Desalination and Water Treatment
www.deswater.com

51 (2013) 19–25
January

1944-3994/1944-3986 © 2013 Desalination Publications. All rights reserved
doi: 10.1080/19443994.2012.714895

Optimum operation of desalination plant to minimize power consumption and water shortage risks in Okinawa, Japan

Takuya Ishida[a], Satoshi Takizawa[a,*], Naoko Watanabe[a], Michio Murakami[b], Hiroshi Sakai[a], Kumiko Oguma[a]

[a]*Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
Tel. +81 3 5841 6241; Fax: +81 3 5841 8532; email: takizawa@env.t.u-tokyo.ac.jp
[b]*"Wisdom of Water" (Suntory), Corporate Sponsored Research Program, Organization for Interdisciplinary Research Projects, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

Received 29 February 2012; Accepted 18 July 2012

ABSTRACT

Okinawa Island is located in the southern region of Japan and has a population of 1.22 million. Okinawa Prefectural Enterprise Bureau (OPEB) supplies 410,000 m^3/d of water to 24 municipalities. Although OPEB uses multiple water resources including dam reservoirs and groundwater, increased water demand resulted in occasional water shortages until a seawater desalination plant (40,000 m^3/d) started operations in 1997. In this study, a model was developed to simulate the water supply system of Okinawa Island using precipitation and OPEB operational data from 2009 to evaluate the role of the desalination plant in reducing risks associated with drought and power consumption of the plant. The simulation results indicate that without the desalination plant, the dam reservoir storage falls below 50% for 70 days, whereas with the desalination plant, storage remains above 50%. If the plant was operated at full capacity, the dam reservoir storage increased by 17.2% after 1 year of simulation time. However, the desalination plant consumes 4.5–14.7 times more electricity per unit volume of water than other water resources. Although the desalination plant plays an important role in avoiding water shortage in Okinawa Island, operational protocols to minimize power consumption need to be developed further using simulation models such as the one developed in this study.

Keywords: Desalination; Drought risk; Islands; Operation policy; Power consumption

1. Introduction

Because of the increasing water demand from population growth, securing safe drinking water has become a difficult task in many countries, especially in arid and semiarid regions and on small islands [1]. Seawater desalination is expected to be one of the solutions to worldwide water shortage and has been implemented in many countries. Seawater desalination has been used in arid countries as a major water resource, but a growing number of countries, including Australia and China, employ seawater desalination to augment other water resources. Although seawater desalination can be a reliable water resource, one of the drawbacks is the high energy cost. The reported electricity consumption of desalination plants is 4–7 kWh/m^3 of fresh water produced [2]. The state-of-the-art reverse osmosis processes were reported to

---

*Corresponding author.

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

be able to produce water at ca. 2.0 kWh/m^3 based on laboratory-scale experiments [3,4]. To mitigate the environmental impact of desalination, it was proposed to lower the energy consumption of desalination to 3.0 kWh/m^3 [5].

In cases where there are alternative water resources other than seawater, the evaluation of the reliability and the cost of the whole water supply systems, including all the water resources, is necessary to determine the effect of operating a desalination plant or to develop an optimum operational protocol. Merabtene et al. [6] assessed the drought risks of the municipal water supply system of Fukuoka City, Japan, which has a desalination plant. Jenkins et al. [7] evaluated the economy of California's water supply system to minimize the drought risks. Most of the previous researches focused on the reduction of drought risks, but the energy consumption of the water supply system was not fully considered in these studies. When desalination is integrated into other water resources such as surface and ground waters, it is necessary to take energy consumption of the total water supply systems into consideration in order to balance water supply stability and the carbon footprint of the water supply systems.

Okinawa Prefectural Enterprise Bureau (OPEB), which is a bulk supply company in Okinawa Island, Japan, had experienced serious water shortages and the prolonged supply outages. In 1997, a seawater desalination plant with a production capacity of 40,000 m^3/d started operation [8]. Since then, there have been no water supply outages. Due to the increased electricity consumption of the desalination plant, OPEB is facing the need to operate the total water supply system more efficiently, optimizing the costs, carbon footprint, and the stability of the water supply system.

