Report cards for aging and maintenance assessment of water-supply infrastructure

Hiroshi Sakai, Mei Satake, Yasuhiro Arai and Satoshi Takizawa

ABSTRACT

During past periods of rapid economic growth, infrastructure development in Japan was intense. This infrastructure now requires both renovation and replacement. Appropriate management of infrastructure is critical as the population falls, budgets become reduced, and staff numbers dwindle. The Japan Society of Civil Engineers evaluates infrastructure soundness and publishes the results to promote understanding of the current situation and to emphasize the importance of maintenance. We devised indices for evaluating deterioration of drinking-water distribution pipelines and maintenance management systems for the pipelines. The indices are the percentage of old pipelines, the percentage of ineffective water, change in the number of technical staff per unit length of pipe, and the repair rate of water leaks. Using these indices, the evaluation result for Japan overall was a C (Caution) in terms of deterioration and Downward in terms of maintenance management.

Key words | asset management, maintenance, pipe renewal

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INTRODUCTION

During past periods of rapid economic growth, infrastructure development in Japan was intense. This infrastructure now requires both renovation and replacement. Obviously, infrastructure quality greatly affects daily life; when infrastructure ages, the risk of accidents increases, which has an enormous impact on daily life and many long-term economic activities. Appropriate infrastructure management is critical as the population falls, budgets are reduced, and the number of technical staff dwindles. Thus, the Japan Society of Civil Engineers evaluated infrastructure soundness and published the results in 2018. Similar efforts have been made in the United States (National Council on Public Works Improvement (US) 1988; American Society of Civil Engineers 2017), the United Kingdom (Institute of Civil Engineers 2014), Australia (Engineers Australia 2010), and South Africa (South African Institution of Civil Engineering 2017); these evaluations, published as infrastructure report cards, inform policy on infrastructure development. In the United States, evaluations have been performed periodically since 1988 (National Council on Public Works Improvement (US) 1988), covering 16 categories (Aviation, Bridges, Dams, Drinking water, Energy, Hazardous waste, Inland waterways, Levees, Ports, Public parks, Rail, Roads, Schools, Solid waste, Transit systems, and Wastewater). The evaluation items include Capacity, Condition, Funding, Future needs, Operation and maintenance, Public safety, Resilience, and Innovation.

Japanese report cards have focused on infrastructure soundness, based on statistics and published reports. Using these data, the Japan Society of Civil Engineers (2018) devised indices evaluating deterioration and maintenance management systems. The reports were published by sector (such as roads, rivers, and wastewater); a draft report on the drinking-water sector had been planned for 2019. In the financial year (FY) 2020, a general report will be published, evaluating various types of infrastructure. The current status of the drinking-water sector has attracted much attention recently.

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A new water-supply vision was formulated in 2013 by the Ministry of Health, Labour and Welfare (2013), and water-supply laws were amended in 2018 (Umeda 2018). Certain tools for evaluating the drinking-water sector are already available; these include performance indicators (guidelines) for water utilities (Japan Water Works Association 2016), the Replacement Criteria for Waterworks Facilities (Japan Water Works Association 2005), a business-focused analysis of municipal utilities conducted by the Ministry of Internal Affairs and Communications (2017), and a cost-effectiveness analysis performed by the Ministry of Health, Labour and Welfare (2011). Although several evaluations using these tools have appeared (Koizumi *et al.* 2006; Ishii *et al.* 2008; Inakazu *et al.* 2012, 2017; Nishimura *et al.* 2017), no report has comprehensively examined the deterioration of, and maintenance management systems for, drinking-water pipelines in the context of infrastructure aging.

Therefore, we attempted to devise appropriate indices when preparing the 2019 draft Infrastructure Report Card on drinking water. Multiple indices were formulated that can be calculated using water-supply statistics; these were then used to evaluate water utilities.

