Development of Integrated Decision Support System for the Water Supply System in Fukuoka, Japan

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Summary

This study introduces the development of an integrated decision support system (DSS) for the water supply system in Fukuoka City, Japan. The objective is to conceive a comprehensive tool that may aid decision-makers to derive the best water supply alternatives from a multi-reservoir system in order to minimize the long-term drought damages and threat of water shortage. The present DSS consists of a database manager, and simulation models for runoff analysis, water demand forecasting, and reservoir operation. The methodology applied explicitly integrates the drought risk assessment, based on the concept of reliability, resiliency, and vulnerability, as constraints to derive the management operation. The application of the DSS to the existing water supply system in Fukuoka City was found to be an efficient tool to facilitate the examination of a sequence of water supply scenarios toward an improved performance of the actual water supply system during periods of drought.

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 and 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 is considered as the best way to deal with the increasing complexity of water supply systems.

The notion of decision support systems (DSS) for water resources planning and management was introduced more than a decade ago (e.g., [1] and [4]). However, it is only in recent years that comprehensive DSSs have been developed and applied to real-world water supply systems and river basin management (e.g., [3], [6] and [7]). Nevertheless, despite the increasing complexity of actual water supply systems, only few developed DSSs were concerned with drought and risk related aspects in water supply (e.g. [8]).

The present paper introduces a risk-based decision support system for operation of water supply systems. The objective is to develop a comprehensive tool 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 supply alternatives, among a group of sources, that satisfy an acceptable "risk level" introduced to minimize the drought damages and threat of water shortage. The current DSS consists of two main modules, a database manager, and simulation modules. The database manager was integrated to provide information on the water supply components, i.e., reservoirs, water heads and purification stations, and perform some fundamental time series analysis. The simulation models are the mathematical base of the DSS incorporating (1) a rainfall-runoff analysis by tank model using the Kalman filtering technique to update model parameters, (2) a water demand forecast model, (3) a reservoir operation model, and (4) a drought risk assessment model. To evaluate the water supply alternatives from multi-sources water supply system, the methodology is based on a genetic algorithm (GA). The DSS systematically links, through a user-friendly interface mainly written in Microsoft visual basic, the database manager for hydrological data to the mathematical models.

The developed DSS is applied to the optimal operation of water supply system in Fukuoka City, Japan, by conducting risk assessment for different water supply alternatives. The results demonstrate that the advantage of integrating DSS technique and risk analysis in the operation of complex water supply system is highly significant.

2. Study area

Fukuoka City, western Japan, is constantly facing a threat of water rationing due to lack of water resources and water demand growth, deepened by the occurrence of several periods of drought. The water supply sources are characterized by a limited groundwater supply (1% of the total daily domestic water supply) due to shallow aquifers, salt intrusion, and groundwater pollution caused by chlorinated hydrocarbons. Thus, the major supply is from surface water (99% of the total daily domestic water supply). The major components of the present water supply system and waterworks facilities are illustrated in Figure 1 and include: (1) Five purification plants with a maximum water supply capacity of 704,800 m^3/day, (2) Five water intake stations implemented on the surrounding small rivers with a maximum water supply capacity of 275,700 m^3/day, (3) Seven dams with a total effective capacity of 45 million m^3. The capacity directed to city water represents is about 25 million m^3, and (4) direct water right from the Chikugo river basin yielding a maximum of 118,000 m^3/day, which represents about one third of the total daily water supply.

