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Risk assessment for optimal drought management of an integrated water resources system using a genetic algorithm

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Abstract:

A decision support system (DSS) is developed and applied to assess the susceptibility of water supply systems to droughts, and to aid decision-makers in determining optimal supply strategies. The DSS integrates three fundamental modules for water resources management: (1) a real time rainfall-runoff forecasting model enhanced by Kalman filtering; (2) a water demand forecast model; and (3) a reservoir operation model. Simulation and optimization procedures for the reservoir operation model are based on risk analysis to evaluate the system performance and to derive the most appropriate supply strategy of minimum risk, for the designed operating conditions. The optimization technique, based on genetic algorithms, introduces two new and distinct features, with the aim of minimizing the risks of drought damage and improving the convergence of the model toward practical solutions. Firstly, risk-based measures of system performance, termed reliability, resiliency and vulnerability, are combined into a global risk index, referred to as the drought risk index (DRI). The DRI, formulated as a weighted function of the risk measures, serves as the objective function to be minimized during the search for the optimal operation. Secondly, in the genetic algorithm search, each new generation of water supply solutions is created from solutions with risk levels clustered inside a defined 'acceptable risk space'. In other words, the convergence of the algorithm is improved by retaining only those solutions with DRI values smaller than the maximum acceptable risk. As a case study, the DSS is applied to the water resources system in Fukuoka City, western Japan. The DSS is believed to be an efficient tool for the assessment of a sequence of water supply scenarios, leading to the improved utilization of existing water resources during drought. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS decision support system (DSS); integrated water resources management; optimization; water supply scenarios

INTRODUCTION

With the increasing scarcity of drinking water, the analysis of water supply systems during periods of drought is drawing increasing attention (e.g. Hirsch, 1981; Frick *et al.*, 1990; Randall *et al.*, 1990; Johnson and Kohne, 1995; Smithers, 1997). In addition to the general constraints and difficulties of water supply system management under normal operating conditions (where simulation and optimization techniques have been widely applied; see Yeh (1985)), drought management is particularly concerned with determining the risk of non-recovery of the system's water availability to the minimum level necessary to satisfy the continuous water demand. Therefore, the primary objective of water management is to determine the most effective operation strategy that maximizes the safety of water distribution and minimizes the threat of water shortage in time and space. As demonstrated in several studies, in order to enhance the robustness of existing water supply systems effectively, and to minimize the harmful effects of droughts (particularly in highly developed areas that are

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completely dependent on a stable water supply), risk management should be the primary consideration (e.g. Hugo and Mariño, 1986; Simonovic *et al.*, 1992; Tatano *et al.*, 1992; Jinno *et al.*, 1995, Cancelliere *et al.*, 1998). Hashimoto *et al.* (1982) introduced the reliability, resiliency, and vulnerability criteria to assess the susceptibility of water supply systems under specified operating conditions. The reliability is best described as overall system performance over time, and is defined as the probability of the system to perform in a satisfactory mode during a defined operation period. However, owing to water scarcity or restricted availability during periods of drought, the system is likely to experience failures. Resiliency analysis aims to capture the statistical characteristics of any failures that occur. The result may be used to predict the likelihood of a failure, and evaluate the potential of the water supply system to recover from failure, given that a failure has occurred. Finally, the concept of vulnerability may be introduced as a measure of the risk impact and severity level at social and economic levels. The vulnerability analysis results in an understanding of the level of exposure of the water supply system to the various hazards identified.

Recently, with the rapid development of computers and information technology, decision support systems (DSSs) are considered the best, if not the only, practical tool for integrated water resources management and the operation of complex water supply systems (e.g. Fedra and Loucks, 1985; Palmer and Tull, 1987; Simonovic and Savic, 1989; Dunn *et al.*, 1996; Fedra and Jamieson, 1996; Jamieson and Fedra, 1996; Raman and Sunilkumar, 1996; Reitsma, 1996; Simonovic and Bender, 1996). However, to date, only a few DSSs have been developed to consider the issue of drought management explicitly, and to take advantage of the risk assessment approach. Walker *et al.* (1993) described the DroughtWatch Decision Support System developed for the drought management of North West Water, UK. Based on data for the current reservoir levels and starting month, simulation is carried out to determine the monthly storage patterns under different cumulative runoff conditions, using a range of runoff sequences having specified exceedence probabilities. Their risk analysis model estimates the likelihood of failure, and predicts the month in which such a failure will occur. Andreu *et al.* (1996) presented the Aquatool DSS for planning and operational management. In particular, this DSS is a risk assessment module for simulating the performance of the system using synthesized hydrological records updated using the initial hydrological state of the system. The output from the model of Andreu *et al.* (1996) comprises the probability of failure for each element of the water system in each time period.

The present study demonstrates the implementation of risk assessment in a DSS as a fundamental approach in: (1) analysing the performance of an existing water supply system under defined sequences of daily water supply and drought scenarios; (2) deriving the most appropriate management strategy to improve the system storage recovery, which is generally acknowledged as the most prevalent limitation to attaining improved water supply systems when drought occurs. The DSS for drought management integrates advanced tools for both database management and for mathematical modelling for rainfall-runoff analysis, water demand forecasting, and reservoir operation. The rainfall-runoff model is a conceptual storage model enhanced by the use of Kalman filtering for adaptive parameters optimization. The water demand model utilizes a straightforward regression model to forecast the domestic water demand on a daily basis. The methodology developed for reservoir operation integrates simulation procedures and optimization techniques based on genetic algorithms (GAs). The use of GAs in the management and operation of water resources systems has been recently used to great effect. For example, Hirayama *et al.* (1996) discussed the application of GAs for the operation of a single reservoir, using a risk-based optimization model to minimize the expected loss of system performance. Milutin and Bogardi (1996, 1997) also demonstrated the use of GAs for deriving and assessing operation strategies for multi-reservoir water supply systems. Their model attempted to determine the water allocation pattern of each reservoir by minimizing the deviation from the target water demand. Risk assessment was carried out to derive the deviation penalty functions based on system reliability, average recovery from failure, mean monthly deficit, and vulnerability.

In this study, the simulation and optimization models for reservoir operation use risk indices as basic criteria in determining the daily optimal release policy from each source of the system. The optimization technique is based on GAs, and introduces two new and distinct features with the aim of speeding up the convergence, and primarily to cluster the optimal solutions inside a physically realistic operation space. Firstly, the performance measures (reliability, resiliency, and vulnerability) are combined to derive a linear weighted objective function, referred to as the drought risk index (DRI). The threshold limit value of the DRI gives an 'acceptable risk level', below which it is acknowledged that the drought damages are not harmful to public health, and the minimum standard of living is maintained. Secondly, in the GA run, by selecting parents (i.e. daily water supply solutions) from inside the acceptable risk space, the solutions are improved through successive generations. Thus, before the GA operators are applied to create a new generation, all solutions with DRI values above an acceptable threshold are replaced by solutions from within the acceptable risk space. As a result, the newly derived population contains only low-risk supply operations, effectively excluding all high-risk solutions for practical operation.

DSS

The drought DSS introduced in this study is an expanding model attempting to assimilate efficient and comprehensive tools for integrated water resources management and reservoir operation during drought (Kawamura *et al.*, 1999). To offer decision-makers more flexibility in assimilating and optimizing the use of available functions, the software is designed to be fully mouse-driven and user-friendly (Figure 1). As depicted in Figure 2, the DSS integrates a database management work-frame and a mathematical module. The database manager is interactively linked to all components of the DSS, and plays the roles of a data communication network for data acquisition and analysis, selecting of data for model calibration and validation, and organization of the mathematical models' outputs in tabular and graphical forms (Merabtene *et al.*, 1997a).

