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Risk Assessment of a Water Supply System during Drought

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ABSTRACT *In this paper the feasibility of using risk analysis for the planning and operation of a water supply system is evaluated through a case study where limited water resources have to be shared by Fukuoka city and the small neighbouring communities when drought occurs. Actual data of water demand and water supply together with actual reservoir inflow data are used. An application of the method which analyses two existing water supply subsystems is presented. The possible situations, in which drought occurs or the water demand target increases, are simulated and the risk is calculated and analysed.*

Introduction

Humankind has always been faced with water resource problems, i.e. having too much or too little water. Recently, water quality problems have also been experienced, effectively reducing the available resources and thus increasing the severity of a water shortage. The notion of drought has several meanings. Meteorological drought means having no precipitation for a long period. Hydrological drought is an extended period of low flows, low stage of surface waters or low groundwater levels. Ecological drought may be regarded as shortage of water which affects the life of plants and animals. Agricultural drought occurs when soil moisture content is insufficient for crops (Kundzewicz *et al.*, 1993). Droughts are generally caused by low precipitation persisting over a long period and high temperature causing high evapotranspiration. Another reason for drought is excessive water use, which may cause water stages to drop rapidly during short periods. The problem of making optimal decisions in planning and operation of water supply systems taking droughts into consideration has received continued attention from hydrologists in recent years. However, control of droughts, as with many other problems in water resources, is typically 'ill-structured' and subject to a high degree of uncertainty. It is necessary to carry out research from various aspects, for example using an expert system (ES), a decision support system (DSS) or risk analysis (Kojiri & Sakakima, 1993; Moy, 1986; Napiorkowski *et al.*, 1993; Tajiri *et al.*, 1994), etc.

Water supply systems are generally operated by a set of rules predetermined on the basis of historical inflow, storage capacity and safety criteria, and are expected to meet the target water demand. Generally speaking, safe yield operation is adequate under normal situations, but is unlikely to be sufficient

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during extreme circumstances such as prolonged droughts and sudden changes in water demand patterns. During these periods the normal operating procedures may result in single periods of severe shortage of supply or sequences of consecutive shortage of supplies, either of which may induce additional damages and irreversible consequences. In order to avoid the unacceptable risk of either brief extreme shortages or lengthy smaller shortages during critical periods and to evaluate various types of failures for a water supply system, additional risk criteria need to be identified and studied. Quantifying these criteria and incorporating them into mathematical models of planning and operation may result in improved policies for water supply systems.

Risk can be measured in numerous ways. In flood analysis risk is generally defined as the probability that exceedence flood occurs (Rasmussen & Rosbjerg, 1991; Xu, 1993). In the planning and operation of water resources risk is generally measured in the following ways: (i) probability of occurrence of a specified undesirable outcome, and (ii) the number of occurrences of a specified length of time. However, these measures of failure constitute only a partial measure of risk. We do not claim that these measures of risk are unsuitable, but they are insufficient for our study. As mentioned above, generally in the planning and operation of a water supply system, risk is measured by the probability of failure, or the number of failures likely to be realized in 10 years, 20 years, etc. In safe yield analysis, one may be confronted with a design in which a water supply system may fail, say, in one twentieth of 30-year sequences. Such characterization of a design statement makes at least two unsuitable assumptions:

(1) All failures are seemingly counted at the same probability; there is no difference between failures by magnitude and consequence.
(2) Failures are treated as though their effects are independent of one another. In fact the shortage in a consecutive deficit period is certainly of greater damage than that in which the shortage periods are separated by periods of adequate supply.

In planning and operation of water supply systems these assumptions, which have been widely used, are indeed simplistic. Certainly all failures are very unlikely to be of the same magnitude and importance. It is very obvious that a failure with a deficit of 2 million tons per day (MTD) from a 50 MTD target does not imply the same damages as a 20 MTD deficit from the same target. Furthermore, from the viewpoint of the users of a water supply system, five periods of failure within one year with each shortfall followed by a period of no shortage are likely to be more acceptable compared with a situation of a shortage in five consecutive periods during the same time-span.

Aiming at the problems of risk analysis in water supply systems as mentioned earlier, other risk criteria, not only reliability but also resiliency and vulnerability, are investigated and used in this paper. These criteria have been considered by a few researchers in other similar fields of research (Hashimoto *et al.*, 1982; Simonovic *et al.*, 1992), although some of the mathematical expressions are different from those presented in this paper. The definitions of reliability, resiliency and vulnerability are given and the corresponding mathematical expressions are derived. In order to compare the risk among different systems or subsystems an integrated risk criterion, defined as drought risk index (DRI), is also introduced in our study. These criteria are applied to the actual system and several simulation studies are carried out for situations such as the occurrence drought with a 20-year return period, or population increases in the cities studied. The results show that the introduction of other risk criteria in the planning and operation of a water supply system is necessary and significant.

Risk and Water Supply System

In the planning and operation of water resources, reliability has been studied intensively in recent years, and many significant achievements have been made. Reliabilities considered in the literature are mainly related to mechanical failures of pumps and pipes, limited capacity of distribution storage and the fluctuation in flows or heads at a lumped demand node. A number of different reliability measures are discussed in the literature (Damelin *et al.*, 1972; Fujiwara & Geanesharajah, 1993; Su *et al.*, 1987; Wagner *et al.*, 1988a, 1988b). For example, the concepts of isolation, availability, connectivity, minimal cut set and expected unserved demand have been proposed. In these studies the operational status of the water resources system is described as either satisfactory or unsatisfactory. A failure may correspond to the collapse of a pipeline due to an earthquake, while in our study, the failure is defined as the situation or state in which water supply cannot meet water demand and thus water deficit occurs.

An actual water supply system generally consists of three types of components: water supply sources, water treatment facilities and water demand zones, as shown in Figure 1. Our analysis of system performance focuses on system failure, i.e. the risk analysis for a water supply system. As already mentioned, the traditional measure of risk, the ratio of the number of system failures to the number of periods of operation, is without question a reasonable criterion and should not be abandoned. There is a need, however, to incorporate an additional alternative risk criterion into the evaluation of a water supply system operation strategy (Hashimoto *et al.*, 1982). In other words, the system performance can be described from three different aspects: (i) how often the system is in a satisfactory state (reliability), (ii) how quickly the system returns to a satisfactory state once a failure occurs (resiliency), and (iii) how significant the likely consequences of a failure may be (vulnerability). Moreover, in order easily to diagnose the different system it is necessary to introduce an integrated index. In our study the fourth criterion, drought risk index (DRI), is discussed as a linear weighted function of reliability and resiliency and vulnerability.