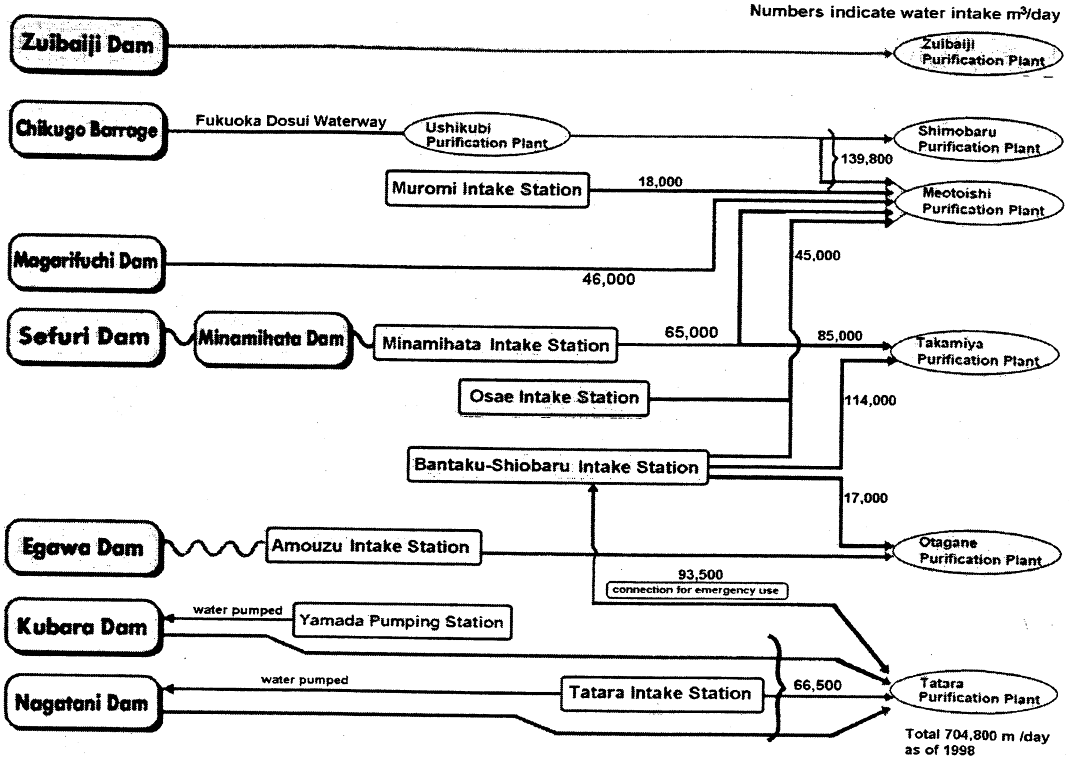


Figure 1. Fukuoka City water supply network.

During periods of drought, significant reduction in yield from the Chikugo river basin and surrounding rivers 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 as experienced during the past droughts.

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 (*DRI*) ([2] and [9]).

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:

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

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:

$$Res = \frac{1}{\frac{1}{NF}\sum_{i=1}^{NF} FS_i} \tag{2}$$

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.

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:

$$Vul = \sum_{t=1}^{T} \frac{Wd_t - WDS_t}{Wd_t} \tag{3}$$

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

In order to determine whether derived water take scenario is acceptable from the viewpoint of drought damages, maximum acceptable "risk level" is introduced. The maximum risk level is defined as the threshold of the drought risk index (*DRI*) [9] formulated as a weighted function of the risk of failure (*1-Rel*), risk of non-recovery (*1-Res*), and vulnerability (*Vul*):

$$DRI_{max} = w_1\,(1\text{-}Rel)_{max} + w_2\,(1\text{-}Res)_{max} + w_3\,Vul_{max} \qquad (4)$$

where $\sum_{i=1}^{3} w_i = 1$, and $(1\text{-}Rel)_{max}$, $(1\text{-}Res)_{max}$ Vul_{max} are the acceptable risk thresholds.

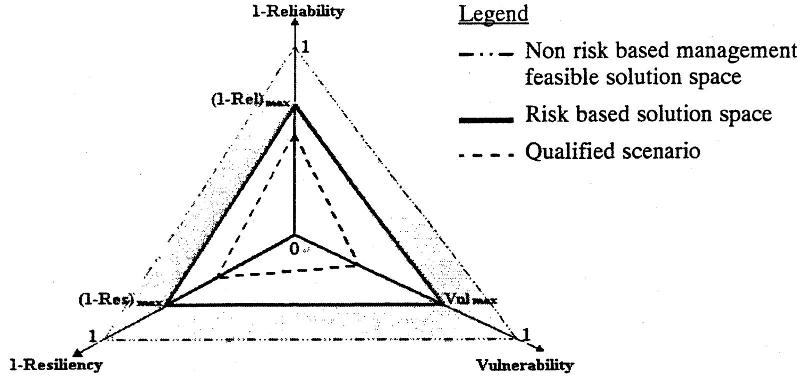


Figure 2. Solution space of risk based management operation.

In (4), w_1, w_2, and w_3 specify the relative weights of the respective risk criteria. For 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 total feasible space ($0 \leq 1\text{-}Rel \leq 1$, $0 \leq 1\text{-}Res \leq 1$, and $0 \leq Vul \leq 1$) depicted in Figure 2 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 2. Under this constraint all solutions with the risk values falling within the shaded space are likely to lead to long-term drought damages. In practice, the acceptable risk levels 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.

