A new planning method for selecting water supply alternatives in an urbanized watershed with a stochastic approach

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Abstract Water supply alternatives to alleviate water shortage damages in urbanized watersheds are itemized and evaluated in terms of cost, life cycle energy (LCE), and damages. A newly developed stochastic model of precipitation and constructed GIS databases are applied to estimation of potential water resources in the Hakata bay watershed in Japan. Based on these results, water supply alternatives in the watershed are selected at several return periods on less annual precipitation in the order of minimizing cost, LCE, and damages. The water supply alternatives selected are cascade reuse in house, groundwater, two kinds of recycled water, and desalinated water. The storage water volume in the reservoirs at initial time, annual precipitation, and annual precipitation patterns are considered as three factors on water shortage from the water supply side. The unit values of cost, LCE, and damages are obtained to estimate damages of water shortage and to consider measures for water supply by applying the above three factors. Finally, based on statistical distribution of damages on water shortage, a new planning method to avoid water shortage is developed and how to decide a design precipitation level is proposed in terms of the return period of damages instead of that of precipitation.

Keywords Cost; GIS; Hakata Bay; LCE; stochastic model; precipitation; water shortage damages

Introduction
It is of great importance to establish a methodology for selection of water supply alternatives to prevent water shortage in arid and semi-arid urbanized watersheds. Stochastic prediction of annual precipitation in terms of long term data, estimation of runoff and infiltration ratios as well as water consumption rates, itemization of water supply alternatives, evaluation of the alternatives based on indices socially demanded, and selection of appropriate alternatives for sufficient water supply are major elements of the methodology. Although plenty of research on stochastic characteristics of annual precipitation (Aramaki and Matsuo, 1998a; Shiraiwa et al., 1998), on runoff and infiltration rates of rainfall (Aramaki and Matsuo, 1998b; Dunn and Ferrier, 1999), on water consumption rates in urban areas (Wada et al., 1998), and on alternatives for compensation of water shortages (Stevens, 1998; Muraoka, 1999) has been done, integrated water supply management in urbanized watersheds has hardly been used for challenging water shortage. The indices to evaluate measures and to select alternatives to satisfy water demands are cost, life cycle energy (LCE), health risk, damage by water shortage, etc. The most popular index was cost. An index of loading to the environment such as LCE is, however, to be considered toward the global warming century. From the viewpoint of integrated management, a method to select water supply alternatives with GIS data as well as a stochastic approach is considered for an urbanized watershed in Japan.

The region of interest is the watershed of the semi-closed Hakata Bay in Kyushu, western Japan. Features of the watershed are such that its catchment area is 690 km², its population was about 1.7 million in 1998, its main enterprise is its commercial department,
and water quality of this bay is deteriorating because of eutrophication by nutrient loading from land (Fukuoka Prefecture Government, 1996). Characteristics of this watershed regarding water resources are as follows: average annual precipitation is 1,625 mm yr\(^{-1}\) and precipitation concentrates on rainy and typhoon seasons; a part of raw water for drinking water is conveyed from the outside of this watershed at a rate of 2.5 m\(^3\) sec\(^{-1}\) (about 33% of the total demand on this watershed); and less annual precipitation for this decade causes a water shortage by a ratio of once in two years.

**Method**

**Construction of GIS database**

The ground information system (GIS) is a powerful tool to scrutinize characteristics of a watershed (Maidment, 1993; Yoon, 1998). First of all, the boundary of the Hakata Bay watershed, shown in Figure 1, was drawn on maps with a scale of 1/2,500. Then, the watershed was sectioned into 63,444 pixels of a size of about 100 × 100 (m) grid using the axis code of the Japanese numeric information data on land. Altitude in each pixel was computed as the average of the four corner’s points in it. Population density is constructed considering land use and the administration district of each pixel. The land use data were constructed by using the same database. The kinds of constructed GIS data sets are precipitation, temperature, land use, locations of rivers and reservoirs, the amounts of water supply and wastewater, municipal reuses, wastewater reclamation and reuse, and contaminant loading.

**Water resources and alternatives**

Several alternatives to prevent from water shortage are considered as shown in Figure 2. The most reliable measure is reservoir construction. It is, however, restricted because of no large rivers and no appropriate places for reservoirs in this watershed; the integrated water supply management in this watershed is to be considered from both aspects, water supply including water reuse and water demand control. Figure 2 elucidates water supply, recycle, and reuse passes considered here.

