Optimum Size of District Metered Areas

Osama Hunaidi* and Ken Brothers**

* National Research Council, Institute for Research in Construction, Ottawa, ON, Canada, K1A 0R6
(email: osama.hunaidi@nrc.ca)

** City of Ottawa, Utility Services Branch, 100 Constellation Crescent, Ottawa, ON, Canada, K2G 6J8
(e-mail: Ken.Brothers@ottawa.ca)

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Abstract

The size of DMAs traditionally ranged from 500 to 3000 service connections, depending on the ease of establishing the boundary of the DMA and/or the criterion for smallest detectable leak. Economics has not been considered in the past in determining DMA size. An economically optimum DMA size is established in this paper based on theoretical models for the cost of DMA-based leakage management strategies with 3 different intervention criteria.

Introduction

District metered areas (DMAs) are not commonly used in Canada and the United States. However, an increasing number of utilities, encouraged by the widespread use and success of this leakage management method in the United Kingdom, are considering its use. An important aspect of the design of DMAs that needs to be addressed by new users is the DMA size. Traditionally, size ranged from 500 to 3000 service connections.

In most cases, actual DMA size is governed by ease of isolation of the area and/or the criterion for smallest detectable leak. The smaller the DMA size, the smaller the leak size that can be differentiated from background leakage and legitimate night demand. To be able to easily differentiate a single typical service connection leak (~27 L/minute), it's usually necessary for the DMA size to be less than 1000 services. For DMAs that comprise more than 3000 service connections, it's usually difficult to differentiate a break in a 150 mm diameter distribution pipe.

DMA size should also be governed by economics but this has not been considered in the past. In this paper, an economically optimum DMA size will be established based on theoretical models for the cost of DMA-based leakage management strategies with 3 different intervention criteria. Minimum annual costs of these strategies and their corresponding water loss, i.e., economic leakage levels, will also be established. Using a large water distribution system as an example, it will be shown that optimum DMA size depends on the marginal cost of water, leak frequency, cost of leak detection, and intervention criterion.

Optimum Timing of Acoustic Surveys for DMAs

To determine the optimum timing of acoustic surveys for district metered areas, it's assumed that interventions to survey a DMA acoustically occur periodically, at the end of periods that are T_I long. The amount of water lost during the period T_I, assuming a constant leak frequency, is then given by:

[1] $$WL^{T_I} = \int_0^{T_I} RL_{DMA}F_o(T_I - t)dt = RL_{DMA}F_oT_I^2/2$$

where R is the average volume of water lost in m^3 per year per leak, L_{DMA} is the length of distribution pipes in the DMA in km, F_o is the frequency of unreported leaks per km of pipe per year, and t is time.

The total yearly cost, C_{DMA}^{annual}, i.e., combined cost of lost water and acoustic surveys, is given by:

[2] $$C_{DMA}^{annual} = \left[cRL_{DMA}F_oT_I^2/2 + C_{survey}^{DMA}\right]/T_I = cRL_{DMA}F_oT_I\ /2 + C_{survey}^{DMA}/T_I$$

where c is the marginal cost of lost water (\$/m^3), and C_{survey}^{DMA} is the cost of acoustically surveying the whole DMA. The survey is assumed to be performed in a very short time compared to the period T_I, and hence the volume of water lost during the survey is assumed to be small and not taken into account.

The optimum intervention period, $T_I^{optimum}$, is the period that minimizes the total yearly cost. It's found by equating the derivative of the total yearly cost, C_{DMA}^{annual}, with respect to T_I, to zero, i.e.:

[3] $$cRL_{DMA}F_o/2 - C_{survey}^{DMA}/T_I^2 = 0$$

Hence:

[4] $$T_I^{optimum} = \sqrt{\frac{2C_{survey}^{DMA}}{cRL_{DMA}F_o}}$$

Eqs. [1] and [3] are the same as the equations that would have been obtained if acoustic surveys were performed uniformly over the period T_I. This may be taken as an indication that the uniformity of the survey is not necessary for these equations to hold. The cost of surveying the DMA is given by:

[5] C_{survey}^{DMA} = *Length of DMA's distribution pipes in km / survey rate (km / year /team)*
x *No. of persons per team x annual salary per person x overhead factor*

The minimum annual combined cost of lost water and acoustic surveys is obtained by substituting Eq. [4] in Eq. [2] as follows:

[6] $$C_{\min}^{annual} = \sqrt{2cRL_{DMA}F_oC_{survey}^{DMA}}$$

From Eq. [4], it is found that:

[7] $$cRL_{DMA}F_o(T_I^{optimum})^2/2 = C_{survey}^{DMA}$$

The term on the left hand side of Eq. [7] is the volume of water lost during the period $T_I^{optimum}$. In words, Eq. [7] means that the most economic time to undertake an acoustic leak detection survey for DMAs is when the accumulated cost of lost water is equal to the cost of the survey. In the long term, the average length of the intervention period will be equal to $T_I^{optimum}$ given by Eq. [3]. However, as demonstrated further on, this intervention criterion alone does not lead to the minimum cost under most conditions.

Intervention Criteria for DMAs and Corresponding Minimum Cost

The following three intervention criteria to survey DMAs for leaks are considered. It's assumed that the exit level, i.e., the leakage level of a DMA at which acoustic leak surveys are concluded, is equal to the background leakage level. It's also assumed that night flows of DMAs are continuously monitored via telemetry.

Criterion 1 – Major Leakage Event

Intervention to survey the whole DMA is triggered by the detection of a major leak, e.g., distribution pipe break, in the DMA's minimum night flow record. All leaks found by the survey are repaired. In the long-term, this intervention criterion is equivalent to surveying the DMA at time periods equal to:

$$T_I = \frac{1}{F_o^{mains} L_{DMA}} \tag{8}$$

where F_o^{mains} is the frequency of leaks in distribution pipes and L_{DMA} is the total length of distribution pipes in the DMA. The minimum total yearly cost of leakage management, i.e., combined cost of lost water and leak detection surveys excluding the cost of initial DMA setup, maintenance and night flow monitoring, is equal to:

$$\begin{aligned} C_{\min}^{annual} &= \textit{cost of water lost due to mains leaks + cost of mains leak detection surveys} \\ &\quad \textit{+ cost of water lost due to service pipe leaks} \\ &= N_{DMA} c R_{mains} L_{DMA} F_o^{mains} (T_{awareness} + T_{location} + T_{repair}) + N_{DMA} L_{DMA} F_o^{mains} C_{survey}^{DMA} \\ &\quad + N_{DMA} c R_{services} L_{DMA} F_o^{services} \left(\frac{1}{F_o^{mains} L_{DMA}} \right) / 2 \end{aligned} \tag{9}$$

and the corresponding annual total water loss, excluding loss from background and reported leaks, is equal to:

$$\begin{aligned} WL_{total}^{annual} &= N_{DMA} R_{mains} L_{DMA} F_o^{mains} (T_{awareness} + T_{location} + T_{repair}) \\ &\quad + N_{DMA} R_{services} L_{DMA} F_o^{services} \left(\frac{1}{F_o^{mains} L_{DMA}} \right) / 2 \end{aligned} \tag{10}$$

where N_{DMA} is the total number of DMAs in the distribution system, c is the marginal cost of lost water (\$/m^3), R_{mains} is the average flow rate for a mains leak (m^3/year), L_{DMA} is the length of distribution pipes (mains) in the DMA, F_o^{mains} is the leak frequency for distribution pipes (leaks / km / year), $T_{awareness}$ is the time it takes to detect the leak in minimum night flow record, in years, $T_{location}$ is the average time it takes to locate a leak, equal to one-half the time it takes to survey the whole DMA, T_{repair} is the wait time for the leak to be repaired, C_{survey}^{DMA} is the cost of acoustically surveying the whole DMA, $R_{services}$ is the average flow rate for a service pipe leak (m^3/year), and $F_o^{services}$ is the frequency of service pipe leaks (leaks / km of distribution pipe / year).

This criterion may not lead to minimum cost if the optimum intervention time based on the frequency and size of service pipe leaks is less than the intervention interval given by Eq. [32], i.e.:

[11] $$\sqrt{\frac{2C_{survey}^{DMA}}{cR_{service}L_{DMA}F_o^{service}}} \leq \frac{1}{F_o^{mains}L_{DMA}}$$

Possibly, this can be avoided if a secondary trigger occurs when the accumulated cost of lost water, excluding losses from background and reported leaks, monitored via continuous night flow measurement exceeds the cost of surveying the DMA. Frequently, however, especially in the case of large and frequent distribution pipe leaks, Criterion 1 is more economic than Criterion 3 and sometimes Criterion 2 below, which incorporate this secondary trigger. This is because for Criterions 1 and 2, the survey is synchronized with the time at which a large distribution pipe leak occurs. Subsequently, this reduces the duration of large leaks to at most few days, instead of half the optimum survey interval had their occurrence been assumed random (as when surveying without the aid of DMAs). Criterion 1 can be more economic than Criterion 2 when the inequality sign in Eq. [11] changes direction.

