this study, the water supply policy is evaluated using the concept of an acceptable "risk level" aiming to reduce long-term drought damages and water shortage threats. The developed DSS includes a database manager and a number of mathematical modeling frameworks involving tools for simulation and optimization as well as expert system procedures. An application of the DSS to the operation of the water supply system of Fukuoka City, western Japan, is presented and discussed.

Keywords: Decision support system, Reservoir operation, Risk assessment, Rainfall-runoff models, Water demand, Database management

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 in order 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. To mention only a few, Randall et al.[1)] discussed a multi-objective linear programming model to analyze the operation of a metropolitan water supply system. Their model includes a reliability criterion based on the minimum ratio of consumption to demand.

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Cancelliere et al.[2], based on a linear relationship between water shortage and performance indices, investigated the susceptibility of a water supply reservoir to drought conditions for different demand patterns by using either a standard operating policy or hedging policies.

Recently, using so-called decision support systems (DSS) is considered the best, if not the only, way to deal with the increasing complexity of water supply systems[3]. Palmer and Holmes[4] utilized a linear programming model and expert system based rules to derive specific operating policies for drought operation of the Seattle, Washington, water supply system. More generalized real-world water management DSSs are discussed in, e.g., Jamieson and Fedra[5], Dunn et al.[6], Simonovic and Bender[7], and Reistman[8].

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 a 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 damages that may be caused by the daily water deficit during periods of drought. The difficulties of such operation, and of management of multi-source systems in general, are due to the serious uncertainties involved. These uncertainties are particularly associated with the river discharge forecast[9],[10], the prediction and forecast of daily water demands[11], 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, and an expert system. To overcome the problem of imperfect streamflow forecast, the DSS includes the tank model[12] combined with Kalman filtering and genetic algorithm (GA) optimization. Furthermore, to predict the daily water demand, a one-dimensional regression model is utilized[11]. In the following sections, we discuss the functionality of the DSS and apply it to a real world multi-source water supply system in Fukuoka City, Japan.

The study area is a fast-growing economic center in western Japan, where governmental agencies give a high priority to the safety and sustainability of water resources management.

2. Decision support system

DSSs were introduced in water management more than a decade ago[13]. However, it is only in recent years that comprehensive DSSs have been developed, aided by the rapid advances in computer technology. Still today, only a limited number of real-world applications have been published. 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 frist topic, water resources management, are presented and applied. As depicted in **Fig. 1,** the DSS integrates three main components: a graphical user interface (GUI), a database manager, and a mathematical modeling module.

2.1 Graphical user interface

Interactivity and graphical presentation is an important issue in DSS development. The design of the interface has a great impact on the user's ability to assimilate information from the DSS and optimize the use of available functions[7]. Therefore, the developed DSS is designed to be fully interactive and user-friendly. The interaction with the user and presentation of information take place through a graphical user interface (GUI). As shown in **Fig. 2,** all DSS components may be invoked from the main menu of the

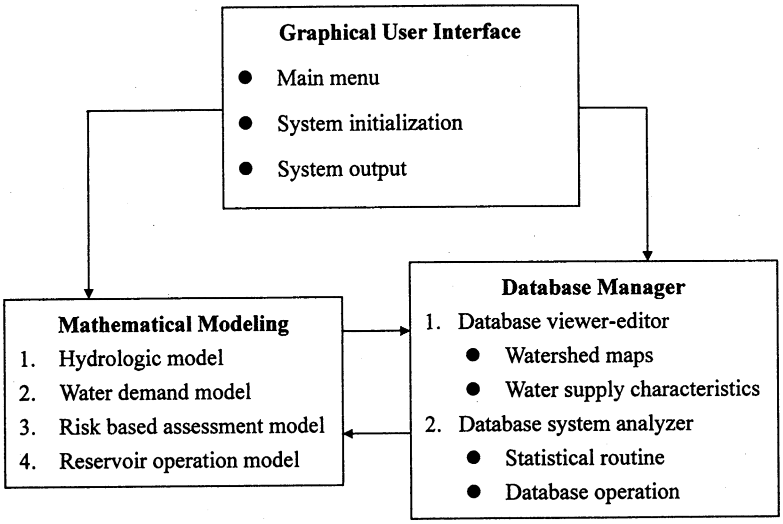


Fig. 1 Decision support system flowchart.

