Guidance for the Water Loss Economic Model

Updating Default Parameters

This document is intended to aid in the understanding of the water loss economic model and to help suppliers understand how to update the default parameters. The methods and calculations provided in this document to update the default parameters may not be the only available method to calculate a given parameter, and any method may be used as long as it is appropriate and referenced.

SECTION 1: Model Overview

The economic model conducts a benefit-cost analysis for each urban retail water supplier. The model assumes 2022 through 2027 to be the implementation period for water loss control, based on the regulatory timeline for adoption of the standards.

The model consists of the following individual sheets:

Inputs: This sheet is where the individual leak characteristics, unit costs of leak detection and repair, the efficiency of leak detection, and value of water are entered into the model. These are based on inputs or default values as described in the following sections of the guidance. The real discount rate and effective lifecycle timeline have been determined by The State Water Board.

Calculations: All model inputs entered in the Inputs tab are used to calculate reported, unreported, and background leakage as described in the report. The calculated unreported leakage is used as the initial leakage that can potentially be reduced by the supplier depending on the average leak detection survey frequency. Reducing background leakage specifically requires either asset management or pressure management, while reducing reported leakage requires reducing response time to repairs. Assuming reasonable specifics for asset or pressure management programs or repair response time reduction involves a high amount of uncertainty. Hence, the model assumes that only unreported leakage can be potentially reduced, and any standard industry approach including pressure and asset management and reducing response time for repairs can be used to reduce unreported leakage. The model uses active leak detection and repair as a standard approach to reduce leakage to conduct the benefit-cost analysis based on data collected from industry vendors and water suppliers. However, water suppliers are not required to solely use active leak detection and repair to meet their water loss standards. Suppliers may use any water loss control actions they deem feasible and effective.

The model assumes that all leaks found within a month would be repaired within that month. On an annual average, the total number of leaks repaired would be the same whether they were repaired within the same month or beyond the month of detection.

The average leak detection frequency is used to divide the entire water distribution system into parts that can be surveyed each month. The model calculates the impact of surveying the water distribution system at the average leak detection frequency on real loss during each month (described in later sections of the guidance). The model calculates the total cost of leak detection by multiplying the unit cost of leak detection for each mile surveyed with the average number of miles surveyed per month. The model calculates the number of unreported leaks to be repaired and the cost of leak repair per month by multiplying the unit cost of repair for each leak with the number of unreported leaks and dividing by the leak detection efficiency to account for false positives. These costs constitute the total associated costs and are calculated for each month. The real monthly discount rate is applied to the costs to calculate the present value of costs in 2020.

The water saved from water loss control is calculated as the difference between the real loss after implementing active leak detection and repair and the baseline average real loss, which is the supplier's current real loss assuming they would maintain the real loss without water loss intervention. This water saved contributes to the benefits of water loss control.

The model applies the annual real rise in price of water to calculate the price of water at the beginning of 2022, after which a monthly rise is applied to the price of water. The price of water is multiplied by the water saved through water loss control. The water saved through water loss control constitutes the benefits. The monthly discount rate is applied to each month of benefits after 2022 to calculate the present value in 2020.

The present values of both benefits and costs are calculated over a period of 30 years from 2022 through 2051. The net benefit is calculated as the difference between the present value of benefits and the present value of costs associated with active leak detection and repair.

<u>Output</u>: This sheet calculates the standard. If the net benefit over 30 years is positive, the model calculates the unreported real loss over the year 2027 by summing the unreported leakage occurring in the 12 months of 2027. The standard is calculated by adding the average annual reported and background leakage to the unreported real loss in 2027, as the model assumes that only unreported leakage can be reduced by all standard industry approaches. If the net benefit over this time period is zero or negative, the standard is raised to the point at which the net benefits are positive, if possible. Otherwise, the standard is set equal to the current average baseline real loss.

SECTION 2: Technical background on water loss control

Distribution system characteristics and the nature of real loss determine the type of intervention strategies systems can use to reduce real loss. Real loss can occur in several forms described as follows (Sturm, Gasner, Wilson, Preston, & Dickinson, 2014; American Water Works Association, 2016):

- <u>Reported</u> leakage that occurs in the form of visible failures over the ground.
- <u>Unreported</u> leakage that is not visible above ground but detectable by surveying the distribution system through specialized leak detection equipment.

- Background leakage that is too small to be detected with leak detection equipment but can be reduced by replacing or rehabilitating infrastructure or managing operational pressure.