4. Decision support system

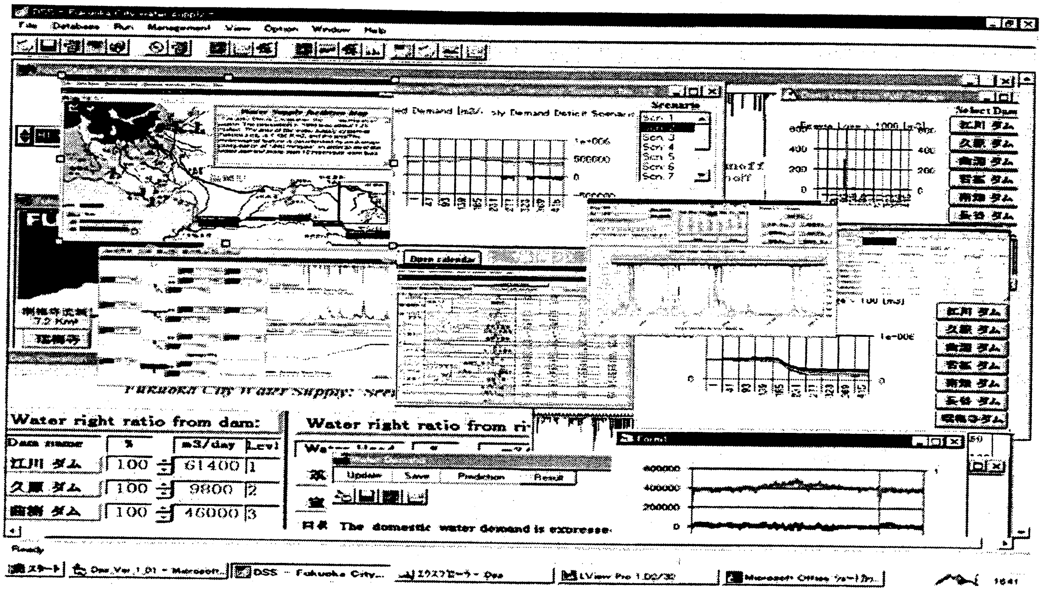
The DSS introduced in this study is an expanding model which attempts to include several aspects of water resources, water quality, and groundwater management. In this paper, the components of the DSS related to the first topic, water resources management, are presented.

4.1 Graphical user interface

The software environment of the present DSS (see Figure 3) was developed on a DOS\V computer under the Windows 95 operating system. The user-interface is mouse driven and short cuts tool menu to the DSS components. 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 optimized for a Pentium II 400 MHz, 64 MB of memory, and a 16 high color screen. The 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 memory use. The FORTRAN language was used particularly to write the Kalman filter version of the tank model and some statistical routines such as exceedance probability whereas the language offers a higher flexibility to manage complicated mathematical formulations.

4.2 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 the Microsoft Windows environment, such as Microsoft Excel and Microsoft Access, for subsequent data processing.



Water right ratio from dam:

Dam name	%	m3/day	Levl
江川 ダム	100	61400	1
久原 ダム	100	9800	2
曲渕 ダム	100	46000	3

The domestic water demand is exoresse

Figure 3. Enviroment and graphical user interface of the DSS for Fukuoka City water resources management

4.3 Mathematical models

In addition to the risk assessment model discussed earlier, the present DSS incorporates three mathematical models for rainfall-runoff analysis, water demand forecasting, and reservoir operation. The rainfall-runoff model is based on the application of the tank model ([5] and [11]). In order to alleviate the problems associated with imperfect streamflow prediction the developed model integrates the Kalman filtering technique to optimize the model parameters in adaptive mode. The water demand model considers only the forecasting of daily domestic demand. The temporal variation of the water demand is expressed by a straightforward linear regression model expressing weekly and yearly cycles superimposed on an overall trend [10].

In the reservoir operation model both simulation and optimization procedures are proposed. The simulation model is based on the risk assessment analysis and performance of the system to modify of the operation policy toward an improved solution. In other words, the system operation and control actions are derived to minimize drought damages and consequently reduce the shortage threats during the operation horizon. Despite the advantage of the model to define most appropriate water supply alternatives according to the risk output, it should be noticed that the performance the system may exhibit a strong sensitivity to the changes in the release distribution among the existing sources. Thereafter a non-optimal release operation from at least one of the reservoirs will undoubtedly lead to the deterioration of the entire system performance. In the present DSS the optimization procedure applied to derive the best water take policy from a multi-reservoir supply system is based on a genetic algorithm (GA).