MATERIALS AND METHODS

Waterworks' infrastructure includes pipelines, treatment plants, and pumping stations. As treatment plants and pumping stations include electrical and mechanical equipment, they were not evaluated in this study. Of the various pipelines, we evaluated only distribution pipelines; raw water pipes, transmission pipes, and service pipes were not included. Bulk water-supply systems were also excluded because they generally lack distribution pipes. As for other sectors, we evaluated deterioration and maintenance management systems (Table 1). Deterioration was graded from A to E. Maintenance management systems were graded as Upward, Flat, or Downward. Upward, Flat, or Downward means the current state of deterioration will improve, will not change, or worsen, respectively, when current maintenance management system continues. We developed multiple indices of deterioration and maintenance management systems and weighted them equally when making overall evaluations. Deterioration was scored as A (≥80), B (≥60), C (≥40), D (≥20), or E (<20). After evaluating the deterioration of all water utilities, overall evaluations were performed for various supply categories, and for Japan overall. The average values of all indices in specific categories were used for the analysis. We established five categories of water-supply sizes based on population served: (i) ≥600,000 (Tokyo and ordinance-designated cities), (ii) 100,000–600,000, (iii) 30,000–100,000, (iv) 10,000–30,000, and (v) <10,000. Overall maintenance management system indices were calculated based on Equation (1); if the value was $\geq +0.1$ or higher, the result was classified as Upward, versus Flat for -0.1 to $+0.1$, and Downward for < -0.1:

$$\frac{\text{No. of Upward utilities} \times 1 + \text{No. of Flat utilities} \times 0 + \text{No. of Downward utilities} \times -1}{\text{Total No. of utilities}} \quad (1)$$

Table 1 | Definitions of deterioration and maintenance management systems

Deterioration condition

A (Sound)	B (Satisfactory)	C (Caution)	D (Warning)	E (Critical)
Deterioration has not occurred in most water utilities	Deterioration has occurred at some water utilities	Deterioration has occurred at moderate numbers of water utilities	Deterioration has occurred in many facilities and repairs/reinforcement are needed	Deterioration is severe, and needs urgent countermeasures

Maintenance management system

Upward	Flat	Downward
If current maintenance management system continues, current state of deterioration will improve	If current maintenance management system continues, current state of deterioration will not change	Unless current maintenance management system is not improved, deterioration will worsen

All indices were calculated using the latest statistical data on water supplies. The number of water utilities recognized in FY 2015 (Japan Water Works Association 2017) was 1,381. Data from FYs 2010–2014 (Japan Water Works Association 2012–2016) were also used to calculate the average of the past three years, or the difference from five years before. When two utilities merged during the evaluation period, each index value was calculated based on the features of the utility in FY 2015. All the statistical data used in this study were obtained from Statistics on Water Supply, which is published by Japan Water Works Association based on annually collected data from all water supply utilities in Japan.

RESULTS AND DISCUSSION

The indices

Indices of deterioration and maintenance management systems were selected from candidate lists. Generally, pipe deterioration results in leakage, poorer water quality, and periods of no supply. An index of the proportion of water wasted was devised to cover these parameters; the data were readily available, reliable, and easy to interpret. The fundamental cause of pipe deterioration is aging. Therefore, pipeline age was used as another index of deterioration.

For maintenance management systems, we considered various resources including people, goods and services, and money. Of these, the number of technical staff and the leakage repair rate were included as indices due to the data availability and reliability, and ease of interpretation.

Pipeline age

Possible indices of deterioration were sought among water-supply statistics. As drinking-water pipelines are buried, visible inspection of the outer surface is difficult and expensive, unlike with bridges or roads. Moreover, drinking-water pipelines are pressurized to distribute water of appropriate quality to all households. Therefore, pipelines are always filled with purified water, rendering it near-impossible to inspect the inner surfaces with low cost at whole nation level. Thus, as neither the inner nor outer surfaces of pipes can easily be evaluated, we took the length of pipe above the statutory useful life (40 years) as an index of deterioration, calculated for each utility as follows:

$$\text{Percentage of old pipeline (\%)} = \frac{\text{Length of pipe aged over 40 years (m)}}{\text{Total length of distribution pipe (m)}} \quad (2)$$

We have employed this index due to data availability. Actual useful life will be different for pipe material and diameter; however, the Japanese accounting system employs the same statutory useful life for all pipe materials and diameters. Furthermore, statistical data are available only for the total length of aged pipes, and breakdown data for materials and diameters are not available.

We scored each utility based on Table 2. The histograms in Figure 1 show the results for each population category. In FY 2015, the average value for all utilities was 10.85; values tended to be higher for large utilities and lower for small utilities, as in Table 3. The average value for utilities supplying populations <10,000 was 9.09% versus 17.41% for utilities supplying populations ≥600,000. For utilities supplying populations <30,000, the dominant class was 0–1.5%; for utilities supplying populations ≥30,000, it was 10.0–30.0%.

In addition, a relationship was evident between the population supplied and the commencement of water supply. Many large utilities are old, while many small utilities are relatively new. Pipeline age reflects the date of water-supply commencement.

