Efficient minimum night flow analysis using Bayesian inference

Taeho Choi, Mijin Hong, Jinkeun Kim and Jayong Koo

ABSTRACT

This study examines a plan for efficient leakage investigation to decide the number of survey-subjected water meters in the Option A method, which requires considerable manpower and expense, along with possible civil complaints, among the possible methods for determining the minimum night flow. The Bayesian approach was adopted, and the prior distribution of night use and water supply pipe night flow losses were proposed in order to estimate the most efficient survey rate in Option A test. From the results, the prior distribution was decided as the gamma distribution by surveying the minimum night flow for all the water meters for district metered area A. The estimated value of the posterior distribution, i.e., the minimum night flow, was determined by using the Bayesian inference by changing the survey rate of water meters. From the results, the survey rate for maximizing the survey efficiency was calculated. The most effective survey rate was 58% for household water meters and 78% for non-household water meters.

Key words | Bayesian inference, minimum night flow, Option A test, posterior distribution, prior distribution

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INTRODUCTION

For effective leakage management in water pipe networks, the leakage management status has to be assessed correctly and promptly. The evaluation methods for leakage management include representative methods for analyzing the flow data that are collected for a specified duration, including water balance and leakage component based analyses, and site inspection through the measurement of the minimum night flow. However, water balance and leakage component based analyses are not efficient for prompt leakage management due to the difficulty of the rapid flow data acquisition. On the contrary, the assessment method for leakage management through measuring minimum night flow can give an insight into the efficiency of leakage management with only limited data during a short span, which enables the leakage to be attended to promptly. In particular, the analysis method for minimum night flow, provided that the size of the water supply area is set appropriately, is a very useful method and is the most fundamental and basic approach for solving the problem; it is a simple method in comparison to water balance and leakage component based analyses (Hirner 1998; Lambert & McKenzie 2002; Farley & Trow 2003).

The two possible survey methods for minimum night flow in the UK Water Industry (WRC 1994) are Option A test and Option B test. Option A test is an analysis method that uses a water meter installed outside of a building in order to analyze customer night use and water supply pipe night flow losses. Option B test is a method that shuts all of the flow meter's valves outside of the house during the night in order to analyze the leakage from the water distribution pipe and the water communication pipe by using the changed value from the inlet flow meter of the District Metered Area (DMA). These two methods enable quick analysis of the leakage and usage from water supply pipes, water distribution pipes, and water communication pipes during the night time if SMART Metering is not being used. However, the investigation of numerous water meters should be carried out during limited hours, since

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they suffer the drawback of requiring considerable manpower and expense as well as civil complaints, because of the night-time operation.

Therefore, a plan for an efficient leakage investigation to decide the number of survey-subjected water meters in the Option A test as a method to determine the minimum night flow was examined in this study. A Bayesian approach was adopted as the prior and posterior distribution method for this test.

THEORETICAL BACKGROUND

Minimum night flow

Minimum night flow is the flow rate that inflows into a certain network or zone/DMA during the night-time when water use is at a minimum. It can be estimated by actually measuring the inflow rate that flows during a specified time when minimum night flow is incurred from household and non-household customers including that from official purposes, commercial purposes, and public bathhouses.

During the daytime, it is impossible to measure or predict water use since water inflow into the zone fluctuates largely according to water use of customers in the DMA and because the water use patterns by all of the customers are different. Therefore, measurement of the water flow during the minimum water inflow into the zone will reduce the usage deviation and determine when the leakage/inflow ratio is the largest.

From any zone, exceptional customer night use and normal night use are included to some extent, as well as the usual background flow loss from water distribution pipes, water communication pipes, and water supply pipes, in order to determine minimum night flow. In the case of burst water distribution pipes or water supply pipes, minimum night flow abruptly increases, but then returns to the original level after the pipes are repaired. If the scale of the pipe burst is large enough to be found easily and is quickly repaired due to a complaint from a resident, then the lead-time is short. However, if the scale of the pipe burst is relatively small, it cannot be detected easily, and it must be repaired by leak detection work by the water supplier rather than by a complaint made by residents. In this case, a larger water loss may occur due to the longer leak duration. Therefore, the total water loss depends on how fast the water provider discovers the unreported burst and allocates the resources to fix it. This is largely affected by the monitoring of the minimum night flows.