Selection of water supply alternatives (water resources) depends on water quality in use in the watersheds. The alternatives in this watershed are cascade reuse, groundwater (shallow well pumping), two types of recycled water, and desalinated water. The highest in quality is drinking water and the lowest may be toilet flushing. There are several levels in between. As far as water quality meets the standards, the water is reusable more than once in a house.

![Figure 1 Location of Hakata Bay watershed](https://iwaponline.com/ws/article-pdf/3/3/271/407469/271.pdf)
Based on the ratio of water usage, a ratio of 66% of the daily water consumption in this watershed is as high as drinking water; the rest is acceptable in quality up to about 100 mg/l of BOD. The potential ratio of cascade water reuse is a ratio of 34% in house without any cost and LCE. It amounts to a ratio of 24.7% on the total water consumption because the ratio of the domestic water use is 73% of the total consumption in 1995.

There are three ways to recycle municipal wastewater; a large scale of reclamation in sewage treatment plants, regional reclamation and reuse in a district, and reclamation and reuse at individual buildings (Watanabe, 1994). The regional recycling and that in individual buildings are for such as office buildings, school buildings and public facilities. In considering the present situation, the potential amount of recycling water was shared between the large scale reclamation and the reclamation and reuse in individual buildings. They amounted to 6,100 and 4,900 m³ d⁻¹, respectively.

The potential abstraction rate of groundwater following nourishment was calculated. Because availability of groundwater without land subsidence is usually said to be several tenths of the infiltration rate, the possible abstraction rate of groundwater was set at half of the infiltration rate. Its use is restricted to lower quality demands. The maximum rate is 34% of the water demands as explained before. The rate of desalinated water supply was assumed to be 50,000 m³ d⁻¹ considering the current construction plan in the watershed.

**Prediction of water shortage with stochastic model of precipitation**

*Stochastic model of precipitation.* It is impossible to directly calculate the runoff rate in this watershed, because of few existing data on flowrates in rivers. Then, net runoff rates and inflow rates to the reservoirs were calculated by using a stochastic model of precipitation developed here. To construct the stochastic model of precipitation, annual precipitation pattern and long term (annual) and short term (5 days) changes were considered. Annual precipitation data for 107 years in the watershed were analyzed to make design precipitation patterns for several return periods by assuming a lognormal distribution. Because the auto correlation coefficient of annual precipitation for 107 years is less than 0.2, the annual precipitation of each year is considered to be independent and at random. The selected return periods of precipitation are the normal (2) year, 5-year, 10-year, 25-year, 50-year, 100-year,
and 100-year periods respectively. To calculate short term (5-day) precipitation, it is classified as 4 patterns by rainfall peaks. These annual precipitation patterns are characterized by a rainy season peak, heavy rain double peaks, a typhoon peak and no peak with drought, respectively. The stochastic probability of each pattern is as follows; rainy season (40.2%), heavy rain (32.7%), typhoon (9.2%) and drought (17.6%), and others. Figure 3 shows each pattern with 5-day precipitation. To calculate short-term (5-day) precipitation, its distribution is assumed exponential. From January 1 of a year 5-day precipitation was estimated stochastically on the basis of the distribution of 5-day precipitation for 107 years to determine a pattern of precipitation for a year.

Based on statistically simulated precipitation, 5-day precipitation through a year was obtained as follows; first of all, annual precipitation is calculated by the log-normal distribution. Next, an annual precipitation pattern is determined according to the above precipitation pattern distribution. Finally, 5-day precipitation under the determined annual precipitation was generated randomly by exponential distribution, and adjusted by summing up to meet with the annual precipitation.

**Calculation of water storage in the reservoirs.** Water stored in reservoirs is the major water resource in the watershed. The runoff rates were simulated with a four-layered tank model. The coefficients of the model were adjusted comparing observed data with simulated ones. The discharge in the most severe drought period is known to decrease by 50% of the normal one, so that the decrease in discharge is assumed to be of the same extent for simulation. The initial condition was set stochastically fluctuated to obtain long-term changes.