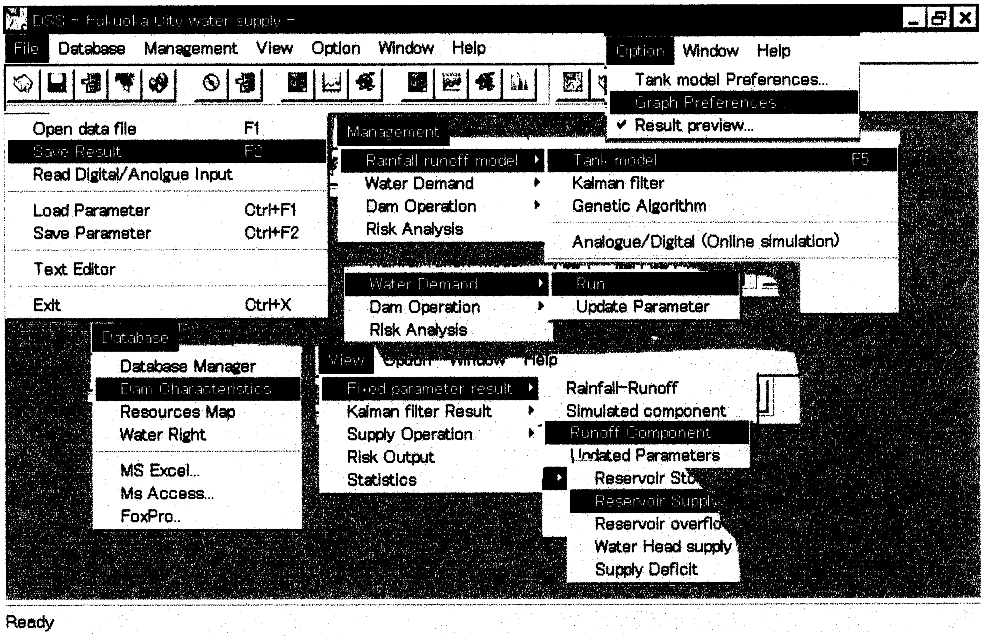


Fig. 2 Decision support system graphical user interface: main menu.

DSS software. The DSS environment was developed under Windows 95/NT and requires 13 MB of free hard-disk space. The GUI is written in Microsoft Visual Basic with a few modules in Microsoft Visual C++, particularly the GA components.

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.[14]. 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 softwares operating within a Microsoft Windows environment, such as Microsoft Excel and Microsoft Access, for subsequent data processing.

2.3 Mathematical models

The mathematical modeling module is the heart of the DSS. The integrated frameworks are designed to perform hydrological analysis, domestic water demand forecasting, risk based assessment, and aid multi-reservoir operation.

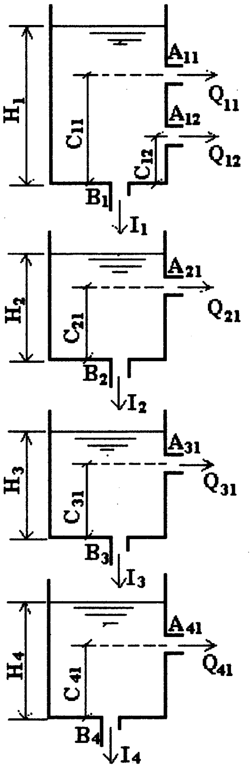


Fig. 3 Four-stage tank model.

2.3.1 Rainfall-runoff model

The rainfall-runoff model is designed to account for a large variety of hydrological processes. It uses the tank model[12] combined with an extended Kalman filtering technique for streamflow forecasting in adaptive mode. The tank model is a conceptual rainfall-runoff model characterized by several tanks to account for surface, intermediate, and groundwater runoff components. **Fig. 3** introduces the four-stage tank model applicable in catchment characterization. The runoff components from the outlets are usually expressed as linear functions of the storage amount, i.e., water level in each tank. When a linear function does not generate satisfactory results, a non-linear expression may be employed[15].

2.3.2 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 as[11]:

$$Wd(\mathrm{t}) = trend * t + MDD * Mcoef * Dcoef \tag{9}$$

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* is the intercept of linear trend at the beginning of the period 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.

2.3.3 Risk assessment model

A number of indicators can be used to describe the performance of a water resources system. In the present DSS, the performance of a multi-source system under drought conditions is evaluated by means of four indices: reliability, resiliency, vulnerability, and drought risk index[16),17)].