Bayesian theory

The basic concept of Bayesian statistics, although its concept of the population parameter is not known because the parameter is considered to be a random variable rather than a fixed one, shows a large difference from traditional statistic concepts. In other words, general statistical inference uses population parameters with only observed sample values for inference from the probability test, whereas the Bayesian inference offers a more precise outcome, because it implies both the parameter's characteristics and its characteristics from the population. The most outstanding qualities of Bayesian inference is that it uses subjective probability in a population parameter, it is not limited to only the data collected in the process of inference, and it goes through a posterior distribution of which the conditions are the observed data, while assuming unknown population parameters as random variables. As a result, it extracts and tests a countless number of samples.

RESEARCH METHODS

This study estimates the efficient investigation ratio of the water meter in the Option A test among the analysis methods for minimum night flow. The procedures and detailed method are presented below.

Deciding the study subject area

The experimental study was performed in the S and J districts of Gyeonggi-do, Korea, due to the ease of obtaining facility-related data, operational data about the water meter, and water pipe network, inflow, and water pressure data for different small DMAs that are monitored in real time and receive minimum night flow surveys.

The total number of water meters in the investigated area was 65,000, of which 10,373 (16%) were non-household water meters. Therefore, the area showed mixed characteristics with both commercial and residential areas. It was composed of 68 small DMAs. The facility data and operational data from the 68 small DMAs were used to rate the leakage feature and the use feature for the different DMAs. A total inspection was carried out for the two small DMAs where the fluctuation was judged to be less, because these were clearly isolated, the flow data were relatively accurate, the revenue water ratio was higher than 70% with less seasonal fluctuation, and the water supply area fluctuated less with fewer changes in the number of water meters.

Assessment for feature classification for the different DMAs

The objective of this study was to decide the efficient number of water meters to include during the investigation of minimum night flow. However, the night use, water supply pipe night flow losses, and prior distribution for different DMAs can be different, because the DMAs have different features. Therefore, by performing a feature analysis based on the leakage and use features for different DMAs and by determining the prior distribution of water supply pipe customer night use and night flow water supply pipe losses, the proposed method can effectively be implemented in another area in the future. In order to classify the features for the different DMAs, the leakage and use features subjected to 68 small DMAs in S and J districts of South Korea were classified.

Classification by the use feature

In residential areas, water use is higher during the morning and evening hours than it is during the middle of the day and night time. In comparison, water use in commercial areas is higher during evening and night hours than it is during morning and daytime. Because of the prominent difference in the water use patterns between residential and commercial users, the use feature in a water supply area should be different according to the occupancy ratio between household and non-household water meters. The use feature for each supply area was classified into three categories according to this ratio and displayed in Table 1.

Classification by the leakage feature

The leakage feature in the water supply area was classified using indirect assessment of pipe soundness calculated through data from the pipe network facilities as well as the operation data from the water pipe network. Soundness assessment was performed using a scoring method in which points were assigned to the assessment indices that affected the leakage. In addition, six assessment indices for the DMA, including the average age of the pipes, the ratio of pipes more than 21 years old to those younger, and the ratio of non-corrosive to corrosive pipes considering the length and volume of the pipes, were used to assess the soundness of the different water supply areas. By calculating the values for these assessment indices according to the water supply area, the overall score was calculated for each water supply area. These scores were classified into the four categories displayed in Table 1.