The mathematical modelling module is designed to perform real-time rainfall-runoff analysis, domestic water demand forecasting, and reservoir operation. The tank model for rainfall-runoff analysis (e.g. Sugawara, 1974) is a conceptual model characterized by four interconnected storage units to account for surface,

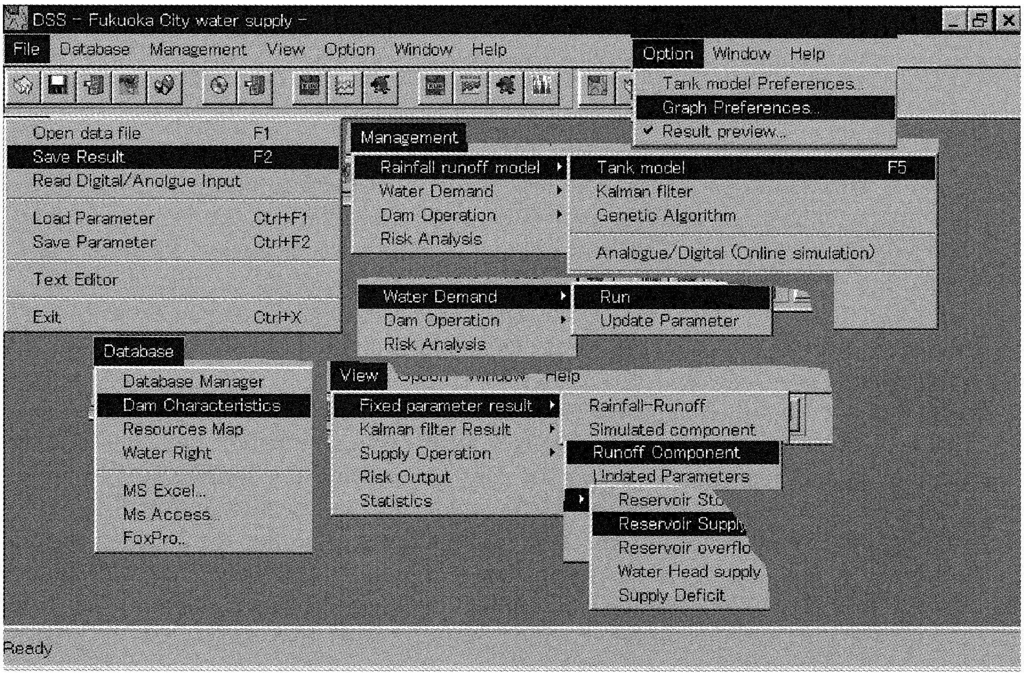
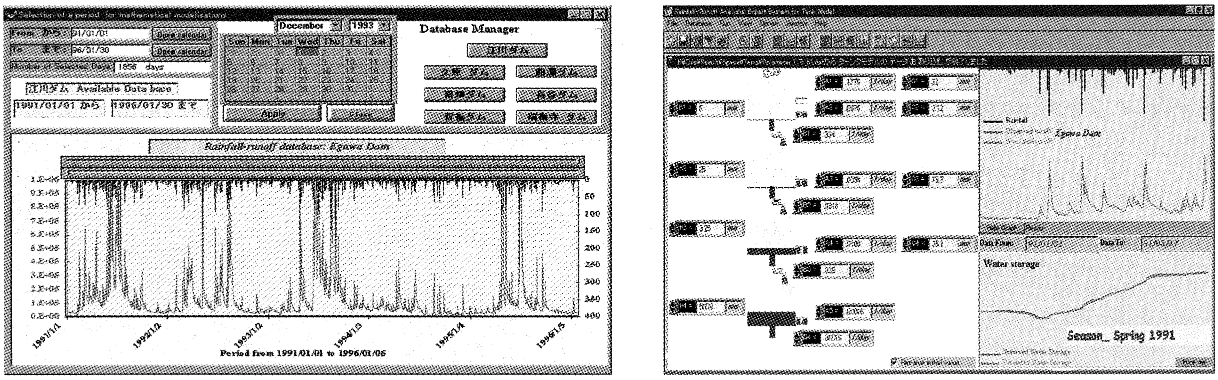


Figure 1. Graphical user interface of the DSS system



Selection of a period for mathematical modelisations

From から: 91/01/01

To まで: 96/01/30

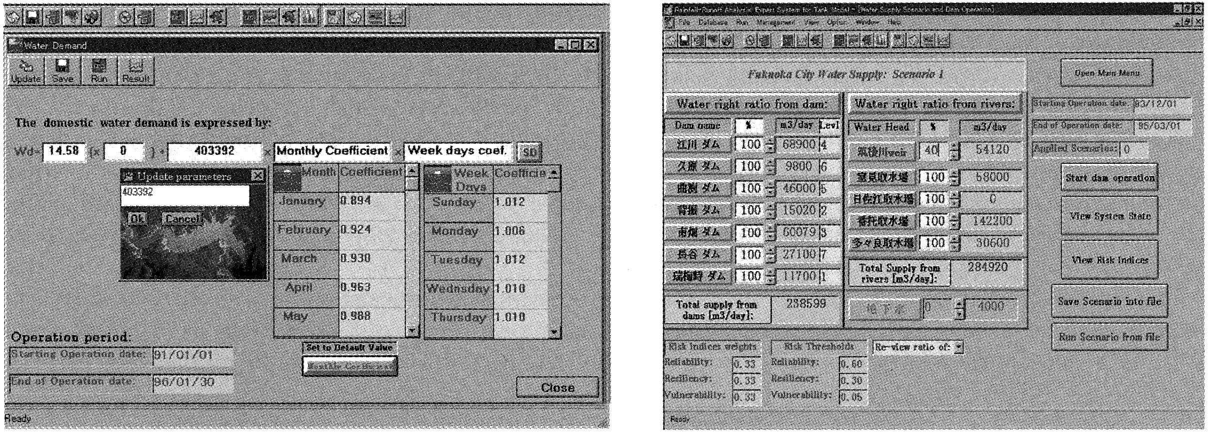
Number of Selected Days: 1856 days

江川ダム Available Data base

1991/01/01 から 1996/01/30 まで

Database manager interface

Rainfall-runoff model interface



Water Demand

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
Wednesday	1.010
Thursday	1.010

Operation period:

Starting Operation date: 91/01/01

End of Operation date: 96/01/30

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river	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 0 4000

Starting Operation date: 93/12/01

End of Operation date: 95/03/01

Applied Scenarios: 0

Risk Indices weights

Reliability: 0.33

Resiliency: 0.33

Vulnerability: 0.33

Risk Thresholds

Reliability: 0.60

Resiliency: 0.30

Vulnerability: 0.05

Water demand interface

Reservoir operation interface

Figure 2. Main model components of the DSS

intermediates, and groundwater runoff components. To facilitate its use for wide-ranging applications—flood and catchment characterization in particular—the tank model user-interface offers high flexibility in setting up the most appropriate model structure for individual cases, i.e. selecting the number of tanks and the number of runoff outlets in each tank. The optimization of the model parameters for real-time forecasting is enhanced by the use of Kalman filtering. To facilitate the analysis of the results, the module is further enhanced by advanced computer graphics support. This includes statistical output, total flow hydrograph, hydrograph separation, temporal variation of parameters updated by Kalman filtering, and the output from different trials (Merabtene *et al.*, 1997b).

The only function of the water demand model is the forecasting of the daily domestic demand. It is assumed that the industrial and irrigation water demands are given for the operation period, and may be retrieved from the DSS through the database manager. The domestic daily water demand is introduced as a straightforward linear regression model expressed as weekly and yearly cycles superimposed on an overall trend. A thorough description of the model can be found in Xu *et al.* (1998). To increase the reliability of the model with respect to planning and forecasting, the model parameters (e.g. trend value, daily average demand, daily and monthly parameters) may be interactively updated through the graphical user-interface. The output of the model comprises the temporal variation of the observed demand versus predicted values, the prediction error, and the forecasted horizon (Merabtene *et al.*, 1998a,b).

The formulation of the risk-based multi-reservoir operation model is presented next.

RISK-BASED ASSESSMENT MODEL

Although it must be realized that the total daily water demand cannot be completely satisfied, during droughts the public often reacts strongly and negatively to water shortages. Therefore, besides public education and water saving campaigns, it is of primary concern to the water managers to define the optimal operation strategy to ensure an acceptable standard of water supply, and to protect public health while considering economic functions.

In today's practice, the concept of an acceptable standard of water supply during the inherently unpredictable drought periods is still an ill-defined concept that is strongly influenced by various social, political, economical, and physical constraints. It is recognized that the definition of acceptable risk levels for the planning and assessment of water supply system reliability should not only depend on the preferences of water officials, i.e. the experience of decision-makers, but it must also include the expectations and experience of the public. Although it is clear that the public has limited experience with drought damages and water shortage (Howe and Smith, 1993), effort should be made to conduct general surveys aimed at setting up priority indicators to define the levels of risk accepted by the society. It is believed that public involvement can play a valuable part in developing more responsive service in both the short- and the long-term, particularly in areas where water shortage has been severe.

Hashimoto *et al.* (1982) presented an application of reliability, resiliency, and vulnerability criteria to evaluate the performance of a water supply system under alternative operations. According to Simonovic *et al.* (1992), the significant conclusion from previous studies (e.g. Moy *et al.*, 1986; Weeratene *et al.*, 1986) is that each problem requires a unique formulation of the risk-based measure. In drought management of water supply systems, the operational risks include the frequency and magnitude of failures to meet the targeted water demand, and failures of reservoir storage to recover to acceptable levels.

