Water Resources Management **12:** 13–30, 1998.

Performance Risk Analysis for Fukuoka Water Supply System

XU ZONGXUE[1,⋆], K. JINNO[2], A. KAWAMURA[2], S. TAKESAKI[3] and K. ITO[4]
[1] *Tsinghua University, P.R. China*
[2] *Dept. of Civil Engineering, Kyushu University, Fukuoka 812, Japan*
[3] *Nihon Suido Consultant Co. Ltd, Fukuoka 812, Japan*
[4] *CTI Engineering Co. Ltd, Tokyo 103, Japan*

(Received: 1 May 1996; in final form: 14 October 1996)

Abstract. In this study, simulation is used to evaluate the performance of the municipal water system in Fukuoka city. In combination with daily simulation model, a kind of risk model incorporating water demand prediction is presented. This model applies five risk indices: reliability, resiliency, vulnerability, drought risk index (DRI) and drought damage index (DDI). They aid in the identification of operation policies for the municipal water system, and the planning and operational policies obtained are aimed at achieving minimum risk for a given scenario of operation. In this paper, the performance risk of the municipal water system is investigated under three alternatives: (1) the existing system operation when available supply from the Chikugo river is decreased; (2) water restrictions for different percentages of reduction are implemented; and (3) available water supply increases when desalination of sea water is implemented. The results obtained show that savings of between 5 and 12% of water consumption from May 1, or increasing of daily desalination of sea water about 30 000 m^3 or more, may efficiently decrease the performance risk of the Fukuoka water supply system. Potentials also exist for further increase of reservoir storage by more rational operation. The measure that more attention should be paid to increasing the water supply from stable sources is recommended as well.

Key words: risk, reliability, resiliency, vulnerability, drought risk index, drought damage index, simulation, water supply, reservoir operation

1. Introduction

Periods of water shortage may occur frequently in a municipal water system, especially when naturally variable surface water is the main supply source. Fluctuations in weather conditions may cause serious risk in this kind of water system. In recent years, the influence of drought in the performance of municipal water systems has been studied intensively, and many significant achievements have been made, especially on the combined effects of mechanical failures, excessive demands, fluctuation in flows or heads at a lumped demand node, and related water quality problems (Wan and Kuczera, 1993; Radwan and Shaw, 1994; Shin and ReVelle, 1994; Vogel and Bolognese, 1995). However, few studies have addressed the performance risk of municipal water systems up to date.

⋆ Presently at CTI Engineering Co. Ltd, Tokyo 103, Japan.

The notion of drought has several meanings. For example, hydrological drought is an extended period of low flows, low stage of surface waters or low groundwater levels. In this paper, drought is defined as a period during which streamflows are inadequate to supply established uses. Although drought happens infrequently, the need to modify operation policies occurs more often, even if an incipient drought does not develop to its full potential (Walker *et al*., 1993). It is important to have contingency plans available to deal with such situations, with the relevant risk analysis available to provide appropriate information in a timely way so that appropriate management action can be recommended (Mckinney *et al*., 1993).

This paper presents an approach of risk analysis for a municipal water system. The impacts of various drought and response measures on water supply are also investigated. This investigation shows that the municipal water system of Fukuoka city is indeed vulnerable and poses great risk. It is suggested that the development of new water resources with stable flow or the increase of desalination of sea water may be the most efficient means of maintaining system reliability for this water system.

2. Fukuoka Water Supply System

The municipal water system of Fukuoka city caters to a population of approximately 1 200 000 and seeks to maintain a reliable supply of water. Fukuoka is a typical city in the rainy region, but often experiences a shortage of water. Water is precious in Fukuoka city, and to maintain a water supply of suitable quality and quantity with reasonable reliability is a challenging task not only today but also in the future. There are eight reservoirs available that supply water to Fukuoka city. However, the available water supply from the existing reservoirs has been insufficient in the majority of the years during past decades. This fact has long been recognized by the government, and so a pipe network has been constructed to supplement the available catchment runoff from the Chikugo river, about 40 km south of Fukuoka city. The Chikugo river is the largest river and the major water resource in the northern Kyushu region. Storage within the Chikugo river basin and a predetermined entitlement agreement ensures that the water in the Chikugo river is available for the water supply of Fukuoka city, even under conditions of drought.

The municipal water system of Fukuoka city is shown schematically in Figure 1. This water system is a typical run-of-the-river water supply system. Water may be pumped from the Chikugo river, eight reservoirs and three rivers (four intakes), as seen in Figure 2. Recently, due to increased levels of urbanization and consumer demand, the municipal water system of Fukuoka city has become increasingly complex. Water supply authorities are fundamentally concerned with the problem of drought risk. This kind of risk can be decreased by developing new sources or through supply transfer between neighboring water authorities which may achieve both economic and system reliability benefits. When looking for alternative water sources to eliminate a water deficit in a region, water supply alternatives must