Reliability

Reliability is defined as the probability of the system being in a satisfactory state. Denote the state of system by random variable X_t at time t, where t takes on discrete values $1,2,\ldots,n$. Then the possible X_t values can be partitioned into two sets: S, the set of all satisfactory outputs, and F, the set of all unsatisfactory outputs. The reliability of the system can be expressed as (Hashimoto *et al.*, 1982)

$$\alpha = P\{ X_t \in S \} \tag{1}$$

The formulation of reliability for a water supply system is straightforward, in which a failure is defined as the state at which the water supply is less than the water demand. Therefore, the reliability is the ratio of the period of non-failure time (days) to the total period of the water supply period, that is

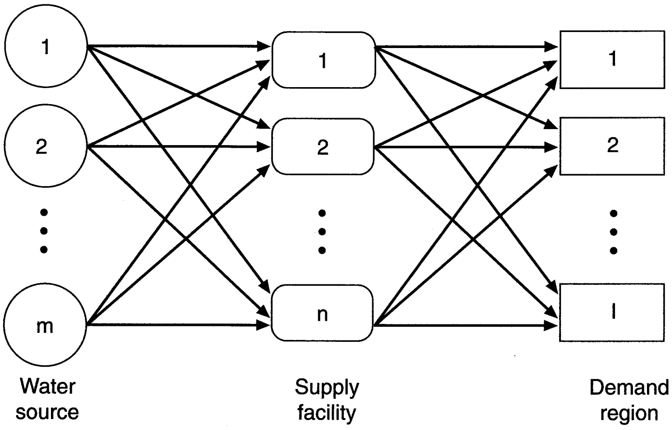

Figure 1. Generalized water supply system.

$$\alpha = \frac{1}{NS} \sum_{i=1}^{NS} I_{[i]} \tag{2}$$

in which

$$I_{[i]} = \begin{cases} 1, & \text{no deficit} \\ 0, & \text{deficit occurs} \end{cases} \tag{3}$$

where α is the reliability; NS is the total days of water supply period; $I_{[i]}$ is the state variable of the water supply system.

Resiliency

Resiliency describes the capacity of a system to return to a satisfactory state from a state of failure. Therefore, resiliency may be defined as the conditional probability

$$\beta = P\{X_t \in S / X_{t-1} \in F\} \tag{4}$$

By the fundamental theorem of probability, equation (4) may be expressed as

$$\beta = \frac{P\{X_{t-1} \in F, X_t \in S\}}{P\{X_{t-1} \in F\}} \tag{5}$$

Introducing a zero–one integer variable,

$$Y_t = \begin{cases} 1, & X_t \in F \\ 0, & X_t \in S \end{cases} \tag{6}$$

The total time in the state F may be expressed as

$$T_F = \sum_{t=1}^{n} Y_t \tag{7}$$

and the probability that a system is in state F may be expressed as

$$P_F = P\{X_{t-1} \in F\} = \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} Y_t \tag{8}$$

Another zero–one integer variable Z_t is used to indicate a transition from an unsatisfactory state to a satisfactory state,

$$Z_t = \begin{cases} 1, & X_{t-1} \in F, X_t \in S \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

The probability that a system is in state F in period t-1 and enters state S in the following period may then be expressed as

$$p_s = P\{X_{t-1} \in F, X_t \in S\} = \lim_{n \to \infty} \frac{1}{n} \sum_{t=1}^{n} Z_t \tag{10}$$

From equation (5) we have

$$\beta \approx \sum_{t=1}^{n} Z_t \Big/ \sum_{t=1}^{n} Y_t \tag{11}$$

On the other hand, the number of times that the system is in state F is

$$n_F = \sum_{t=1}^{n} Z_t \tag{12}$$

Equation (11) may be expressed as

$$\beta = \frac{n_F}{\bar{T}_F} \tag{13}$$

or

$$\beta = \frac{1}{\bar{T}_F} \tag{14}$$

in which $\bar{T}_F$ is the expected failure period. Equation (14) indicates that the resiliency of the system is the inverse of the expected failure period. In our study, resiliency is defined as the inverse of the average period of water deficit. From equation (14) we may obtain

$$\beta = \begin{cases} \dfrac{1}{\frac{1}{NF} \sum\limits_{i=1}^{NF} FP_i} & NF \neq 0 \\ 1, & NF = 0 \end{cases} \tag{15}$$

where β is the resiliency; NF is the total number of times the water supply system enters a failure state during supply period; FP_i is the ith number of failure days. If the whole supply period is in the state of water deficit, i.e. $NF = 1$ and $FP = NS$, then β takes on its smallest value, $\beta = 1/NS$. This expresses that the system is in a serious state and has difficulties in returning to a satisfactory state should failure occur. If $NF = 0$ which means $FP = 0$ then $\beta = 1$. This expresses that the system is in its satisfactory state during the whole water supply period. In the general situation, $0 < \beta < 1$, which means that the water supply system is in its unsatisfactory state (deficit occurs), but it will return to its satisfactory state. The longer the average water deficit period is, the smaller the resiliency. This means that if water deficit occurs over a longer period, it is more difficult to supply rational water.

Vulnerability

Even though the probability of failure is very low, attention should also be paid to the damage of a possible failure. On the other hand, few systems can be made so large or so redundant that failures are impossible. Even when it is possible to raise levees high enough or make water supply facilities large enough that failure is unlikely to occur, it is in fact not economical. Therefore, efforts should be made to enable the damages of a failure to become less severe. The decision maker should be aware of the severity of a failure should a failure occur. The vulnerability is an important criterion to describe the severity of failures for a water supply system. In order to create the quantitative indicator of system vulnerability, assume that the numerical indicator of the severity for the ith failure is s_i and the corresponding occurrence probability is p_i, then the expected severity may be regarded as the system vulnerability, that is

$$\gamma = E\{S\} = \sum_{i=1}^{NF} p_i s_i \tag{16}$$

in which γ is the vulnerability of a system and NF is the total number of failures.

In risk analysis of water supply systems the deficit of water may be taken as the severity of the failure. As a preliminary study, we can assume $p_1 = p_2 = \ldots = p_{NF} = 1/NF$ which means that each failure with different water deficit occurs with the same probability, rewriting (16) as

$$\gamma = \frac{1}{NF} \sum_{i=1}^{NF} VE_i \tag{17}$$

in which VE_i is the ith water deficit. Equation (17) states that the average water deficit may be regarded as the vulnerability of the water supply system.