Rating according to DMA features

With the variables that represent the use feature and the leakage feature that have been explained earlier, the DMA was rated as a combination by which the characteristics of

Table 1 | Categories of the use feature and the leak feature

Category	Property	Criteria	Symbol
Use feature	Typical residential area	Household over 70%	A1
	Residential area ≒ commercial district	Household 30 ~ 70%	B1
	Typical commercial district	Household below 30%	C1
Leak feature	Excellent area	$2.5 < \text{Grade} \leq 3.0$	G1
	Good area	$2.0 < \text{Grade} \leq 2.5$	G2
	Average area	$1.5 \leq \text{Grade} < 2.0$	G3
	Bad area	$1.0 \leq \text{Grade} < 1.5$	G4

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the DMA could be determined. As shown in Table 1, the use feature was classified into a typical residential area where the household water meter was prominently high (A1), the area where the ratio of the residential to commercial area was similar (B1), and a commercial area where the non-household water meter was prominently high (C1). The leakage feature was classified into excellent area (G1), good area (G2), average area (G3), and bad area (G4) according to the overall score obtained from the scoring method, as previously explained.

By combining the rating for the use feature and the leakage feature as noted above, the features for different DMAs were constructed as 12 combinations. The use feature and the leakage feature for two small DMAs, A and B, are presented below in Table 2. Since DMAs A and B exhibited the same use feature and leakage feature, the research results were only drawn for DMA A. Implementing this result in DMA B enabled it to be used as data to judge the adoptability of the study results.

Table 2 | Classification according to the customer night use characteristic

Category	Use feature	Leak feature	Total evaluation
DMA A	A1 Household: 83.7% Non-household: 16.3%	G2 Grade = 2.04	(A1, G2)
DMA B	A1 Household: 85.7% Non-household: 14.3%	G2 Grade = 2.46	(A1, G2)

Performing the Option A test

The Option A test was performed for DMAs A and B among the study subject areas, but since the situation in Korea where the night time active population is relatively large in comparison to the UK where the night time active population is smaller, a modified Option A test was developed from the UK Water Industry Option A test.

As with the test procedure, the water use type was classified using meter reading data for the sample selection in advance and all of the samples were surveyed as much as possible. Prior to the site inspection, the indicator needle was checked to make sure it was properly pointing to the third decimal point and the survey-subjected water meters were obtained by marking the meter with tape.

The measurement was performed twice from the water meter outside of the house gate at midnight when the water usage was almost zero. In the case of the Option A test in the UK, if the water meter reading was simply changed, it was classified as use or leakage, but in the Modified Option A, if the needle in the water meter was static, it was marked as 'x', if it moved faster than one full rotation per second it was marked as '◎', and if it moved slowly it was marked as '○'. One turn was measured with a stopwatch and the observation was recorded. In order to distinguish between the usage and the water supply pipe losses, as shown below in Table 3, more variable criteria were set up and the metering results were compared. The

Table 3 | Reading method for modified Option A test

Rotation of needle on water meter	1st reading	2nd reading	Difference of reading	Classification
No rotation	x	x	Same reading	No night use
	x	x	+ difference	Normal customer night use
One rotation	○	x	+ difference	
	x	○	+ difference	
Both rotation	○	○	+ difference	
	◎	◎	+ difference	
	◎*	◎*	+ difference	Exceptional customer night use
	○*	○*	+ difference	Water supply pipe night flow losses

◎: moving faster than 1 rotation/s.
◎*: customer night use over 500 L/conn/h.
○: moving slower than 1 rotation/second.
○*: difference of time (seconds/rotation) over 10 s.
x: no rotation (stopped).

exceptional customer night use, normal customer night use, and water supply pipe night flow losses were estimated.

Efficient investigation of the minimum night flow using the Bayesian inference

Various possible prior distributions were considered using Bayesian inference and the water meter survey rate, which was efficient during the minimum night flow, was determined. The Bayesian inference statistical analysis was performed using the *R* program.