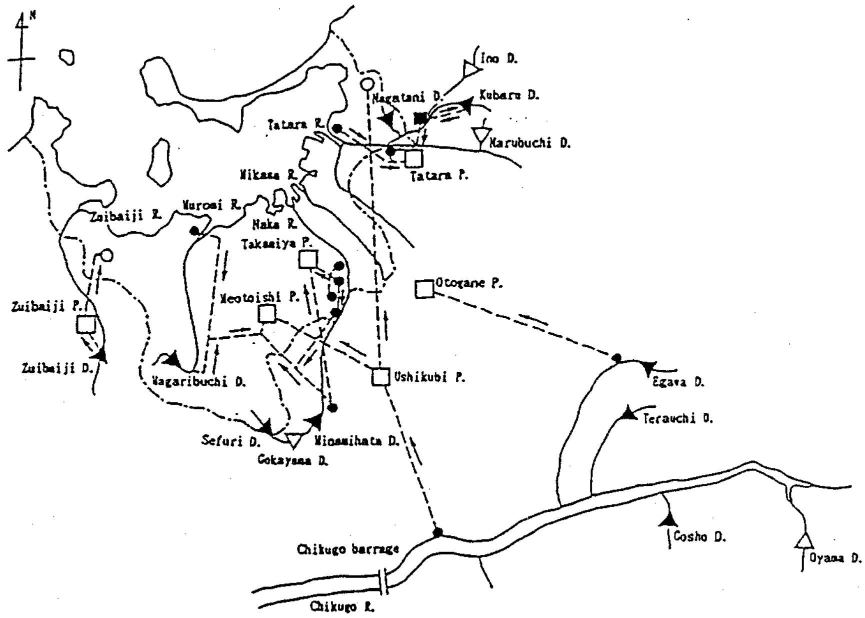

Figure 1. The municipal water system of Fukuoka city.

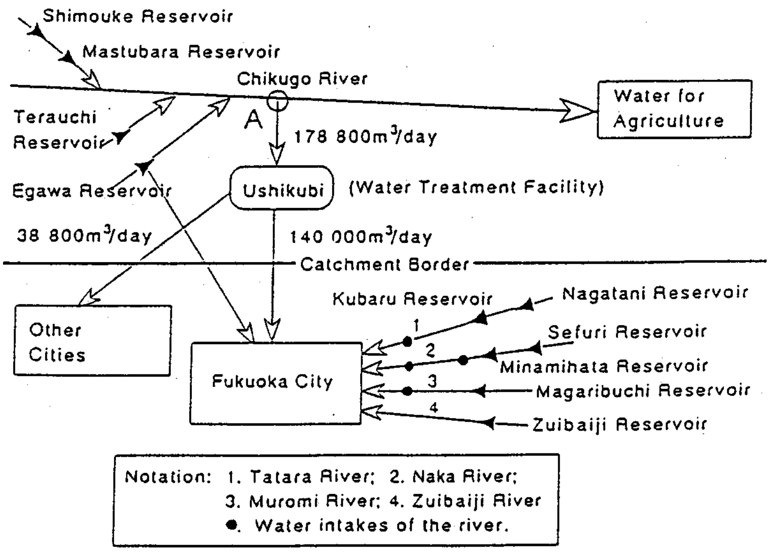

Figure 2. Water transfer from the Chikugo river to Fukuoka city.

be analyzed to ensure that they comply with established rules and regulations. The rules, regulations, and procedures governing the implementation of a water resources project must be studied beforehand.

3. Simulation Model Formulation

The model developed in this project is composed of three components: demand part, simulation part, and risk assessment part. Because of drought, water restrictions imposed in 1994 led to a substantial drop in water consumption, the water demand data during that period thereby cannot directly be used for risk analysis. Therefore, it is necessary to establish the water demand model. On the other hand, reservoirs are the most important elements of complex water resources systems, which are used for spatial and temporal distribution of water. The simulation model of reservoir operation was developed in this study as well. Different risk indices were defined and formulated to perform a risk analysis for the municipal water system of Fukuoka city.

3.1. WATER DEMAND MODEL

Water demand models are widely used in practice, but most of the models are annually, monthly, or weekly based models. For example, Radwan and Shaw (1994) suggested the weekly water demand model as

$$D(cfs) = D_{\text{base}} + D_{\text{potential}}[1 + p_i \cdot f(t)] + \varepsilon \tag{1}$$

where
D_{base} = base (indoor) water use;
$D_{\text{potential}}$ = potential use;
p_i = rainfall response coefficient;
$f(t)$ = number of rainy days in a week; and
ε = a normally distributed independent random variable.

Based on residential consumption data, Wan and Kuczera (1993) defined a trend extrapolation model to forecast the future residential annually water demand as

$$D_t = [a + b(t - 1983) + \varepsilon_{d,t}] \cdot CN_t \tag{2}$$

where
D_t = annual residential demand for year t;
CN_t = number of water connections;
a, b = intercept and slope of the trend line, respectively; and
$\varepsilon_{d,t}$ = a normally distributed variable.

Water supply management is more interested in a daily based water demand model. During the year the water demand gradually increases except for a few days near the New Year, till August and September in which the peak is attained, then decreases gradually except for a few days in May and August which are holidays. The changes are also obvious during any week, as shown in Figure 3.