Criterion 2 – Major Leakage Event or Leakage Exceeding a Threshold

Intervention to survey DMAs is triggered by the detection of a major leak in the DMA's minimum night flow record. The DMA is first step-tested to narrow down the area of the leak and then the suspected sub-area is surveyed acoustically to locate the leak. In the long-term, this is equivalent to step-testing / surveying the DMA at time intervals given by Eq. [8]. Also, an intervention to survey the whole DMA is triggered when the accumulated cost of lost water, excluding losses from background and reported leaks, is equal to the cost of surveying the DMA. In the long-term, considering only service pipe leaks, this is equivalent to surveying the DMA at time intervals equal to:

[12] $$T_{service}^{optimum} = \sqrt{\frac{2C_{survey}^{DMA}}{cR_{service}L_{DMA}F_o^{service}}}$$

The minimum total yearly cost of leakage management, i.e., combined cost of lost water and step-testing / leak detection surveys excluding the cost of the initial cost of DMA setup, and maintenance and night flow monitoring costs, is equal to:

[13] $$\begin{aligned} C_{\min}^{annual} &= \text{cost of water lost due to mains leaks + Cost of mains step-tests / surveys} \\ &\quad \text{+ cost of water lost and leak detection surveys for service pipes} \\ &= N_{DMA}cR_{mains}L_{DMA}F_o^{mains}(T_{awareness}+T_{location}+T_{repair}) + N_{DMA}L_{DMA}F_o^{mains}C_{step-test/survey}^{DMA} \\ &\quad + N_{DMA}\sqrt{2cR_{service}L_{DMA}F_o^{service}C_{survey}^{DMA}} \end{aligned}$$

and the corresponding annual total water loss, excluding loss from background and reported leaks, is equal to:

[14] $$WL_{total}^{annual} = N_{DMA}R_{mains}L_{DMA}F_o^{mains}(T_{awareness} + T_{location} + T_{repair}) + N_{DMA}\sqrt{\frac{R_{service}L_{DMA}F_o^{service}C_{survey}^{DMA}}{2c}}$$

Assuming that each DMA can be subdivided into k sub-areas, and assuming that the cost of step testing is $1/l$ the cost of surveying the whole DMA, then the cost of step-testing and surveying the suspected area for a major leak detected in the DMA's minimum night flow record is equal to:

[15] $$C_{step-test/survey}^{DMA} = \frac{1}{k}C_{survey}^{DMA} + C_{step-test}^{DMA} = \frac{1}{k}C_{survey}^{DMA} + \frac{1}{l}C_{survey}^{DMA} = \frac{k+l}{k\,l}C_{survey}^{DMA}$$

In Eq. [15], it's assumed that the whole sub-area where the leak is suspected will be surveyed acoustically since it may not be possible to distinguish the major leak from smaller ones. All leaks found in the sub-area will be repaired. The cost of water saved by repairing service leaks found in the sub-area is assumed to be small and hence not taken into account in Eq. [13]. Like *Criterion 1*, especially in the case of frequent large leaks in distribution pipes, *Criterion 2* is often more economical than *Criterion 3* below.

Criterion 3 – Leakage Exceeding a Threshold

Intervention to survey the whole DMA is triggered only when the accumulated cost of lost water, including that due to unreported leaks in both distribution and service pipes but excluding losses from background and reported leaks, is equal to the cost of surveying the DMA. In the long-term, this is equivalent to surveying the DMA at the end of time intervals equal to:

[16] $$T_I = \sqrt{\frac{2C_{survey}^{DMA}}{cR_{weighted}L_{DMA}F_o^{total}}}$$

where

[17] $$F_o^{total} = F_o^{mains} + F_o^{service}$$

and

[18] $$R_{weighted} = \frac{R_{mains}F_o^{mains} + R_{service}F_o^{service}}{F_o^{total}}$$

The minimum total yearly cost of leakage management, i.e., combined cost of lost water and leak detection surveys but excluding the cost of the initial cost of DMA setup, and maintenance and night flow monitoring costs, is equal to:

[19] $$\begin{aligned} C_{\min}^{annual} &= \textit{cost of water lost due to mains leaks} + \textit{cost of water lost due to service leaks} \\ &\quad + \textit{cost of surveying the whole DMA} \\ &= N_{DMA}cR_{mains}L_{DMA}F_o^{mains}T_I/2 + N_{DMA}cR_{service}L_{DMA}F_o^{service}T_I/2 \\ &\quad + N_{DMA}C_{survey}^{DMA}/T_I \end{aligned}$$

$$= N_{DMA} c \left(\frac{R_{mains} F_o^{mains} + R_{service} F_o^{service}}{F_o^{total}} \right) L_{DMA} F_o^{total} T_I / 2$$

$$+ N_{DMA} C_{survey}^{DMA} / T_I$$

and the corresponding annual total water loss, excluding loss from background and reported leaks, is equal to:

[20] $$WL_{total}^{annual} = N_{DMA} \left(\frac{R_{mains} F_o^{mains} + R_{service} F_o^{service}}{F_o^{total}} \right) L_{DMA} F_o^{total} T_I / 2$$

Initial Setup and Maintenance Cost of Equipment

The initial setup cost of DMAs and acoustic leak detection equipment is factored into the annual cost of leakage management strategies by spreading it over several years. If the initial cost of equipment, *P*, is spread over *n* years at the utility's discount rate, *r*, the yearly cost, *a*, is given by:

[21] $$a = P \frac{r(1+r)^n}{(1+r)^n - 1}$$

The yearly maintenance cost of equipment is assumed to be equal to fixed percentage of its yearly cost.

Example

The application of the above theoretical models to perform an economic comparison between periodic acoustic surveys and DMA-based leakage management strategies is demonstrated for a large distribution system. The system is comprised of 2,391 km of distribution pipes, of which 39% is cast iron, 34% is ductile iron, and 26% is PVC. The system has 168,704 service connections, with an average pipe length of 15 m, and it services 765,000 people. The average pressure in the system is 47.6 m (70 psi). The average volume of water pumped into the system is 368 ML/day, and the average volume delivered is 312.6 ML/day. The current leakage management strategy is passive. The infrastructure is assumed to be in an average condition. The system's marginal cost of water is 4.6 ¢/m^3.

It's assumed that each DMA can be divided into 5 sub-areas for step-testing and the cost of step-testing is equal to 1/5th the cost of acoustic surveys (irrespective of DMA size) . Leak frequencies of distribution pipes are assumed to be 0.24, 0.064,and 0.006 leaks/km/year for cast iron, ductile iron, and PVC pipes, respectively. It's assumed that 50% of distribution pipe leaks are unreported and the average leak size is 65.7 ML/year (150 L/minute, based on a night-to-day flow rate conversion factor equal to 20). It's also assumed that the leak frequency of service connection pipes is 0.5 leaks/km/year (distribution pipe kms), 50% of leaks are unreported and the average leak size is 11.8 ML/year (27 L/minute). It's assumed that it takes 3 and 14 days to pinpoint and repair unreported leaks in distribution and service pipes, respectively; reported leaks are assumed to take 1 and 7 days for distribution and service pipes, respectively. The cost of leak repair is assumed to be independent of the leakage management strategy and hence not considered in the analysis.

Equipment and maintenance cost for each DMA is $7,222/year based on the following assumptions: initial setup cost is $75,000 (irrespective of DMA size), service life is 20 years, maintenance cost is 20% of amortized initial cost, and discount rate is 5%. Cost for all DMAs is $606,648/year. Equipment and maintenance cost for a 2-person leak correlation team is $23,559/year based on the following assumptions: initial setup cost is $85,000 (2 vehicles at $30,0000 each and 1 correlator/locate equipment at $25,000), service life is 5 years, maintenance cost is 20% of amortized initial cost, and discount rate is 5%. Equipment and maintenance cost for a 1-person correlation team is $15,244/year based on the following assumptions: initial setup cost is $55,000 (1 vehicle at $30,0000 and 1 correlator at $25,000), service life is 5 years, maintenance cost is 20% of amortized initial cost, and discount rate is 5%. Equipment and maintenance cost for a 1-person leak sounding team is $9,700/year based on the following assumptions: initial setup cost is $35,000 (1 vehicle at $30,0000 and 1 listening device at $5,000), service life is 5 years, maintenance cost is 20% of amortized initial cost, and discount rate is 5%.