Measurement of average water deficit may be adequate for the evaluation of a single water supply system, but is insufficient or inadequate for comparison among different systems or different periods for the same system. This fact can be universally acknowledged: a failure with a water deficit of 5 million tons per day (MTD) from a 50 MTD target does not lead to the same damage as the same water deficit from a 200 MTD target. Therefore, in our study the previous definition of vulnerability, Equation (17), is normalized by the demand target during the corresponding period. The vulnerability used here is the average deficit during the whole water supply period divided by the average water demand during this period

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

or

$$\gamma = \sum_{i=1}^{NF} VE_i \Big/ \sum_{i=1}^{NF} VD_i \tag{19}$$

in which VE_i is the ith water deficit; VD_i is the ith water demand during the ith deficit period; NF is the total number of failures. If $NF = 1$, $FP_i = NS$ and $VE_i = VD_i$ then $\gamma = 1$, which means that the system is in its most vulnerable state and has no water to supply (although in fact this is impossible). If $NF = 0$, which means $VE_i = 0$, then $\gamma = 0$. It expresses that the system is in its satisfactory state and no water deficit occurs. In general situations, γ is less than one and greater than zero. In a certain period, the larger the water deficit is, the larger the vulnerability is, which corresponds to the actual situation.

Drought Risk Index (DRI)

When the water supply system includes many subsystems and there is a need to compare different systems or subsystems, the use of reliability, resiliency and vulnerability alone is inconvenient. In this paper the integrated criterion drought risk index is introduced and defined as

$$\mu = w_1{}^*(1-\alpha) + w_2{}^*(1-\beta) + w_3{}^*\gamma \tag{20}$$

in which

$$\sum_{i=1}^{3} w_i = 1.0 \tag{21}$$

where w_1, w_2 and w_3 are weights. As the simplest situation, all weights are assumed to be equal, i.e. $w_1 = w_2 = w_3 = 1/3$. However, because generally risk is the opposite of reliability, it is possible to use $w_1 = 1/2$ and $w_2 = w_3 = 1/4$, etc.

The severity of the water deficit may be expressed from different aspects by reliability, resiliency and vulnerability. By combining these three criteria into the drought risk index, the risk of failure of the water supply system can be obtained. Using the information obtained from the risk criteria, through the simulation model, a specific water transfer ratio for each subsystem can finally be decided, which is the closest to a reasonable value.

Case Study: Fukuoka Water Supply System

The area of study is located in the southern part of Japan. In this area there is a large city with a population of 1.25 million. Neighbouring this metropolis there are nearly 20 small communities, as seen in Figure 2. The area of the water supply system of the Fukuoka region is 1,156 km^2 and the total population is 2.02 million. The hydrological features of this area are characterized by an average precipitation of about 1800 mm per year. In the past few decades the economy and the population have increased rapidly. The insufficient capacity to store water in reservoirs and the low flow in rivers may lead to water deficit, which has occurred several times in the past. The changes in water supply, water demand and population for both Fukuoka region and Fukuoka city are shown in Figure 3. It is obvious that the increase in population of Fukuoka region is larger than that of Fukuoka city, thus the necessary increase in water supply is greater in these small neighbouring communities.

In order to meet the water demand for the city and the adjacent small communities more than 10 reservoirs were built. However, the water supply situation was still vulnerable. About 10 years ago another water supply source along the Chikugo river, which is beyond Fukuoka catchment and has a bigger drainage area and therefore a more stable flow compared with the small rivers in the catchment of the metropolis region, was developed. However, in Japan waterworks are generally managed by public organizations, and on general principles each community is responsible for its own water supply (Kawamura *et al.*, 1994). There is no mutual water share among Fukuoka city and these small communities except in the case of droughts. The water transfer from Chikugo

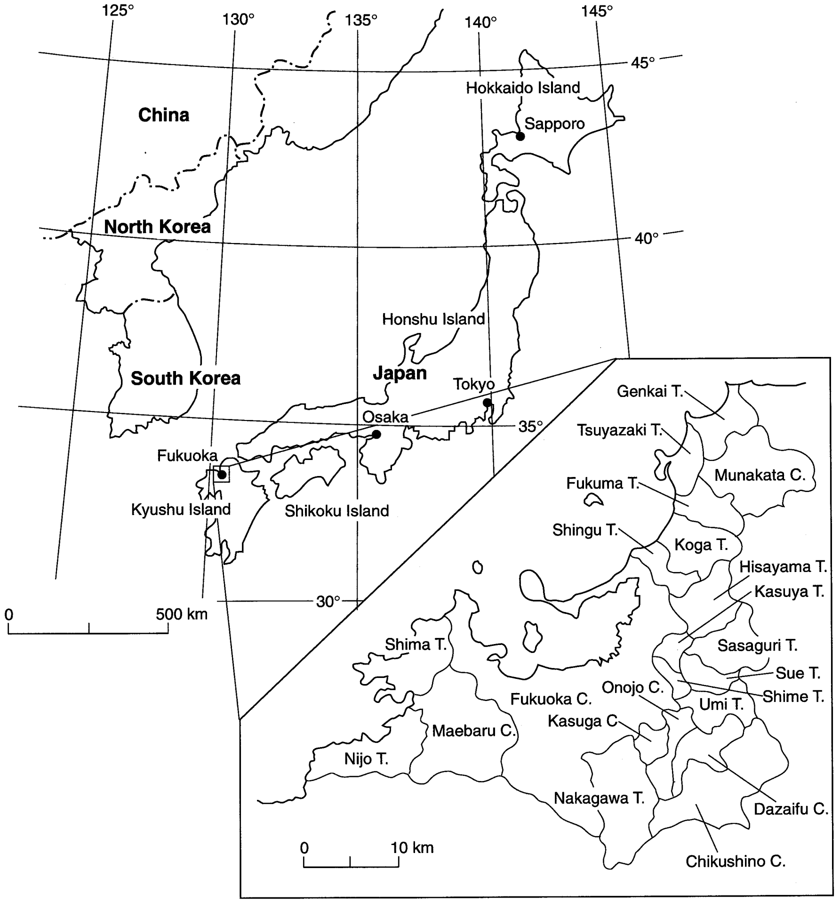

Figure 2. Location of Fukuoka city and communities in Fukuoka region.

river to Fukuoka city and these small communities is shown in Figure 4. From Chikugo river at point A the maximum water intake per day is about 178 800 m^3, of which about 78%, 140 000 m^3, is supplied to Fukuoka city under entitled agreement. The existing water supply system of Fukuoka city is shown in Figure 5. In the normal situation, the water supply problem is not too serious in the study area and the risk of water shortage is not so high. However, once drought occurs, for example, a drought with a 20-years return period happens, a question arises: what is the risk of water deficit for Fukuoka city and the neighbouring communities?