The criterion reliability (Rel) is introduced to account for the potential of a water supply system to remain in a satisfactory state for a given operation period under specified operating conditions. The fundamental definition of reliability is heavily dependent upon concepts derived from probability theory, and the definitions of time, operating conditions, and satisfactory performance. Time is a critical parameter in reliability analysis, since it is a measure to which the system performance can be related. The operating conditions specify the basic criteria under which the water supply system is expected to function, such as water availability in each reservoir and current operation rules. Our concept of satisfactory performance ('acceptable state') is introduced below.

The reliability is assumed to be an exponentially distributed random variable. Thus, the probability density function of random variable X may be derived from the Poisson formula with $X = 0$ (probability of zero failure in the specified time interval):

$$P(X) = \frac{\mathrm{e}^{-\lambda t}\,(\lambda t)^X}{X!} \qquad \text{for} \quad X = 0, \quad P(0) = \mathrm{e}^{-\lambda t} = \mathrm{Rel} \quad t \geq 0 \tag{1}$$

where P stands for probability, t is the operation period, e is the base of natural system logarithm, and λ is the failure rate. The failure rate is defined as the anticipated number of times f the water supply system fails to satisfy the target daily demand in a specified design period t:

$$\lambda = \frac{f}{t} \tag{2}$$

For water resources management, the design period t is system dependent. It is generally determined by the preference of decision-makers and the water demand–supply cycle. In reality, it is difficult to evaluate the reliability of a water supply system accurately due to the difficulties in precisely evaluating the failure rate of each component of the system. Common practice is to estimate the reliability as the ratio of the number of satisfactory days (ns) to the total operation period T:

$$\mathrm{Rel} = \frac{\mathrm{ns}}{T} \tag{3}$$

The second risk criterion, resiliency (Res), is introduced to describe the ability of a water supply system to recover from failure to an 'acceptable state', once a failure has occurred. A number of resiliency formulations have been applied to water resources (e.g. Siminovic *et al.*, 1992). Following Jinno *et al.* (1995), the resiliency may be defined as the conditional probability of entering a failure state at day t, given that the state was satisfactory at day $t-1$. In this study, the resiliency of a water supply system corresponds to the inverse of the expected failure period, and may thus be formulated as the inverse of the average period of water deficit:

$$\mathrm{Res} = \begin{cases} \dfrac{1}{\dfrac{1}{f}\displaystyle\sum_{i=1}^{f} \mathrm{df}_i} & \text{if} \quad f \neq 0 \\ 1 & \text{if} \quad f = 0 \end{cases} \tag{4}$$

where f is the total number of failures, and df_i the number of days of water deficit during the ith failure.

To account for the severity of occurring failures, the vulnerability (Vul) criterion is introduced as the ratio of the average water deficit to the average water demand during the operation period T:

$$\mathrm{Vul} = \frac{\dfrac{1}{T}\displaystyle\sum_{t=1}^{T}(\mathrm{Wd}_t - \mathrm{Ws}_t)}{\dfrac{1}{T}\displaystyle\sum_{t=1}^{T}\mathrm{Wd}_t} = \frac{\displaystyle\sum_{t=1}^{T}(\mathrm{Wd}_t - \mathrm{Ws}_t)}{\displaystyle\sum_{t=1}^{T}\mathrm{Wd}_t} \tag{5}$$

where Wd_t and Ws_t are the water demand and the water supply respectively for day t.

In order to integrate the aspects discussed above, reliability, resiliency, and vulnerability are combined to define a total risk exposure, referred to as the DRI:

$$\mathrm{DRI} = w_1(1 - \mathrm{Rel}) + w_2(1 - \mathrm{Res}) + w_3\mathrm{Vul} \tag{6}$$

where w_i is subject to $\sum_{i=1}^{3} w_i = 1$.

As can be seen from Equation (6), the DRI is formulated as a linear weighted function of the risk of failure $(1 - \mathrm{Rel})$, the risk of non-recovery from failure $(1 - \mathrm{Res})$, and the level of water shortage, i.e. vulnerability (Vul). The terms $w_1(1 - \mathrm{Rel})$, $w_2(1 - \mathrm{Res})$ and $w_3\mathrm{Vul}$ define probabilistic measures to analyse all contributing component failure modes systematically and identify the resulting effects on the system. In addition to a direct indication of the relative performance with respect to each risk criterion, the weightings w_1, w_2, and w_3 reflect the conflict between system stability and system failure mode. In practice, although a system may exhibit a high degree of reliability, it may in fact be extremely slow to recover, i.e. a low degree of resiliency, once a failure occurs. The estimation of the appropriate weightings to formulate the DRI function is not an easy or straightforward task. The evaluation process requires a full understanding of the concept of risk, and of the advanced statistical methods and other tools currently applied in risk estimation and management (e.g. ruin probability, zero-order analysis, and classical risk process; e.g. see Buhlmann (1970) and Novosyolov (1998)). Thus, the evaluation of the appropriate weightings requires much decision-making, and such decisions can only be properly made with an intimate knowledge of the water supply system and an accurate understanding of the drought process and cycle in the region under study. Furthermore, a proper evaluation of the degree of vulnerability requires an understanding of the physical performance of each component of the system under normal and drought conditions, and knowledge of the levels of acceptable water shortage. In other words, when recognizing that a risk exists, the objective is to define its characteristics quantitatively. These include the magnitude, spatial scale, duration, and intensity of adverse consequences, and their associated probabilities, as well as a description of the cause and effect links. It should be emphasized that the weighting values reflect judgments about the significance and acceptability of the risk associated with an individual component of the water supply system, as well as the performance of the entire system. For example, if equal values are assigned to the weights ($w_1 = w_2 = w_3 = 1/3$), the water supply system would be characterized by a particular equilibrium between the risk criteria.

Concurrent with a proper definition of the risk weights, for practical applications, risk thresholds must be defined to evaluate actual systems:

$$\begin{cases} 1 - \mathrm{Rel} \le (1 - \mathrm{Rel})_{\max} \\ 1 - \mathrm{Res} \le (1 - \mathrm{Res})_{\max} \\ \mathrm{Vul} \le \mathrm{Vul}_{\max} \end{cases} \tag{7}$$

In application to the reservoir operation the risks are negatively correlated with the system water storage, and increase exponentially as the drought period is prolonged. As depicted schematically in Figure 3, the risk may evolve from simple performance failures to major catastrophes ($0 \le 1 - \mathrm{Rel} \le 1$, $0 \le 1 - \mathrm{Res} \le 1$, and $0 \le \mathrm{Vul} \le 1$). The primary concern is to manage the daily water supply operation so as to maintain the maximum risk below the risk threshold limits. In Figure 3, this threshold is marked by the solid line, which represents the maximum acceptable values of the risk criteria. For practical risk management, the thresholds of the three risk indices are combined to derive the maximum global risk index $\mathrm{DRI}_{\max}$ as:

$$\mathrm{DRI}_{\max} = w_1(1 - \mathrm{Rel})_{\max} + w_2(1 - \mathrm{Res})_{\max} + w_3\mathrm{Vul}_{\max} \tag{8}$$

$\mathrm{DRI}_{\max}$ is used in the reservoir operation model as an objective function when evaluating the performance of the water supply system and simulating alternative scenarios. Only scenarios with $\mathrm{DRI} < \mathrm{DRI}_{\max}$ are selected for evaluation. The reservoir operation model based on simulation and optimization by GA is described in the following section.