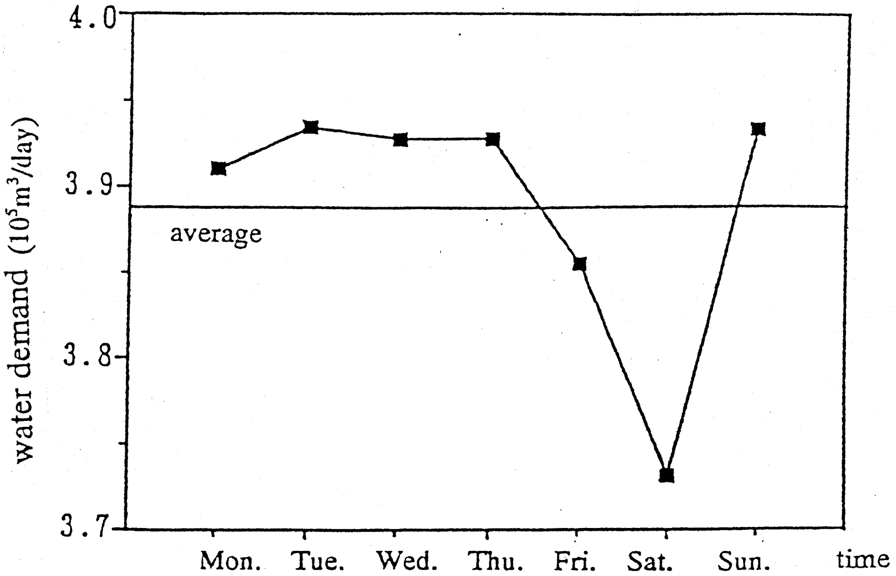

Figure 3. Changing trend of water demand during one week.

At the beginning of this study, a simple one-dimensional regression model was developed. In order to reflect the demand changes during different periods, two special coefficients are included in this model

$$QD(t) = at + b \cdot \gamma_m \cdot \gamma_d, \tag{3}$$

where

a, b = intercept and slope of the trend line, respectively;

γ_m = monthly coefficient which describes the changes of water demand in one month;

γ_d = daily coefficient which reflects the changes of water demand in one week or on some special holidays.

With the combination of water consumption data in Fukuoka city during period of 1987–1993, it is estimated by using the least-squares method that a = 14.91 and b = 403391.6. The values of γ_m and γ_d are shown in Tables I, II and III, respectively.

At the present stage in this study, the demand prediction considered for the application refers to the year 1994 just after an extrapolation of the model and does not take into account the demand increase because of the drought effect. This should be improved in future research.

3.2. SIMULATION MODEL OF RESERVOIR OPERATION

Simulation is an established technique for evaluating the future performance of systems (Crawley and Dandy, 1993). This kind of model is a useful tool for

Table I. Daily coefficients of the water demand model

Time	Coefficients
Monday	1.009
Tuesday	1.014
Wednesday	1.008
Thursday	1.013
Friday	0.983
Saturday	0.963
Sunday	1.012

Table II. Monthly coefficients of the water demand model

Time	Coefficients
January	0.924
February	0.943
March	0.943
April	0.987
May	0.999
June	1.046
July	1.094
August	1.045
September	1.048
October	1.016
November	0.997
December	0.975

Table III. Daily coefficients for special holidays

Time	Coefficients	Time	Coefficients	Time	Coefficients
1/1	0.713	5/1	0.949	9/15	1.001
1/2	0.767	5/2	0.914	date 2	0.998
1/3	0.836	5/3	0.905	10/10	0.949
1/15	1.039	5/4	0.898	11/3	1.005
2/1	1.024	5/5	0.991	11/23	0.967
date 1	0.984	8/13	0.895	12/23	1.034
4/29	1.013	8/14	0.817	12/30	1.035
4/30	1.001	8/15	0.832	12/31	0.975

estimating the hydrological, economical, and environmental impacts associated with future planning and operation of municipal water systems (Yeh, 1985). Given some assumption about future water demand and runoff resulting from changing climate or land uses, simulation models may tell managers the consequences which may occur in the future.

Fukuoka city has a shortage of ground water. Besides the water taken from intakes near the Chikugo weir and three small rivers near or through the city, about 70% of the supply is taken from reservoirs, including Egawa and Terauchi reservoirs which are situated in the upper reaches of the Chikugo weir. Therefore, the key to simulate the municipal water system of Fukuoka city is to simulate the operation of reservoirs. The continuity equation for one reservoir is usually defined as

$$S_t - S_{t-1} = I_t - Q_t - R_t \,, \quad t = 1, 2, \ldots, n \tag{4}$$

subject to

$$S_t \geq S_0 \,, \quad t = 1, 2, \ldots, n,$$

$$S_t \leq S_M \,, \quad t = 1, 2, \ldots, n,$$

$$Q_t \leq Q_M \,, \quad t = 1, 2, \ldots, n,$$

where
S_t = storage in m^3 at the end of period of t;
I_t = inflow in m^3 that occurs during period t;
Q_t = domestic water supply in m^3 in period t;
R_t = release in m^3 in period t which includes spill, water use for agriculture and navigation, etc.;
S_0 = minimum storage of reservoirs;
S_M = capacity of reservoir;
Q_M = permitted water right, may be taken from the reservoir for municipal use.

The water deficit QE_t for each period is

$$QE_t = QD_t - QS_t, \tag{5}$$

where
QD_t = target demand in period t;
QS_t = available water supply.

QS_t may also be expressed as follows

$$QS_t = \sum_{i=1}^{8} QR_t^i + \sum_{i=1}^{4} QI_t^i + \zeta \cdot QC_t, \tag{6}$$

where
QR_t^i = flow taken from reservoir i;
QI_t^i = flow taken from the *i*th intake along the three rivers;
QC_t = flow taken from the intake near the Chikugo weir;
ζ = water transfer ratio from the Chikugo weir, as shown in Figure 2.