Table 2 | Scoring of deterioration

Score	Percentage of old pipeline (%)	Percentage of ineffective water (%)
10	<0.5	<1.5
9	0.5–1.0	1.5–3.0
8	1.0–1.5	3.0–5.0
7	1.5–2.0	5.0–7.5
6	2.0–2.5	7.5–10.0
5	2.5–5.0	10.0–12.5
4	5.0–10.0	12.5–15.0
3	10.0–20.0	15.0–20.0
2	20.0–30.0	20.0–30.0
1	30.0–50.0	30.0–50.0
0	≥50.0	≥50.0

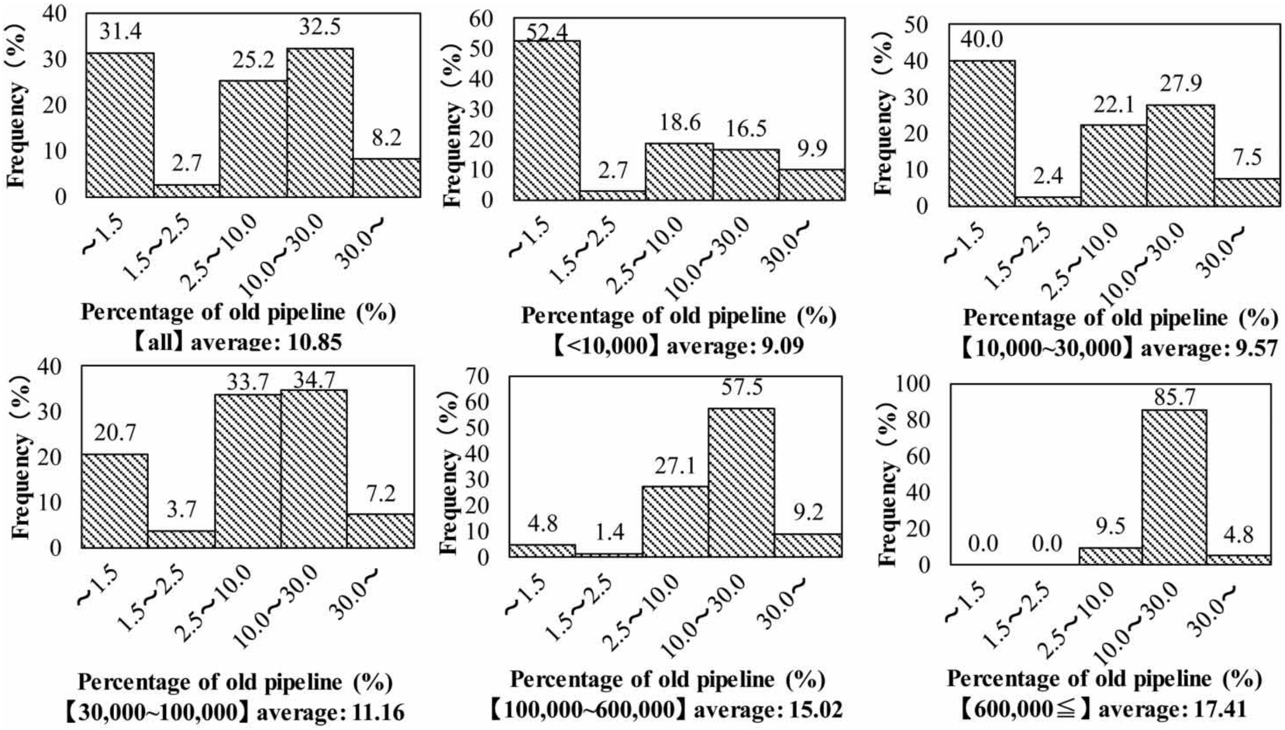

Figure 1 | Histograms showing the percentage of old pipeline.

Table 3 | Evaluation of deterioration

	Percentage of old pipeline		Percentage of ineffective water		State of deterioration	
Population supplied	**(%)**	**(Out of 10 points)**	**(%)**	**(Out of 10 points)**	**(Out of 100 points)**	**Evaluation**
≥600,000	17.41	3	4.94	8	55	C
100,000–600,000	15.02	3	6.78	7	50	C
30,000–100,000	11.16	3	10.04	5	40	C
10,000–30,000	9.57	4	13.80	4	40	C
<10,000	9.09	4	16.64	3	35	D
All	10.85	3	12.22	5	40	C