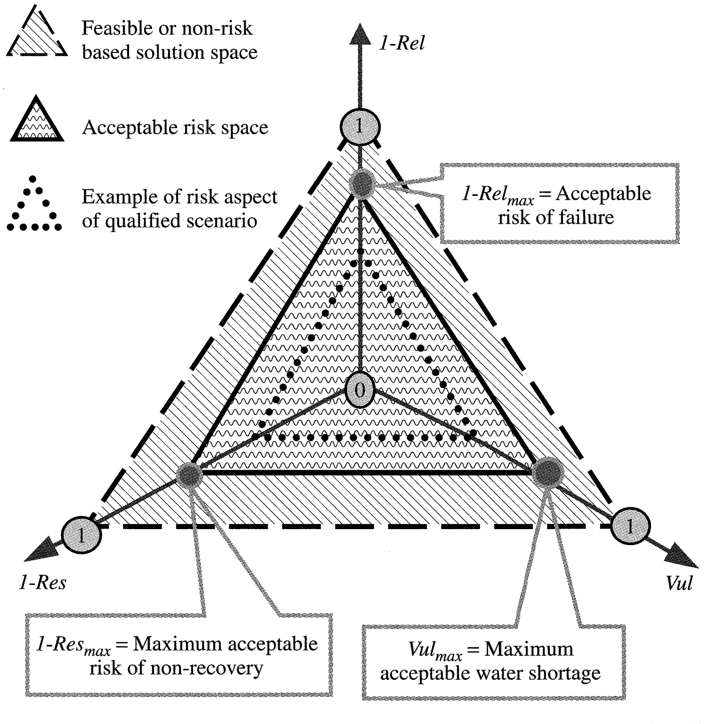


Figure 3. Non-risk management feasible space, acceptable risk space and risk aspect of qualified scenario

RESERVOIR OPERATION MODEL

As mentioned above, the aim of the methodology developed for drought operation of water resource systems is to offer water managers a practical tool for determining the optimal daily release strategy from each source. The optimal solution is defined as the one that (1) results in a minimum risk of relative failure of each individual component (reservoirs in particular) and (2) increases the reliability of the system by improving its storage recovery ability, thus minimizing the threat of water shortage when a severe drought occurs.

The daily release decision from each reservoir is based on the general rule of reservoir operation:

$$S_t(r) = S_{t-1}(r) + I_t(r) - R_t(r) - L_t(r) \quad t = 1, \ldots, T \tag{9}$$

where T (days) is the total operation period. $S_t(r)$ and $S_{t-1}(r)$ are the water storage in reservoir r at day t and $t-1$ respectively. $I_t(r)$ denotes the inflow and $L_t(r)$ the total losses (including evaporation and release for minimum river flow). As mentioned earlier, the inflow $I_t(r)$ to each reservoir is evaluated by means of the tank model and Kalman filtering for real-time forecasting. The total release to all users $R_t(r)$ is subject to:

$$\begin{cases} R_t(r) = \mathrm{Is}_t(r) + \mathrm{Ds}_t(r) & \text{if} \quad S_t(r) \le S_{\max}(r) \\ R_t(r) = \mathrm{Is}_t(r) + \mathrm{Ds}_t(r) + \mathrm{Ov}_t(r) & \text{if} \quad S_t(r) > S_{\max}(r) \end{cases} \tag{10}$$

where $S_{\max}(r)$ and $S_t(r)$ are the maximum and actual storage respectively. $\mathrm{Is}_t(r)$ is the partial water release attributed to irrigation and industrial consumptions, $\mathrm{Ds}_t(r)$ the partial water release attributed to domestic water supply, and $\mathrm{Ov}_t(r)$ the overflow. In the case of serially coupled reservoirs, $\mathrm{Ov}_t(r)$ is treated as an additional inflow to the downstream reservoir.

A particular complexity of many water supply systems arises from the sharing regulations among users of the storage capacity and the total inflow to each reservoir. Such sharing regulations may state that the maximum release to user U, from reservoir r at time t, is subject to the user's own available partial water storage, which in turn relies on the percentage of observed inflow at time t allocated to user U (domestic supply, irrigation, and industry). Moreover, given that different domestic demands may share the same domestic storage capacity, the maximum reservoir supply Ds_t to a specified demand target is often subject to a daily water right. The constraints for domestic water supply may be written as:

$$\mathrm{Ds}_t(r) \le v_t(r) \tag{11}$$

$$\mathrm{Ds}_t(r) \le \mathrm{cr}_t(r) \tag{12}$$

where $v_t(r)$ is the available partial storage for domestic water supply and $\mathrm{cr}_t(r)$ the water right from reservoir r to the specified demand target.

In addition to the above, more than one source (river take or reservoir) is usually linked to a unique water treatment plant. Therefore, the total water supply from linked sources is also related to the maximum treatment capacity:

$$\sum \mathrm{Ds}_t + \sum \mathrm{Hs}_t \le P_m \tag{13}$$

where Hs_t is the daily domestic water supply from water heads, i.e. supply stations from rivers, and P_m the maximum water treatment capacity of purification station m. The summation in Equation (13) applies to all reservoirs and water heads linked to the same purification station m.

Considering the above, the daily domestic water supply may be formulated as:

$$\mathrm{Ws}_t = \mathrm{As}_t + \sum_{r}^{\mathrm{Tr}} \mathrm{Ds}_t + \sum_{j}^{\mathrm{Th}} \mathrm{Hs}_t \tag{14}$$

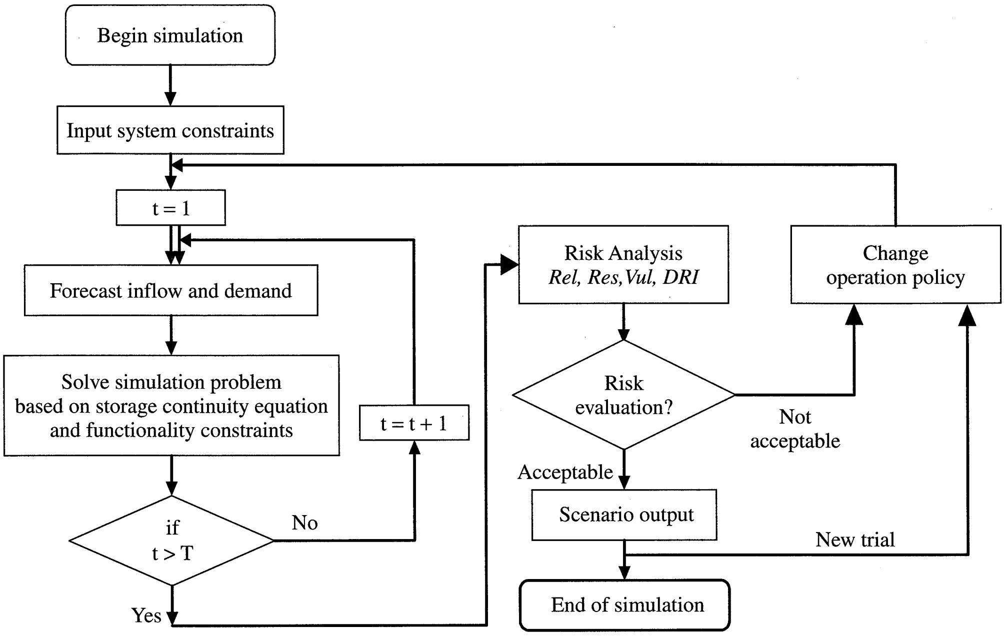


Figure 4. Flow diagram of the risk-based simulation model for reservoir operation

where Ws_t is the total daily supply (equal to the daily demand under normal operation conditions) and As_t the known additional water supply from other sources (e.g. wells and desalinization plants). Tr and Th stand for the total number of reservoirs and water heads respectively.

Figure 4 illustrates the flow diagram of the simulation model using the risk analysis formulated above as the basis to assess the water supply alternatives. The simulation for evaluating the water supply alternatives is carried out by: (1) computing the real-time inflow forecasts to each reservoir using the tank model; (2) estimating the daily water demand for domestic use, and retrieving all other demand targets using the database manager; (3) selecting a water take alternative from each water source using the interactive user-interface for reservoir operation; (4) evaluating the risk level for each alternative; and (5) proceeding to a new trial or recalling the DSS database manager to retrieve the best, risk-minimized operation from all trials.

It is important to note that the procedure is heavily time consuming. Furthermore, the resulting solutions rely heavily on the experience and intuition of the local water management engineer. Past drought records and practices have demonstrated that engineers with different prior drought experience may behave differently during a particular drought event (Jinno *et al.*, 1989). In other words, the selected solution of minimum risk must be viewed in light of the experience of the actual water-managers, who are often limited by time constraints in making the right decision. On the other hand, the optimal performance of large and complex water supply systems often exhibits strong sensitivity to the optimal performance of each individual source and reservoir (Milutin and Bogardi, 1996). Therefore, in order to streamline the decision process, an optimization procedure based on a GA was implemented, as discussed in the following section.

