Efficiency Assessment of Renewing Aging Water Supply Pipelines from the Viewpoint of Demographic Changes: A Case Study of Water Supply Service in Kashiwa City

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Abstract: Against the background of an aging society in Japan, the higher maintenance and replacement costs of an aging infrastructure pose big challenges to the whole society, especially as Japan has experienced population decline since 2010. These demographic changes are expected to affect society in many ways including labor market decline, increased tax burdens, and economic stagnation. In this paper, we use a model that combines the aging situation of water supply pipelines and the Efficiency rate which ensures more citizens can use newer pipelines, this study focuses on the policy implications for setting priorities for water supply pipeline renewal, and suggests that increasing attention should be paid to how to make the most efficient use of public resources for newly built pipelines while facing the inevitable issue of spatial disparity.

Key words: aging water supply pipelines, depopulation, efficiency assessment, community disparities

1. INTRODUCTION

The aging of society has become a social issue nationwide in Japan, as both the population and public social infrastructure shrink. The peak of social infrastructure investment in Japan was in the 1950s. Much of that infrastructure is still in active service, far beyond its original intended life span. At the same time, Japan has experienced a population decline since 2010 and the situation is expected to become more severe after 2030, with forecasts indicating an expected 30% decline from 2005 to 2055. These demographic changes are expected to affect society in many ways including labor market decline, increased tax burdens, and economic stagnation. How to balance the population decline with the need to fund infrastructure maintenance and renewal poses a challenge to the whole society.

In the context of increasing replacement costs of water supply systems and decreasing population in Japan, prioritizing the order of water supply pipeline renewal is required. This study aims to provide the policy implications of using population information in establishing water supply pipeline renewal priorities in Japan.

2. METHODOLOGY AND STUDY AREA

2.1 Study area

Kashiwa is a city located in northwestern Chiba Prefecture, Japan. As of December 1, 2015, the city had an estimated population of 411,602 and a population density of 3,590 persons per square km.

The installation of the modern public water supply in Kashiwa began in the 1950s, and those pipelines now need renewal. There is currently significant discussion on how to schedule the renewal of aging water supply pipelines in Kashiwa, and also on planning the maintenance of relatively new pipelines in advance.

2.2 Pipe aging rates

In this work, we mainly discuss how population change in one city may influence the decision-making process about which area's pipelines should be given comparatively higher priority for renewal. Hence, we simplified the model for calculating a pipe's aging rate, an index to describe the aging extent of a pipe, to include only the material, construction year, and current age.

We defined aging rate by the following formula:

$$r_i = \frac{(T - T_i)}{M_i}$$

Where r_i represents the aging rate of pipe i, T is the current year, T_i is the year in which pipe i was installed, and M_i is the expected lifespan of pipe i.

According to the newest Kashiwa Water Supply Vision (2016), the annual pipeline replacement plan is 15 kilometers per year from 2016 to 2036, 17 kilometers per year from 2036 to 2066. We take this plan as the replacement standard and decide the replacement priority based on the aging rate index simulate pipeline's aging situation in the future.

2.3 Pipeline catchment areas

To calculate the population served by each pipeline, the catchment areas of each pipeline were calculated. We considered the whole water supply network as an alongside-network and used the concept of a Network Voronoi diagram (N-VD) (Okabe et al., 2000, Section 3.9) to determine the catchment areas.

The analysis was based on the basic principles of Voronoi diagram and used the method of N-VD to calculate the catchment area of each pipe with the Grass geographic information system (GIS).

2.4 Pipe efficiency rates

As mentioned above, absolutely correct prediction of the impact of population decline on the replacement priority of water supply pipelines was difficult. However, in order to create the foundation for this research, in this section we describe how we combined pipeline aging rates with population changes in Kashiwa to demonstrate how population changes have impacts on the replacement priority of water supply pipelines.

Based on the method referenced in 2.3, the catchment area of each pipe was determined. We defined a pipe's efficiency rate, an index to describe how much the priority given to the renewal of a pipe is influenced by the population change in an area, by the following formula:

$$\mathrm{e_i} = \frac{(T - T_i)}{M_i} \log(a_i \times d_i)$$

Where e_i represents pipe i's Efficiency rate, a_i is the catchment area of pipe i, and d_i is population density of pipe i's catchment area

Results of e_i indicate pipeline's efficiency rate; where the number is higher, the pipeline efficiency is higher. In this study, to show the community disparities on a map, we took an efficiency rate value of 1.5 as a threshold to show how many pipelines are in need of renewal in every community. Using this formula, the effects of communities' disparities caused by population changes were obtained. By comparing the results calculated by the methodology in section 2.2, the influence of population changes on the priority of water supply renewal plans will be discussed.

3. RESULTS

a) Estimated pipeline situations from 2016 to 2066

As described in the methodology section 2.2, based on the renewal standards for water supply pipelines, we estimated pipeline physical situations in the future. To illustrate the overall estimated results, GIS maps of the pipelines are used to demonstrate how the pipeline situation changes in the next 50 years from 2016 to 2066.