In this study, the current operational method of the desalination plant by OPEB was evaluated in terms of the reduction of drought risk and the power consumption. A model was developed to simulate the OPEB water supply system from precipitation data, and the effectiveness of the desalination plant was assessed for different scenarios in terms of the stability of the water supply and the electricity consumption.

2. Water sources and water supply system in Okinawa Island

2.1. Water resources

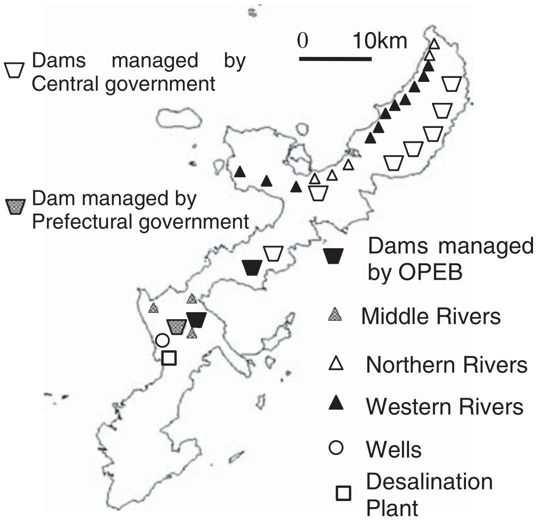


Fig. 1. Location of water resources (2010).

Okinawa Island is located in the southwestern region of Japan between the East China Sea and the Pacific Ocean. It has an area of 1,207 km^2 and a population of 1.22 million. Since the 1970s, water demand has increased considerably because of urban population growth and an increase in the number of tourists. To meet the increasing water demand, various water resources, including surface water and desalination, have been developed during the last few decades.

OPEB uses multiple water resources throughout the island (Fig. 1). There are four different kinds of water sources, they are: 10 reservoirs, 20 rivers, groundwater wells, and a seawater desalination plant. The reservoirs are located in mountainous northern and middle part of the island, but water demand is higher in the southern region where urban areas are concentrated. Therefore, a 40-km aqueduct was constructed to bring the water from the northern region to the south.

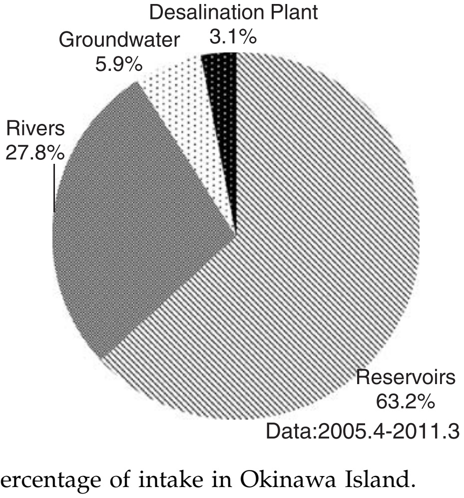


Fig. 2. Percentage of intake in Okinawa Island.

The percentages of water resources used between 2005 and 2011 are shown in Fig. 2. The dam reservoirs account for 63.2% of the total intake from all water resources, the rivers provide 27.8%, wells provide 5.9%, and the desalination plant provides 3.1% of the source water.

There are differences in the stabilities of various water resources. The dam reservoirs and rivers have a large available volume of water and account for the majority (91.0%) of the water resources. However, they are not stable resources because the availability depends on annual precipitation. The wells and the desalination plant are more stable than reservoirs and rivers, but they only account for less than 10%. Therefore, in Okinawa Island, it is necessary to combine stable and fluctuating water resources to meet the two goals: reduction of drought risk and minimization of electricity consumption.

2.2. Reservoirs

Among the 10 reservoirs being utilized for the water supply, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Government of Japan manages seven reservoirs located in the northeast region. The refectural government manages one of the 10 reservoirs (Kurashiki dam), which is located in the middle region. The OPEB manages two reservoirs with relatively small storage capacity. However, these reservoirs are very important because they are used exclusively for water supply and can be managed at OPEB's discretion.