RISK-BASED OPTIMIZATION USING A GA

As mentioned above, the time available for decision making during drought events represents one important constraint limiting the ability of water managers to make a quick and reliable decision when drought occurs. Among the many types of mathematical optimization technique, GAs were selected for their ability to generate numerous solutions at each time step, and for their inherent freedom to choose desirable optima according to design specifications. The basic principles of the GA were first introduced by Holland (1975). The GA is inspired by the mechanism of natural selection, where stronger, fitter individuals are likely to guide the search toward a better solution. A GA requires an encoding of the unknown decision variables, i.e. percentage of water supply from each reservoir, into a 'genetic code' of finite alphabet. The binary coding used in this study, based on [0;1] bit or alphabet, is the most common coding from theoretical and practical aspects (Mitchell, 1996; Grefenstette, 1992). Each decision variable is coded into a four-bits long string in the range [0000 1111]. The total length L of the so-called chromosome solution, i.e. daily supply from all reservoirs, is a function of the number of reservoirs (nr) and number of days (nd) in the operation period:

$$L = 4 \times \text{nr} \times \text{nd} \qquad \text{[bit long]} \tag{15}$$

As illustrated in Figure 5, a simple GA procedure starts with the generation of a random initial population of chromosomes of length L. In each cycle of the genetic operation, a population of chromosomes, termed parents, is randomly generated. The population size N is a function of chromosome length L, and chosen in the range $2^6 \leq N \leq 2^{20}$ with respect to the schema growth theory. To form good offspring in the next generation, parents with higher fitness, i.e. with a minimum value of the objective function, are selected via a specific selection method. Many selection techniques, such as the roulette wheel mechanism, are based on stochastic sampling with replacement. The chance of selecting one chromosome as a parent is directly proportional to the number of offspring produced. In this process, it is expected that the better chromosomes will create a larger number of offspring, and thus have a higher chance of surviving in the subsequent generation. The selected pool of parents is recombined using two fundamental operators, known as crossover and mutation (Grefenstette, 1986). Crossover involves a pair of chromosomes exchanging a portion of their bit sequence at randomly set crossover points (see Figure 6a). The probability of crossover is typically between 0·6 and 0·9.

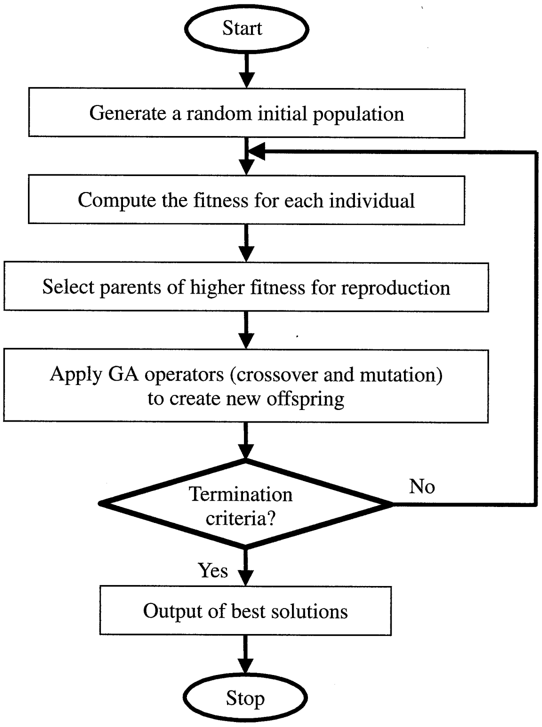


Figure 5. Flow diagram of a simple GA

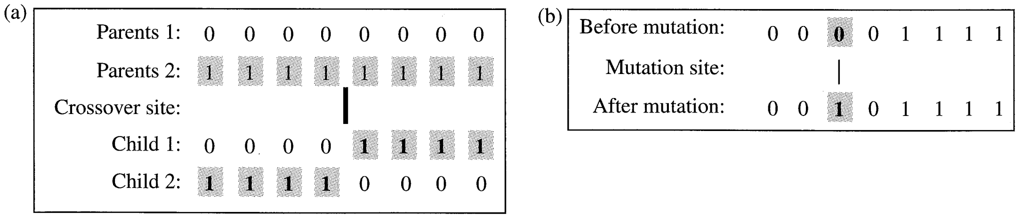


Figure 6. (a) Example of one-point crossover. (b) Example of single bit mutation at the third position

Mutation is applied to each offspring individually after the crossover exercise. This allows the reintroduction of genetic diversity to avoid becoming trapped in local optima and to avoid disruption of an appropriate solution. Mutation consists of randomly flipping each bit, or gene, assuming a low mutation probability (generally in the range [0·001 0·01]) depending on the population size and number of bits in the chromosome (see Figure 6b).

Figure 7 illustrates the flow diagram of the present reservoir operation model developed using GA in risk analysis. (1) The procedure is initiated by evaluating the standard parameters and inputs for reservoir operation (e.g. time horizon, inflow to each reservoir, daily water demand, and physical constraints). (2) A random solution of water releases from each source is initially generated. The water supply from each reservoir is an integer value in the range [0 100], and represents a percentage of the daily available water right. For computational convenience, and to reduce the dimensionality problem, the parameters' coding takes only integer values in the range [0 15] or [0000 1111] in binary coding, assuming that the variation of the water release from a given source has a practical impact only if it is a fraction of about 7% of the water right. (3) For each chromosome solution generated, the fitness value is evaluated. In the present GA scheme, the DRI (see section entitled Reservoir operation model) is used as an objective function. To maintain uniformity in the range of values that each chromosome may take, the objective function is mapped as a fitness value. The present study uses the Sigma truncation scaling method (Man *et al.*, 1999) to preserve the characteristics of the DRI (e.g. non-negative value and range). Thus, the reproduction process is carried out using the value of DRI to select the best parents to form the offspring in the next generation. In other words, the parents qualified to form the next generation of water release solutions are those within the feasible operation space, defined by the risk thresholds (Equations (5) to (8)). The resulting scheme is expected to improve the performance and consistency of the selection method compared with existing alternatives. Furthermore, the generation of future solutions from within the defined acceptable risk level is likely to produce more accurate practical decisions. In other words, if an emergency solution is required, the GA process may be aborted prematurely and the best solutions of minimum risk can be selected and evaluated appropriately by the decision-maker before application.

It is important to note that the major inconvenience of such restricted selection of parents occurs in terms of risk of premature convergence and that of reducing the population size (so-called 'population bereavement') from generation to generation. The risk of premature convergence to local optima is higher at the end of the operation period. Thus, as a severe drought prolongs in time, the limit of the DRI values of the chromosomes are likely to equal or exceed the DRI threshold value. The exclusion of unqualified chromosomes, with $\mathrm{DRI} > \mathrm{DRI}_{\max}$, induces population bereavement and increases the risk of clustering the solution around local optima close to the solution boundary $\mathrm{DRI}_{\max}$. On the other hand, the exclusion of unqualified chromosomes is likely to minimize the individuals' spread. Thus, in order to maintain the breeding of contributing chromosomes to the new generations, additional random chromosomes are selected from the qualified solutions from within the acceptable risk space.

FUKUOKA CITY WATER SUPPLY SYSTEM AS A CASE STUDY

Fukuoka City is a growing economic centre in western Japan, where the water officials are currently undergoing intensive training to increase the efficiency and sustainability of the complex existing water resources system