Ineffective water

Water leakage is a typical pipeline failure; the risk increases with pipeline deterioration. Therefore, we used leakage as an index of deterioration. Water-supply statistics list 'ineffective water' and 'leaked water'. Ineffective water is a unique term in Japanese Statistics on Water Supply (Japan Water Works Association 2002). It defines the non-chargeable water, consisting of unbilled metered consumption and real losses in the IWA definition in Table 4 (Lambert & Hirner 2000). Unbilled metered consumption is defined as 'deduced consumption by settlement' by Japan Water Works Association (2002). Although ineffective water is different from the concept of non-revenue water, we employed this indicator because it has been used in Japan for a long time. Another reason is that ineffective water will be closer to real losses than non-revenue water, if we assume unbilled metered consumption is negligible. 'Leaked water' accounts only for water wasted prior to repair, and not for undetected (and thus unknown) leakage;

Table 4 | IWA best practice water balance and performance indicator (originally published in Lambert & Hirner 2000)

System input volume	Authorized consumption	Billed authorized consumption	Billed metered consumption Billed unmetered consumption	Revenue water
		Unbilled authorized consumption	Unbilled metered consumption Unbilled unmetered consumption	Non-revenue water
	Water losses	Apparent losses	Unauthorized consumption Customer metering inaccuracies	
		Real losses	Leakage on transmission and/or distribution mains Leakage and overflows at storage tanks Leakage on service connections up to point of customer metering	

leaked water may not reflect real leakage volume. In total, 229 of 1,381 water utilities reported leaked water as 0 (or blank) in FY 2015. Therefore, we used the ineffective water volume as an indicator rather than leaked water. The ineffective water percentage was calculated using Equation (3):

$$\text{Percentage of ineffective water (\%)} = \frac{\text{Amount of ineffective water } (10^3\text{m}^3)}{\text{Amount of water supply } (10^3\text{m}^3)} \quad (3)$$

We scored each utility based on Table 2. Histograms are shown in Figure 2. For the FY 2015 data, the average percentage for all water utilities was 12.22%. For some utilities, the percentage exceeded 40%; most were assumed to supply resorts or vacation homes (Nishimura *et al.* 2017). For utilities supplying populations ≥600,000, the average percentage was relatively small (4.94%). For utilities supplying populations <10,000, the percentage was 16.64%, i.e., approximately three-fold greater than the 4.94% mentioned above. The ineffective water percentage was lower for large utilities, and higher for small utilities, presumably reflecting the maintenance management systems; large-scale utilities can afford to take measures to reduce the ineffective water percentage.

Rate of change in the numbers of technical staff per unit length of pipeline

Next, we developed indices for maintenance management systems. The number of technical staff per unit length of pipe was selected as a human resource index; other possible indices could explore goods and services, or money. Equation (4.1) was used to calculate the staff index:

$$\text{Number of technical staff}/10^3\text{ km of pipeline} = \frac{\text{Number of technical staff in the utility (people)}}{\text{Total length of distribution pipe } (10^3\text{ km})} \quad (4.1)$$

'Technical staff' included engineers, mechanics, staff on consignment to a third party, and staff on consignment to an entity other than a third party. The rate of change in staff numbers was calculated using Equation (4.2), because it is difficult to evaluate the absolute value of Equation (4.1):

$$\begin{aligned}&\text{Rate of change in the number of technical staff per unit length of pipeline (\%)}\\ &= \frac{\text{Unit number of technical staff } \left(\frac{\text{people}}{(10^3\text{ km})\text{ in}}\text{ year X}\right)}{\text{Unit number of technical staff (people}/10^3\text{ km) in year (X} - 5)}\end{aligned} \quad (4.2)$$

During calculation of Equation (4.2), the following rules were applied to handle instances of 0 and 100%:

i. If both the denominator and numerator are zero, the index value is 0%.
ii. If the denominator is zero and the numerator is not, the index value is 100%.
iii. If the calculated value exceeds 100%, the value is replaced by 100%.