2.3. Rivers

There are 20 small rivers that are used as water resources by OPEB. These rivers are categorized into three groups geographically and by the developed periods, namely: 12 western rivers, 5 northern rivers, and 3 middle rivers. The western rivers are relatively small and provide good water quality. The raw water taken from them is pumped to the Kurashiki Dam Reservoir. The northern rivers also have good water quality and most of the water taken from them is transmitted to the south-central area with the remaining fraction consumed in the northern area. The middle rivers are relatively large and thus, provide a steady raw water supply. However, the water in these rivers has high

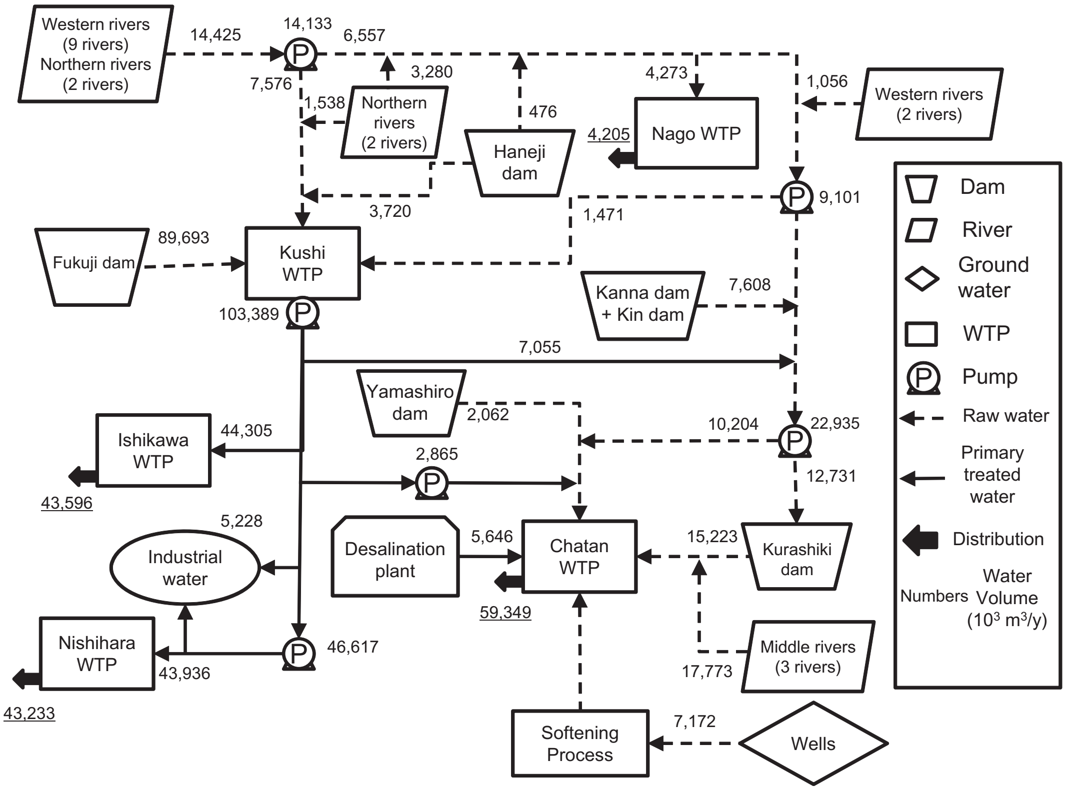


Fig. 3. Diagram of water flow from intake to distribution (Data in 2008).

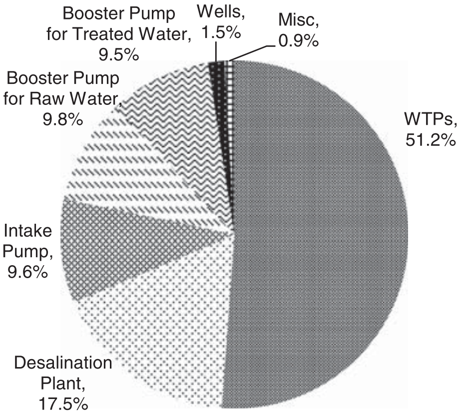


Fig. 4. Percentage of electricity consumption of OPEB (2008) [9].

hardness arising from the Ryukyu Limestone, which covers this area, and is also affected by urban activities.