Real loss reduction has four key approaches per industry practices that are suited for each form of leakage:

- Active leak detection and repair involves surveying the distribution system for leaks with specialized equipment and repairing those leaks. This method is used to reduce unreported leakage. Water distribution system infrastructure (i.e. pipes, valves, hydrants) is surveyed using specialized leak detection equipment to detect and locate leaks, and then repair them. Leak detection equipment are available commercially and typically use acoustic signals, imaging, or pressure differentials.
- Reducing time between locating and repairing a leak minimizes the amount of water lost through visible or detectable leaks.
- Pressure management to reduce excessively high water pressure or spikes in water pressure (water hammer effect) that strain distribution system infrastructure and increase leakage through existing infrastructure defects.
- Systematic asset management by prioritizing replacement of pipes and other appurtenances, which are leakiest and have most failures, especially located in areas of high consequence, for example, hospitals and dense commercial centers.

Pressure and asset management are the only approaches that can be used to reduce background leakage that is too small to be detected through leak detection equipment (American Water Works Association, 2016, pp. 220,259; Fanner, Thornton, Liemberger, & Sturm, 2007, p. 15). Additionally, reducing repair time with pressure and asset management reduce the occurrence and loss of water through reported leaks. The feasibility of implementing pressure management and asset management and the estimated volume of leakage reduction depends on operational characteristics for each distribution system. Estimating the amount of leakage that is recoverable through pressure management and asset management for urban retail water suppliers is influenced by the operating pressure, the hydraulic design of the distribution system, and the amount of water leaking through pipes needing replacement.

On the other hand, the associated costs and benefits of implementing active leak detection and repair for each supplier can be determined to a much greater degree of accuracy due to the availability of data. The amount of leakage that is recoverable can be determined from data on length of pipeline, number of service connections and operational water pressure, as reported by suppliers. Hence pressure and asset management are excluded from the scope of the model.

SECTION 3: Input parameters

There are twenty-seven input parameters in the model. There are default values provided for all but four of these, and supplier-specific values may be provided for all but two parameters. A supplier may request an adjustment to the default values by providing supplier-specific values no later than July 1, 2023. Adjusting the default values will ultimately adjust the water loss standard for the supplier. If the supplier requests an adjustment, it must provide supporting documentation to adjust a particular input. It must also assess the impacts of the adjustment. General guidance for an adjustment request and supporting documentation is provided for each input parameter. The input parameters are described below within their respective model sections.

***Model Section 1*: Input parameters from water loss audit reports submitted by urban retail water suppliers per Water Code 10608.34 to the California Department of Water Resources**

Drawing from the 2017 to 2020 water loss audits, State Water Board staff determined several input parameters by calculating the average of the parameters shown below. **Note**: For calendar year audits, this will be the time period from January 2017 to December 2020; for fiscal year audits, this will be the time period from July 2016 to June 2020. A supplier may choose to exclude one outlier year to improve data quality. An outlier year has a real loss value that is negative or varies by more than 10 gallons per connection per day (or by more than 740 gallons per mile per day, if a supplier's standard is mileage-based) from the values reported for the other three years. **If possible, adjustments should be made directly to the appropriate water loss audits and resubmitted to DWR.**

Average baseline real loss: Average of current annual real loss.

Adjustment: The data in the water loss audit leading to the adjustment and its supporting evidence for the change in underlying data should be identified.

Average length of mains: Average of length of mains.

Average number of service connections: Average of number of active and inactive service connections.

Adjustments: For adjusting the average length of mains or number of service connections, supporting evidence for the cause for this change should be included in the adjustment request.

Average variable production cost of water: Average of variable production cost.

Adjustment: The request should include the calculation of the new variable production cost, with the cause for change from the previously reported value identified.

Average operating pressure: Average of the annually reported average operating pressure.

Adjustment: The request should include the calculation of the new average operating pressure, with the cause for change from the previously reported value identified. It should also include a summary of the extent and frequency of pressure monitoring in the supplier's water distribution system.

Model Section 2a: Leakage profile of urban retail water supplier

The model uses default values per the AWWA M36 manual, such as the reported, unreported, and background leakage and underlying leakage characteristics. The American Water Works Association M36 manual provides equations for estimating volumes of different types of leakage that exist in a distribution system (American Water Works Association, Fourth edition, 2016, pp. 199-201). The model uses these equations to calculate background leakage and reported leakage that a supplier would have in their distribution system. The model then calculates unreported leakage by deducting the minimum background and reported leakage from the supplier's total leakage as reported in the water loss audits.

Rate of rise of leakage: Default value is 5 gallons per connection per day per year.

Adjustment: The supplier should provide a measurement of rising leakage in a representative portion of their water distribution system. The rising leakage can be measured using leak detection and repair surveys conducted across time by measuring the rise in leakage between surveys divided by the time between surveys and number of connections.