As stated above, with increasing population the problem of water shortage became more serious in the small communities than in Fukuoka city. When drought occurs in the metropolis region these small communities hope to share more water taken from Chikugo river with Fukuoka city under urgent negotiation. For example, in the case of drought, Dazaifu city may share about 3.7%, 6700 m^3 water taken from point A at most per day from Chikugo river, and Chikushino city may share about 1%, 1800 m^3 water taken from point A at most per day with Fukuoka city and other small communities under the entitled

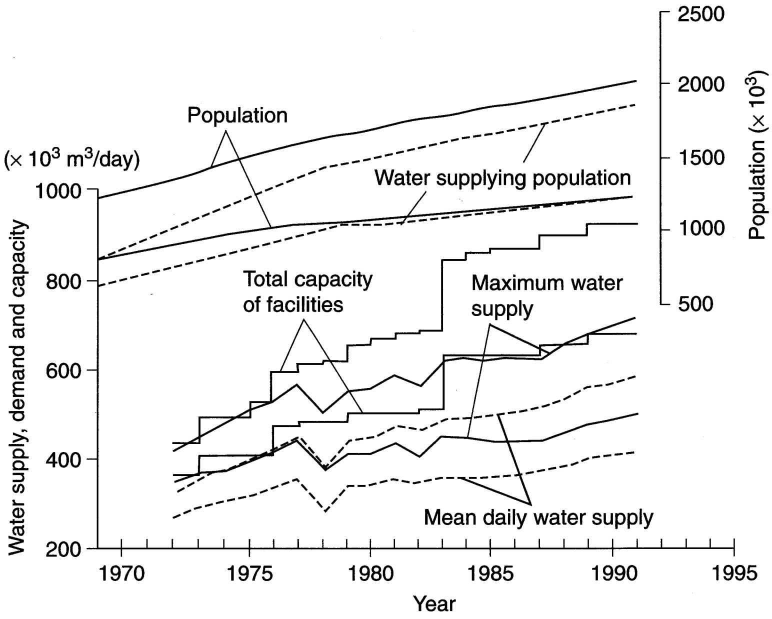

Figure 3. Changes in water supply, water demand and population.

agreement. This amount of water is seriously insufficient for them when drought occurs. What share-ratios of the water, expressed as ζ for Fukuoka city, ξ for Dazaifu city and ξ_i for other small communities, are feasible in case of drought? If it is feasible, there is a decrease of perhaps only 1% or 2% or less of the water taken from Chikugo river for the water supply of Fukuoka city, which may not increase the damage due to water shortage in Fukuoka city if the storage in the reservoirs of Fukuoka city is sufficient. But it is quite important for the communities which are short of water. For instance, as noted earlier, in the normal situation Dazaifu city can share 3.7% of the water taken from Chikugo river at point A at most with Fukuoka city and other small communities. If drought occurs is it possible to increase this ratio from 3.7% to 4.7% and at the same time decrease the ratio of water transfer for Fukuoka city from 78% to 77%? The increased amount of water is not greater compared with the total amount of water taken from Chikugo river. This perhaps does not have a greater effect on the water supply of Fukuoka city and the risk of water shortage for Fukuoka city is almost unchanged. But it can fundamentally solve the problem of water shortage in Dazaifu city, in which the result is just like "lending me a leaflet, giving me a stretch of shade" for small communities which are short of water. These questions are quite important and significant, being worthy of study. In this paper, as an example, the risk of water deficit for Fukuoka and Dazaifu city, and the feasibility for Dazaifu city to share more water with Fukuoka city in case of drought, were studied.

As mentioned earlier, Fukuoka city, the economic centre of Kyushu in Japan,

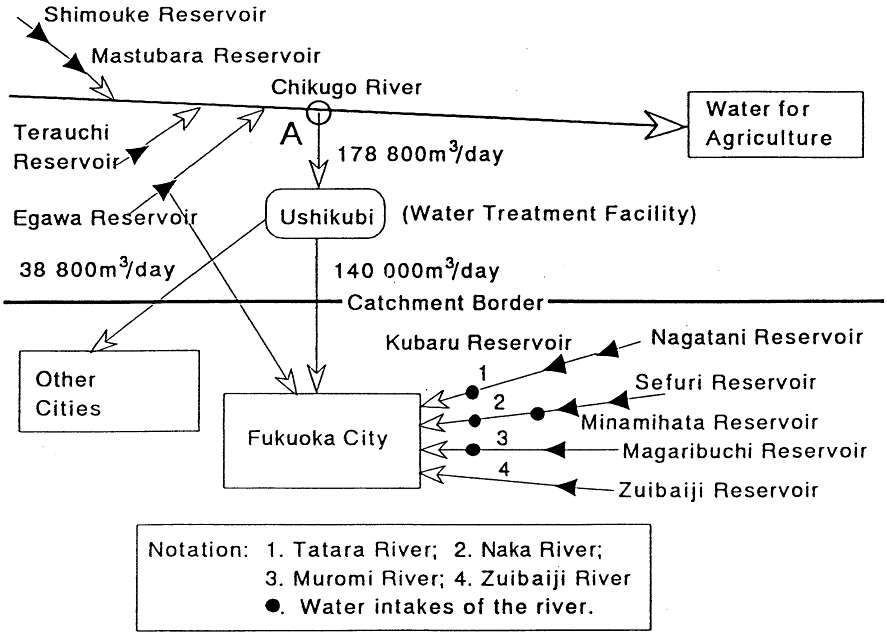

Figure 4. Water transfer from Chikugo river to Fukuoka city and small communities.
Note: Nagatani reservoir was not in use at that time.

has a population of 1.25 million. The main water supply sources of Fukuoka city include three types: the first is the Chikugo river; the second is three smaller rivers; and the third is six reservoirs near the city. The data related to the six reservoirs are listed in Table 1. The capacity of the water supply facilities in Dazaifu city is presented in Table 2.

Simulation Model for Water Supply System

Combining the features of the water supply system in Fukuoka region the framework of risk analysis in our study may be expressed as in Figure 6. For Fukuoka city the water supply sources include Chikugo river, the other three rivers and six reservoirs. The continuity equation for each reservoir may be expressed as

$$\frac{\mathrm{d}s(t)}{\mathrm{d}t} = I(t) - R(t) - E(t) \tag{22}$$

in which $S(t)$ is the storage; $I(t)$ is the inflow process; $R(t)$ is the release; and $E(t)$ is the evaporation.