Depending on the results of Equation (4.2), maintenance systems were graded as Upward (≥5.0%), Flat (from

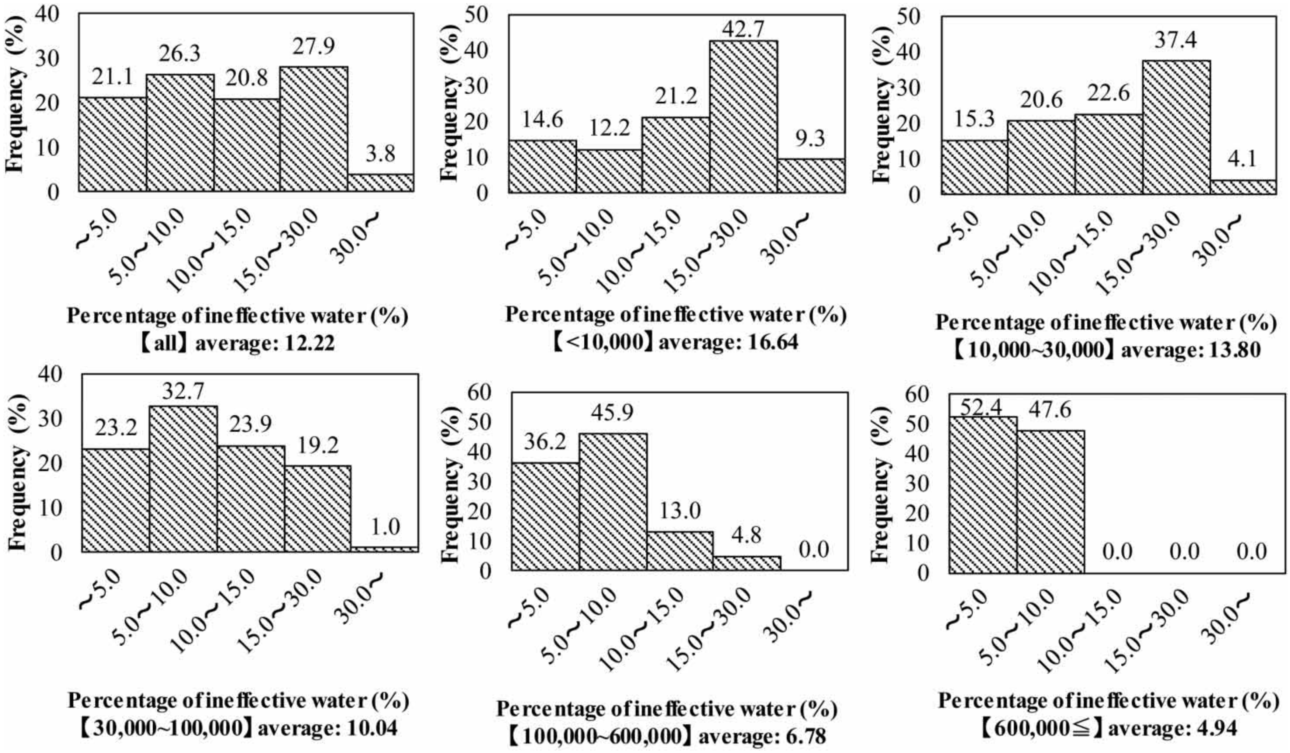

Figure 2 | Histograms showing the percentage of ineffective water.

−5.0% to 5.0%), or Downward (<− 5.0%), based on Table 5. The average unit number of technical staff (Equation (4.1)) tended to be higher for large water utilities. The average unit number for utilities serving populations ≥600,000 was 82.44 people/1,000 pipeline km, more than four-fold greater than the average of 20.18 for utilities serving populations <10,000, as in Table 6. Therefore, larger utilities can afford more technical maintenance staff.

In terms of the percentage change in the unit number of technical staff (Equation (4.2)), the average value for all water utilities was −6.15% (Figure 3). We then evaluated the situation for each population category (Equation (1)); all outcomes were Downward. Therefore, human resources for maintenance management systems are shrinking overall. As far as the authors are aware, automation has not been employed for pipe replacement for the last 10 years in Japan, to improve efficiency. Therefore, human resources would reflect the maintenance management system.

The number of utilities classified as Downward was almost twice the number classified as Upward. Excluding systems supplying populations ≥600,000, the rate of decline (Equation (4.2)) was greater for small water utilities, inevitably reducing the number of technical staff of such utilities.