2.4. Groundwater

The groundwater pumping wells are located in Kadena-Cho, which lies in the middle area of the island. This well water represents a stable source of water, but, similar to the middle rivers, the groundwater contains high hardness. Therefore, the water is pretreated to decrease hardness prior to it being supplied to the Chatan water treatment plant (WTP).

2.5. Seawater desalination

Although the seawater desalination plant has a total capacity of 40,000 m^3/d, it is operated at full capacity only when the water level in the reservoirs is less than a designated level. Regularly, the plant is operated at 5,000 m^3/d, one-eighths of the full capacity, to reduce costs and power consumption. The production of fresh water by the desalination plant is gradually increased as needed.

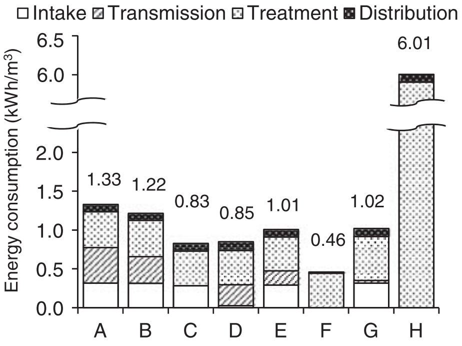
2.6. Water supply systems

Water supply in Okinawa is managed by OPEB. OPEB is a bulk supply company that takes raw water from the various resources mentioned above and treats and supplies the water to the 24 municipalities of Okinawa Island. Each municipality is responsible for supplying tap water to the customers.

The flow diagram of the water supply systems managed by OPEB is shown in Fig. 3. The numbers in Fig. 3 indicate the volumes of water ($10^3\ m^3/y$) transmitted or distributed in 2008. Surface water resources, including the northern and western rivers, and the Fukuji and Haneji Dams are transmitted to the Kushi WTP, where raw water undergoes primary treatment, i.e. chemical coagulation and gravity settling. The primary-treated water is further transmitted to Ishikawa, Nishihara, and Chatan WTPs, where the water undergoes further treatment. A small volume of surface water from the northern and the western rivers is transmitted to Nago WTP and then distributed to municipalities. Chatan WTP is the largest WTP in Okinawa Island and has multiple water treatment processes including an advanced treatment process of ozonation and granular activated carbon adsorption for surface water treatment, groundwater softening, and seawater desalination.

3. Estimation of electric power consumption by water supply

The power consumption in 2008 is shown in Fig. 4. WTPs accounted for more than a half of the total power consumption. This is because the reported power consumption by each WTP contains not only power consumption for water treatment, but also for distribution to the municipalities. The second largest power consuming facility is the desalination plant, followed by the intake pumps, and the transmission pumps. The desalination plant consumed approximately 3.0×10^7 kWh/year, which accounted for 17.5% of the total power consumption, whereas the desalinated water volume accounted only for 3.1% of the total water supply (Fig. 2). As a result, power consumption per unit volume of the desalination plant is much higher than other water sources. The intake and



ID	Water sources	ID	Water sources
A	Western rivers	E	Dams managed by OPEB
B	Northern rivers	F	Kurashiki dam
C	Middles rivers	G	Wells
D	Dams managed by central government	H	Desalination plant

Fig. 5. Electricity consumption of OPEB [10].

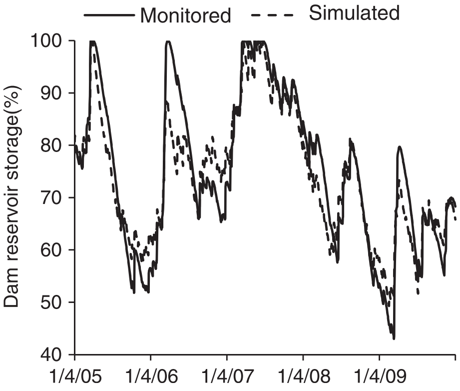


Fig. 6. Monitored and simulated data of dam storage.

transmission pumps, which transmit raw water over long distances, are also power consuming facilities, accounting for 19.3% of the total power consumption.