In our study the evaporation term $E(t)$ was ignored and equation (22) was rewritten as

$$S_t - S_{t-1} = I_t \times \Delta t - Q_t \times \Delta t - O_t \times \Delta t, \qquad t = 1,2,\ldots,n \tag{23}$$

where S_t is the storage at the end of period t. Q_t is the water release for urban water supply. O_t is the other release which includes spill, the water for agriculture and hydroelectric generation, etc. The continuity constraint must hold for all periods of analysis. The capacity constraint is used to ensure that

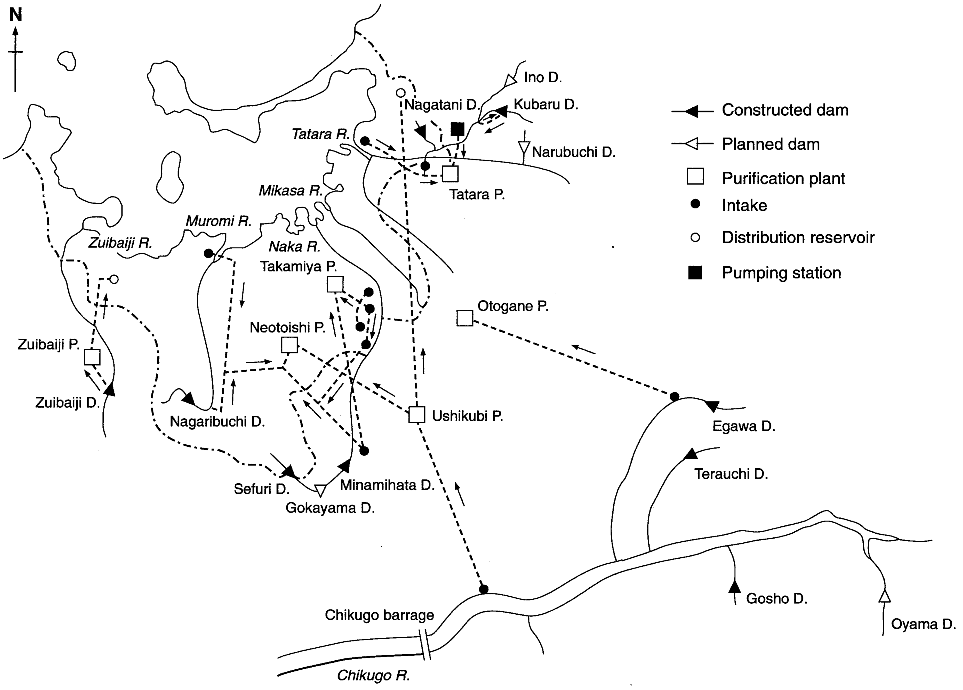

Figure 5. Water supply system of Fukuoka city.

storage volumes at the end of all periods are less than or equal to the reservoir capacity

$$S_t \leq SM, \qquad t = 1,2,\ldots,n \tag{24}$$

where SM is the capacity of the reservoir. The storage volumes at the end of all periods are greater than or equal to the minimum storage S_0, i.e.

Table 1. Reservoirs of Fukuoka city.

Reservoir	Catchment Area (km^2)	Capacity (100m^3)	Purpose	Jurisdiction
Minami Hata	27.5	5 560	F, IR, C, E	Prefecture
Kubaru	0.9	1 460	C	City
Magari Buchi	11.4	2 270	C	City
Egawa	30.0	24 000	Ir, C, In, E	Corp. of WRD
Sefuri	5.5	14 401	C	City
Zuibaiji	7.2	2 270	F, Ir, C	Prefecture

Note: F: flood control; Ir: irrigation; C: city water supply; E: electric power; In: Industry.

Table 2. Water supply capacity in Dazaifu.

Facility	Capacity (m^3/day)
Matsugo Reservoir	3 000
Osano Reservoir	3 400
Ochiai Well	1 500
Mizuki Well	1 500
Fukuoka Waterworks Agency	6 700
Total	16 100

$$S_t \geq S_0, \qquad t = 1,2,\ldots,n \tag{25}$$

The water taken in each period for water supply from each river or reservoir should be less than or equal to the corresponding permitted water right

$$Q_t \leq QM, \qquad t = 1,2,\ldots,n \tag{26}$$

The water deficit for each period, QE_t is computed as the difference between target demand QD_t and the actual supply QS_t

$$QE_t = QD_t - QS_t, \qquad t = 1,2,\ldots,n \tag{27}$$

in which,

$$QS_t = QR_t + QI_t + \zeta \times QC_t, \qquad t = 1,2,\ldots,n \tag{28}$$

$$QR_t = \sum_{k=1}^{6} QR_t^k \tag{29}$$

$$QI_t = \sum_{k=1}^{3} QI_t^k \tag{30}$$

where QI_t is the flow taken from the three rivers in period t; QR_t is the flow

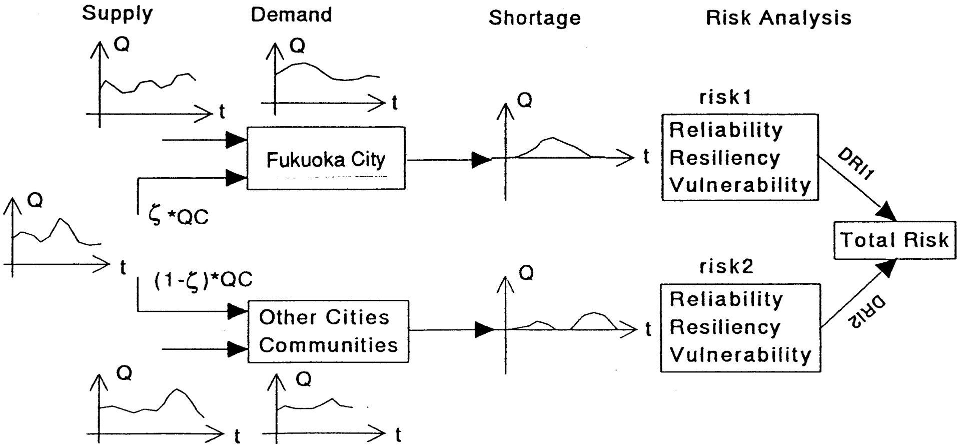

Figure 6. Framework of risk analysis.