Infrastructure Condition Factor (ICF): Default value is 1.0.

The ICF is used to calculate the minimum amount of background leakage occurring in the water distribution system to then estimate the potential unreported leakage that can be reduced.

Adjustment: In addition to any ICF calculations submitted, the supplier should provide a calculation of the weighted average age of their system using pipe inventory on the age of existing pipes. The weighted average can be calculated using the formula below, where 'L' is the total pipeline length for the distribution system, 'L#' is the pipeline length for a given section, and 'A#' is the pipeline age for a given section.

$$\frac{A1 \times L1 + A2 \times L2 + \cdots}{L}$$

To calculate a new ICF, the supplier should average the ICFs for the following two scenarios:

A. Scenario where there is minimum background leakage. No calculation needed; the ICF for this scenario is always 1.0.
B. Scenario where the total water loss is equal to background leakage, such that ICF = (average real loss)/(unavoidable background leakage), where unavoidable background leakage is calculated as:

$$\left(0.2\left[\frac{thousand\ gallons}{mile \cdot day}\right] \times \text{Length of mains}\ [miles] + 0.008\left[\frac{thousand\ gallons}{service\ connection \cdot day}\right] \times \text{Number of service connections}\right) \times \left(\frac{\text{Average operating pressure}\ [psi]}{70[psi]}\right)^{1.5}$$

There are several methods that can be used to calculate ICF, such as using district metered areas or pressure step tests. Any appropriately used and referenced methods may be used instead of the methods described in this document.

<u>Annual background leakage</u>: No default value; this value is calculated in the model.

The model uses equation 7-5 from the AWWA M36 manual (American Water Works Association, 2016, p. 201) for the unavoidable background leakage which is calculated as follows:

$$\left(0.2\left[\frac{thousand\ gallons}{mile \cdot day}\right] \times \text{Length of mains}\ [miles] + 0.008\left[\frac{thousand\ gallons}{service\ connection \cdot day}\right] \times \text{Number of service connections}\right)$$
$$\times \left(\frac{\text{Average operating pressure}\ [psi]}{70[psi]}\right)^{1.5} \times \text{Infrastructure Condition Factor} \times \left[\frac{1{,}000\ gallons}{thousand\ gallons}\right] \times \left[\frac{1\ acre - foot}{325{,}851\ gallons}\right] \times \left[\frac{365\ days}{year}\right]$$

$$\text{Total Background leakage} = \text{UBL} \times \text{ICF}$$

<u>Adjustment</u>: The supplier should provide documentation on the calculation of this parameter per equation 7-5 from the AWWA M36 manual. This should include the methodology used to determine the ICF (per the adjustment documentation specified for the ICF) and the average operating pressure (per the adjustment documentation specified for the average operating pressure).

<u>Average duration between reporting of and repair of reported leaks on mains</u>: Default value is 3 days.

<u>Adjustment</u>: The supplier should provide logs of the average time taken to repair leaks over 2017 through 2020. If data is unavailable throughout 2017 through 2020, data should be provided for the years available.

<u>Number of reported leaks per year on mains</u>: Default value is 0.2 leaks per mile per year.

<u>Adjustment</u>: The supplier should provide logs of the average annual number of annual reported leaks for the years 2017 through 2020 or the most recent years that data was collected within these years.

<u>Average flow rate of reported leaks on mains</u>: Default value is 50 gallons per minute per leak.

<u>Adjustment</u>: The supplier should provide logs of annual reported leaks and estimated flow rates. These values can be based on size of leak and average operating pressure as calculated in the American Water Works Association M36 Manual, fourth edition, Table 7.3 and equation 7-24. The leak flow rate can also be calculated using in-field methods for measurement. The method and calculations should be described.

Average duration between reporting of and repair of reported leaks on laterals and service lines: Default value is 8 days.

Adjustment: The supplier should provide logs of the average time taken to repair leaks over 2017 through 2020. If data is unavailable throughout 2017 through 2020, data should be provided for the years available.

Number of reported leaks per year on laterals and service lines: Default value is 2.3 leaks per 1,000 connections per year.

Adjustment: The supplier should provide logs of the average annual number of annual reported leaks for the years 2017 through 2020 or the most recent years that data was collected within these years.

Average flow rate of reported leaks on laterals and service lines: Default value is 7 gallons per minute per leak.

Adjustment: The supplier should provide logs of annual reported leaks and estimated flow rates. These values can be based on size of leak and average operating pressure as calculated in the American Water Works Association M36 Manual, fourth edition, Table 7.3 and equation 7-24. The leak flow rate can also be calculated using in-field methods for measurement. The method and calculations should be described.