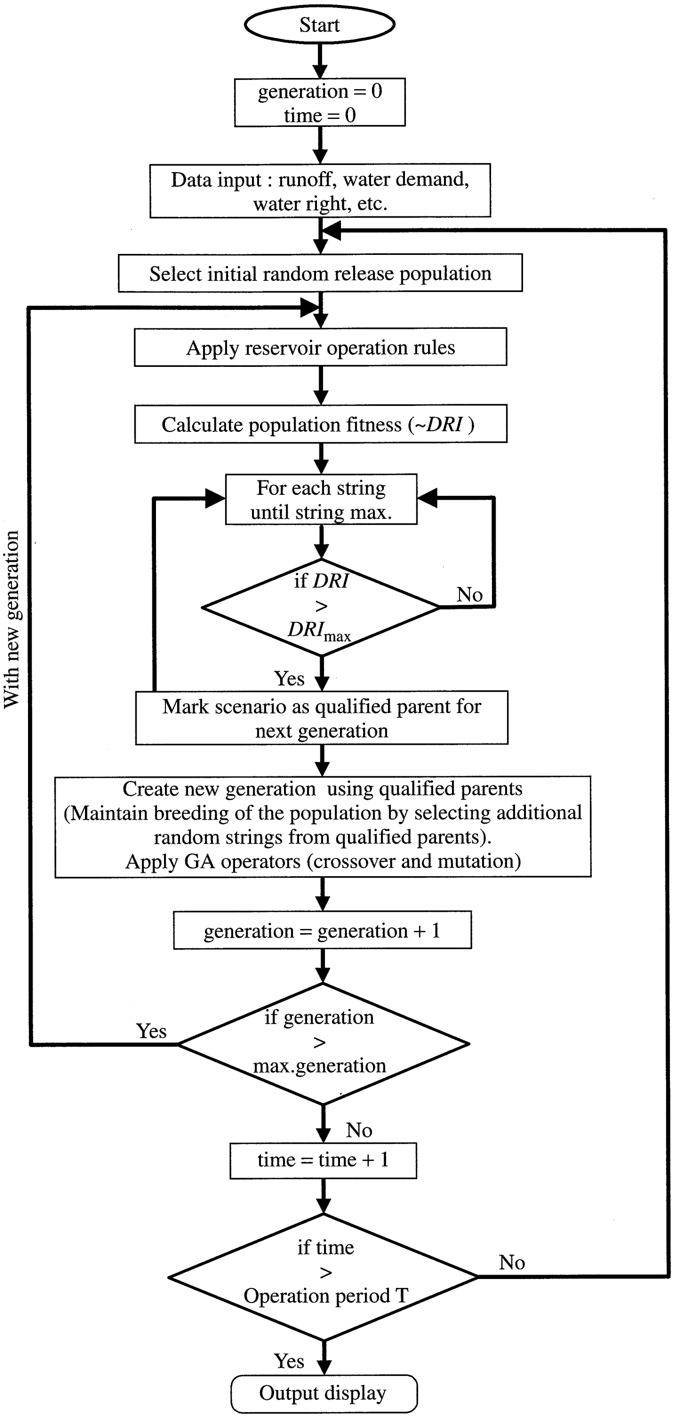


Figure 7. Flowchart of the reservoir operation model by GA based on the concept of risk analysis for drought management (time: a sequence of 100 days)

management (Kawamura and Jinno, 1996). It is understood from the drought analysis that unless a fundamental strategy for the water resources planning and operation during drought is considered, the robustness and safety of the water supply system in Fukuoka City may not be enhanced.

Fukuoka City is characterized by a moderate climate. No severe earthquake has ever been recorded, and flooding is very rare. Because of seasonal winds, there is both an early rainy season (June to July) and a later typhoon season (September to October). The hydrological regime is characterized by pronounced seasonal variation, with an annual average precipitation of 1600 mm, and only a fraction occurring as snow. The annual average evapotranspiration is about 960 mm/year (Kondo *et al.*, 1992).

The Fukuoka City water supply provides direct service to about 1·3 million residents, with this increasing at a rate of about 1% per year (Fukuoka Waterworks Bureau, 1997). The major source of supply is surface water, which accounts for 99% of the total supply. Groundwater resources are limited to 1% of the daily supply, due to shallow aquifers, salt intrusion, and groundwater pollution caused by chlorinated hydrocarbons (as reported by Jinno *et al.* (1986)). Figure 8 illustrates the major components of the actual water supply system. (1) Six purification stations with a maximum capacity of about 704 800 m^3 day^{-1}. (2) Direct water right from the Chikugo River basin, yielding a maximum of 118 000 m^3 day^{-1} (one-third of the total daily water supply). The Chikugo River basin belongs to a different jurisdiction and the water is supplied to Fukuoka City under entitled agreement. Significant reductions in yield can be expected during prolonged droughts (duration longer than 1–1·5 years) because of water share conflicts among users, streamflow depletion, and water quality deterioration as experienced during past droughts (Fukuoka Waterworks Bureau, 1997). (3) Water heads include five pumping stations situated in the surrounding small rivers. The maximum water right may vary monthly or seasonally. Moreover, the rivers are characterized by an unusual unstable discharge because of their small respective catchment areas. Much of the river streamflow is presently used for irrigation, particularly during the rice crop season (May to September). (4) There are seven dams with an effective

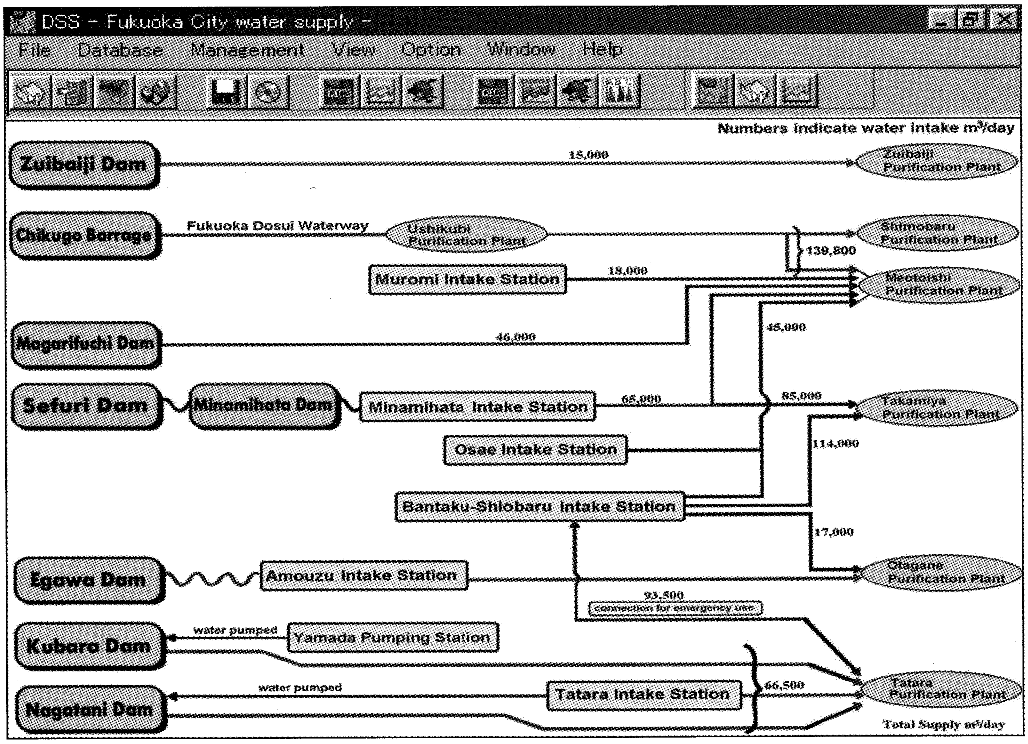


Figure 8. Fukuoka City water supply system

total capacity of about 45×10^6 m^3. The domestic water supply represents about 56% of the total capacity (a maximum of 346 700 m^3 day^{-1}, with high variability of the water right on both a monthly and a daily basis). Despite the large capacity of the dam reservoirs, they are very vulnerable to drought due to their slow recovery rate (small catchment area and steep surface slope). The average precipitation from May to August is about 950 mm. Therefore, for the successful operation of the reservoir, storage levels must recover to near capacity after the rainy season. The system also depends partially on the typhoon season to refill its capacity. Unusual climatic events, such as the droughts of 1978 and 1994, triggered the system storage to decline to levels that required severe restrictions in water use.

Since Fukuoka City started its water supply service in 1923, several droughts of different magnitudes, severity and duration have been recorded. The 1994 drought, the worst on record, began in the late spring of 1994 and continued until the early summer of 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 did not reach their normal storage level. By mid-July 1994, there were attempts to reduce water usage by pressure reduction, and, on 4 August, water rationing was initiated and continued until early July 1995. By early September 1994, the water supply crisis worsened due to the complete drying up of the Egawa reservoir (the most important structure of the city's water supply system), and concurrent drought in the Chikugo River basin. The flow of the Chikugo River decreased by about 70%) by late July 1994, resulting in the rapid deterioration of the river water quality (Fukuoka Waterworks Bureau, 1997).

DSS APPLICATION TO DROUGHT MANAGEMENT

In order to demonstrate the capability of the DSS developed to aid planning and management, the drought management scheme of the water resources system in Fukuoka City, Japan, is introduced in this section. The aim of the present application is threefold. First, it is of great importance to analyse the risk of water supply restriction from the Chikugo River basin during periods of drought. Such analysis is important to isolate the water supply system risk related to the Chikugo River subsystems, in order to understand better and optimize the functionality of the local subsystem. The second aim is to demonstrate the applicability of the DSS in simulating water supply scenarios using the concept of risk management. The third aim is to show the efficiency of the global search method developed in minimizing the water supply risk by using the concept of acceptable risk levels with the DRI as the objective function.

Water supply Scenario 1

In this water supply scenario, the susceptibility of the water supply system is assessed, with simulations of the way in which water supply restrictions from the Chikugo River are carried out under the climatologic conditions. In previous studies (Jinno *et al.*, 1995; Xu *et al.*, 1998), we analysed and discussed the water supply risk due to water yield restrictions from the Chikugo River basin and the increase in water demand.