The Bayesian inference for deciding the water meter ratio to survey the minimum night flow was a method in which the Option A test results that had been surveyed for all of the numbers from DMA A were treated as a constant prior to distribution. Then, the survey ratio of the water meter was made into a likelihood function and the posterior distribution, i.e., population parameter, was assessed. The prior distribution used in the Bayesian inference could be any of the following: uniform distribution, chi-square distribution, exponential distribution, or gamma distribution. The prior distribution was determined through the Option A test from the test subject area, DMA A. Next, with DMA A, the data sampling frequency was decided by the appropriate prior distribution and the likelihood function of the assumed and non-assumed customer night use and water supply pipe night flow losses. After that, the error and standard deviation for the estimated values from the decided prior distribution and the data sampling frequency were calculated, and the estimation was drawn according to the water meter survey rate with a 5% interval ranging from 10 to 100%. Lastly, the adoptability of the developed method was evaluated by implementing the prior distribution and survey ratio in order to connect the minimum night flow drawn from DMA A.

The water meter survey rate in the Option A test was minimized to estimate customer night use and water supply pipe night flow losses. In addition, this result could be used in the Option B test. At the same time range as that of the Option A test, the flow meter installed at the inlet of the DMA value was read and it was determined that by subtracting the customer night use and the water supply pipe night flow losses values estimated in the Option A test, the leakage from the water distribution pipe and the water communication pipe could be efficiently estimated.

RESULTS AND DISCUSSION

The Bayesian inference was utilized to decide the efficient water meter survey rate when analyzing minimum night flow. The area feature was classified into use and leakage features for the study subject DMAs A and B. Both areas were determined as typical residential areas (A1) and acceptable areas (G2) in terms of use and leakage features, respectively. For the area features, the minimum night flow for all of the surveyed water meters, prior distribution according to the area features, and efficient water meter survey ratio, etc., were drawn from Bayesian inference.

Investigation results for the minimum night flow

The modified Option A test was performed for the study subject areas DMAs A and B. In addition, the Option A test was performed by categorizing the household use and non-household use for the estimation of customer night use and water supply pipe night flow losses. Customer night use was estimated by further dividing it into exceptional night use and normal customer night use. The estimation results for DMAs A and B are presented in Table 4.

Decision of the optimum prior distribution for the minimum night flow

The analysis results for the household customer night use, household water supply pipe night flow losses, non-household customer night use, and non-household water supply pipe night flow losses for the subject area DMA A showed that the gamma distribution yielded the least error among the investigated distribution methods including the uniform distribution, chi-square distribution, exponential distribution, and gamma distribution, as shown below in Table 5.

Therefore, the prior distribution of DMA A, with a use feature of a typical residential area (A) and a leakage feature of an acceptable area (G2), can be judged as reasonable

Table 4 | The results of the analysis measurements of the minimum night flow

Category		Measured DMA A	DMA B	Unit
Exceptional night use	Household	19.921818	9.065142	m^3/h
		766	1,072	Service connection
		0.026008	0.008456	m^3/conn h
	Non-household	2.453755	0.604463	m^3/h
		195	168	Service connection
		0.012583	0.003598	m^3/conn h
Normal customer night use	Household	18.170431	18.709462	m^3/h
		766	1,072	Service connection
		0.023721	0.017453	m^3/conn h
	Non-household	3.516586	2.766268	m^3/h
		195	168	Service connection
		0.018034	0.016466	m^3/conn h
Water supply pipe night flow losses	Household	33.760541	19.721105	m^3/h
		766	1,072	Service connection
		0.044074	0.018397	m^3/conn h
	Non-household	6.310821	0.440203	m^3/h
		195	168	Service connection
		0.032363	0.010576	m^3/conn h

Table 5 | Error factor of the night minimum flow according to the prior distribution in DMA A

	Household		Non-household	
Prior distribution	Customer night use	Water supply pipe night flow losses	Customer night use	Water supply pipe night flow losses
Uniform distribution	2.45%	2.45%	15.99%	13.64%
Chi-square distribution	1.13%	1.05%	7.67%	5.87%
Exponential distribution	2.45%	0.00%	0.64%	1.96%
Gamma distribution	0.01%	0.01%	0.01%	0.03%

for using the gamma distribution according to the following equation:

$$g(\lambda) = \frac{1}{\Gamma(\alpha)\beta^{\alpha}}\lambda^{\alpha-1}e^{-(\lambda/\beta)}$$

where α: shape parameter, β: scale parameter, λ: random variable, $\alpha, \beta > 0$, $\lambda \geq 0$.