In this study the genetic algorithm scheme applied for the optimal operation of the actual multi-reservoir water supply system is based on the integration of risk assessment theory to improve important features of the genetic algorithm theory and increase its practical applicability for drought reservoir operation and decision making.

The decision variables to be optimized are the daily water supply alternatives from each reservoir during period of drought. In the present GA scheme, two new and distinct features are introduced: (1) a unique risk-based measure is used as objective function. In other words the fitness of the objective function to be evaluated at each generation represents the total risk of water supply failure expressed by the drought risk index (*DRI*), (2) a constraint on the qualification of selected strings, i.e., water supply solutions, as parents for the next generation is imposed. The strings qualified as parents for the next generation are those being in the acceptable operation space, defined by the risk thresholds or acceptable risk levels (see **Figure 2**). There are two reasons for selecting strings only from the acceptable risk operation space: (1) speed-up of the convergence process which is particularly important in real-time operation, and (2) generation of future chromosomes which cluster within the defined acceptable risk space leading to more efficient practical decisions. However, an inconvenience of such restricted selection of parents is a risk of population inbreeding from generation to generation. Therefore, in order to maintain the breeding of contributing chromosomes to the new generations, random structures are selected from qualified solutions inside the acceptable operation space.

As for the simulation model, the fitness evaluation of the GA procedure for the drought operation is based on the system balance equation and physical constraints according to the standard reservoir operating rules over a given time period. Since the fitness value *DRI* index can be evaluated only for a sequence of time periods *Nd*, the algorithm starts by generating a random release allocation R_i from each reservoir *i* and for each day $t=1$ *to* Nd. Thus each chromosome of the population is mapped over a binary coding of total length *L* defined as:

$$L = (m * l_i) * Nd \qquad (5)$$

where *m* is the number of reservoirs, *Nd* a period of *n* consecutive days in the total operation period *T*, and l_i the length of the encoded representation of the water supply solution from reservoir *i*.

The parameters encoding is performed using a binary alphabet 0 and 1. In general, if the solution of the problem is a scalar, the string represents in fact a binary number of a given length. However, if the solution is a vector, as it is in this particular application (the water supply from multiple reservoirs), the string is created by concatenating the binary coding of vector coordinates into a single string, keeping track of locations of sub-strings (i.e., water supply from each reservoir) that represent different components of the solution. The relationship between a value of a real parameter R_i (supply from reservoir *i*) and its binary coding b_i is given by:

$$R_i = R_{min} + \frac{R_{max} - R_{min}}{2^L - 1} * \sum_{i=1}^{L} b_i \; * \; 2^{i-1} \qquad (6)$$

where R_{max} and R_{min} represent the maximum and minimum release from the reservoir i.

$$R_{min} \leq R_i \leq R_{max} \qquad (7)$$

In other words, a real number between R_{min} and R_{max} is mapped over an interval of *L* bits binary integers with values between 0 and 2^L-1. The precision $\varepsilon_L(R)$ of such a representation is given by:

$$\varepsilon_L(R) = \frac{R_{max} - R_{min}}{2^L - 1} \qquad (8)$$

Therefore, the decision variable is not a unique value, but a finite number of supply decisions. In this application, each binary string of length l_i was mapped between a minimum value 0 and a maximum value wr_i (maximum supply from reservoir *i*). The sub-string of length $m*l_i$ for day *t* is the maximum water supply from all reservoirs.

To alleviate some of the problems associated with the scaling discussed above, the release decision from each reservoir is mapped between 0 and 100 representing the percentage of maximum and minimum water right, respectively. The advantage of such transformation is to avoid the manipulation of real numbers of different maximum and minimum limits. Moreover, a straightforward transformation function (**Eq. 9**) can be formulated to evaluate the relation between the percentage and corresponding to the water supply value to be used in the *DRI* calculation.

$$R_i = \frac{R_i(\%) * wr_i}{100} \qquad (9)$$

where $R_i(\%)$ is the water supply from reservoir *i* in percent of maximum water right.

5. 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 runoff to each reservoir in the water resources system is then evaluated. The domestic water demand is estimated next. The industrial and irrigation demands are assumed to be given for the operation period and retrieved to the system through the database manager. The reservoir operation model is then applied by introducing the management and planning preferences, e.g., acceptable risk thresholds, initial water take proprieties from sources, (i.e., initial water take order among sources), and maximum number of trials. The output of the DSS 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.

In the following results, the susceptibility of Fukuoka City 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 it is assumed that the full water right from surrounding rivers could be supplied.