Reliability (*Rel*) is defined as the probability that the 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:

$$Rel = \frac{1}{T}\sum_{t=1}^{T} SS_t \tag{10}$$

where SS_t is the state variable of the water supply system. SS_t equals 1 if no deficit occurs on day t, and 0 if deficit occurs. Risk of failure may be expressed as *1-Rel.*

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:

$$Res = \frac{1}{\frac{1}{NF}\sum_{i=1}^{NF} FS_i} \tag{11}$$

where NF is the number of times that the water system enters a failure state during the operation period, and FS_i the ith failure day. Risk of non-recovery from failure may be expressed as *1-Res.*

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 operation period:

$$Vul = \sum_{t=1}^{T} \frac{Wd_t - WDS_t}{Wd_t} \tag{12}$$

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, risk of non-recovery from failure, and vulnerability) may be summarized in the drought risk index (*DRI*) defined by the linearly weighted function:

$$DRI = w_1(1-Rel) + w_2(1-Res) + w_3 Vul \tag{13}$$

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

In Eq. (13), 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 perfomance of the water supply system and assess the simulated water supply scenarios. Thus, in order to determine whether a derived water take scenario is acceptable from the point of drought damages, maximum acceptable "risk levels" are defined:

$$1-Rel<=(1-Rel)_{max} \tag{14}$$

$$1-Res<=(1-Res)_{max} \tag{15}$$

$$Vul<=Vul_{max} \tag{16}$$

The drought risk index threshold may be then formulated as:

$$DRI_{max}=w_1(1-Rel)_{max}+w_2(1-Res)_{max}+w_3 Vul_{max} \tag{17}$$

The risk levels may be visualized as a three dimensional "solution space" where the axes represent the three risk indices (**Fig. 4**).

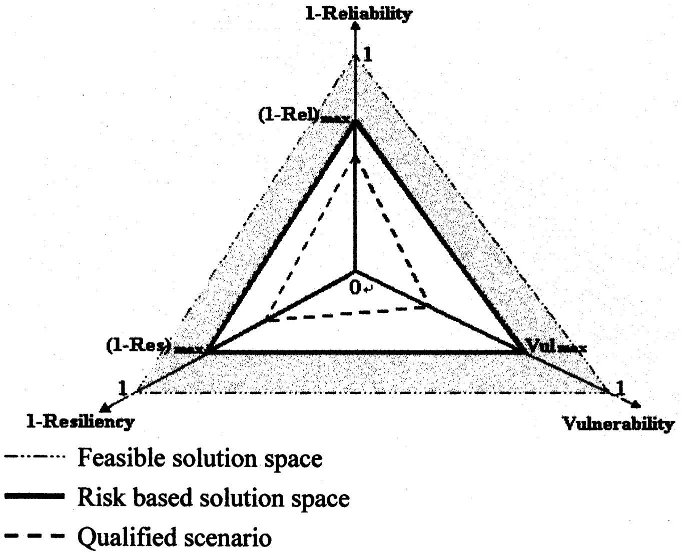


Fig. 4 Feasible space, acceptable risk space, and qualified scenario.

In **Fig. 4** the total feasible space ($0\leq 1-Rel\leq 1, 0\leq 1-Res\leq 1$, 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 solid line in **Fig. 4.** On the other hand, solutions with risk values falling within the shaded space are likely to lead to long-term drought damages. In practice, the acceptable risk levels (Eqs. 14 to 17) 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[18], 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 acceptable risk level.

2.3.4 Reservoir operation model

A simulation model is used in this study to derive and optimize the water release policy from a group of sources. The equation system below (Eqs. 18 to 22) defines a mathematical model for daily operation of a single reservoir based on the available stream forecast information and the initial state of the water resources. Similar equation systems are written for each reservoir in the water supply system.
The reservoir operation model is derived from the continuity equation:

$$S_t = S_{t-1} + I_t - R_t - L_t \quad t = 1, \ldots, T \tag{18}$$

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, and L_t the reservoir losses. In Eq. (18) the release operation is subjected to the constraints on storage capacity and maximum water right for domestic water take:

$$\begin{cases} R_t = WI_t + WDD_t & \text{if} \quad S_t \leq S_{max} \\ R_t = WI_t + WDD_t + Ov_t & \text{if} \quad S_t \geq S_{max} \end{cases} \tag{19}$$

$$S_{min} \leq R_t \leq S_{max} \tag{20}$$

$$WDD_t \leq WP_t \tag{21}$$

$$WDD_t \leq WR_t \tag{22}$$

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

The water take from each source is further subjected to water right constraints and constraints on the maximum purification treatment capacities of each linked group of sources:

$$WDR_t \leq WR_t \tag{23}$$

$$\Sigma\ WDD_t + \Sigma\ WDR_t \leq P_m \tag{24}$$

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. (24) is done for all reservoirs and water heads linked to purification station m.