Annual reported leakage, if known: No default input; this value is calculated in the model.

The volume of reported leakage is calculated based on average number of reported leaks over 2017 through 2020 and estimated average flow rate of reported leaks using the following equation:

Adjustment: If this values is known to the supplier, the supplier should provide documentation on average number of reported leaks as specified for adjustments for number of reported leaks, duration of leaks and corresponding flow rates, and a document showing the calculation of the total volume.

Unreported leakage, if known: No default input; this value is calculated in the model.

This value is calculated in the model using the following equation:

$$\text{Average baseline real loss} - \text{total background leakage} - \text{reported leakage}$$

Adjustment: If this value is known to the supplier, the supplier should provide documentation on the average number of unreported leaks from 2017 through 2020 as specified for adjustments for number of unreported leaks and corresponding flow rates. The supplier should also provide a document showing the calculation of unreported leakage, in addition to results from leak detection surveys for representative portions of the supplier-owned water distribution system. The sum of the annual unreported leakage, annual reported leakage and annual background leakage should be equal to the average baseline real loss.

Number of unreported leaks per year on mains: Default value is 0.01 leaks per 100 miles of mains.

Number of unreported leaks per year on service lines or laterals: Default value is 0.75 leaks per 1,000 service connections.

Adjustment: The supplier should provide documentation on how these values were calculated, in addition to results from leak detection surveys for representative portions of the supplier-owned water distribution system.

***Model Section 2b*: Associated unit costs and marginal avoided costs of water**

Average leak detection survey frequency: Default values are provided by system size in Table 1.

Table 1. Average leak detection frequency in economic model

Total pipe length (miles)	Survey Frequency Assumptions
Less than 500	Survey once every 2 years
500 to 1,000	Survey once every 2.5 years
1,000 to 4,000	Survey once every 3 years
4,000 to 6,000	Survey 114 miles per month
Above 6,000	Survey 130 miles per month

Adjustment: If active leak detection and repair is the only method that would be used to meet the standard, supporting documentation should include previous leak detection surveys, efficiency achieved, and identification of the portions of the water distribution system for which active leak detection and survey cannot be conducted. Based on this supporting evidence, the supplier may request to adjust the average leak detection survey frequency that is feasible for the supplier, including all types of proactive leak detection, such as visual surveying. Suppliers may also use the survey frequency provided by the UC Davis economic model *if they intend to survey at that frequency*.

Unit average cost of leak detection surveying: Default value is $595 per mile.

Adjustment: The supplier should provide competitive estimates from vendors for leak detection for which the supplier plans to opt.

Efficiency of leak detection equipment: Default value is 70%.

This value represents the average percentage of actual leaks found on excavation, as a percentage of the total detected leaks including false positives expected to be pinpointed by leak detection equipment. The efficiency of leak detection increases with higher training and field implementation experience. This parameter adds the cost of additional excavation associated with locating leaks pinpointed by false positives, without the benefits of water loss reduction, to the overall costs of leak detection and repair.

Adjustment: The supplier should provide results of active leak detection and repair of a representative portion of the supplier-owned water distribution system. The supplier should outline the number of leaks detected using pinpointing that resulted in excavation and repairs, and the number of actual leaks found during excavation.

Average unit leak repair costs for mains: Default value is $5,946 per leak repaired.

Average unit cost of leak repair costs for laterals and service lines: Default value is $2,330 per leak repaired.

Adjustments: The supplier should provide a summary of the historical unit repair costs over the years of 2017 through 2022 for unit repair costs of mains and service connections or lateral lines, respectively.

Marginal avoided cost of water: Default value is $1,275 per acre-foot of water loss reduced.

Some suppliers may have expanded their water portfolios by including alternative water sources in their variable production costs, while suppliers relying on local water resources (e.g. only groundwater or local snowmelt) may not have incorporated long-term avoided costs in their variable production costs. The State Water Board values water lost through leakage at the higher value between variable production cost and the avoided cost of water. The present value of the avoided cost has been calculated for 2020.

Adjustment: The supplier should provide an estimate of the marginal avoided cost of water. This estimate should consider future water resilience as well as any future costs that would be avoided due to water loss savings and improved monitoring and maintenance of the supplier-owned water distribution system. Water resilience and avoided costs may include avoided costs in obtaining new water supplies, environmental impacts due to additional surface or groundwater extractions, rise in costs due to additional volumes of imported water purchased, prevented unexpected water distribution infrastructure failures, water treatment necessary to address PFOA and PFAS, and sustainable groundwater management practices.

Average annual rise in price of water: Default value is 4.2%.