Then

$$QE_t - Z_t \cdot QD_t \leq 0 \,, \quad t = 1, 2, \ldots, n \tag{7}$$

where Z_t is a zero-one integer variable. If there is a deficit in period t, i.e. QE_t, takes a value from zero to the target demand, Z_t is equal to 1. If QE_t is zero, the value of Z_t is forced to zero.

The total days of the *i*th consecutive periods of water deficit, FP_i, is

$$FP_i = \sum_{t \in M_i} Z_t, \tag{8}$$

where M_i is the set of the *i*th failure period. The deficit VE_i of the *i*th consecutive periods and the corresponding demand VD_i are

$$VE_i = \sum_{t \in M_i} QE_t \cdot \Delta t, \tag{9}$$

$$VD_i = \sum_{t \in M_i} QD_t \cdot \Delta t, \tag{10}$$

in which Δt is a calculation period.

In this study, Δt is taken as 1 (day). The reservoirs are operated according to the normal operational rule in which demand is supplied whenever possible. This means that a demand shortfall occurs only when the storage in the system is smaller than the minimum storage corresponding to the predetermined water right.

3.3. RISK MODEL FORMULATION

In water resources engineering, risk has been studied intensively in recent years and many significant achievements have been made. Flood risk, in particular, has been studied widely (Rasmussen and Rosbjerg, 1991; Xu, 1993). In water supply systems, both water supplies and demands are driven by the variability of climate conditions such as rainfall and temperature. In order to avoid the unacceptable risk of either extreme shortage or lengthy smaller shortages during critical periods and to evaluate various types of failures for a municipal water system, different kinds of risk criteria should be identified and studied. Quantifying these criteria and incorporating them into mathematical models of planning and operation may result in improved policies for a municipal water system.

3.3.1. *Reliability*

Reliability sometimes means the possibility of nonfailure system operations over an *N*-year planning period (Vogel and Bolognese, 1995). It is usually defined as the probability of the system being in a satisfactory state

$$\alpha = P\{X_t \in S\}, \tag{11}$$

where S is the set of all satisfactory outputs.

In water resource systems, reliability may be defined as the probability of a system to deliver the desired water demand to users, that is

$$\alpha = \frac{1}{NS} \sum_{i=1}^{NS} I_{[i]}, \tag{12}$$

where
NS = total days of water supply period;
$I_{[i]}$ = state variable of the water supply system. $I_{[i]}$ is equal to 1 if no deficit occurs, and is equal to zero if deficit occurs.

3.3.2. *Resiliency*

The definition of resiliency for reservoir systems had been given for the first time many years ago, and recently has been used widely. Hashimoto *et al*. (1982) suggested that resiliency can be a measure of the probability of being in a period of no failure. According to this definition a resilient system is one that is capable of recovery from a deficit state to normal operation in a short time. Moy *et al*. (1986) further developed the resiliency concept with an emphasis on the time element to ease the quantification of the criterion and its incorporation into a mathematical programming model. They formulated a resilience measure as the maximum number of consecutive periods of shortages that occur prior to recovery.

In this study, resiliency is adopted to describe the capability of a system to return to a satisfactory state from a state of failure, which may be defined as the conditional probability

$$\beta = P\{X_t \in S / X_{t-1} \in F\}, \tag{13}$$

in which F is the set of all unsatisfactory outputs. According to necessary mathematical derivation, which may be expressed as (Jinno *et al*., 1995)

$$\beta = \frac{1}{E[T_F]}, \tag{14}$$

where $E[T_F]$ is the expected failure period. In this study, resiliency is defined as the inverse of the average period of water deficit, that is

$$\beta = \begin{cases} \frac{1}{(1/NF)\sum_{i=1}^{NF} FP_i}\ , & NF \neq 0, \\ 1\ , & NF = 0. \end{cases} \tag{15}$$

If NF = 0 which means FP = 0 then β = 1. This indicates that the system is in a satisfactory state during the whole water supply period. In the general situation, 0 $< \beta <$ 1, which means that the water supply system is in an unsatisfactory state (deficit occurs), and will return to a satisfactory state. The longer the average water deficit period, the smaller the resiliency. This means that if water deficit occurs during a longer period, it is more difficult to supply rational water.

3.3.3. *Vulnerability*

Vulnerability is a measure of the significance of failure. Measurement of the average release for water supply may be adequate for long-term performance evaluation but is inadequate to account for the infrequent and extreme events that a reservoir will experience in its economic life. Hashimoto *et al*. (1982) provided clear illustrations of the concept of vulnerability and has derived a mathematical notion. Then Moy *et al*. (1986) and Simonovic *et al*. (1992) further developed the concept of vulnerability. For example, vulnerability may be defined as the magnitude of the largest deficit of water during the period of operation. In the present study, vulnerability is used to describe the significant consequence of drought

$$\gamma = E\{Se\}, \tag{16}$$

in which Se is the numerical indicator of drought severity. In combination with the situations of the municipal water system in Fukuoka city, the indicator used here is the average deficit during the whole supply period divided by the average water demand during same period,

$$\gamma = \frac{(1/NF)\sum_{i=1}^{NF}\ VE_i}{(1/NF)\sum_{i=1}^{NF}\ VD_i} \tag{17}$$

or

$$\gamma = \frac{\sum_{i=1}^{NF}\ VE_i}{\sum_{i=1}^{NF}\ VD_i}, \tag{18}$$

where
VE_i = the *i*th water deficit in m^3;
VD_i = the *i*th water demand in m^3 during the *i*th deficit period.