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, Japan, is used as an example. The region is a growing economic center in the western Japan, where the water officials are currently undergoing intensive training to incerase the efficiency and sustainability of the existing complex water resources system management.

3.1 Fukuoka City water supply system

Fukuoka City has a mild weather and no severe earthquake or flood has ever been recorded. Because of seasonal winds there are both an early rainy season (June to July) and a later typhoon season (September to October). The hydrologic regime is characterized by a pronounced seasonal variation with an annual average precipitation of 1600 mm/year, only a fraction occurring as snow. The annual average evapotranspiration is about 960 mm/year[19]. Fukuoka City water supply provides direct service to 1,295,832 residents with an increasing rate of about 1% per year[20]. 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[21]. Thus, the major supply is from surface water (99%). The major components of the actual water supply system, as schematically illustrated in **Fig. 5**, include:

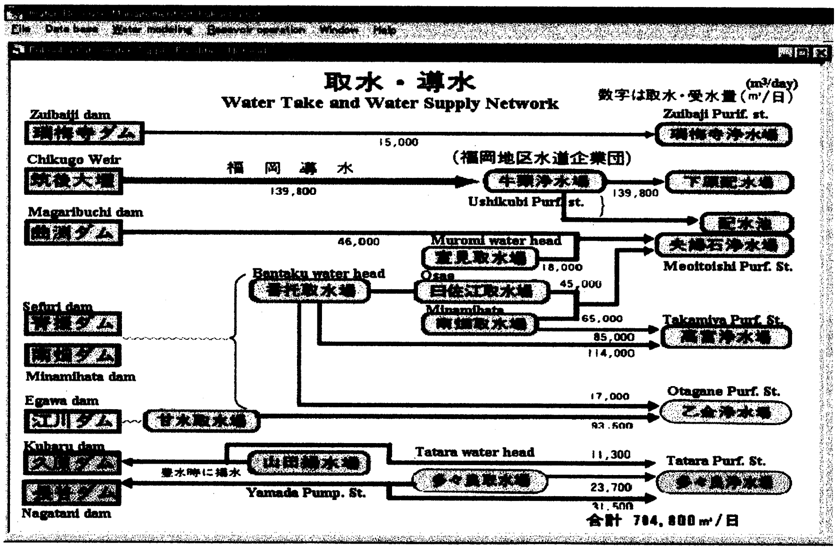


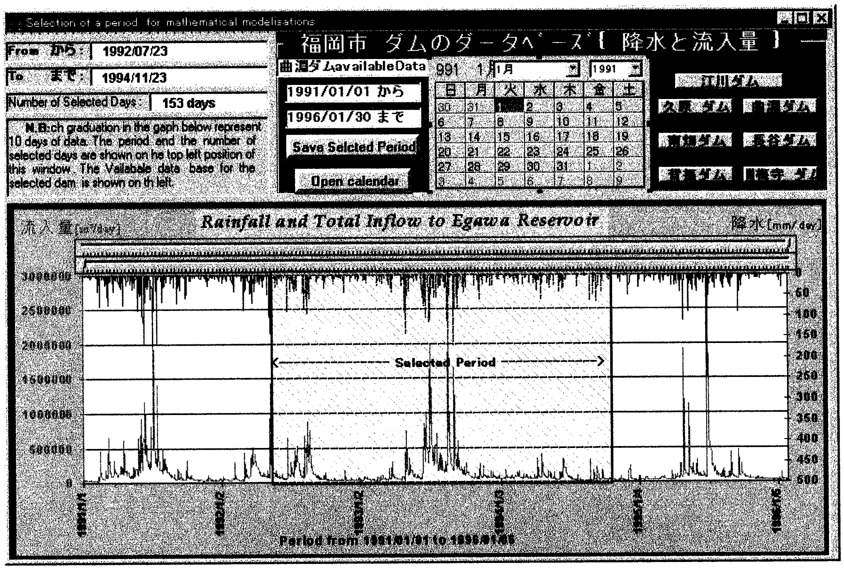
Fig. 5 Principal structure of the Fukuoka City water supply network.