Adjustment: The supplier should provide evidence and calculations of the proposed rise in price of water value, which may include costs for the supplier over time. **The rise in price of water value cannot be less than the real discount rate** (3.5%) **and must be developed and certified by a licensed engineer** (proposed regulations section 984(b)(1)).

***Model Section 3*: State determined inputs to the model (cannot be adjusted)**

Real discount rate: The value is estimated to be 3.5%.

The associated costs and benefits would be discounted annually at a rate of 3.5% per stakeholder recommendation. This is also in line with the US EPA's Guidelines for Preparing Economic Analysis (2014), which suggests that the real discount rate should fall in the range of 3%-7%, depending on whether costs and benefits are incurred within the specified time horizon. In general, lower discount rates are adopted if the impact is anticipated to last longer.

Effective timeline for lifecycle benefit-cost analysis: The estimated lifecycle period is 30 years.

Leak detection equipment and pipe repair material have lifecycle periods that extend beyond the regulatory compliance date of 2028. The model accounts for the useful life of leak detection and repair equipment in the time horizon.

SECTION 4: Calculation of impact of intervention on real loss

The intent of this regulation is to provide suppliers the flexibility to choose any approach best suited for their system and budget to reduce the leakage to the volumetric standard. The economic model developed by the State Water Board to calculate the individual volumetric standards focuses on unreported, hidden leakage to ensure flexibility in choice of approach.

The State Water Board developed a model to calculate volumetric standards for urban retail water suppliers by analyzing the costs and benefits associated with leakage reduction. If the leakage reduction results in a net positive benefit to the supplier, the supplier would reduce the amount of leakage during the compliance period, based on its distribution system characteristics.

Calculating reduction in leakage with regular surveying per the assumed survey frequencies.

The model uses the following methodology to calculate the reduction in leakage due to regular active leak detection.

The model relies on simplifying assumptions:

- All detected leaks are repaired by the supplier within the same month as detected.
- The model is applied to various system sizes and allows for partial leak detection surveys. The model divides the water distribution system for each supplier into parts that can be surveyed within a month and calculates the associated benefits and costs across a 30 year time horizon. It is assumed, for simplicity, that at any point in time, a part of the system is being surveyed. The rate of surveying is an average rate for the entire system.

The model calculates the reduced water loss that occurs as a result of active leak detection and repair and compares it to the water loss that would occur if the supplier maintained their water loss at the baseline or current level. The model calculates additional costs the system would incur in order to reduce water loss through leak detection and repair. If the net benefit is positive, the supplier is required to reduce the water loss to the standard calculated. The 2028 standard is equivalent to the water loss occurring during the year prior to compliance in 2028, since water loss is reported annually.

The model calculates the effect of active leak detection and repair on the backlog of leakage and rising leakage in order to determine its overall impact on water loss. The model employs the following simplified procedure to estimate the impact of intervention:

Variables Used

The following variables are used in the equations described below:

- N = Number of parts into which the distribution system is divided (equivalent to n which is equivalent to the Number of months taken to survey entire system) (cell B60)
- ΔT = Duration of time step in model (equivalent to one month or one twelfth of a year)
- L_o = Annual unreported leakage
- l_o = Unreported leakage per part of the system (cell B61), calculated as L_o divided by N.
- R = Natural rise in leakage for the entire system
- r = Rate of natural rise of leakage per part of the system occurring (cell B62), calculated as R divided by N

It is assumed, for simplicity, that at any point in time, a part of the system is being surveyed. The rate of surveying is an average rate for the entire system. The model determines the economically achievable volumetric water loss by calculating how much water loss occurs at that time. Thus, the 2028 standard is calculated by calculating the water loss occurring at the time step coinciding with the beginning of 2027.

The model divides the water lost during regular leak detection and surveying into three elements for ease of calculation:

- Water lost due to backlog of unreported leakage
- Water lost due to natural rise in leakage for the never surveyed parts of the system (for the first survey)
- Water lost due to natural rise in leakage for rest of the system not being surveyed in current time step (parts that have been surveyed before)

Figures 1 through 3 show the unreported leakage per month for each of the three leakage components for each section of the system, with the y-axis displaying unreported leakage per month and the x-axis displaying month of implementation. The volume of unreported leakage occurring in each month of implementation is equivalent to the sum of the three water lost columns. Thus, the volume of leakage occurring during each month is equivalent to the area under the curve for each component of leakage.

Water loss due to backlog of leakage from parts not surveyed in each month (Column 2)

This column calculates the water loss from the unsurveyed parts (backlog) of the system. After a full leak detection survey, this column will be zero for the remaining months. As each part of the system is surveyed, leaks are fixed in surveyed parts and the number of unsurveyed parts decreases.