The cost of conducting correlation-based surveys is $107.5/km, or $128/km if equipment and maintenance cost is included, based on the following assumptions: time spent per correlation is 12 minutes, average distance between correlation points is 150 m, net time worked is 1488.5 hours/year (which leads to a survey rate of 1116 km/year/team), salary is $40,000/year/person, overhead cost is 50% of salaries, and each survey team consists of 2 persons. The labour cost of surveying the whole distribution system is $257,010 and the cost of surveying a DMA is $3,047, or $1,219 if a DMA step-test is performed first.

The cost of acoustic listening (sounding) surveys is $203/km, or $241/km if equipment and maintenance cost is included, based on the following assumptions: time spent listening per service is 5 minutes, net time worked is 1488.5 hours/year (leading to a survey rate of 253.2 km/year/team or 17862 services/year/team), salary is $40,000/year/person, overhead cost is 50% of salaries, and each survey team consists of 1 person. The labour cost of sounding the whole system is $485,154 and the cost of surveying a DMA is $5,752, or $1,725 if a DMA step-test is performed first.

The cost of pinpointing both unreported and reported leaks, excluding equipment cost, is $120,000/year based on the following assumptions: salary is $40,000/year/person, overhead cost is 50% of salaries, each survey team consists of 1 person and number of teams is 2.

For a marginal cost of water of ¢4.6/m^3, considered to be the Reference Case (Figure 1), optimum DMA size for criterion 1 is 2250 and 1500 using correlation and listening surveys, respectively. For criterion 2, optimum size is 3500 and 2750 using correlation and listening surveys, respectively. Optimum total cost of criterion 2 is less than that of criterion 1. For criterion 3, total yearly cost decreases continuously with DMA size. Criteria 1 and 2 are more economic than criterion 3 only for DMA size less than ~2000 and ~2250 using correlation and listening surveys, respectively. Hence, the most economic DMA-based leakage management strategy would be to use super-sized DMAs consisting of 10,000 to 15,000 services with intervention criterion 3. This was found to be the case for a marginal cost of water up to ~¢20/m^3.

Optimum DMA size for criteria 1 and 2 increases if leak frequencies for distribution pipes were lower than the values assumed above. This can be seen from Figure 2, which shows yearly total cost when a leak frequency of 0.1 leaks/km/year is used for cast iron pipes instead of the frequency of 0.24 assumed for the Reference Case in

Figure 1. Optimum cost of criterion 1 also becomes less or almost equal to that of criterion 2.

Optimum DMA size changes slightly if the frequency of service pipe leaks decreases relative to the frequency of distribution pipe leaks. This can be seen from Figure 3, which shows yearly total cost when a leak frequency of 0.25 leaks/km/year is used for service pipes instead of the frequency of 0.5 assumed for the Reference Case in Figure 1. However, total cost of criterion 2 becomes increasingly more optimum than that of criterion 1. Also, the DMA size for which criterion 1 or 2 are more economic than criterion 3 increases as the leak frequency for service pipes deceases. As can be seen from Figure 4, optimum DMA size for criterion 1 and 2 also changed slightly as the percentage of unreported leaks increased to 90%, in comparison to 50% used for the Reference Case in Figure 1.

As the salaries of leak detection staff decrease, optimum size of DMAs increases and total cost decreases for criteria 1 and 2. This can be seen from Figure 5 for a staff salary of \$20,000/year, in comparison \$40,000/year for the Reference Case in Figure 1. Also, the DMA size for which criterion 1 or 2 are more economic than criterion 3 increases as staff salaries decrease. Figure 6 shows the yearly total cost for longer times to perform the correlation and listening operations of 30 and 10 minutes, respectively, instead of the 12 and 5 minutes used for the Reference Case. It can be seen that as a result of the increased duration, optimum DMA size decreased significantly from 2250 and 1500 for criteria 1 and 2, respectively, to 1500 and 1250.

Figures 7 to10 show yearly total costs versus DMA size for marginal costs of water of ¢25, ¢50, \$1 and \$2/m^3, respectively. It can be seen that for criterion 1, optimum DMA size increases significantly as the marginal cost of water increases; e.g., it increased from 3000 at ¢25/m^3 to 5000 at \$2/m^3 for correlation-base surveys. However, for criterion 2, optimum DMA size decreases slightly as the marginal cost of water increases; e.g., it decreased from 3500 at ¢25/m^3 to 3000 at \$2/m^{3}for correlation-based surveys. Optimum total cost of criterion 1 became less than that of criterion 2 for a marginal cost of water of ¢25/m^3 and remained so up to a cost between \$1 and \$2/ m^3. The DMA size below which criterion 1 or 2 is more economic than criterion 3 is about 5000 for a marginal cost of water of ¢25/m^3. The DMA size below which this occurs increases with the marginal cost of water.