1. Six purification stations with a maximum supply capacity of about 704,800m^3/day.
2. Direct water right from the Chikugo river basin yielding a maximum of 118,000m^3/day. Actually, the Chikugo river basin belongs to a different jurisdiction and the water supplied to Fukuoka City is made under entitled agreement. Significant reductions in yield can be expected during prolonged droughts of duration longer than 1-1.5 year because of water share conflicts among users, streamflow depletion, and water quality deterioration as experienced during the past droughts[20].
3. Water heads including five pumping stations implemented in the surrounding small rivers. The maximum water right may vary monthly or seasonally. Moreover, the rivers are particarly characterized by unstable discharge because of their respective small catchment area. Much of the river streamflow is presently used for irrigation, particularly during the rice crop season (May to September).
4. Seven dams with a total effective capacity of 45 x 10^{6}m^3. The capacity directed to the municipal water supply is about 25 x 10^{6}m^3 yielding a maximum of about 346,700m^3/day with a high monthly water right variability. 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 slope). For successful operation the reservoir storage levels must recover to near the capacity after the rainy season. The average precipitation from May to August is about 950 mm, and the system also depends on the typhoon season to partially refill its capacity. Unusual climatic events, such as the droughts occurring in 1978 and 1994, cause the system storage to decline to levels that require water use restriction.

Since Fukuoka City started its water supply service in 1923, several droughts with different magnitudes (severity and duration) have been recorded. The 1994 drought, the worst on record, began in the late spring 1994 and continued until the early summer 1995. The total precipitation in 1994 was about 60% of the annual average. Warm winds, abnormally high temperatures, and low precipitation were the perpetual characteristics of the drought. The river flows during July and August were drastically below average and the reservoirs could not reach their maximum water supply capacity. By mid-July 1994 restriction on water use by pressure reduction was applied. On August 4, water rationing was initiated which continued until early July 1995. The water supply crisis deepened by early September 1994 because of the complete drying up of the Egawa reservoir, the most important structure of the city's water supply system, and simultaneous drought in the Chikugo river basin. Beside the 50% flow decrease in Fukuoka City rivers, the Chikugo river flow decreased by about 70% by late July 1994 resulting in a rapid deterioration of the river water quality[20].

3.2 DSS application



From から: 1992/07/23
To まで: 1994/11/23
Number of Selected Days: 153 days

N.B.:ch graduation in the gaph below represent 10 days of data. The period and the number of selected days are shown on he top left position of this window. The Vailabale data base for the selected dam is shown on th left.

1991/01/01 から
1996/01/30 まで

Period from 1991/01/01 to 1996/01/30

Fig. 6 Database manager: graphical data selection interface.

To derive a water take policy from different sources using the present DSS, the user starts by selecting the operation period from the database manager. **Fig. 6** is a graphic presentation of 5 years (1991-1995) of observed rainfall-runoff data from the Egawa reservoir. The user may select any basin, reservoir, or water head from the water supply map to analyze the corresponding data. 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 selected from the database manager. Next, the water demand is estimated by updating the appropriate parameters for each time step. The user is then requested to input the management and planning preferences, 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.

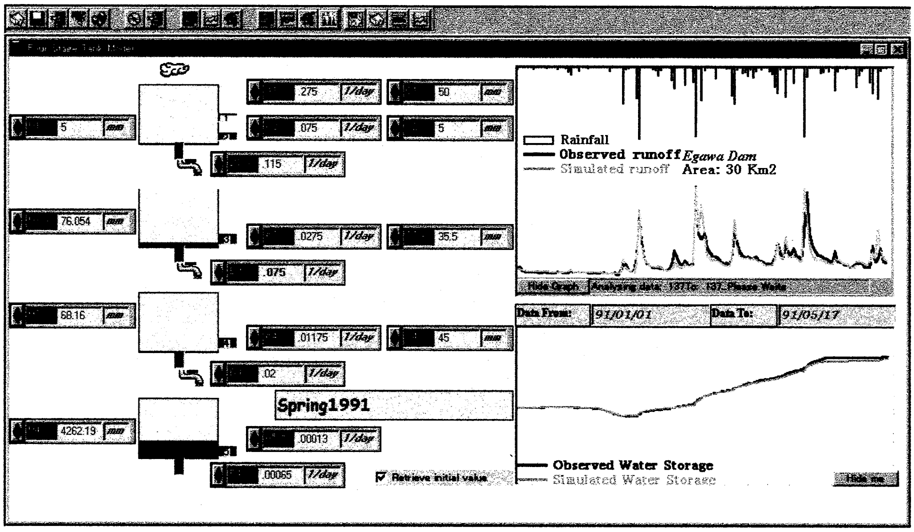
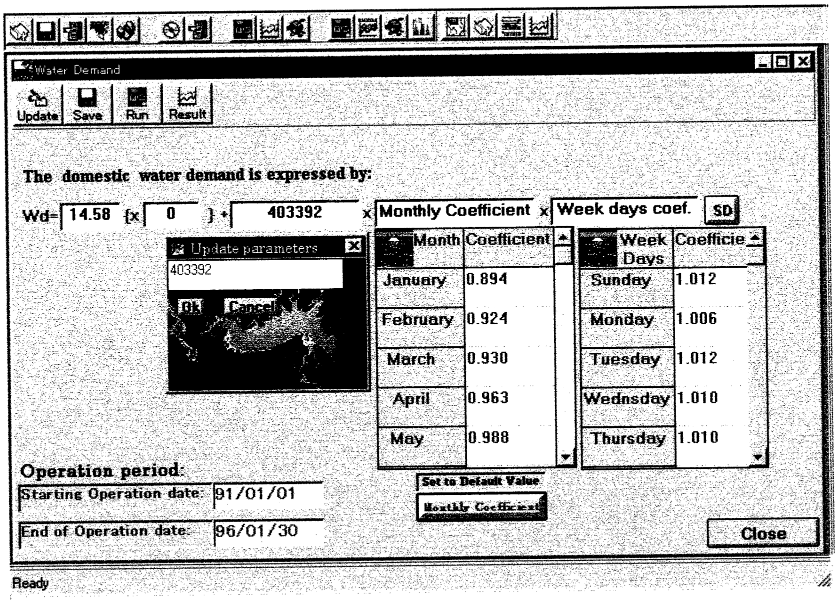