Table 5 | Evaluation criteria for maintenance management systems

Evaluation	Number of technical staff per length of distribution pipe Rate of change (%)	Percentage of water leaks repaired Rate of change (%)
Upward	≥5.0	≥80.0
Flat	−5.0 ± 5.0	20.0–80.0
Downward	<− 5.0	<20.0

Repair rate of water leaks

Another possible index for assessing maintenance management systems is the repair rate of water leaks; this is a goods and services measure. Earlier, we mentioned that leaked water in water-supply statistics refers only to known (repaired) leaks; ineffective water was assumed to be the real leakage volume. Thus, we established a 'repair

Table 6 | Evaluation of maintenance management systems

	Number of technical staff per 1,000 km of distribution pipe			Repair rate of water leaks	
Population supplied	**(people/1,000 km)**	**Rate of change (%)**	**Evaluation**	**(%)**	**Evaluation**
≥600,000	82.44	−11.13	Downward	85.63	Upward
100,000–600,000	48.13	−3.17	Downward	68.93	Upward
30,000–100,000	27.66	−5.82	Downward	52.83	Flat
10,000–30,000	19.59	−6.34	Downward	50.57	Flat
<10,000	20.18	−8.17	Downward	49.89	Flat
All	27.36	−6.15	Downward	54.47	Flat

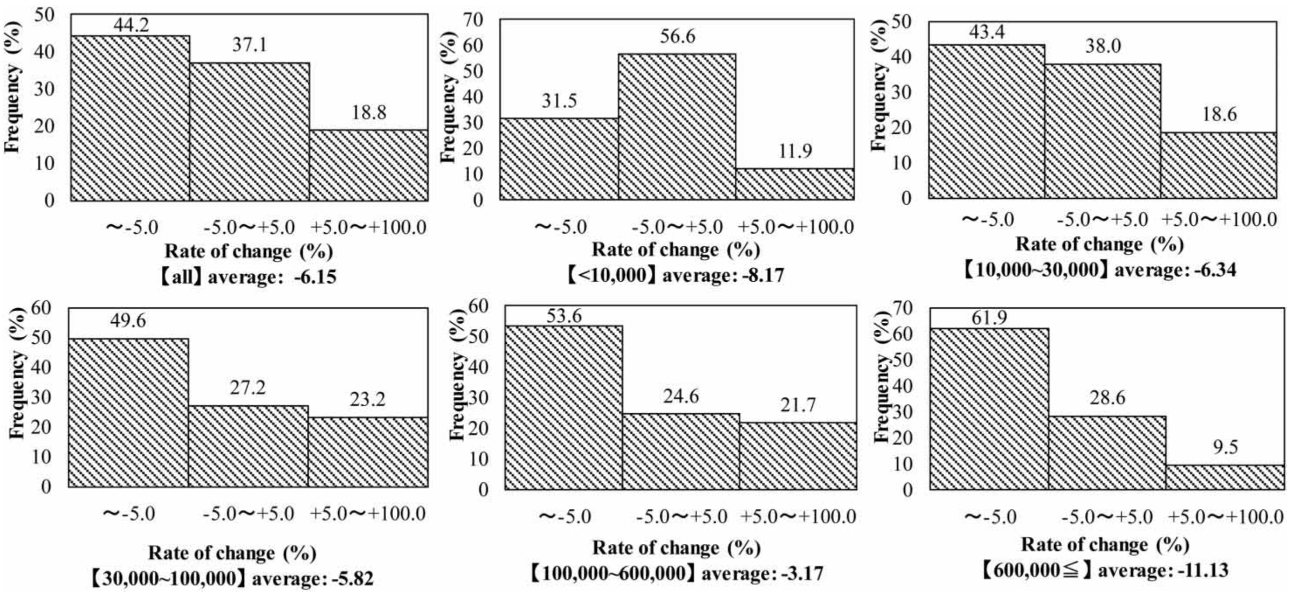

Figure 3 | Histograms showing the rates of change in the number of technical staff.

rate of water leakage' index (Equation (5)). As leakage volume may vary annually, we used the three-year average of Equation (5), as the index value. If all leaks are detected and repaired, the index should be 100%.

$$\text{Repair rate of water leakage (\%)} = \frac{\text{Amount of leaked water } (m^3)}{\text{Amount of ineffective water } (10^3 m^3) \times 1{,}000} \quad (5)$$

The possible grades were Downward (<20%), Flat (20–80%), and Upward (≥80%) (Table 5); histograms are shown in Figure 4. Of all utilities, 46.55% were graded Upward and 37.61% Downward. An obvious divide was apparent; for utilities serving populations <100,000, the histograms showed two peaks, indicating major differences in efforts to repair water leakage. However, most utilities supplying populations ≥100,000 were graded Upward.

The repair rate was 85.63% for water utilities supplying populations ≥600,000; such utilities detected and repaired the most leaks. On the other hand, the figure was 49.89% for utilities supplying populations <10,000; only about half of the leaks were repaired. The overall average repair rate was 54.47%; nationwide, most leaks were not repaired. The grade was Upward for water utilities serving populations ≥100,000 and Flat for the others. Large utilities repaired leaks more effectively.