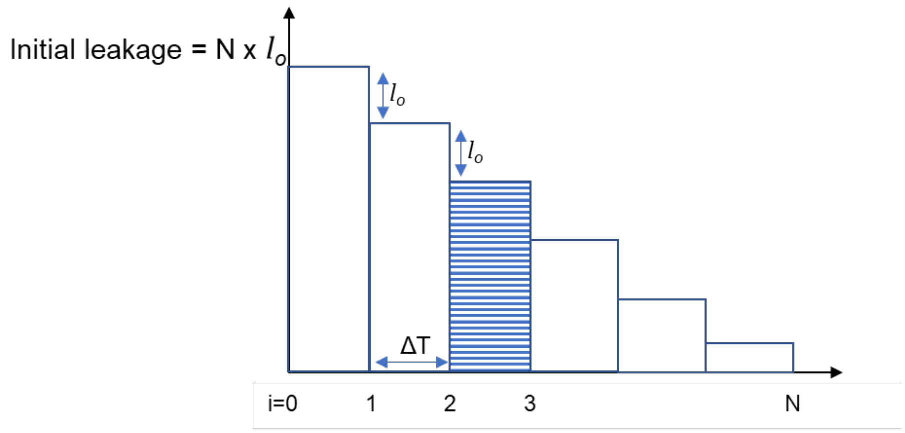

Figure 1. Decrease in backlog unreported leakage as each part of the distribution system is surveyed

Error! Not a valid bookmark self-reference. shows how the backlog of unreported leakage for the entire system is impacted after each part of the system is surveyed. The backlog element considered here do not include any rise in leakage, as elements including rising leakage are calculated separately. As parts of the system are surveyed serially, the overall backlog of unreported leakage drops by l_o in each time step (the backlog unreported leakage per part of the system).

At time step *i*, the survey would begin for the i^{th} part of the system. Thus, during each month, leakage would occur from the parts that have not been surveyed yet, that is, $(N - i)$, and one additional part to be surveyed by the end of the current time step, such that the number of parts of the system not surveyed yet is equal to $(N – i) + 1$.

Each part of the system will leak at l_o during the duration of the current month ΔT as shown in the dashed part of the schematic. The water loss occurring in the month of implementation *i* from all parts in the system due to only backlog leakage is represented as $\Delta T \times l_o \times (N – i + 1)$.

Water loss due to natural rise in leakage in never surveyed parts in each month (Column 3)

Figure 2 shows how the rising unreported leakage for the entire system is impacted after each part of the system is surveyed for the first time. Leakage levels for each part of the system increase at the rate of rise of leakage, until that part of the system is surveyed. All the parts of the system which have not been surveyed before are at the same leakage level by a particular month of implementation.

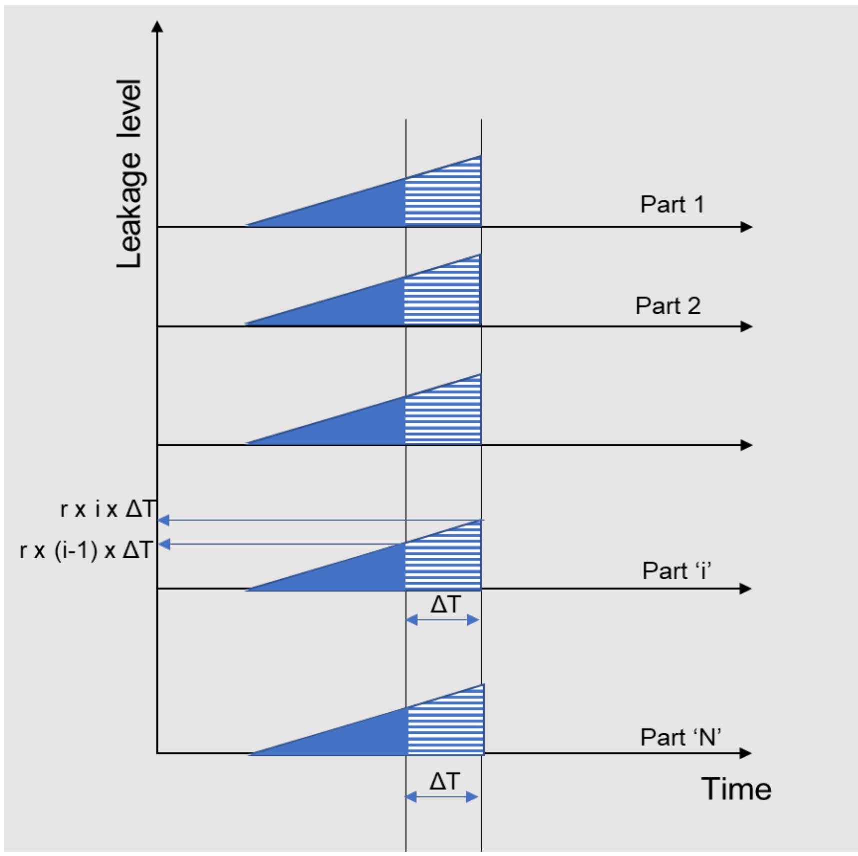

Figure 2. Rise in leakage in parts of the system never surveyed before

The leakage occurring in each time step is the area under the curve traced by the leakage level and time. The area under the leakage curve for each duration of a month is marked by the dashed area in the schematic.