Based on the power consumption data and the water volumes are shown in Fig. 3, the power consumption per unit volume (1 m^3) of water produced from each water resource was calculated (Fig. 5). The variation between different water resources is high and ranges over two orders of magnitude. The unit power consumption by the desalination plant was by far the highest among all the water resources.

Comparison of the unit power consumption between different processes showed that the electricity consumption associated with water transmission is high. The western rivers, the northern rivers, the dams managed by Central Government, and the dams managed by OPEB are located far from the WTPs. These locations relative to the WTPs result in higher energy consumption per unit volume of water for transmission. The difference in the unit power consumption in water treatment processes was small for surface and ground waters because of electricity required for groundwater pumping and softening.

4. Simulation of desalination plant operation

4.1. Modeling the dam reservoirs

A model was developed to simulate the water flow diagram shown in Fig. 3. This model was used to evaluate the effectiveness of the seawater desalination plant in reducing the risk of a water shortage. The power consumption required to operate the desalination plant was estimated as well. The simulation model employs a tank-in-series model to predict the water stored in the reservoirs. The model parameters were estimated from a best fit to the dam storage data by the least-squares method (Fig. 6) using the rainfall data and the dam storage data from 1 April 2005 to 31 May 2010. The mean precipitation data of the Nago (26°-35.60´N, 127°-57.90´E) and Oku (26°-50.10´N, 128°-16.30´E) weather monitoring stations [11], located in the middle and in the north of Okinawa Island, were used in the simulation of the dams managed by the MLIT. The precipitation data of Yomitan (26°-24.31´N, 27°-44.50´E) were used in the simulations of the dams managed by the OPEB and the Kurashiki dam.

The monitored and simulated data of the total dam storage between 2005 and 2010 are shown in Fig. 6. The simulated storage of the total dam reservoirs is in good agreement with the monitored water storage in these reservoirs. A small difference between the simulated dam storage and the monitored data might arise from intense precipitation in some small, localized areas that is not reflected in the rainfall data of the monitored weather stations. However, because of the excellent qualitative agreement between the monitored and simulated results, these model parameters were deemed sufficient for use in our evaluation of the desalination plant.

4.2. Scenario-based simulation

In order to quantitatively estimate the reduction of the drought risk by the desalination plant, three scenarios for operation of the desalination plant were compared (Table 1).

Scenario Des09 is the water management scenario exactly the same as the operations by OPEB in 2009. Scenario NoDes simulates conditions when there was no desalination plant and the water volume that was produced by the desalination plant in 2009 is augmented from the dam reservoirs. Scenario FuDes assumes full-capacity operation of the desalination plant throughout the year to maximize the water storage in the dam reservoirs.

The data for water intake from rivers, groundwater wells, and dam reservoirs and the data for water production by the desalination plant and precipitation in 2009 were used as inputs to the simulation model

Table 1
Scenarios of desalination plant operation

Name	Scenarios
Des09	Following the existing data of the intake and desalinated water
NoDes	Assuming that there is not the desalination plant and complements the lack water with the water of the dam reservoirs
FuDes	Assuming that the desalination plant is operated at its full capacity to save the water of the dam reservoirs

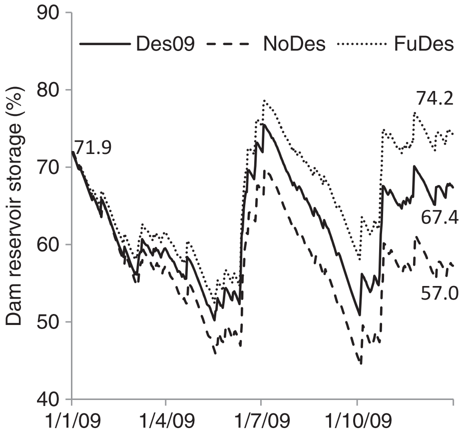


Fig. 7. Simulated dam storage under three scenarios.