Finally, total yearly cost is unsymmetrical around the optimum DMA size. The variation of the cost with DMA size is much greater below the optimum size. As the marginal cost of water increases, the variation of total yearly cost with DMA size above the optimum size decreases. This is especially so for criterion 1.

Conclusions

An economically optimum DMA size was established based on theoretical models for the cost of DMA-based leakage management strategies with 3 different intervention criteria. Minimum annual costs of these strategies and their corresponding economic leakage levels were also established. Using a large water distribution system as an example, it was demonstrated that optimum DMA size depends on the marginal cost of water, leak frequency, cost of leak detection, and intervention criterion.

For intervention criteria 1 and 2, optimum DMA size increases if leak frequencies for distribution pipes decreases; changes slightly if the frequency of service pipe leaks decreases relative to the frequency of distribution pipe leaks; change slightly as the percentage of unreported leaks increases; and increases as the cost of leak surveys increases. For criterion 3, total yearly cost decreases continuously with increasing DMA size.

At marginal cost of water up to ¢20/m^3, and other characteristics similar to those of the distribution system used as example in this paper, the most economic DMA-based leakage management strategy would be to use super-sized DMAs consisting of 10,000 to 15,000 services with intervention criterion 3. For more expensive water, the most economic strategy would be to use optimum DMA size corresponding to intervention criterion 1.

For simplicity in determining optimum DMA size for the example used in this paper, it was assumed, although may be unrealistic in practice, that costs of step-testing and initial setup of DMAs are constant, irrespective of DMA size. For more optimum size, the impact of DMA size on these two costs should be taken into account.

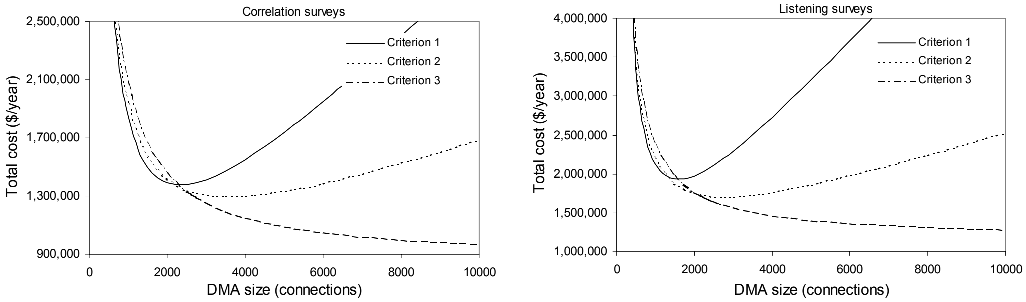

Figure 1: Minimum yearly cost versus DMA size and intervention criterion (Reference Case).

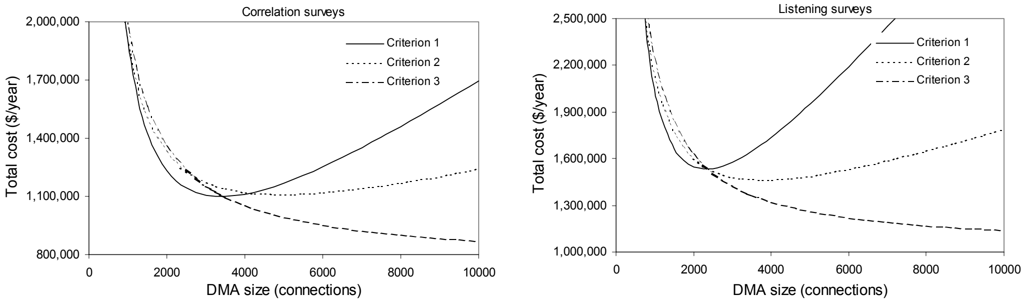

Figure 2: Minimum yearly cost using leak frequency of 0.1 leaks/km/year for cast iron pipes.