Data From: 91/01/01
Data To: 91/05/17
Spring1991
☑ Retrieve initial value

Fig. 7 Four-stage tank model interface: results from a rainfall-runoff analysis of the Egawa reservoir.

Fig. 7 presents an application of the four-stage tank model to the Egawa reservoir. The applied tank model configuration included four linear tanks with 17 parameters, four tank storage levels, five lateral runoff parameters, four side outlet thresholds, and four bottom parameters for infiltration and deep percolation. The tank model parameters' optimization procedures (GA or Kalman filter) may be selected from the main menu of the DSS. The trial and error method can be started by inputting the desired parameters values in the appropriate box and click the run button from the menu. For each basin, the daily output from the tank model is the runoff components (surface, intermediate, low, and base flow), the water level in each tank, the parameters updated by Kalman filtering, and the prediction error. If several trials are conducted, e.g., by using different configurations of the tank model or using different sets of parameters and data for calibration and validation, the results are tabulated and stored by trial in the database manager. The graphical output for each trial can be invoked from the graphical user interface.

The parameters of the domestic daily water demand model applied to Fukuoka City are given in Xu et al.[11]. For the prospect of planning and forecasting, the model parameters may be updated through the water demand model interface as shown in

Fig. 8 (a). The prediction reliability of the model is about 96% (±4% of actual value). The output of the model are the observed and predicted demands, and the prediction error. As shown in **Fig. 8 (b),** the yearly average water demand (400,000m^3/day) does not show any significant variation during the operation period extending from January 1, 1991, to January 30, 1996. This is a result of the water saving campaign that the local government has been carrying out since the 1978 drought. During New Year holidays (December 31 to January 2) the demand decreases to about 60% of the daily average. The highest records are during the summer season (June 26 to August 1) when the



The domestic water demand is expressed by:

Wd= 14.58 {x 0 } + 403392 x Monthly Coefficient x Week days coef.

Update parameters: 403392

Month	Coefficient
January	0.894
February	0.924
March	0.930
April	0.963
May	0.988

Week Days	Coefficie
Sunday	1.012
Monday	1.006
Tuesday	1.012
Wednsday	1.010
Thursday	1.010

Operation period:

Starting Operation date: 91/01/01

End of Operation date: 96/01/30

Fig. 8 (a) Water demand model interface.