γ is generally less than 1 and greater than 0, which means that the larger the water deficit, the greater the vulnerability.

It should be pointed out that some shortcomings exist in definitions (15) and (18) of resilience and vulnerability, because they are defined in a mean domain of drought period. For example, a quick recovery after many failures yields the same resiliency as a long recovery after a single failure. These should be further improved in future study.

3.3.4. *Drought Risk Index (DRI)*

In order to easily diagnose different systems or subsystems, an integrated risk index–drought risk index (DRI), as a linear weighted function of reliability and resiliency and vulnerability, is defined as

$$\nu = w_1 \cdot (1-\alpha) + w_2 \cdot (1-\beta) + w_3 \cdot \gamma, \tag{19}$$

in which

$$\sum_{i=1}^{3} w_i = 1.0, \tag{20}$$

where w_1, w_2 and w_3 are weights which need to be predetermined. In this paper, the weight is presently taken as the same value for all, i.e. $w_1 = w_2 = w_3 = 1/3$.

3.3.5. *Drought Damage Index (DDI)*

The risk measures derived in previous sections are without question a kind of reasonable criteria. There is also a need to incorporate additional alternative risk criteria into the evaluation of operation strategy for a municipal water system. When a drought occurs, managers and public usually pay particular attention to damage caused by the drought. However, unlike the damage caused by flood, drought damage is very difficult to estimate. In this study, a damage index which has been used for a few years in Japan (Kazuto, 1991) is adopted and named the drought damage index (DDI),

$$\mathrm{DDI}_t = \left(\frac{VE_t}{VD_t} \cdot 100\%\right)^2 \cdot \Delta t, \tag{21}$$

where
VE_t = water deficit during period $(t-1, t)$;
VD_t = water demand during period $(t-1, t)$.

Then, the cumulative drought damage index (CDDI) is

$$\mathrm{CDDI} = \int_0^T \mathrm{DDI}_t \, \mathrm{d}t, \tag{22}$$

which describes the total damage caused by drought during the period $(0, T)$. It usually expresses the total damage during the drought from the beginning to date. DDI_t and CDDI may be used to evaluate the drought damage in a relative way.

4. Risk Analysis for Different Water-Supply Measures

The municipal water system of Fukuoka city is a typical run-of-the-river water supply system, which has limited storage and a lack of redundant components. System reliability is seriously influenced by fluctuations in weather or temperature. Recently, the frequent onset of drought poses great risk for the development of Fukuoka city. Because of a drought in 1978, water restriction continued for 287 days. A more serious drought began in July 1994, and continued for more than 330 days. The water restrictions exceeded 15 hours per day during serious periods, which not only caused difficulties in industry and agriculture, but also caused great inconvenience for the public. The drought occurred not only in Fukuoka city but also in the Chikugo river catchment, in the Kyushu region and a large part of Japan. The reduction in the water supply from the Chikugo river to Fukuoka city reached nearly 50% during serious periods. The storage in reservoirs of Fukuoka city also decreased to its lowest value. Therefore, some data of the water supply in 1994 was used in the risk analysis in this study.

The simulation model developed in previous sections is used to make a risk analysis for the municipal water system of Fukuoka city. The flowchart of the risk analysis is shown in Figure 4. Some of these results are outlined in the following sections.

4.1. CURRENT SCENARIO-BASED ANALYSIS

Firstly it is assumed that water was supplied in accordance with all practical needs before 8 July, the beginning of the water restriction. Fukuoka city then took water from eight reservoirs under a predetermined water right after 8 July. According to the different ratio of water restriction from the Chikugo river, the amount of water that can possibly be supplied to Fukuoka city may be calculated, and the risk can also be calculated, as shown in Figure 5.

If the Chikugo river authority stops supplying water to Fukuoka city, the decrease ratio is equal to 100% and the risk is 0.55, which is quite large. If the ratio decreases to 0.0, the risk is 0.3. It can be seen that even if the Chikugo river authority supplied water for Fukuoka city under a predetermined water right, the water was still not enough in 1994. Figure 6 shows the DDI curve corresponding to a transfer ratio of 1.0 (100%). From Figure 6 it can be seen that the first major drought damage occurs during the second ten days of July. At that time, storage in the reservoirs is low. Because of the precipitation in August, the storage in the reservoirs increases slightly and the problem decreases. Storage then decreases gradually, and the drought problem exacerbates after September.

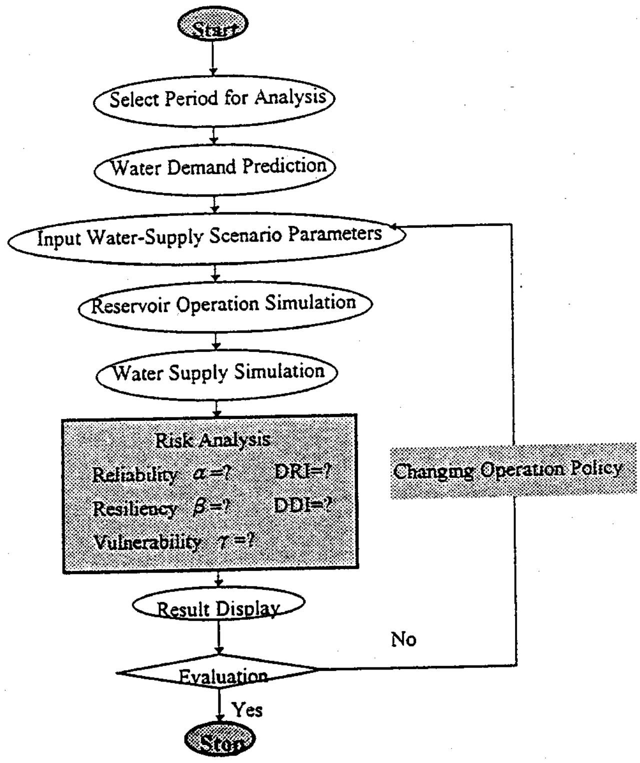

Figure 4. Flowchart of risk analysis.