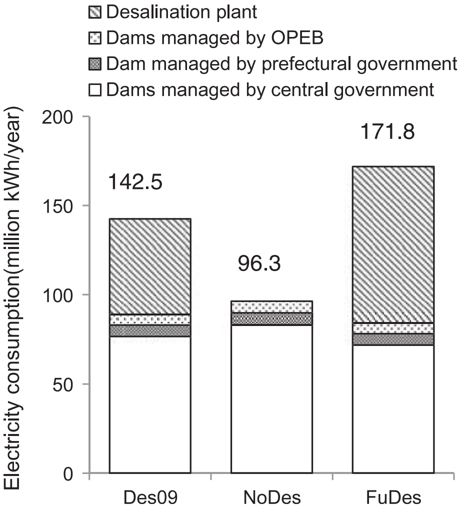


Fig. 8. Electricity consumption by scenarios.

under the three operational scenarios of the desalination plant. The 2009 data were selected because 2009 was the latest year with very small precipitation.

The simulated dam storage under the three scenarios is shown in Fig. 7. In Des09, though the dam storage in January was 71.9%, it ended the year in December at 67.4%. This simulation scenario predicted a decrease in the dam storage by 4.5% in 2009. In NoDes, the dam storage in December was only 57.0%. This result shows that the operation of the desalination plant in 2009 raised the dam storage in December by 10.4%. Finally, in FuDes, the dam storage increased to 74.2% in December. This increase represents a 2.3% rise from January and is 17.2% higher than that of NoDes (Fig. 7).

The OPEB operational rules require that, when the dam storage falls below 50%, water rationing is implemented. In the NoDes scenario, there would be 70 days of water rationing in 2009. In other words, the desalination plant was effective in avoiding 70 days of water rationing in 2009. The power consumption by each facility was estimated and compared for the three scenarios shown in Fig. 8. The difference between NoDes and FuDes was 75.5×10^6 kWh/year. The dam storage of FuDes at the end of December was 17.2% larger than that of NoDes (Fig. 7). Therefore, the desalination plant consumed 75.5×10^6 kWh/year to increase dam storage by 17.2%. The comparison between NoDes and Des09 shows that by consuming 46.2×10^6 kWh/y, the desalination operations reduced water rationing by 70 days and preserved the dam storage at the end of the year by 10.4%.

4.3. Drought risk reduction by the desalination plant

In order to estimate the effectiveness of the desalination plant operation in preventing water rationing, the annual precipitation necessary to maintain the dam storage level was calculated and plotted against the annual precipitation percentile (Fig. 9). The mean annual precipitation for the past 34 years from 1977 to 2010 at the Oku and Nago Weather Stations ranged between 1,500 and 4,000 mm. The model year, 2009, had the 10th smallest annual precipitation during this time period.

From the simulation result in the NoDes scenario, 2,099 mm of annual precipitation (shown as a dotted line in Fig. 9) is needed to maintain the dam storage level unchanged at the end of the year without operating the desalination plant. The simulation results show

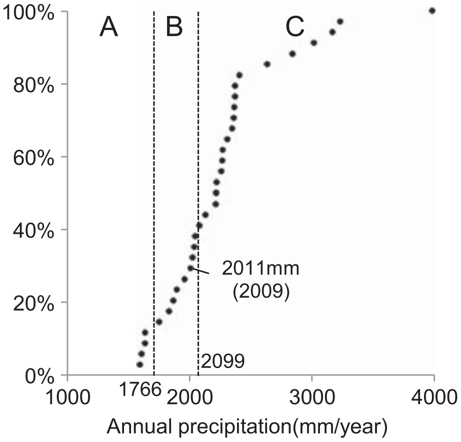


Fig. 9. Annual precipitation percentile (1977–2010) and the evaluation f desalination operation in maintaining dam storage. (A) The dam storage will decrease even with the desalination plant opening at the full capacity throughout the year. (B) Desalination operation is necessary to prevent a net loss in the dam storage. (C) Enough precipitation to maintain the dam storage with desalination operation.

that the dam storage level will not decrease without desalination for approximately 62% of the years. The FuDes scenario corresponds to 333 mm of annual precipitation, thus the minimum annual precipitation of 1,766 mm (= 2,099–333, also shown as a dotted line in Fig. 9) is necessary to prevent a net loss in the dam water storage with desalination. The operation of the desalination plant is necessary to maintain the dam storage level for 26% of the years when the annual precipitation falls between the two dotted lines. In approximately 12% of the years, the annual precipitation is below 1,766 mm. In these years, even with the desalination plant operating at the full capacity throughout the year, the dam storage level will decrease.