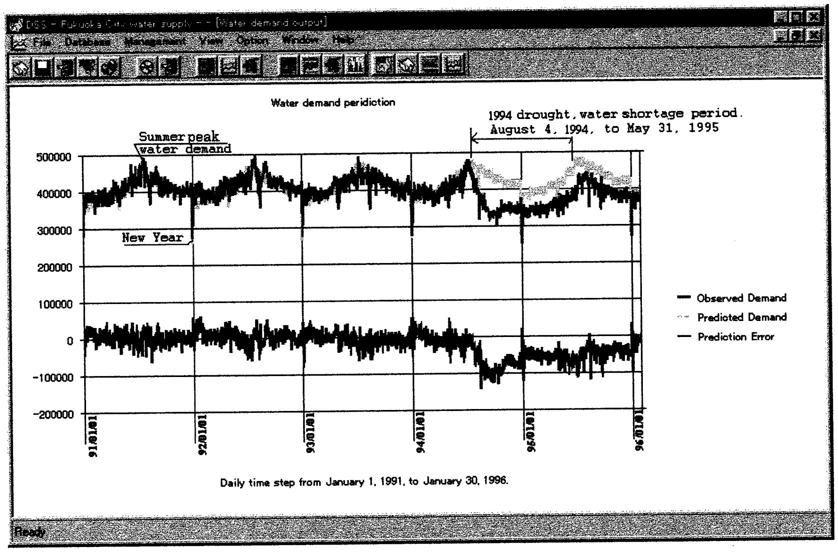
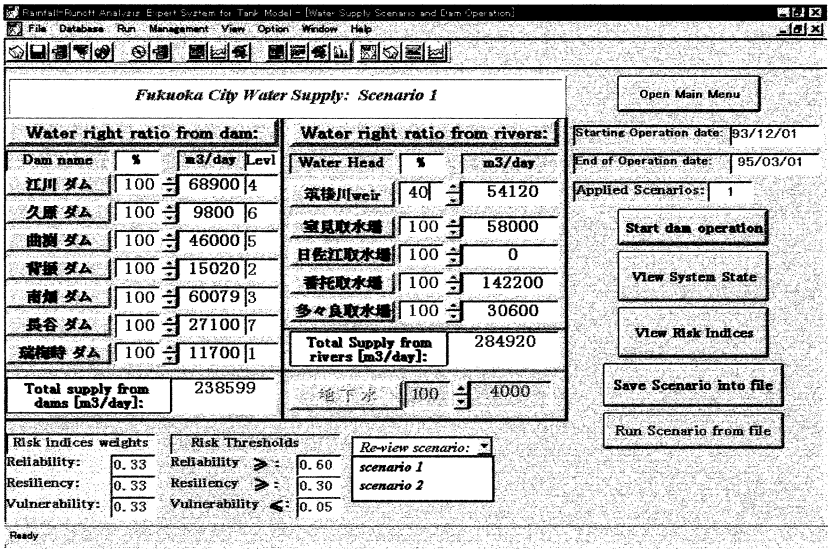


Fig. 8 (b) Daily domestic water demand, observed and predicted demands, and prediction error for the period extending from January 1, 1991, to January 30, 1996.



Fukuoka City Water Supply: Scenario 1

Water right ratio from dam:

Dam name	%	m3/day	Levl
江川 ダム	100	68900	4
久原 ダム	100	9800	6
曲渕 ダム	100	46000	5
背振 ダム	100	15020	2
南畑 ダム	100	60079	3
長谷 ダム	100	27100	7
瑞梅寺 ダム	100	11700	1

Total supply from dams [m3/day]: 238599

Water right ratio from rivers:

Water Head	%	m3/day
筑後川weir	40	54120
室見取水場	100	58000
日佐江取水場	100	0
番托取水場	100	142200
多々良取水場	100	30600

Total Supply from rivers [m3/day]: 284920

地下水 100 4000

Starting Operation date: 93/12/01
End of Operation date: 95/03/01
Applied Scenarios: 1

Risk indices weights		Risk Thresholds	
Reliability:	0.33	Reliability ⩾:	0.60
Resiliency:	0.33	Resiliency ⩾:	0.30
Vulnerability:	0.33	Vulnerability ⩽:	0.05

Re-view scenario:
scenario 1
scenario 2

Fig. 9 Risk assessment and reservoir operation interface.

demand is about 20% above average. During the 1994 drought, the average deficit was about 30-45% from July 14 to December 30, 1994, and about 20% for the rest of the period until early July 1995.

The risk assessment model and reservoir operation model are merged in a single interface as shown in **Fig. 9.** The input to the risk assessment model are limited to the acceptable risk levels $((1-Rel)_{max}, (1-Res)_{max}, Vul_{max})$ and the appropriate risk weights (w_1, w_2, w_3) to formulate the threshold of the drought risk index (DRI_{max}). The output of the model is the performance of the supply system for the qualified water supply scenarios as shown in **Fig. 10** described below.

Through the main interface of the reservoir operation model (**Fig. 9**), the user inputs the related data. The input may include the state of the water supply system at the beginning of the operation period and the acceptable risk levels. The output of the reservoir operation model is the state of the daily water supply for each scenario. This includes the reservoirs' storage and overflow, the daily water take from each source, and the daily supply-demand deficit for each scenario if applicable.