Figure 9 shows the water supply risks when water restrictions from the Chikugo River are applied. Two different climatologic states are considered. The first one is that of 1992, characterized particularly by a drought in the Chikugo River basin, but normal weather conditions in Fukuoka City. The second state represents the conditions of the 1994 drought. The risks associated with the 1992 and 1994 state conditions were evaluated, assuming the same daily water take allocation patterns from all other sources in Fukuoka City. As shown in Figure 9, under normal weather conditions in Fukuoka City (as was the case in 1992 with 1435 mm year^{-1} of precipitation), 20% of the maximum water right from the Chikugo River is necessary to satisfy the daily domestic water supply without need for water rationing, compared with 40% for the 1994 drought operation period. For the 1994 drought scenario (with no water supply from the Chikugo River), all three risk indices, namely the risk of failure ($1 - \text{Rel}$), the risk of non-recovery from failure ($1 - \text{Res}$), and the vulnerability (Vul), were almost four times higher than those of the 1992 drought period. As a result, the DRI under

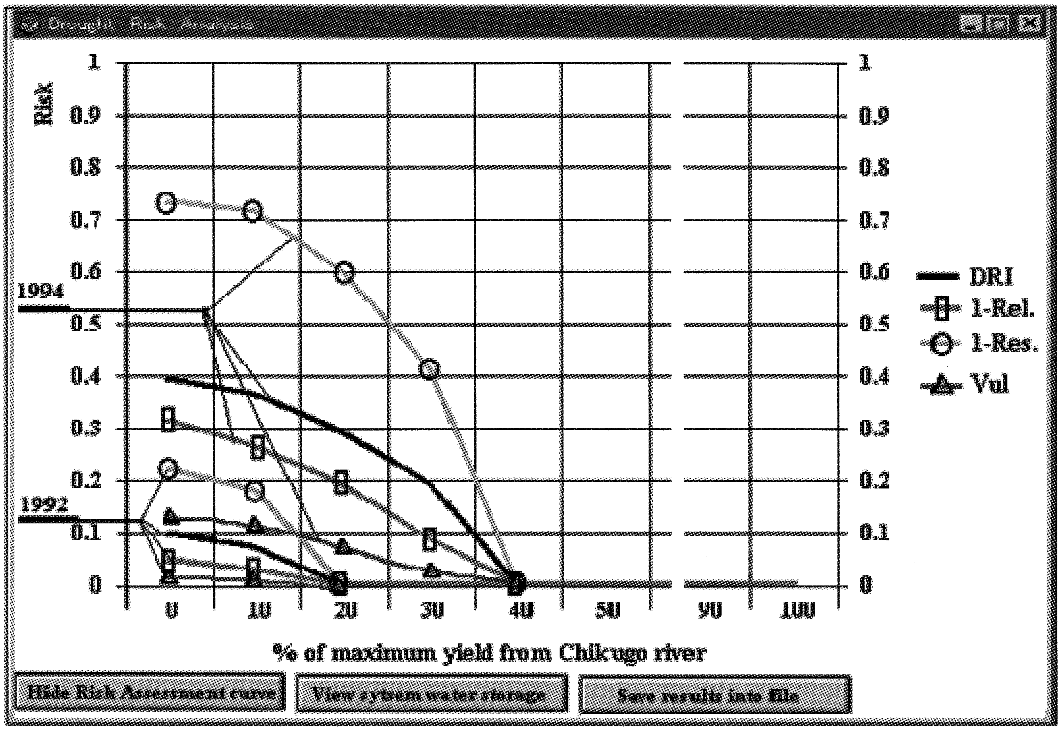


Figure 9. Fukuoka City water supply performance as a function of the water yield from the Chikugo River basin for the weather conditions of 1992 and 1994

the 1994 weather conditions ($DRI_{1994} = 0{\cdot}4$) was four times higher than that of the 1992 drought scenario ($DRI_{1992} = 0{\cdot}1$), for the scenario representing zero water supply from the Chikugo River in both 1992 and 1994. In this scenario simulation, we have assumed equal values of the weights ($w_1 = w_2 = w_3 = 1/3$) in the formulation of the DRI function.

The results revealed that, compared with the other risks, the risk of non-recovery from failure is the crucial weakness of the water supply system studied. Also, the vulnerability was found to be the smallest risk among three risk indices. For example, $(1 - \mathrm{Res})_{1992} = 0{\cdot}22$ and $(1 - \mathrm{Res})_{1994} = 0{\cdot}74$ for the scenario representing zero water supply from Chikugo River in 1992 and 1994 respectively, whereas $(1 - \mathrm{Rel})_{1992} = 0{\cdot}04$ and $(1 - \mathrm{Rel})_{1994} = 0{\cdot}31$, and $\mathrm{Vul}_{1992} = 0{\cdot}01$ and $\mathrm{Vul}_{1994} = 0{\cdot}11$. Moreover, for each scenario shown in Figure 9, the DSS can provide the variation of the water storage in each reservoir and the daily water deficit in terms of quantity and period of sojourn (refer to Merabtene *et al.* (1998a)). The output of the DSS not only provides the solution, it also provides all qualified supply scenarios to facilitate the selection (in the decision-making process) of appropriate actions that minimize the long-term drought impact.

Water supply Scenario 2

In this water supply scenario, the simulation results presented are based on the variation of the maximum water supply ratio from Egawa Reservoir and the variation of its water take priority order. Egawa Reservoir has the largest storage capacity of the seven reservoirs in Fukuoka City, and is the most important structure for a steady, reliable water supply in Fukuoka City. Nevertheless, owing to its relatively small catchment area compared with its capacity, the reservoir is more vulnerable to drought than the other reservoirs. By simply changing the corresponding values in the window of the reservoir operation interface (Figure 2), scenarios can be effectively simulated. A sample of the simulation results is shown in Figure 10. In this case, the simulation period extends from 1 January 1994 to 31 May 1995.

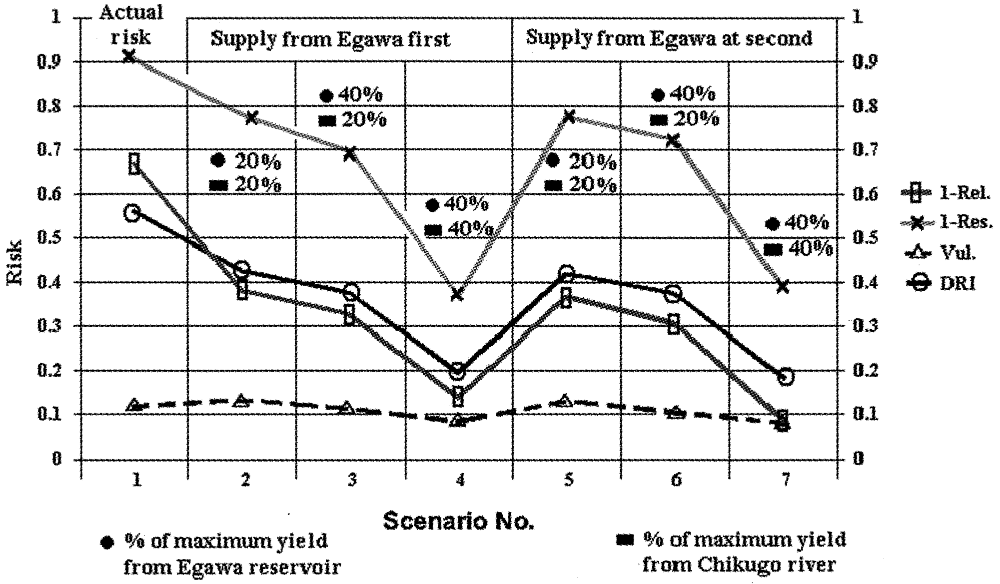


Figure 10. Variation of the risk levels as a function of the variation of the water supply ratio and water take priority order from Egawa Reservoir (risk weights: $w_1 = w_2 = w_3 = 1/3$)

Scenario number 1 in Figure 10 indicates the risk by actual reservoir operation, assuming that 100% of the water supply right from each river water head is satisfied. This assumption is also applied to other scenarios. Scenarios 2 to 4 show the results of the simulation in which water supply from Egawa Reservoir has the first water take priority order among seven reservoirs. In this case, if the daily water supply from the Chikugo River and other river water sources in Fukuoka City did not satisfy the water demand, the deficit was complemented by water supply from reservoirs according to the priority order of each reservoir. Water is taken from the first priority reservoir up to its possible maximum water right to make up the deficit. If the deficit is still not complemented, water is taken from the second priority reservoir, and so on until the deficit is made up. Scenarios 5 to 7 show the results of the case in which Egawa Reservoir has the second water take priority to complement the water deficit.