taken from the six reservoirs in period t; QI_t^k and QR_t^k are the flow taken from the kth river and the kth reservoir in period t, respectively; QC_t is the flow taken from Chikugo river at point A during period t, with a maximum value of 178 800 m^3/day; ζ is the water transfer ratio of Fukuoka city from Chikugo river, which usually is about 78%; and QE_t is the value of water deficit in period t. QE_t can take any value between 0 and the target demand QD_t. If the supply is equal to the target demand, the deficit variable QE_t will have a value of zero. The largest deficit that can be experienced in period t is the target demand QD_t. A zero–one integer variable Z_t is used to indicate if deficit occurs during period t

$$QE_t - Z_t QD_t \leq 0, \qquad t = 1,2,\ldots,n \tag{31}$$

The target demand QD_t is known. If there is any 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. FP_i, which counts the ith number of consecutive days of water deficit, can now be calculated as

$$FP_i = \sum_{t \in M_i} Z_t \tag{32}$$

in which M_i is the set of the ith failure period. The deficit VE_i of the ith consecutive periods and the corresponding demand VD_i are

$$VE_i = \sum_{t \in M_i} QE_t \times \Delta t \tag{33}$$

$$VD_i = \sum_{t \in M_i} QD_t \times \Delta t \tag{34}$$

where Δt is the calculation period. In our case, Δt is equal to one day. The reliability, vulnerability, resiliency and DRI corresponding to different water transfer ratios ζ and different weights w_1, w_2 and w_3 can now easily be calculated.

For Dazaifu city the water supply sources generally include two reservoirs, two groundwater wells and the water taken from Chikugo river at point A, with the ratios 39.8%, 18.6% and 41.6%, respectively. The simulation process is almost the same as for Fukuoka city. The actual water supply QS_t^d is

$$QS_t^d = QR_t^d + QW_t^d + \xi \times QC_t \tag{35}$$

in which QR_t^d is the flow taken from the two reservoirs. QW_t^d is the flow taken from the two wells; and ξ is the ratio of water transfer from Chikugo river to Dazaifu city, which satisfies

$$\zeta + \xi + \Sigma\, \xi_i = 1.0, \qquad i = 1,2,\ldots \tag{36}$$

where ξ_i is the ratio of water transfer from Chikugo river to the other small communities.

With the flow sequence of seven months' water taken from Chikugo river, the other three rivers and the inflows of the six reservoirs for Fukuoka city and the water taken from the two reservoirs and two groundwater wells for Dazaifu city, with corresponding target demands for each period, the above-presented model was used for simulation. The reliability, resiliency, vulnerability and drought risk index were calculated and analysed for Fukuoka and Dazaifu city using a NEC-9821 Ap computer and the Quick C programming code.

Example: Drought from 1992 to 1993

In our paper risk is understood as an integrated index of failure to meet given water demand targets for the city or communities. Interest is focused on the effect of a failure calculated from daily values, as well as on duration and severity of the failure calculated from the number of consecutive days of failure.

From September 1992 to March 1993 the Fukuoka region experienced a drought with a return period of about six years. Not only Fukuoka city but also several small communities suffered water shortage. In particular, the flow in Chikugo river decreased by nearly 40%. The contradiction between water supply and demand for different cities and communities became more acute. What ratio of water transfer is reasonable for each city and community? Under which scenario is the risk of water shortage for the entire water supply system the smallest? In this paper we use a computer to simulate the process of water supply and water demand from September to March of the following year or any other desired day in the following spring. This procedure has the advantage that with one simulation the following information can be obtained: (1) reservoir storage at the end of each period; (2) last storage for each city or community at the end of each period; (3) reliability, resiliency, vulnerability and DRI under different water transfer ratios for each city or community; (4) if a more serious drought occurs, what will the risk for each city or community be?

Fukuoka City

In order to simulate the possible water supply and demand processes for the future, it is vital first to be able to simulate well the known actual supply and demand processes. Then by changing the water transfer ratio from Chikugo river, the corresponding water deficit process can be obtained. The reliability, resiliency, vulnerability and DRI may be calculated, as shown in Figure 7. In this real situation, when the water transfer ratio is greater than 70% there is no risk for the water supply. Thus during that period the transfer ratio of water taken from Chikugo river for the water supply of Fukuoka city may be decreased to 70% from 78%. That is, the water supplied to Fukuoka city under water right during that period allows the transfer of 7000–12 000 m^3 per day to other small cities and communities, and the damage due to water shortage in Fukuoka city does not increase.

In our study, the precipitation and runoff is assumed to have the same occurrence frequency, i.e. the precipitation with return period (RP) 20 years would formulate the runoff with return period also 20 years. From this assumption together with the analysis of precipitation in Fukuoka city, droughts with various return periods are simulated. First we assume that the drought with a return period of 10 years occurs, that is, the inflow to the five reservoirs in the Fukuoka catchment (Egawa reservoir is not included) and the flow in the three rivers will decrease to 94.4% of the flow during the same period from September 1992 to March 1993. By the method described above, the reliability, resiliency, vulnerability and DRI can be calculated, as shown in Figure 8. It is obvious that in this case when the ratio of water transfer from Chikugo river is greater than 77% there is no risk for the water supply of Fukuoka city. It means that when the flow in Chikugo river is nearly the same as in the situation from September 1992 to March 1993 and a drought with a return period of 10 years occurs in

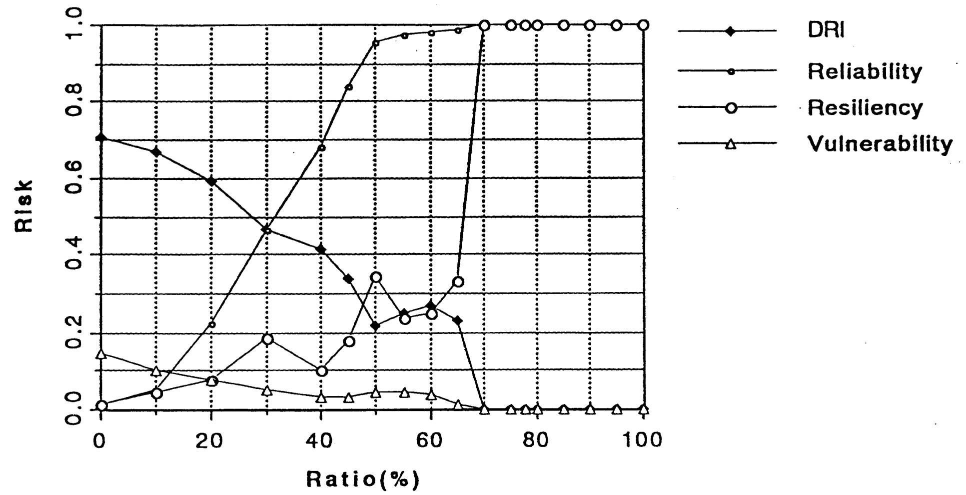

Figure 7. Risk curve for water supply on water right.