The distribution of water supply pipelines in Kashiwa and their aging rates in 2016 and 2066 are shown in Figure 1 and Figure 2, respectively. Numbers in each figure legend indicate the aging rates of pipelines, where 0.0–0.5 represents a pipe that has been in use in less than half of its standard durable years, 0.5–1.0 represents a pipe that has been in use for more than half of its standard durable years, and a number of 1.0 or greater represents a pipe that has been in use for a period that exceeds its standard durable years and is in need of replacement.

These results indicate that the pipeline situation will be getting worse each year even conducted the plan made by the water supply department. The current (2016) proportion of pipelines with an aging rate exceeding 1 is 3.2%. This proportion is estimated to increase to 5% in 2026, 7% in 2036, 10% in 2046, 13% in 2056, and 21% in 2066. Especially in the 10 years from 2056 to 2066, the aging rate of pipelines increases sharply to 21% (15,955 of the total of 75,943 pipelines). This indicates that in the 2050s, a tremendous number of pipelines will be in need of intensive renewal.

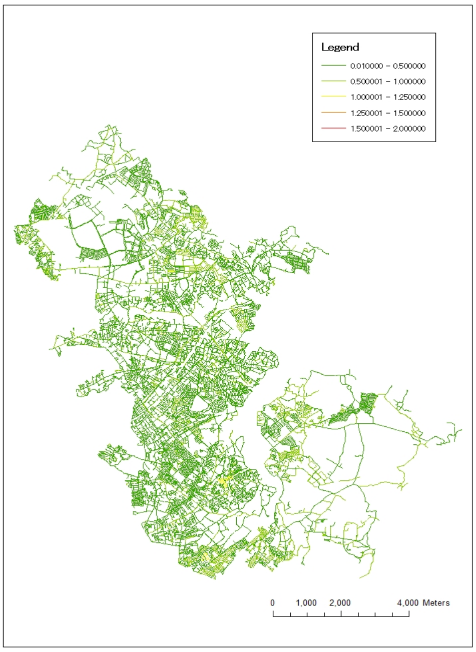

Figure 1 Projected Aging rate of water supply pipelines of Kashiwa City in 2016

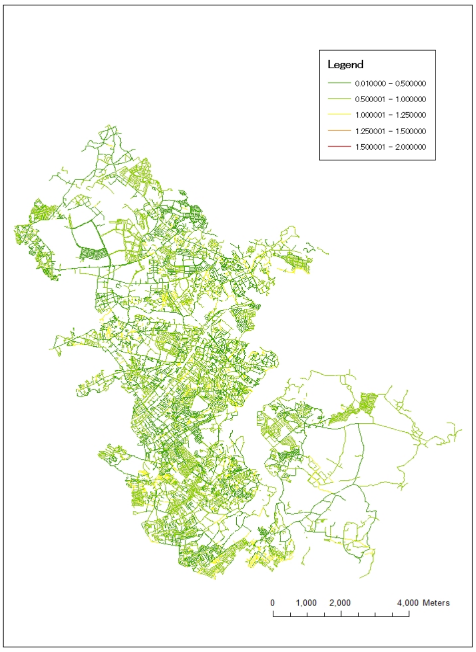

Figure 2 Projected Aging rates of Kashiwa City water supply pipelines in 2066

b) Pipeline efficiency rates

According to the city government's estimation, the current population of Kashiwa (410,000 in 2015) is expected to keep increasing to a peak of 426,000 around 2020. After that, the population is forecast to decline to 403,000 around 2050 and to 298,000 by 2100, which means 30% of the current population will be lost within 90 years.

At the same time, according the newest Population Prediction in Kashiwa City (2015), at the community level, population changes present different trends and may not be limited to decreases. Several communities in Kashiwa, for example, may experience population increases, influenced by the urban development plan of the city.

This result shows that, although the population of Kashiwa as a whole is predicted to decline in the future, the populations in each community in Kashiwa show various characteristics, which should be taken into consideration in planning the water pipeline replacement schedule.

The distribution of water supply pipelines in Kashiwa and their efficiency rates in 2016 and 2066 are shown in Figure 3 and Figure 4, respectively. From the results, it can be concluded that the priority for renewing pipelines calculated by efficiency rate is different from the priority based on the calculation of aging rate. In the calculation of aging rate, the renewal priority is decided by the physical condition of the pipelines. However, when combined with population information to provide the efficiency rate, we found that in some areas where the population is predicted to increase sharply in the future, pipelines that are not the oldest show a greater increase in efficiency rate and show a higher priority for renewal than some older pipelines in other areas.

As a brief summary, the results make it apparent that situations vary across the 20 communities. In future water management planning, those disparities should be considered by every community to make the best effort to ensure more people are using newer water supply pipelines.