Figure 4 shows the variation of the performance of the entire water supply system for different percentages of maximum yield from the Chikugo River basin. The result shows that 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 the operating period the risk of non-recovery of the system (*1-Res*) is 0.22 for a vulnerability *Vul* approximately equal to 0.01. The frequency of failure is still very low for this particular case with *1-Rel* equal 0.05. 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, Figure 4, 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 a vulnerability approximating 0.12 compared to 0.01 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 *1-Rel*=0.31. Therefore, 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 Figure 4, 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).

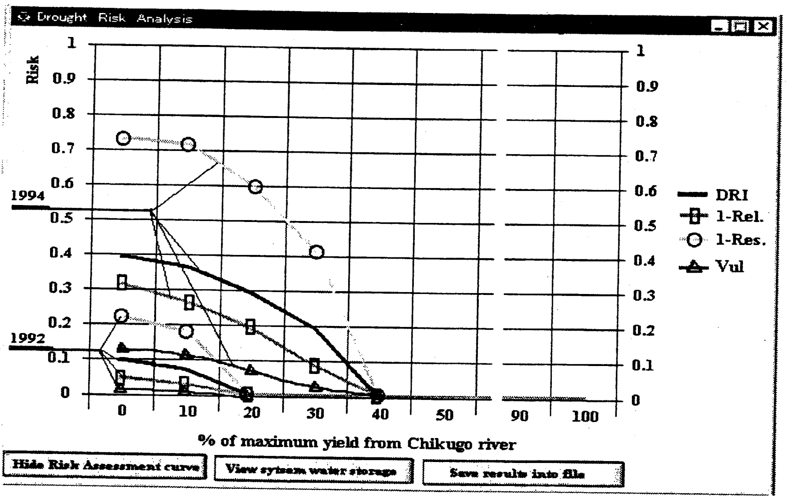
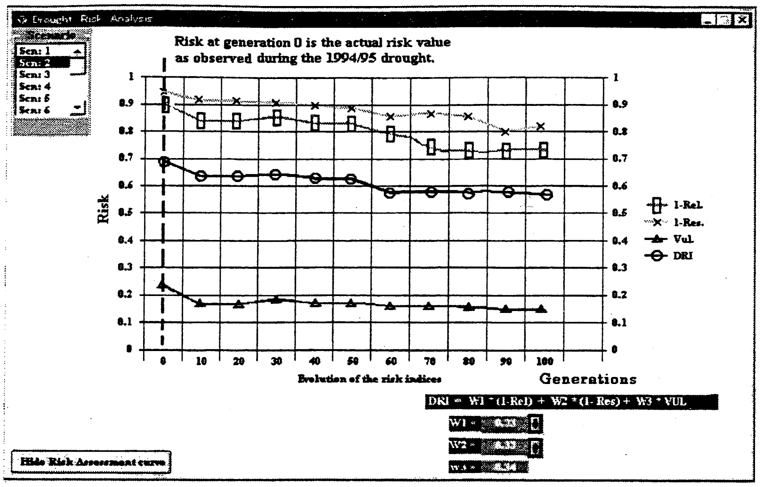


Figure 4. Performance of Fukuoka City water supply system function of the change in daily water supply from the Chikugo River basin for both, 1992 and 1994 hydrologic conditions.

In the GA application, to alleviate the mathematical representation of the system the water supply from the Chikugo River basin and surrounding small rivers were assumed equal to the observed values during the selected drought operation period extending from January 1, 1994 to May 31, 1995. Figure 5 shows the variation of the risk indices, i.e., (*1-Rel*), (*1-Res*), *Vul* and *DRI*, at the end of the selected operation period as a function of the number of generations. The result shows that the water supply risks present slight improvements as the number of generation increases, and further more provides an improved practical water supply operation of less risk compared to the actual operation in 1994.

6. Conclusions and future development

A decision support system (DSS) for the water supply system in Fukuoka City was presented. The DSS was found efficient tool facilitating examination of sequences of scenarios as well as interpretation of the results 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. The application of the DSS reached a very encouraging results to improve drought management operation and to effectively reduce the risk of water deficit. The present DSS is intended to be further improved, and possible future developments include the following: (1) a knowledge-based expert system for incorporating experiences and judgement in the



Risk at generation 0 is the actual risk value as observed during the 1994/95 drought.

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

Figure 5. Variation of the risk indices by GA as a function of the number of generation at the end of the operation period extending from January 1, 1994 to May 31, 1995.

management of the water supply system during periods of drought, (2) 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 is being considered.

Acknowledgments

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