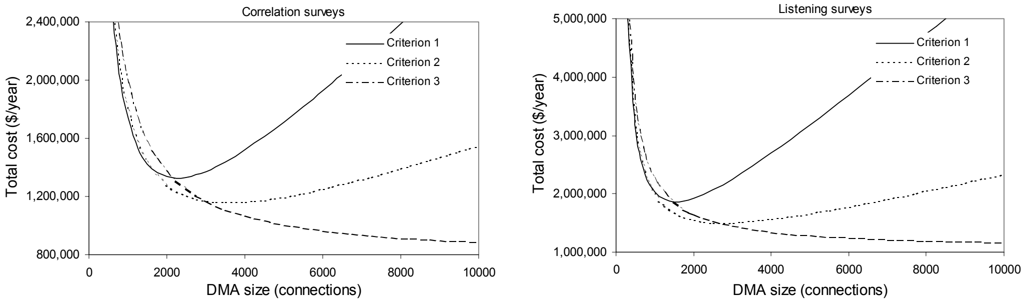

Figure 3: Minimum yearly cost using leak frequency of 0.25 leaks/km/year for service pipes.

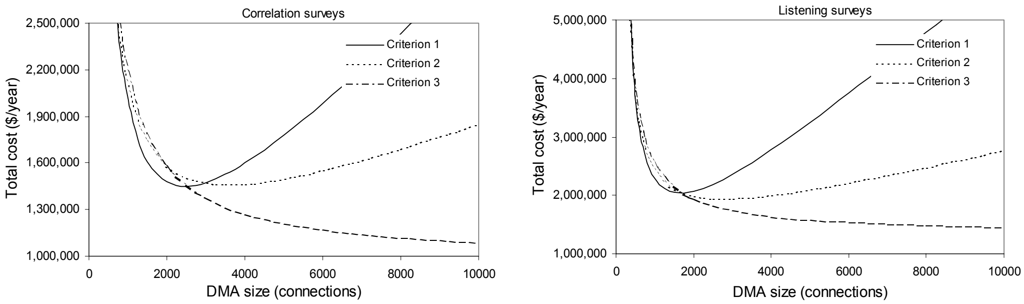

Figure 4: Minimum yearly cost assuming 90% of leaks in service pipes are unreported.

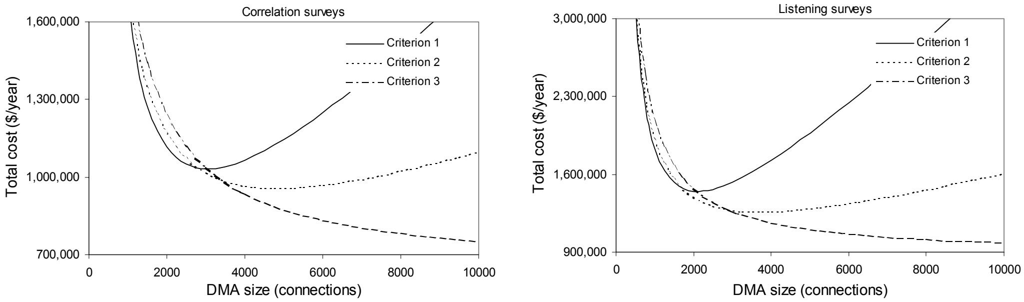

Figure 5: Minimum yearly cost using staff salary of $20,000/year.

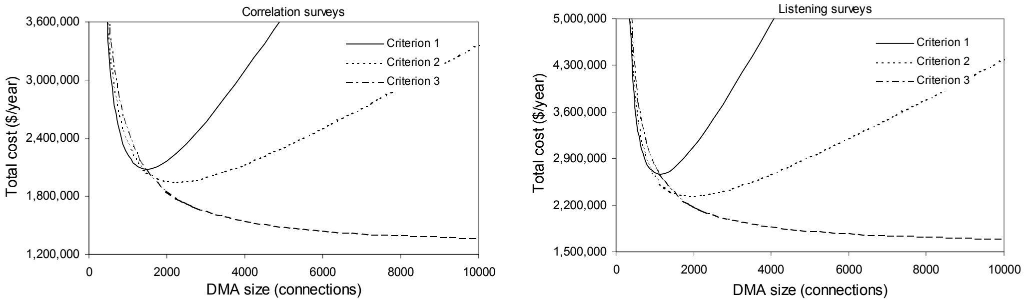

Figure 6: Minimum yearly cost using 30 and 10 minutes for correlation and listening, respectively.