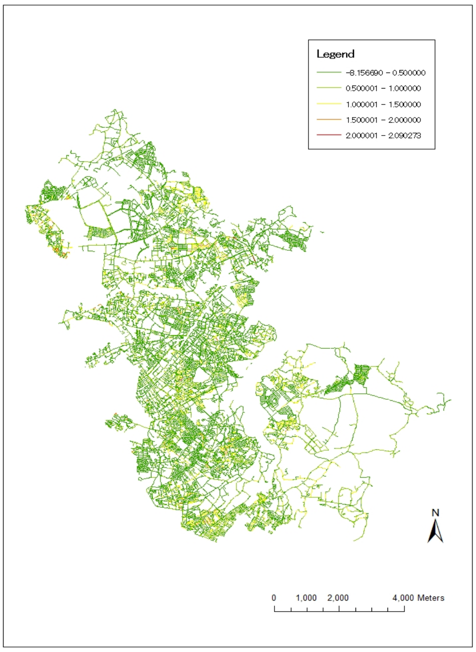

Figure 3 Projected Efficiency rates of Kashiwa City water supply pipelines in 2016

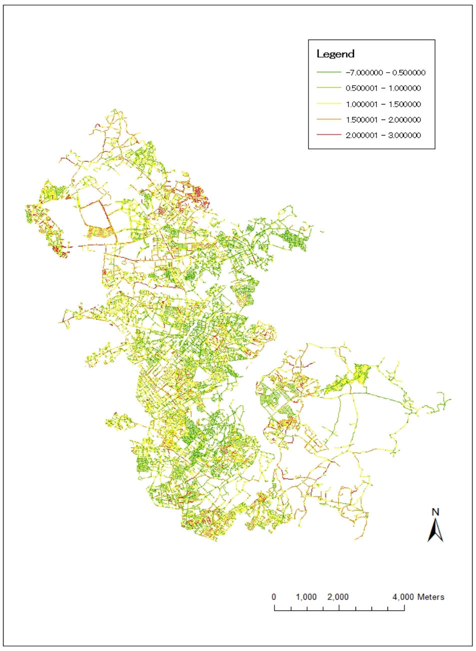

Figure 4 Efficiency rate of water supply pipelines of Kashiwa City in 2066

4. DISCUSSION

To demonstrate the results more explicitly, we take area A, located in Tanaka Community, as a case study to explain how population changes will influence renewal priorities.

The population in area A is expected to keep increasing over the next 50 years. According to the results obtained from 3.1, aging pipelines in area A will be due to be renewed around 2026, as shown in Figure 5 (1). However, as Figure 5 (2) shows, the highest efficiency rate of pipelines in area A will occur around 2056. By taking the aging rate in area A into consideration as Figure 5 (3) shows, even without replacement, the aging rate of pipelines in area A just exceed 1.0, in this sense we suggest that a more appropriate renewal period for pipelines in this area would be around 2046, when more of the population can use the newer pipelines.

As the main conclusion of this study, we point out that because demographic changes have significant impacts on water supply systems and infrastructure, and with the depopulation of Japan in mind, increased attention should be given to how to make the most efficient use of resources for newly built pipelines, while facing the inevitable issue of spatial disparity.

Numerous questions still remain to be answered regarding the impacts of a shrinking population. For example, with respect to changing demand and use, do elderly people need more or less water on average? What will the structure of water demand and use in the future look like? Further research will be conducted to answer these and other questions, thus giving more practical implications to water utilities.

ACKNOWLEDGMENT

We thank the Kashiwa Water Supply Department for many useful comments and for providing the use of the database of water supply pipelines.

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(Received October 28, 2016)

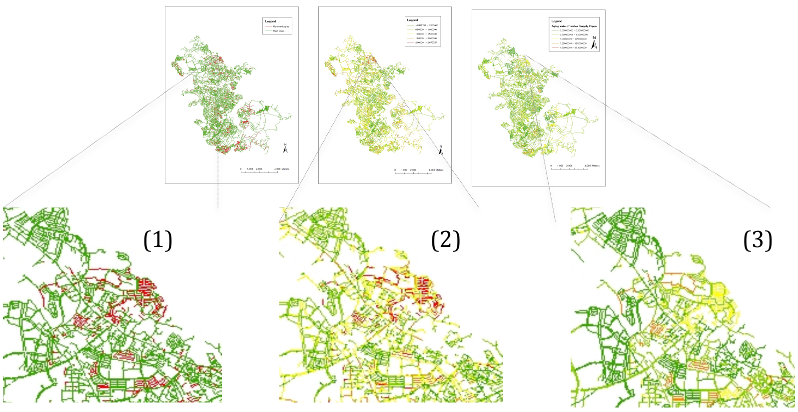

Figure 5 (1) Pipelines renewed around 2026. (2) Pipelines' efficiency rate in 2056. (3) Pipelines' aging rate in 2046.