5. Conclusion

To estimate the effectiveness of the desalination plant in reducing the drought risk in OPEB, a simulation model to estimate the dam storage using the precipitation and water intake data as inputs was developed. The simulated dam storage was in good agreement with the monitored storage data. The developed model was used to estimate the dam storage in three different scenarios of desalination plant operation. The simulation result estimated that, in 2009, 70 days of water rationing was avoided by the operation of the desalination plant. The simulation result also showed that the desalination plant consumes 4.5–14.7 times more electricity per unit volume than other water resources. From the simulation, the actual electricity consumption in 2009 was calculated to be 142.5×10^6 kWh/year to maintain the dam storage level above 50% throughout the year.

In the case of OPEB, the simulation results suggest that the desalination plant is critical in maintaining a steady water supply. In only 62% of the years is there enough precipitation to maintain the dam storage levels without desalination. In 26% of the years, desalination is necessary to avoid the loss of the dam storage water level, and in 12% of the years, the precipitation is not enough to keep the dam storage level even with the desalination plant operating at the full capacity throughout the year.

The desalination plant is critical in meeting water demand, but supplemental in terms of the quantity of water produced in the OPEB water supply systems. The operation level depends on many factors including dam storage, seasons of the year, past precipitation history, and energy consumption. A simulation model of the water supply systems like the one developed in this study is an effective tool in balancing the stability of water supply and the energy consumption, especially when energy consuming desalination is used to augment other water resources with varying energy demand as in the case of OPEB.

Acknowledgments

This research was supported by the Environment Research and Technology Development Fund (S-8) of the Ministry of the Environment, Japan and Grant-in-Aid for Scientific Research (#22404012) by JSPS. The authors appreciate the staff of Okinawa Prefectural Enterprise Bureau for providing valuable assistance to make this research possible.

Reference

[1] IPCC, IPCC 4th Assessment Report, Climate Change 2007, "Summary for Policymakers", 2007.
[2] K. Wangnisk, IDA Worldwide Desalting Plants Inventory Report No.18, Wangnick Consulting GmbH, 27442 Gnarrenburg, Germany, 2004.
[3] M. Busch, W. Mickols, Reducing energy consumption in seawater desalination, Desalination 165 (2004) 299–312.
[4] J. Macharg, T. Seacord, B. Sessions, ADC baseline tests reveal trends in membrane performance, Desalin. Water Reuse (Faversham House Group, South Croydon, Survey, UK) 19 (2008) 30–39.
[5] G. Meerganz von Medeazza, Direct and socially-induced environmental impacts of desalination, Desalination 185 (2005) 57–70.
[6] T. Merabtene, A. Kawamura, K. Jinno, J. Olsson, Risk assessment for optimal drought management of an integrated water resources system using a genetic algorithm, Hydrol. Process. 16(11) (2002) 2189–2208.
[7] M.W. Jenkins, J.R. Lund, R.E. Howitt, A.J. Draper, S.M. Msangi, S.K. Tanaka, R.S. Ritzema, G.F. Marques, Optimization of California's water supply system: Results and insights, Water Resour. Plan. Manage. 130(4) (2004) 271–280.
[8] Okinawa Prefectural Enterprise Bureau, Water in Okinawa Island (in Japanese), 2008.
[9] Okinawa Prefectural Enterprise Bureau, Data book on water intake and water supply volume (in Japanese), 2005–2009.
[10] Okinawa Prefectural Enterprise Bureau, Annual Report of Water Utility Management (in Japanese), 2009.
[11] Japan Meteorological Agency, Ministry of Land, Infrastructure, Transport and Tourism, Statistical Report of Meteorology (in Japanese), 1977–2010.