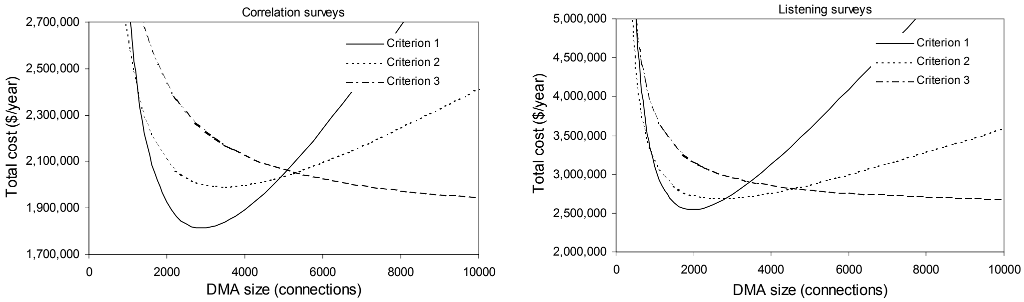

Figure 7: Minimum yearly cost using marginal cost of water of ¢25/m^3.

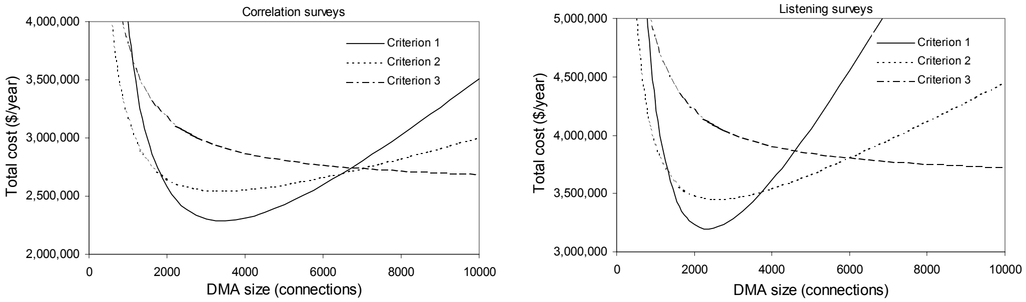

Figure 8: Minimum yearly cost using marginal cost of water of ¢50/m^3.

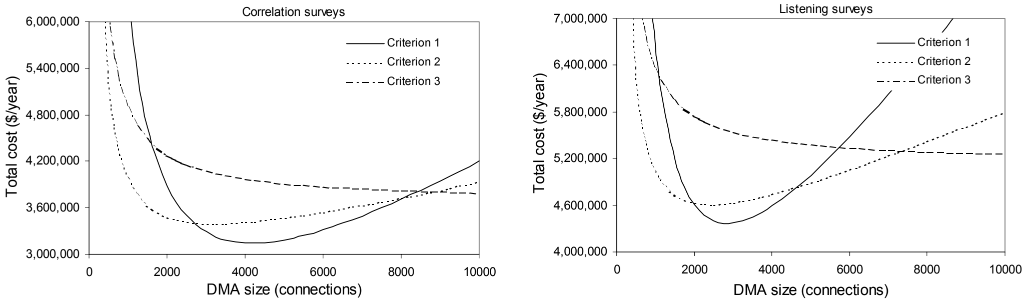

Figure 9: Minimum yearly cost using marginal cost of water of \$1/m^3.

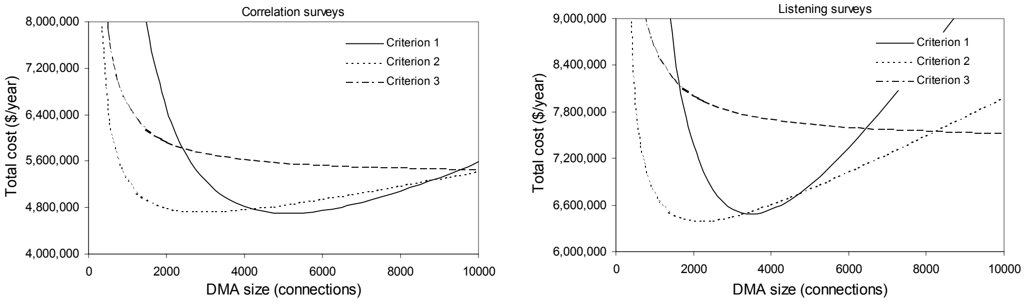

Figure 10: Minimum yearly cost using marginal cost of water of \$2/m^3.