From Figure 10, by comparing Scenarios 3 and 4 (or Scenarios 6 and 7), it is obvious that the water supply from the Chikugo River plays a very important role in reducing the risk, regardless of the water take priority order of Egawa Reservoir. By comparing Scenario numbers 2 and 3 (or Scenario numbers 5 and 6), increasing the water supply ratio from Egawa Reservoir from 20% to 40% reduces the risk significantly (DRI reduces from 0·42 in Scenario number 2 or 5 to 0·38 in Scenario number 3 or 6—a reduction of 0·04). By comparing Scenario numbers 2 to 4 against Scenario numbers 5 to 7, the effect of changing the water take priority order of Egawa Reservoir from second to first appears to be not significant. However, by changing the order, the DRI reduces from 0·20 in Scenario number 4 to 0·18 in Scenario number 7. In other words, by adopting a policy that tries to maintain the water of Egawa Reservoir corresponding to the order change from first priority to a lower priority, the water supply risk situation can be improved by adopting a policy that tries to maintain the water of Egawa Reservoir corresponding to the order change from the first priority to the lower priority, and the water supply risk situation can be improved.

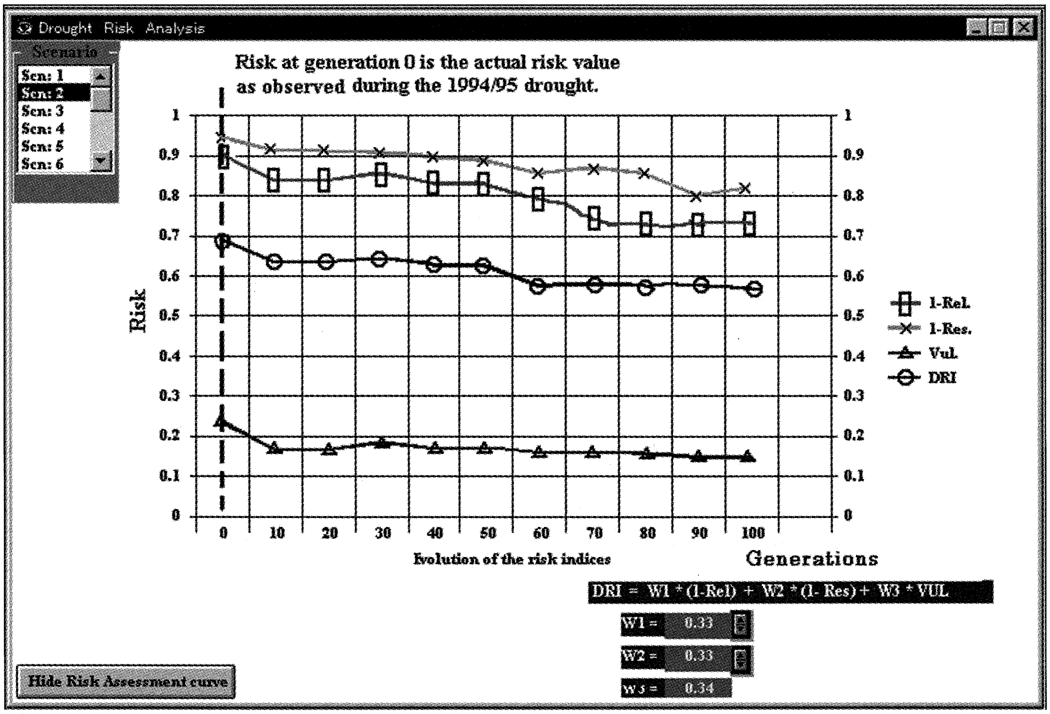
APPLICATION OF THE GA OPTIMIZATION PROCEDURE

The aim of the following application is to demonstrate that the global search method of a GA is an effective part of the proposed DSS in minimizing the water supply risk by using the concept of acceptable levels.

Owing to management constraints (e.g. water supply from the Chikugo River), and to the lack of available data for forecasting the streamflow in each river, it is assumed that the values of the water supply from the Chikugo River basin and surrounding small rivers are equal to those observed during the selected drought operation period.

As mentioned in the section entitled Risk-based optimization using a GA, in the GA scheme, each of the seven decision variables, i.e. water take from the seven reservoirs, was mapped in the range [0 15] ([0000 1111] in binary representation), where each grade represents a fraction of 6·67% of the water right. The length of the chromosome strings is a function of the number of days in the design period. For example, if the whole operation period (400 days) is selected, the length of the resulting string would be $400 \times (7 \times 4) = 11\,200$ bits long in a binary coding or $400 \times (7 \times 1) = 2800$ bits long in hexadecimal coding [0 F], to represent the daily water supply from each reservoir. The optimal length of the chromosome for a specific problem is still debatable. To summarize, a longer operation period is more suitable for evaluating the DRI value; however it has the drawbacks of increasing both the corruption of good chromosomes and the difficulty of combining certain schemes using GA operators (e.g. crossover). To speed up the computation process, the water supply alternatives are calculated on a 10 day basis for a design period of 100 days within the total operation period of 400 days. Thus the water supply solution is coded in a chromosome with a $(100/10) \times 7 = 70$ bits long hexadecimal string or $(100/10) \times (7 \times 4) = 280$ bits long binary string, to represent the seven unknown decision variables at each 10 day interval. The number of chromosomes in each population was 30 and the maximum number of generations was 100. The crossover and mutation rates were set at 0·65 and 0·001 respectively.

Figure 11 shows the variation of the risk indices (1 − Rel), (1 − Res), Vul and DRI at the end of the operation period, as a function of the number of generations. The acceptable risk level employed is derived from the actual risk as observed during the 1994–95 drought, marked by a broken line at generation zero in Figure 11. From the figure, the DRI decreases from 0·69 to 0·63 after ten generations, resulting in a



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

W1 = 0.33

W2 = 0.33

W3 = 0.34

Figure 11. Variation of the risk indices as a function of the number of generations at the end of the operation period extending from 27 April 1994 to 31 May 1995

considerable decrease in the risk of failure (1 − Rel), of the risk of non-recovery (1 − Res) and of the vulnerability (Vul) at generation ten, compared with the actual risk observed at generation zero. Thereafter, the calculated risk indices do not show a steady decrease as the number of generations increases. A noticeable long plateau or 'flat step evolution' stage continues for about 50 generations, and there is no major improvement in the objective function DRI. In general, such plateaus are likely to be related to (1) the variability of the number of failures that occur in each generation, (2) the maximum sojourn in failure state, if failure occurs, and (3) the additional random population generated to avoid in-breeding of the chromosomes in the new generation. Between generations 50 and 60, a second major improvement is achieved by the GA model, and the DRI value drops from 0·62 to 0·59, after which the GA seems to be attracted into the major local minimum to end with a DRI value of 0·58 at generation 100.

DISCUSSION AND CONCLUSIONS

The management of complex water supply systems requires advanced tools to alleviate the persistent uncertainties in hydrological and management issues, and to improve the quality of decision making for different climate conditions. This study introduced a DSS designed for the drought management of water supply systems using risk analysis with simulation and optimization procedures. The results of our application demonstrated the potential to improve the overall performance of a water supply system using the concept of acceptable risk.

Despite the promising capability of the present GA model, a number of theoretical and physical constraints undoubtedly exist, and several issues remain unresolved. These include the encoding procedure, the number of strings matched by a given schema at each new generation (minimum spread of an individual), the mapping of the objective function into a fitness value, the effect of the crossover procedure, and the operation period and chromosome length. The most important issue is the existence of what may be referred to as the 'attributable risk', which can be viewed as the rate of failure of a single reservoir to supply water for a number of days. The attributable risk results from the priority level (i.e. from which reservoir to take water first) assigned to each reservoir, and the rate of water supply at each time step. Nevertheless, it may be concluded that clustering the chromosomes of the new generations inside the acceptable risk space will ensure minimum spread of the best individuals and lead to a better overall performance of the water supply system.

It is important to note that when a GA is applied to evaluate the amount of water supply from reservoirs, the priority level remains constant for a given scenario. It was found that the optimal solution exhibits a clear sensitivity to the propriety level; therefore, it is of primary consideration to improve the GA procedure by implementing a model to integrate the engineers' experience. Fuzzy inference is considered the most promising technique to add a realistic decision aspect to the mathematical models and further improve the system storage recovery during drought. Other improvements within the scope of future research include:

(1) 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 modules into the DSS to develop a tool for completely sustainable management of water resources systems.
(2) By law, the municipal waterworks in Japan must operate on a self-funding basis, so that each municipality has to set its own water rates to compensate for the water development and management costs. Thus, we are currently considering the possibility of including cost analysis for each scenario evaluated.

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