3.3 Water supply scenarios

The scenarios presented in this study attempt to evaluate the susceptibility of the water supply system under different weather conditions and water supply restrictions from the Chikugo river basin. Two sets of climatological conditions are considered. The first is 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 daily supply from the Chikugo river during the 1994 drought was decreased by 40-60% on average.

Fig. 10 shows the variation of the performance of the water supply system for different percentages of maximum yield from the Chikugo river basin. The risk for 1992 and 1994 was evaluated for the same water take allocation pattern from remaining sources in Fukuoka City. As shown in **Fig. 10,** under normal weather conditions in Fukuoka City (as in 1992 with 1435 mm/year of precipitation), 20% of the maximum

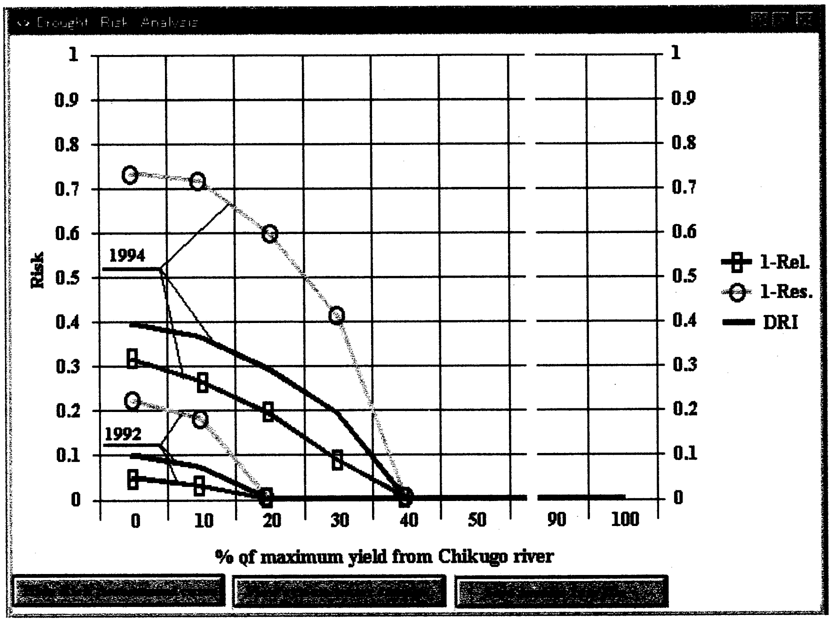


Fig. 10 Fukuoka City water supply performance as a function of the water yield from the Chikugo river basin for the weather conditions of 1992 and 1994.

water right from the Chikugo river is sufficient to satisfy the domestic water supply without need for water rationing. The result also shows that under the 1994 weather conditions, the drought risk index (DRI=0.4) is four times higher than that of the 1992 drought scenario (DRI=0.1). Moreover, the result shows that the risk of non-recovery from failure, if failure occurs (*1-Res*), may be viewed as a warning sign and must be carefully considered for optimal operation of the water supply system during periods of drought. Moreover, for each scenario shown in **Fig. 10,** the DSS provides the variation of the water storage in each reservoir and the daily water deficit in terms of quantity and period of sojourn. The output of the DSS does not only provide the best solution, but all qualified supply scenarios which facilitate the selection of appropriate actions to minimize the long term drought impact in the decision-making process.

4. Conclusions and future developments

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 case study demonstrated some of the risk-based planning and management aiding capability of the developed DSS. By setting an acceptable risk level, several water supply operations can be simulated and assessed to increase the water supply system reliability. 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/ Non-optimal water take allocation from even one single source of the water supply system may lead to inferior performance of the entire system. The present DSS permits the assessment of qualified water take policies by applying a risk based analysis. However, to increase its objectivity, optimization routines may be developed to evaluate a near 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. The expert system will represent a potential benefit to the area of water resources management by DSS and add a realistic decision aspect to the mathematical models. This will further complement the decision when evaluating the daily water take from each source and setting the water take priority among the reservoirs and water heads. This is an important issue for the estimation of system storage recovery during drought.

3/ Water quality and groundwater management, although outside the scope of this paper, are of great concern for all water supplies. It is obviously important to incorporate such model concepts into the DSS to develop a tool for complete sustainability management of water resources systems.

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. Thus, the possibility to include cost information for each evaluated scenario is being considered.

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