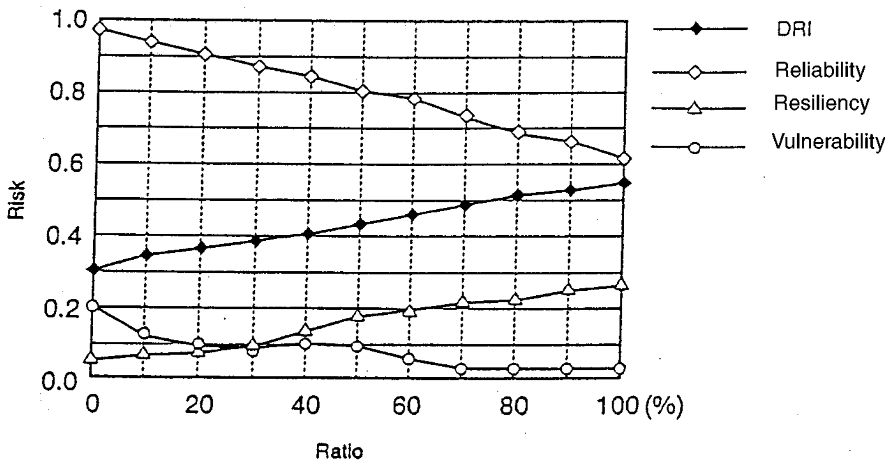

Figure 5. Risk of water supply due to reduction from Chikugo river.

If the amount of water taken from the three rivers and six reservoirs belonging to Fukuoka city is assumed to equal to the practical supply of water, the risk corre-

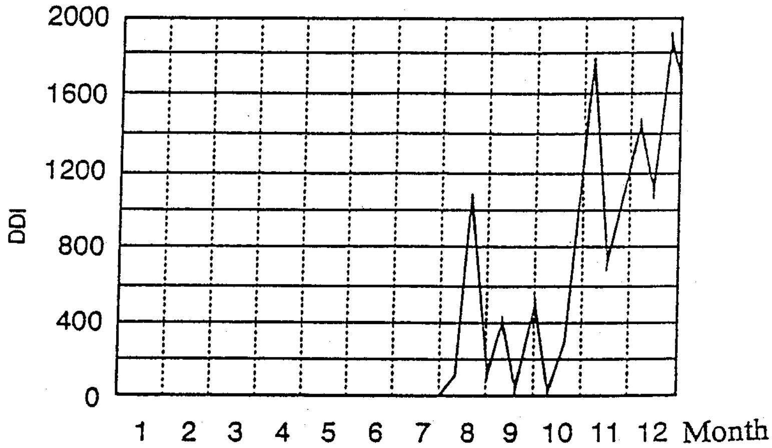

Figure 6. Drought damage when the reduction ratio from the Chikugo river is 1.0.

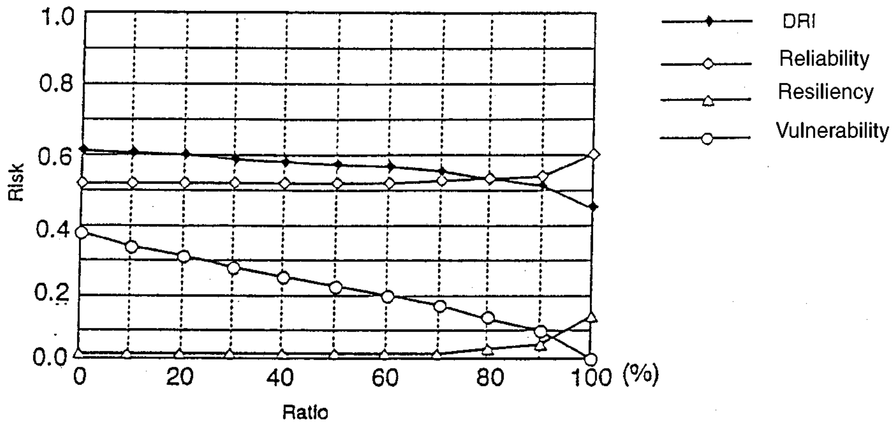

Figure 7. Risk of water supply when reduction from the Chikugo river occurs.

sponding to different percentage of water right from the Chikugo river (including Egawa and Terauchi reservoirs) is shown in Figure 7. Because Fukuoka city did not take as much water as possible from its own reservoirs, even if the Chikugo river supplies water under a water right, the risk is still very great.