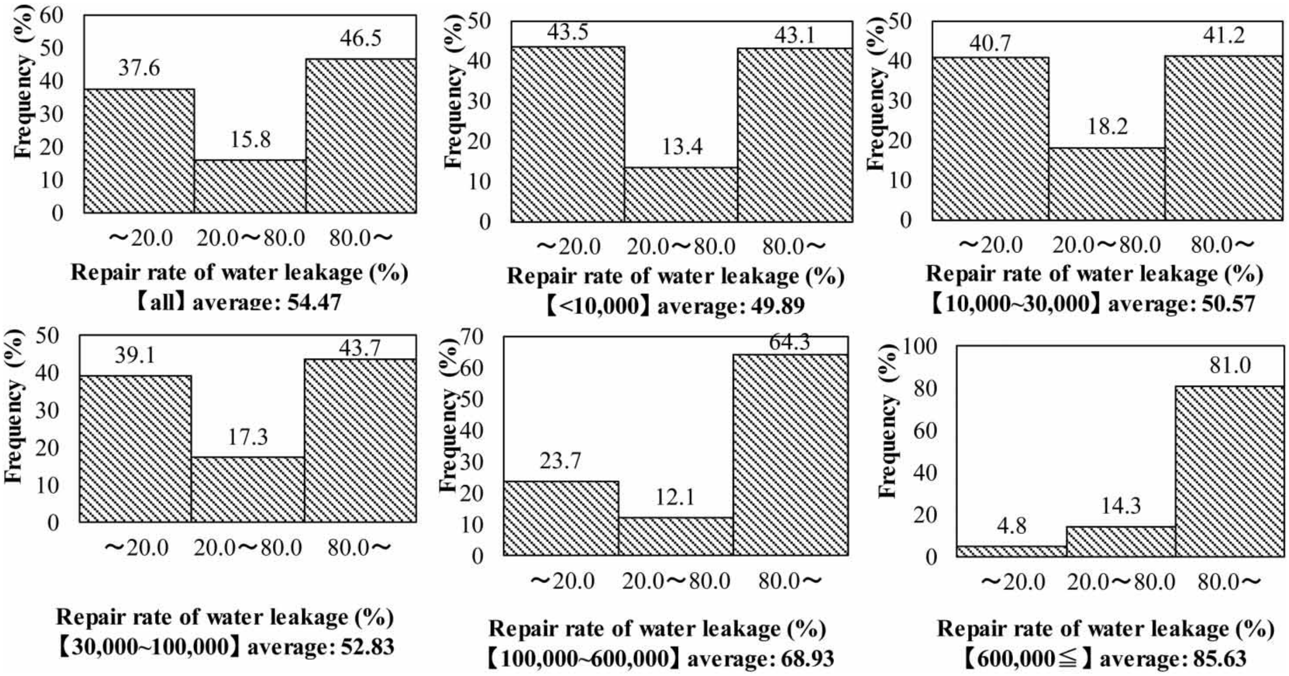

Figure 4 | Histograms showing the repair rates of water leaks.

Overall evaluation

Based on our four indices, we evaluated deterioration and maintenance management systems; the results are summarized in Tables 3 and 6, respectively. Overall, deterioration was classified as a C (Caution) and maintenance management systems were graded as Downward. This report card will be open to the public through Japan Society of Civil Engineers, to inform Japanese citizens of the current status of water supply infrastructure. For that purpose, we have employed a rather simple scoring method, which can be calculated from published statistical data. Criteria for a report card in the US include capacity, condition, funding, future needs, public safety, and resilience and innovation. Among those criteria, the Japanese report card focuses on condition and maintenance, because infrastructure aging is of great concern to Japanese citizens.

In terms of deterioration, for large water utilities, pipelines were generally old, and ineffective water was small. Therefore, the two indices cancelled each other out, yielding overall ratings of C or D. As shown in Figure 5, the proportion of water utilities with total scores of 80–100 (A) increased as the population served decreased, being 12.0% for water utilities serving populations <10,000, 1.9% for those serving populations of 100,000–600,000, and 0% for those serving populations ≥600,000. The proportion of utilities rated E (0–20 points) was 0 for those serving populations ≥100,000. Therefore, for small water utilities, the evaluation results were heavily dependent on the individual utility.