Based on the results noted above, the prior distribution of the household customer night use, household water supply pipe night flow losses, and non-household customer night use were drawn as shown in Table 6.

Deciding the efficient random sampling frequency

The error factor between the household customer night use, household water supply pipe night flow losses, non-household customer night use, and non-household water supply pipe night flow losses values from a random sampling of 100, 500, 1,000, and 2,000 times and an actual measurement value in a complete enumeration survey were calculated as shown in Table 7.

The analysis results indicate that the error increased significantly with an increase in the random sampling frequency up to 1,000 times, but then it plateaued and even decreased in some cases with further increases in the

Table 6 | The results of the prior distribution calculation in DMA A

	Household		Non-household	
Coefficient	Customer night use	Water supply pipe night flow losses	Customer night use	Water supply pipe night flow losses
α	1	1	2	1
β	5	7	13	8

Table 7 | Error factor of night minimum flow according to the number of data sampling in DMA A

	Household		Non-household	
The number of data sampling	Customer night use (%)	Water supply pipe night flow losses (%)	Customer night use (%)	Water supply pipe night flow losses (%)
100	0.02	0.03	0.04	0.01
500	0.01	0.009	0.01	0.03
1,000	0.004	0.005	0.01	0.009
2,000	0.002	0.01	0.02	0.03

random sampling frequency beyond 1,000 times. Therefore, a random sampling frequency of 1,000 times is advisable to estimate an efficient water meter survey rate for accurate results and time-effective program execution.

Estimation of the efficient investigation rate for water meters

In the minimum night flow analysis, random sampling was carried out 1,000 times for each water meter survey rate in order to determine an efficient survey rate, from 10% to 100% at a unit of 5%. The error rate between the posterior distribution value in the random sampling of 1,000 times for the sum of household customer night use and household water supply pipe night flow losses and the value of a complete enumeration survey was calculated. In addition, the error rate between the posterior distribution value in the random sampling of 1,000 times for the sum of non-household customer night use and non-household water supply pipe night flow losses and the value of a complete enumeration survey was calculated. Also, the distribution was calculated by the water meter survey rate with these two results. The distribution calculated by the survey rate was set within a range of 1σ (confidence interval: 68.3%) and the error rate within 10% in order to determine the survey rate for households and non-households. The results of the determination of the water meter survey rate for the households and non-households are as follows.

Determining the survey rate for household water meters

Figure 1 shows the results of the household water meter survey rate for DMA A. By randomly selecting more than 58% of the total household water meters in DMA A and executing the Option A test, it was found that household customer night use and household water supply pipe night flow losses could be estimated at a confidence interval of 68.2% (1σ) with an error factor within 10%.

As a result, by minimizing the number of investigation samples for water connection during estimation of household customer night flow and household water supply pipe night flow losses using Bayesian inference, the investigation efficiency for minimum night flow was increased with high accuracy.