4.2. WATER DEMAND REDUCTION SCHEME-BASED RISK ANALYSIS

In the practical operation of municipal water systems, the demand reduction schemes are usually adopted even if an incipient drought does not develop to its full potential. In this study, the impact of different demand reduction schemes on the municipal water system of Fukuoka city was also simulated. These demand reduction schemes are defined by their target percentage reduction in the overall city demand. Target reductions of 2, 4, 6, 8, 10, 12 and 15% of the normal total

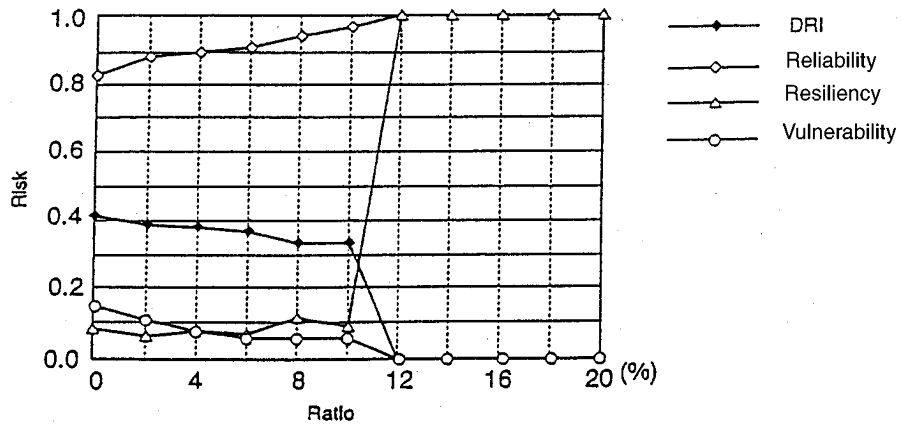

Figure 8. Risk of water supply when water demand decreases.

demand are considered (normal demand is the 'no restriction' demand which was predicted by the demand model, and no restriction programs are in effect). The results are shown in Figure 8. The risk becomes lower with each increase in the demand reduction. If the demand reduction program begins to take effect from 1 May, then the risk decreases from 0.55 to 0.33 when an 8% reduction is adopted, and decreases to zero if a 12% reduction is in effect from the beginning. Figure 9 is the DDI curve corresponding to a 4 and 10% reduction in the water demand. It shows that a 4% reduction is in effect from 1 May, then the drought damage could decrease significantly from July to September. However, because the precipitation was not enough in September or later, the drought damage is significant from October to December. If the reduction attained 10% from 1 May, the damage would decrease to almost nearly zero in October. However, damage is unavoidable in December.

4.3. SEA WATER DESALINIZATION MEASURES-BASED RISK ANALYSIS

Although the desalinization cost of sea water is higher than other measures, the desalinization amount should increase gradually with the development of economics because of its stability as a water source. According to the supply situation in 1994, if the daily desalinization amount of sea water increased about 50 000 m^3 per day from January, the risk could be decreased significantly, as shown in Figure 10. In practice, if the desalinization of sea water increases by 35 000 m^3 per day from January, the risk will decrease to zero. From the drought damage curve for cases on desalinization of 20 000 m^3 and 30 000 m^3, it can be concluded that if the desalinization amount increases to 20 000 m^3 per day from January, damage will decrease to zero up to October, but the damage in November and December is still significant. If desalinization of sea water increases to 30 000 m^3 each day

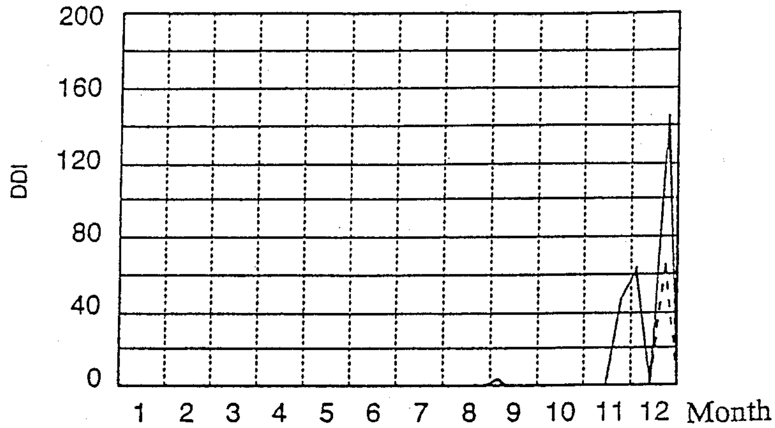

Figure 9. Drought damage when demand decreases by 4 and 10%.

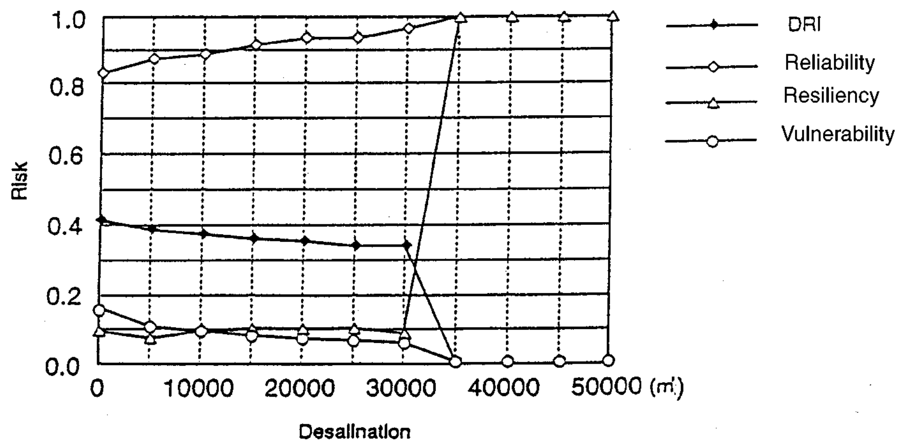

Figure 10. Risk of water supply when desalinization water increases.

from 1 January, the damage in November will become zero. However, the damage in December is unavoidable.