Fukuoka catchment, the existing water transfer ratio from Chikugo river, 78%, is suitable. Then, by the same method, we assume that a drought with a return period of 20 years occurs, that is, inflow to the five reservoirs and flow in three rivers would decrease to 86.1%. The corresponding reliability, resiliency, vulnerability and DRI are shown in Figure 9. The risk for water supply will become larger. If the water transfer ratio from Chikugo river is unchanged and equal to 78%, the DRI is 0.23 for the water supply of Fukuoka city.

From this analysis it seems that for Fukuoka city the water supply is generally no problem. Even if drought with a return period of 10 years occurs, the risk to water supply is low. However, in the real situation in order to have a buffer of water for 10 days' supply or more, Fukuoka city always stores water in the five

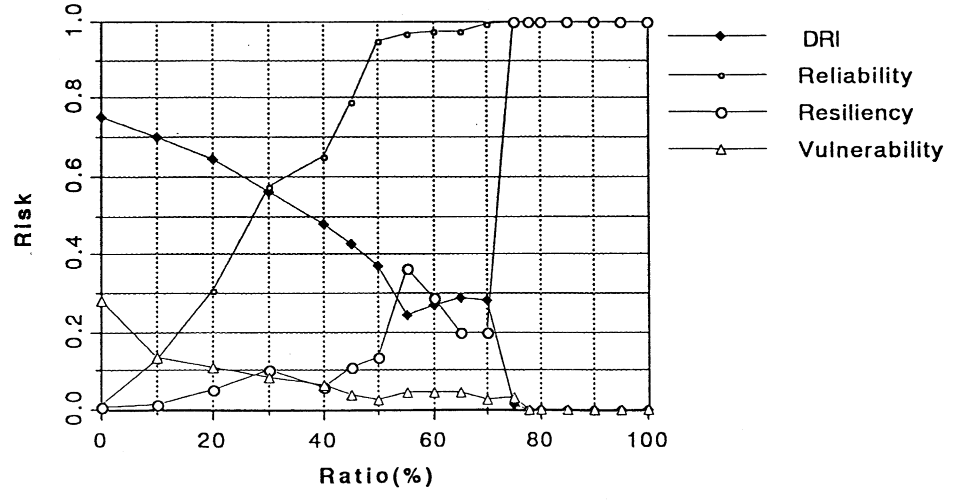

Figure 8. Risk curve for drought with RP = 10.

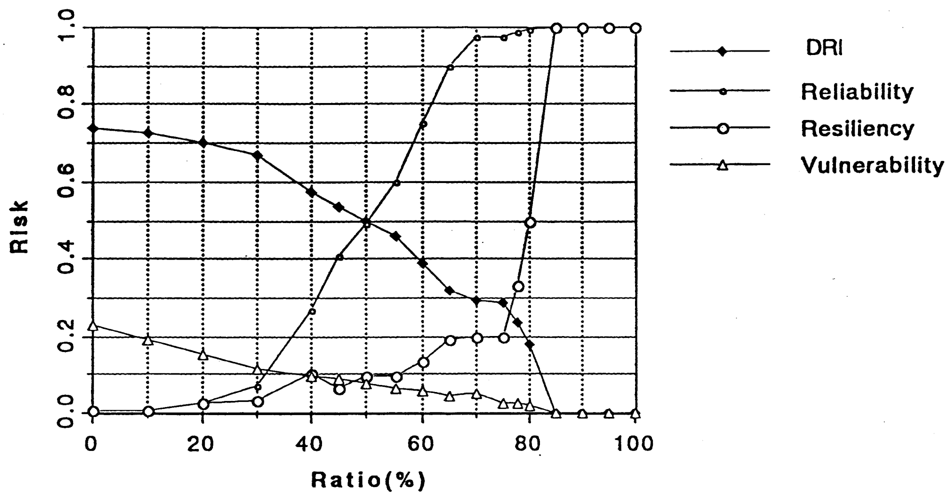

Figure 9. Risk curve for drought with RP = 20.

reservoirs belonging to the city, instead of taking water under predetermined water right for each day. Therefore, the key problem is to predict future precipitation accurately, thereby making it possible for the small cities and communities to share more water with Fukuoka city.

Dazaifu City

By a similar simulation model reliability, resiliency, vulnerability and DRI can be calculated for Dazaifu city. Figure 10 shows the result for the present water supply situation. It can be seen that if the water taken from Chikugo river is decreased by more than 0.7%, there is risk for the water supply of Dazaifu city. If a drought with a return period of 10 years occurs, i.e. the inflow to the reservoirs decreases to 94.1%, the corresponding critical transfer ratio, meaning from which the risk will become zero, will be 3.85%. This implies that in order to ensure the water supply of Dazaifu city, about 300 m^3 or more of water per day is needed. If a drought with a return period of 20 years occurs, the critical transfer ratio will be 4.07%, as shown in Figure 11. This means that an additional 700 m^3 of water per day is needed. If this drought happens during the study period, the result shows that the water taken from Chikugo river to Fukuoka city has to be reduced by 0.5% in order to support the water supply of Dazaifu city. If the water storage in Fukuoka city is sufficient, it would be feasible for Fukuoka city to comply without increasing its own risk of water shortage.

It is worth considering the situation in which the population in the small communities is increasing continuously with the development of the economy and business. Let us assume that the population in Dazaifu city increases by 5%, and correspondingly the water demand increases by 5%. The result is shown in Figure 12. In this case the critical transfer ratio is also 4.07%. This implies that the risk of water shortage is nearly same as for the situation in which a drought with a return period of 20 years occurs. From the result it is not difficult to understand that if the population in Dazaifu city increases continuously new

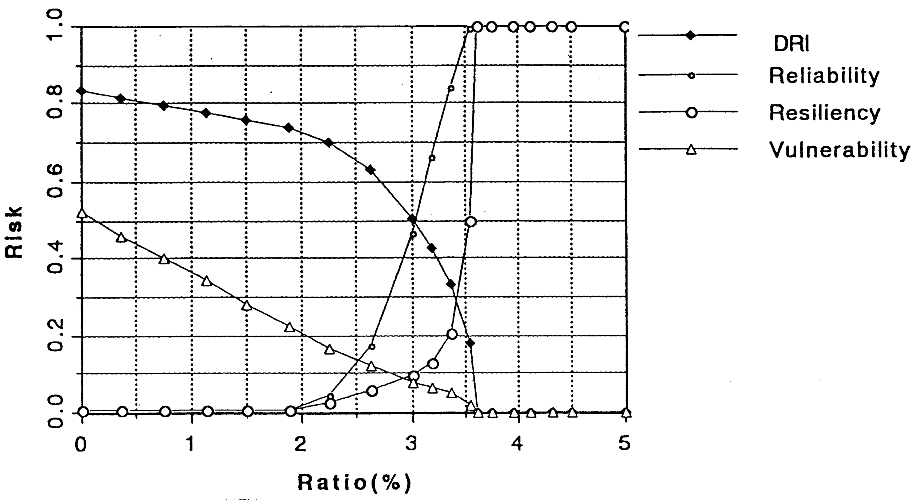

Figure 10. Risk curve for water supply on water right (Dazaifu city).

sources for water supply should be developed or the water intake from Chikugo river should be increased. Otherwise, the risk at the same water transfer ratio will become much higher than that in the present situation.