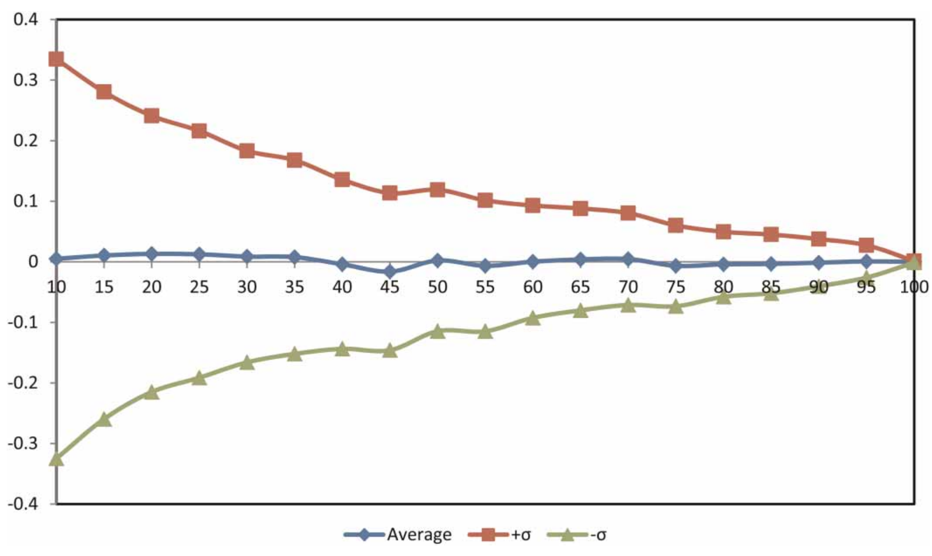

Figure 1 | The results of the decision for the household water meter survey ratio.

Determining the survey rate for non-household water meters

Figure 2 shows the non-household water meter survey rate in DMA A. By randomly selecting more than 78% among the total non-household water meters and by executing the Option A test, it was found that non-household customer night use and non-household water supply pipe night flow losses can be estimated at a confidence interval of 68.2% (1σ) with an error factor within 10%.

However, the non-household water meter survey rate had to include more than 78% of the total non-household water meters in order to match the same confidence level and error factor with the results of the survey rate for household water meters. Although the value was higher than the survey rate of household water meters, the effect was expected to be less on the survey rate for total water meters for the Option A test, since the non-household water meter survey rate was less than that for household water meters.

Implementation of the survey method of efficient minimum night flow using Bayesian inference

The prior distribution was determined as the gamma distribution by surveying the minimum night flow for all of the water meters for DMA A and the estimated value of the posterior distribution, i.e., the minimum night flow, was drawn by Bayesian inference by changing water meter survey rates. From these results, the survey rate which maximizes survey efficiency was calculated; the most effective survey rates were found to be 58% for household water meters and 78% for non-household water meters.

The study results were implemented on DMA B, for which the leakage feature (G2) and the use feature (A1) were the same, in order to evaluate whether or not these results could be applied to the other subject areas. The possible implementation was evaluated and the results are presented in Table 8.

The results indicated that the error factors from the analysis of the night flow were 5.7, 8.6, 11.8, and 13.4% with the error factor of $-\sigma$, and 3, 9.1, 14.7, and 11.9% with the error factor of $+\sigma$, within the error factor range of $\pm 1\sigma$ (at the confidence level of 68.3%). From the survey results of household water meters at DMA B, although the error factor was less than 10%, which is within $\pm 1\sigma$ of that drawn from DMA A, it was determined that there was a higher accuracy than that of DMA A and an error factor higher than 10% was observed from the survey results of non-household water meters, which indicates a lower accuracy than that of DMA A. Since the ratio of non-household water meters in both DMAs A and B is less than the ratio of household water meters, it is judged that the fluctuation of error factor might have been larger than the result of household water meter analysis. By selecting subject areas with