5. Conclusions and Suggestions

It can be concluded that the risk of the municipal water system in Fukuoka city may be decreased if some significant shortage response measures are adopted beforehand. On the basis of the preceding risk analysis, the following conclusions may be drawn: (1) the risk to the municipal water system of Fukuoka city was great in 1994, although a new water source from the Chikugo weir had been developed 10 years previously; (2) 1994 was indeed a serious drought year not only for Fukuoka city, but also for the Chikugo river catchment; and (3) should a drought occur in Fukuoka city as serious as the one in 1994, then the water needed for Fukuoka city will be insufficient even if the water supply from the Chikugo river is normal. Therefore, some measures for the planning and operation of the municipal water system of Fukuoka city are suggested: (1) although an interbasin transfer of water is adopted and Fukuoka city can take much of its water from the Chikugo river, if a drought occurs simultaneously in Fukuoka city and in the Chikugo river, the water supply to Fukuoka city cannot be guaranteed. It is thereby necessary for Fukuoka city to develop a more stable water source as soon as possible. (2) The amount of water (yearly precipitation) in Fukuoka city should be further investigated, and the planning scenarios of the water resource system previously determined should be further analyzed and revised on the basis of this investigation. (3) The potentiality of water supply facilities should be further exploited, for example, to build a new available storage-reservoir for water supply as soon as possible, to increase the desalinization of sea water, more rational regulations for the operation of reservoirs to increase reservoir storage in the rainy season, to establish a water bank in the Fukuoka region, etc. Frankly speaking, because of uncertainty from the model, the data, and the parameters, some errors or uncertainties are unavoidable in our results, but the conclusions may supply significant reference towards the planning and operation of the water supply system of Fukuoka city.

Acknowledgement

The writers wish to extend their appreciation to the staff of Fukuoka Waterworks Bureau for providing valuable assistance to make this study possible. The assistance from Miss Iku Kinoshita for the preparation of this manuscript is appreciated. The authors would also like to thank editors and two anonymous reviewers for their insightful comments and constructive suggestions. The opinions expressed are those of the writers and not those of other individuals or organizations.

References

Crawley, P. D. and Dandy, G. C.: 1993, Optimal operation of multi-reservoir system, *J. Water Resour. Plng. Mgmt., ASCE,* **119**(1), 1–17.

Hashimoto, T., Stedinger, J. R. and Loucks, D. P.: 1982, Reliability, resiliency, and vulnerability criteria for water resources system performance evaluation, *Water Resour. Res.* **18**(1), 14–20.

Kazuto, N.: 1991, *Water Resource Science*, The Asakura Publishing Co. Ltd, Tokyo, Japan.

Jinno, K., Xu, Z. X., Kawamura, A. and Tajiri, K.: 1995, Risk assessment of water supply system during drought, *Water Resour. Develop.* **11**(2), 185–204.

Mckinney, D. C., Maidment, D. R. and Tanriverdi, M.: 1993, Expert geographic information system for Texas water planning, *J. Water Resour. Plng. Mgmt., ASCE,* **119**(2), 170–183.

Moy, W.-S., Cohen, J. L. and ReVelle, C. S.: 1986, A programming model for analysis of the reliability, resiliency and vulnerability of a water supply reservoir, *Water Resour. Res.* **22**(4), 489–498.

Radwan, A. A. and Shaw, D. T.: 1994, Performance of integrated municipal water system during drought, *J. Water Resour. Plng. Mgmt., ASCE,* **120**(4), 531–545.

Rasmussen, P. F. and Rosbjerg, D.: 1991, Evaluation of risk concepts in partial duration series, *Stochastic Hydrol. Hydraul.* **5**, 1–16.

Shin, J.-S. and ReVelle, C.: 1994, Water-supply operations during drought: continuous hedging rule, *J. Water Resour. Plng. Mgmt., ASCE,* **120**(5), 613–629.

Simonovic, S. P., Venema, H. D. and Burn, D. H.: 1992, Risk-based parameter selection for short-term reservoir operation, *J. Hydrol.* **131**, 269–291.
Vogel, R. M. and Bolognese, R. A.: 1995, Storage-reliability-resiliency-yield relations for over-year water supply system, *Water Resour. Res.* **31**(3), 645–654.
Walker, S., Jowitt, P. W. and Bunch, A. H.: 1993, Development of decision support system for drought management within North West Water, *J. Instn. Wat. Envir. Mgmt.* **7**(7), 295–303.
Wan, S. N. and Kuczera, G.: 1993, Incorporating demand uncertainty in water supply headwater simulation, *Water Resour. Res.* **29**(2), 469–477.
Xu, Z. X.: 1993, Homogeneous stochastic point process model for flood risk analysis, in *Proceedings of the Yokohama Symposium*, IAHS Publ. no. 213, pp. 267–276.
Yeh, W. W.-G.: 1985, Reservoir management and operation models: A state-of-the-art review, *Water Resour. Res.* **21**(12), 1797–1818.