Inflow to the reservoirs overflows when the storage ratio is 100%. Simulation on a precipitation pattern in a return period, followed by simulation of runoff with the tank model and by estimation of the water storage ratio in the reservoirs was repeated 1,000 times and the outputs were treated stochastically. Figure 4 shows the relation of precipitation and runoff. In all return periods longer than 10 years, the water storage ratio becomes below 50% and this means a state of drought.

**Estimation of intake rate for water works at several return periods.** When water shortage begins, intake from the reservoirs curtailed almost in proportion to the period of suspension of water supply. The suspension begins at a ratio of 50% of water storage based on the current operation. At 6 hours’ suspension, the amount of water supply reduces to a level of 85% according to the past records. Here, 15% cut down of water supply at 40% of the water storage ratio, 20% cut down at 30%, and 25% cut down at 20% were assumed. The calculation procedure of water supply in water works during water shortage is as follows: first of
all, a daily water supply pattern on the basis of 5-year average was calculated. The water supply was divided into two kinds of intake; one from the reservoirs and the other from the rivers with similar intake patterns. The amount of decrease in daily water supply at a return period is estimated by subtracting the amount from the normal daily water supply. Demands of water supply alternatives were calculated in a similar way.

Estimation of LCE, cost and damages

Calculation of LCE and cost. LCE (kcal m\(^{-3}\)) and cost \((10^4\text{Yen m}^{-3})\) of water supply measures were estimated by the accumulated estimate method (Ikeda and Imura, 1993; Ishikawa, 1998). When this method was inapplicable, the input-output analysis was adopted as the alternative. LCE and cost of the waterworks and municipal sewage are estimated by summing them up based on their operation and construction cost data. Those of other measures to supply water were calculated in the same way (Ishikawa, 1998). The kinds of measures computed are regionally recycled water, recycled water in individual buildings, abstraction of groundwater, and desalinated water. Table 1 explains the LCE and cost for water supply measures.

The ascending order of LCE is abstraction of groundwater (shallow well pumping), sewerage treatment, waterworks, regionally recycled water, recycled water in individual buildings, and desalinated water. The order of cost is different from that of LCE. The ascending order of cost is shallow well pumping, waterworks, municipal sewage treatment, recycled water in individual buildings, desalinated water, and regionally recycled water. Why regionally recycled water is the most expensive is that it contains the cost of sewerage treatment. The LCE and cost in cascade reuse in a house are assumed to be equal to nought. Application of some alternatives is to the extent that the water shortage of water works is compensated.

Table 1 Unit values of LCE and cost

| Water supply               | LCE (kcal m\(^{-3}\)) | Operation (kcal m\(^{-3}\)) | Sum (kcal m\(^{-3}\)) | Cost Yen m\(^{-3}\) | Capacity
<table>
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<tr>
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<tbody>
<tr>
<td>Water works</td>
<td>1,407</td>
<td>1,299</td>
<td>2,706</td>
<td>219</td>
<td>5–10 (\times) (10^4) m(^3) d(^{-1})</td>
</tr>
<tr>
<td>Recycled wt (regional)</td>
<td>1,120</td>
<td>4,453</td>
<td>5,573</td>
<td>608</td>
<td>4,500 m(^3) d(^{-1})</td>
</tr>
<tr>
<td>Recycled wt (individual)</td>
<td>648</td>
<td>7,254</td>
<td>7,902</td>
<td>376</td>
<td>658 m(^3) d(^{-1})</td>
</tr>
<tr>
<td>Desalination</td>
<td>1,540</td>
<td>12,978</td>
<td>14,518</td>
<td>600</td>
<td>40,000 m(^3) d(^{-1})</td>
</tr>
<tr>
<td>Well pumping</td>
<td>96</td>
<td>511</td>
<td>607</td>
<td>22</td>
<td>48 m(^3) d(^{-1})</td>
</tr>
<tr>
<td>Sewage treatment</td>
<td>568</td>
<td>1,258</td>
<td>1,826</td>
<td>274</td>
<td>350,000 m(^3) d(^{-1})</td>
</tr>
</tbody>
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Figure 4 Precipitation and runoff
Calculation of water shortage damages. Water shortage damages are calculated through cutoff ratio (%) of water supply by the cost–effect estimation manual of the Japan Water Works Association. This estimation method is as follows: First of all, the types of water shortage damages are classified. These are domestic, industrial and commercial ones. Then, the total sum of the damages is calculated by multiplying each unit value of the damages by cutoff ratio (x %) and by the type of water shortage damages. This result is shown in Figure 5.