In terms of maintenance and management systems, the grades were higher for large utilities both in terms of 'the rate of change in the number of technical staff per length of distribution pipe' and 'the three-year average repair rate of water leaks'. The rate of change in the number of technical staff was graded Downward, indicating that numbers are shrinking. The repair rate of water leaks was graded Upward at utilities serving populations ≥100,000 and Flat for the others. The overall grade was Flat; thus, the overall maintenance management grade was Downward.

It is one of the characteristics in this study to show each indicator by each population category. As Table 3 shows, larger utilities are scoring higher for percentage of ineffective water, even though the score for percentage of old pipeline is lower. Considering the evaluation of

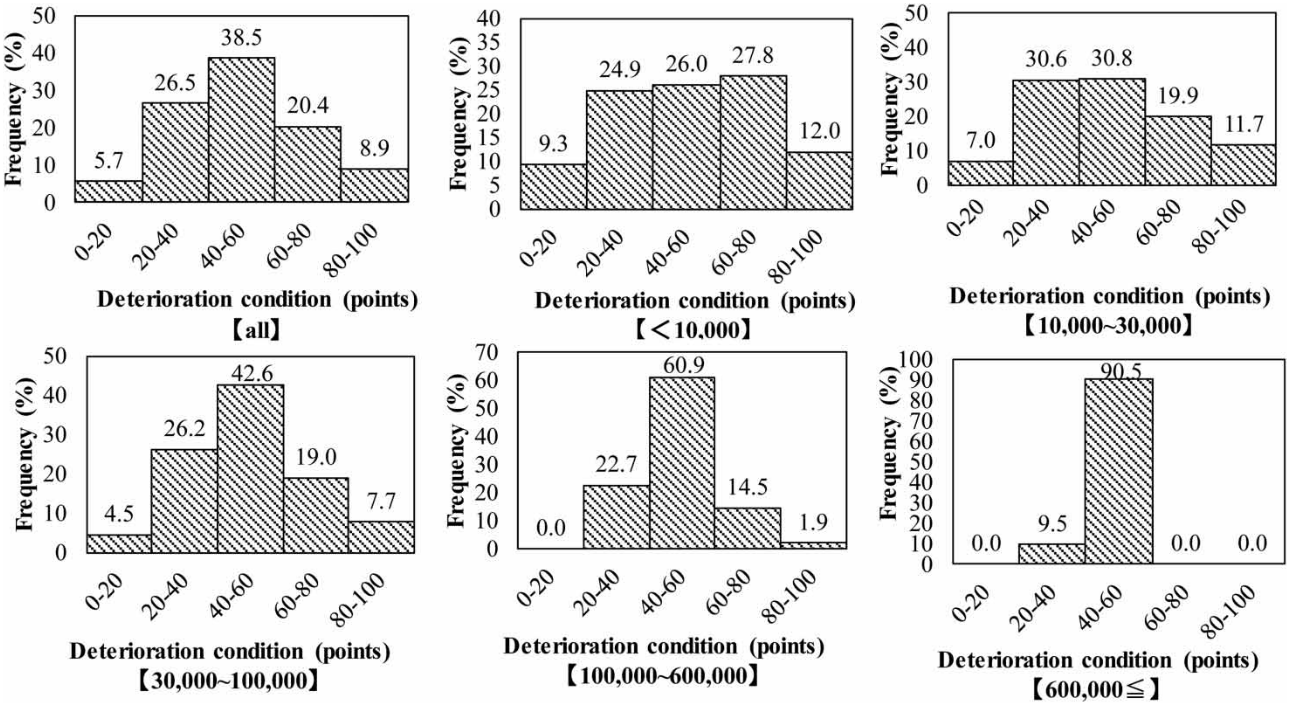

Figure 5 | Histograms showing pipeline deterioration over time.

maintenance management systems in Table 6, it may be suggested that the score of ineffective water is higher in larger utilities because the repair rate of water leaks is higher, which may be due to the larger number of technical staff per length of distribution pipe.

CONCLUSIONS

We devised indices assessing the deterioration of, and maintenance management systems for, drinking-water distribution pipelines. We have employed a rather simpler scoring method than other countries, intending to use this report to be available to the public. The indices were the percentage of old pipelines, the percentage of ineffective water, the change in the number of technical staff per unit length of pipe, and the repair rate of water leaks. Using these indices, we evaluated the extent of deterioration of water pipelines and the effectiveness of maintenance management systems. Overall, Japan scored a C for deterioration and received a grade of Downward in terms of maintenance management. Comparison of indicators by population category suggests larger utilities could reduce ineffective water possibly by a larger number of technical staff.

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