Limitations and Suggested Further Analysis

A few examples, based on an actual situation, have been presented to illustrate how reliability, resiliency, vulnerability and DRI measures may be used. Some significant and practical results have been obtained, which may be used for reference in the planning and operation of water supply. However, this prelim-

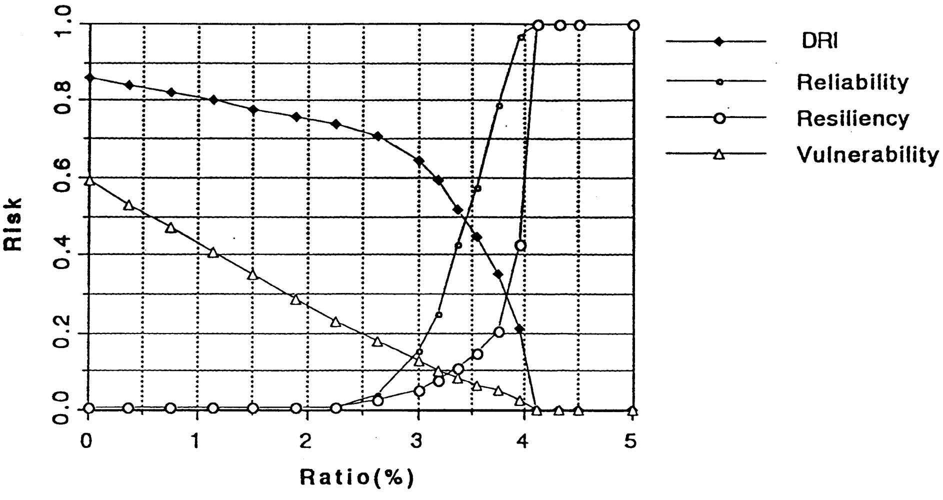

Figure 11. Risk curve for drought with RP = 20 (Dazaifu city).

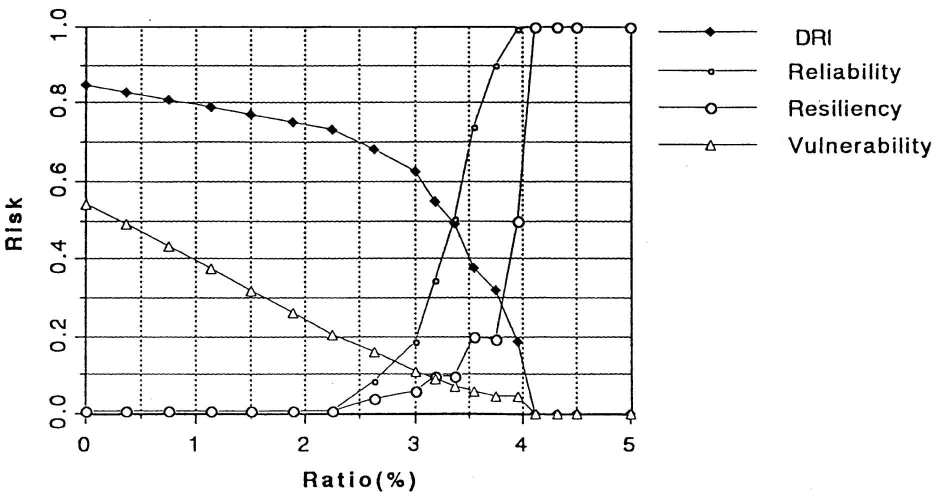

Figure 12. Risk curve for water supply on population increase.

inary study has several limitations and the model needs further improvement. In particular we would point out the following:

(1) In the above examples only two water supply subsystems are considered because of data limitations. With sufficient data collected, the risk of other subsystems may also be calculated and analysed. The risk measure is especially useful in situations where all the subsystems are considered and where the water transfer ratio varies widely among different alternatives.

(2) Up to now only the simulation model has been used to analyse the risk for a water supply system. As one objective of further studies the optimization model should be used for risk analysis to decide the optimal water transfer ratio for various cities and communities. Certainly also the various costs for different scenarios of water supply should be included in future studies.

(3) One of the most essential tasks in risk analysis is to identify and describe in appropriate ways those parameters (water transfer ratio, etc.) which characterize system control and give the best scenarios of water supply. For the water supply system considered here a water demand study should be carried out, taking the possible changes in future policies into full account. Water demand is as important as water supply when considering the risk for the entire system. In this respect, the present study is only a preliminary step.

Conclusions

We have suggested integrating the measures of reliability, resiliency, vulnerability and DRI in the planning and operation of a water supply system. Using a simulation model we have analysed these measures, revealing the relationships among them, by combining the actual data of water supply and demand. Our preliminary conclusions can be summarized as follows:

(1) The water supply system of the Fukuoka region is very vulnerable even if the amount of water taken from Chikugo river is much larger than previously.
(2) If the storage of the reservoirs in Fukuoka city is sufficient it is possible for other small cities and communities to share more water with Fukuoka city. However, if a drought with return period more than 10 years occurs in the Fukuoka catchment, the water in Fukuoka city is insufficient.
(3) In order to decrease the vulnerability, or increase the reliability, of water supply in the Fukuoka region, the development of new water resources is necessary, in particular sources with a stable flow or supply. Otherwise, if drought is prevalent not only in Fukuoka city but also in the neighbouring small cities and communities, the water supply situation in the Fukuoka region will become very threatened.
(4) In order to increase the robustness of the whole water supply system in the Fukuoka region, some of the small cities and communities should, if possible, have the right to take water from some reservoirs of Fukuoka city during any serious drought period. Certainly the reliability of the water supply in Fukuoka city should be higher than in the other small cities and communities because of its greater importance. However, the robustness of the whole water supply system should be improved permanently. These conclusions may serve as a reference for the practical planning and operation of the water supply system in the Fukuoka region.

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