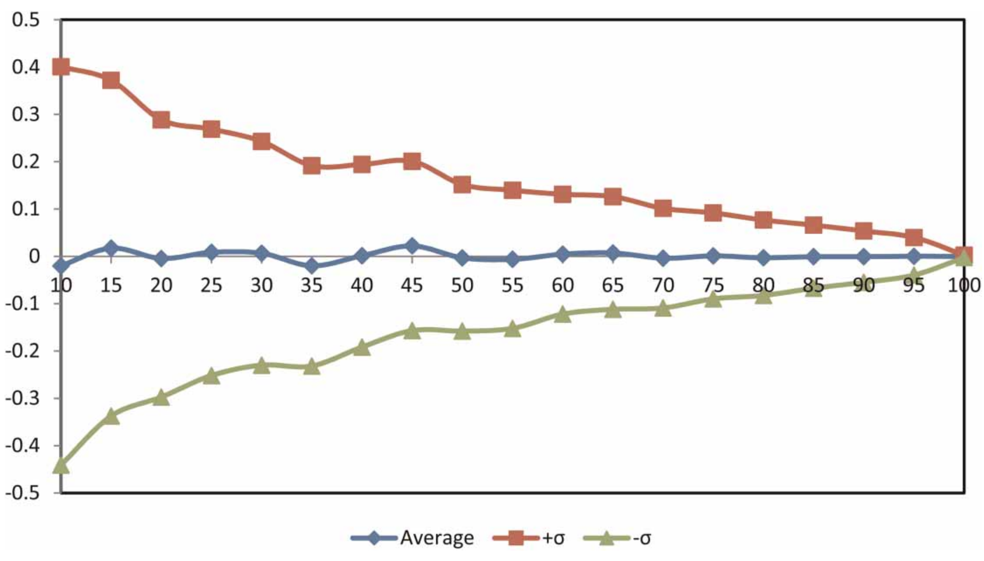

Figure 2 | The decision results for the non-household water meter survey ratio.

Table 8 | The results of applying the prior distribution and efficient water meter investigation ratios in DMA B

Index	Household		Non-household	
	Customer night use	Water supply pipe losses night flow	Customer night use	Water supply pipe losses night flow
Measured (m^3/conn h)	0.025900	0.018397	0.020064	0.010576
Estimated (m^3/conn h)	0.025909	0.018396	0.020056	0.010579
Error factor in $-\sigma$	0.057	0.086	0.118	0.134
Error factor in $+\sigma$	0.030	0.091	0.147	0.119

the same leakage and use features, the method proposed was implemented, but a numerical difference arose when the classification according to the area characteristics was closely examined. Despite a small difference in the use feature between the household water meters and the non-household water meters of DMAs A and B, it was determined that the soundness evaluation results for DMAs A and B could obtain maximum and minimum values within the same G2 rating. Therefore, this would affect the test results and might have affected the error factors in both DMAs.

CONCLUSIONS

In this study, a modified Option A test method for water meter surveys, which requires a considerable amount of manpower and a high expense, was conducted in order to determine the minimum night flow for the efficiency estimation in leakage management. The following steps were taken in order to achieve this objective: (1) the DMA features of the subject area were classified; (2) the minimum night flow from the small DMAs within the area was surveyed; (3) the most efficient water meter survey rate and prior distribution was proposed using Bayesian inference; and (4) the possibility of applying the proposed assessment method to small DMAs with similar characteristics was examined.

The results indicated that the survey rate for household and non-household water meters from DMA A should be more than 58% and more than 78%, respectively. The estimated implementation possibility for the same survey results for DMA B, with the same characteristics as those of DMA A, suggested that the proposed method could be applied to other areas in the future.

However, if the prior distribution is applied according to the DMA characteristics that were proposed through Bayesian inference, an economical survey could be performed, since each usage and loss could be estimated with the rate obtained by a more efficient sampling survey in comparison to that conducted in the present study with the water meter in order to determine the minimum night flow. We concluded that an economical leakage control plan could be established during water meter surveys of many small DMAs at a national level, if the prior distribution and the efficient sampling ratio suitable for the DMA characteristics are determined.

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REFERENCES

Farley, M. & Trow, S. 2003 *Losses in Water Distribution Networks: A Practitioner's Guide to Assessment, Monitoring and Control*. IWA Publishing, London, UK.

Hirner, W. 1998 Evaluation of water performance and distribution system with performance indicators. In: *IWSA Specialised Conference: Master Plans for Water Utilities*. June 17–18, Prague, Czech Republic.

Lambert, A. O. & McKenzie, R. S. 2002 Practical experience in using the infrastructure leakage index. In: *Proceedings of the IWA Specialised Conference: Leakage management – A Practical Approach. International Water Association*, November 20–22, 2002, Lemesos, Cyprus.

Water Research Centre (WRC) 1994 Managing leakage report E, Interpreting measured night flows, Engineering and Operations Committee.

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