Results

Water supply alternatives and their evaluation

As shown partly in Figure 4, runoff rate, intake rate and water shortage were calculated by the time series of annual precipitations for 1000 years and by several return periods of precipitation for 1,000 times. The averaged result from the time series of annual precipitation is shown in Figure 6. Water shortage and damages are lessened by the input of water supply alternatives. They, however, remain even if all alternatives were introduced.

Although a figure is not shown here, water supply alternatives to compensate water shortage at several return periods were calculated, which were computed on the basis of LCE and cost minimum and damages. The longer the return period is, the more the compensated amount is needed.

Water shortage in the normal year is solved by cascade reuse and groundwater. Even at the 10-year return periods, some recycled waters and desalinated water are to be added. As a result, even if all alternatives are provided, water shortage might occur even at the 50-year return periods including a scale of 50,000 m³day⁻¹ of desalination. In spite of the difficulty of quantification of water saving, cascade reuse is the best alternative in both LCE and cost reduction.

As shown in Figure 7, although the longer the return period of precipitation is, the higher...
the water shortage damages; these values have stochastic distributions. From this point of view, damages are varied due to annual precipitation, precipitation pattern, and the initial storage ratio of the reservoirs. This means that the return period of precipitation is not only a factor for the measures of water shortage. It is shown that precipitation is not a preferable criteria for measures of water shortage damages. Thus new criteria are needed. We propose that some measures from water shortage probability instead of return period are useful for constructing new water shortage countermeasures. Figure 8 shows stochastic probability of the damages.

**Discussion**

Because the longer the return period on less precipitation is, the more often water shortage occurs easily, more alternatives are to be applied to compensate water shortage. Although cascade reuse definitely reduces LCE and cost for water supply, it is not a preference by residents in the normal year because it is a troublesome job. Lessening cost does not give any incentive for saving water even if it is one of the important alternatives against water shortage. This means that the ratio of the cost for water works to the total income is too low in Japan. Groundwater has a similar cost and LCE, the municipal governments, however, are reluctant to encourage the residents to use it, because water quality of groundwater in the watershed shows a worsening tendency. Wastewater in urbanized watersheds is thought to be useful as one of water resources. Currently the use of reclaimed wastewater is restricted to toilet flushing and car washing because of unwillingness to use it for other purposes by residents. That regional reclamation and reuse of wastewater in a district is higher in cost than desalination is a technical problem. Since desalination has been decreasing in cost and LCE, the improvement of this system is enough of a technical challenge to reduce LCE.
Finally, although the usage of desalinated water seems unavoidable in this watershed in the current situation, less energy-consuming measures are needed from the viewpoint of global warming and saving of fossil fuels.

The typical measurement for water shortage damages was based on the return period of precipitation. Because water shortage damages are not obtained directly in terms of the return period of precipitation as mentioned above, a newly proposed measure in terms of the stochastic distribution of the damages is preferred to alleviate water shortage damages (see Figure 9). Using this tool, we showed more accurate measures and predicted water shortage damages.

Conclusions
Water supply measures for alleviating water shortage in watersheds were evaluated in terms of LCE, cost, and damages. A stochastic model of precipitation was newly developed for estimation of short-term precipitation and a method to construct regional GIS databases was developed. Associated with these results, water supply alternatives at several return periods on less annual precipitation were selected on the basis of cost and LCE minimum in the Hakata Bay watershed in western Japan. The LCE on the basis of equivalent water supply to that of the normal year becomes minimum at the 10 year return period in the most appropriate combination of several water supply alternatives including cascade reuse in house and groundwater use, and the cost does at the 25 year return period. Cascade reuse reduces both LCE and cost for water supply, it, however, is not a preference by residents in the normal year. Because the ratio of the cost for waterworks to the total income is too low in Japan, low cost does not give any incentive for saving water. Finally it is proposed that measures on the basis of water shortage damages instead of return period of precipitation are a preferable criterion to reduce water shortage damages.

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References