$$\frac{1}{2} \times (r \times (i-1) \times \Delta T) \times \Delta T = \big(r \times \Delta T \times (i-0.5)\big) \times \Delta T = r \times \Delta T^2 \times (i-0.5)$$

During the first survey, while the i^{th} part is being surveyed, *(i-1)* parts would have been surveyed. Hence, out of *N* parts, *(N - i +1)* parts would remain to be surveyed and would have been leaking due to the naturally rising leakage. The total leakage due to this component is as follows:

$$(N - i + 1) \times \left(r \times \Delta T^2 \times (i - 0.5)\right)$$

Water loss due to natural rise in leakage in previously surveyed parts in each month (Column 4)

Figure 3 shows how the rising unreported leakage for the entire system is impacted after each part of the system that has been surveyed at least once before. Each part of the system starts leaking after a survey as the leakage rises naturally in the distribution system after being surveyed. The leakage occurring in each month of implementation is the rise in leakage that occurs over that time step for all parts of the system. Since this component of leakage occurs in previously surveyed parts, all parts are surveyed at different times.

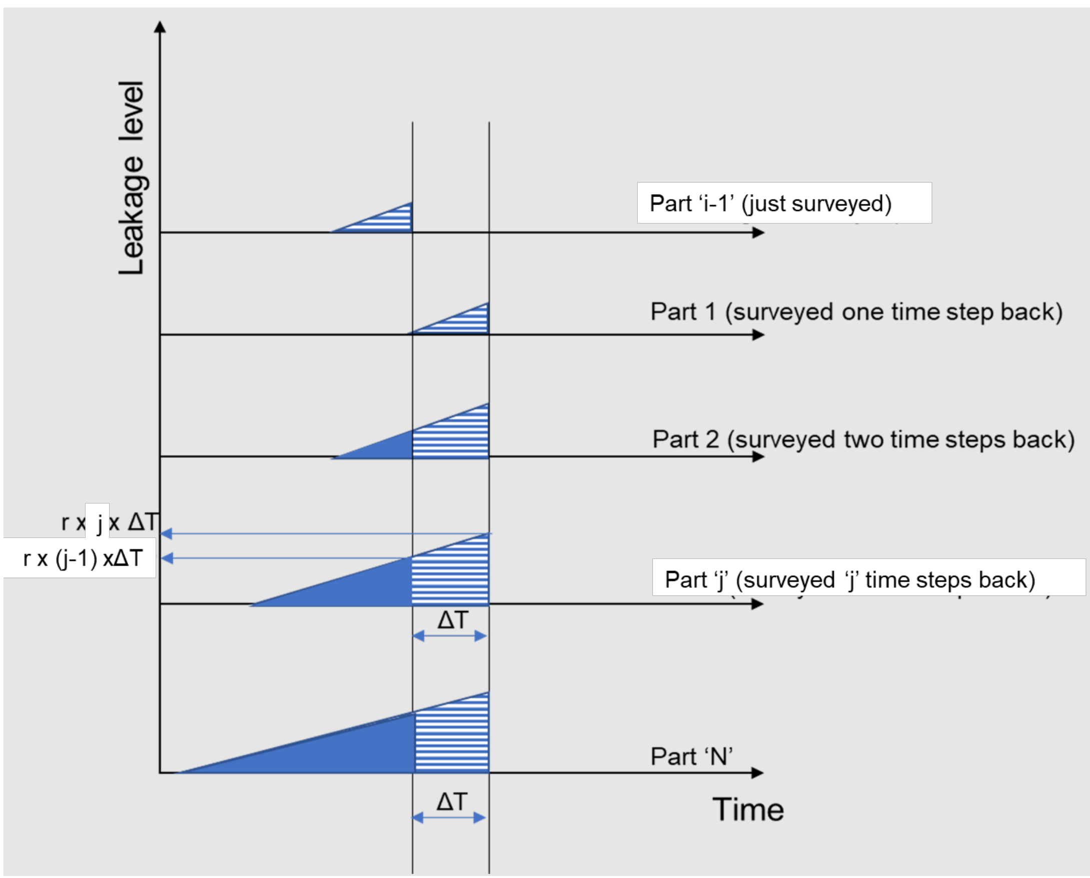

Figure 3. Rise in leakage in parts of the system that have been surveyed before

The rise in leakage up to the beginning of the time step is represented by the rate of rise of leakage times the months since implementation. The leakage level due to natural rise in leakage at the end of the i^{th} month equals $r \times i \times \Delta T$. Each part of the system will contribute to the overall leakage in this component as follows:

$Part\ 1{:}\frac{1}{2}\times(\mathbf{0}+r\times\mathbf{1}\times\Delta T);Part\ 2{:}\ \frac{1}{2}\times(r\times\mathbf{1}\times\Delta T+r\times\mathbf{2}\times\Delta T)\times\Delta T;Part\ 3{:}\ \frac{1}{2}\times(r\times\mathbf{2}\times\Delta T+r\times\mathbf{3}\times\Delta T)\ldots;Part\ i{:}\ \frac{1}{2}\times(r\times(\boldsymbol{j}-\mathbf{1})\times\Delta T+r\times\boldsymbol{j}\times\Delta T)$

The leakage volume lost during the i^{th} month for a single part of the system can be simplified as follows:

$$=\frac{1}{2}\times(r\times(\boldsymbol{j}-\mathbf{1})\times\Delta T+r\times\boldsymbol{j}\times\Delta T)$$

$$=\frac{1}{2}\times(r\times j\times\Delta T-r\times\Delta T+r\times j\times\Delta T)$$

$$=\frac{1}{2}\times(2\times r\times j\times\Delta T-r\times\Delta T)\times\Delta T$$

$$=\left(r\times j\times\Delta T-\frac{1}{2}\times r\times\Delta T\right)\times\Delta T$$

$$=r\times\Delta T^2\times\left(j-\frac{1}{2}\right)$$

If the distribution system is being surveyed for the first time, only *(i-1)* parts have been surveyed when the i^{th} month begins, and will contribute to this element of leakage:

$$=r\times\Delta T^2\times\sum_{j=1}^{i-1}\left(j-\frac{1}{2}\right)$$

$$=\sum_{j=1}^{i-1}\frac{1}{2}\times r\times\Delta T^2\times\left(j-\frac{1}{2}\right)$$

$$=\frac{1}{2}\times r\times\Delta T^2\times\left(\frac{(\boldsymbol{i}-\mathbf{1})\times\left((\boldsymbol{i}-\mathbf{1})+1\right)}{2}-\frac{(\boldsymbol{i}-\mathbf{1})}{2}\right)$$

$$=\frac{1}{2}\times r\times\Delta T^2\times\left(\frac{(\boldsymbol{i}-\mathbf{1})\times(i)}{2}-\frac{(\boldsymbol{i}-\mathbf{1})}{2}\right)$$

$$=\frac{1}{2}\times r\times\Delta T^2\times\left(\frac{i^2-2\times i+1}{2}\right)$$

The loss due to only rising leakage for previously surveyed parts of the system is as follows:

$$\frac{1}{2} \times r \times \Delta T^2 \times \left(\frac{(i-1)^2}{2}\right)$$

Once the system has undergone a complete survey, all *N* parts of the system contribute to the natural rise in leakage in previously surveyed parts. Therefore, the equation used to calculate the natural rise in leakage changes to:

$$= \frac{1}{2} \times r \times \Delta T^2 \times N^2$$

Water loss occurring without intervention in each month (Column 7)

Without any intervention, it is assumed that suppliers would maintain the 2022 real loss for their systems (three-year average of real loss reported by supplier). The 2022 real loss is calculated by adding the rise in leakage from 2020 through 2022 (Figure 4). The leakage occurring during the i^{th} step can be calculated with the following equations:

$$\frac{1}{2} \times (l_o + r \times (i-1) \times \Delta\mathrm{T} + l_o + \mathrm{r} \times \mathrm{i} \times \Delta\mathrm{T}) \times \Delta\mathrm{T}$$

$$= \frac{1}{2} \times (2l_o + 2r \times (i) \times \Delta\mathrm{T} - \mathrm{r} \times \Delta\mathrm{T}) \times \Delta\mathrm{T}$$

$$= (l_o + r \times (i) \times \Delta\mathrm{T} - 0.5 \times \mathrm{r} \times \Delta\mathrm{T}) \times \Delta\mathrm{T}$$

$$= \big(l_o + r \times \Delta\mathrm{T} \times (i - 0.5)\big) \times \Delta\mathrm{T}$$

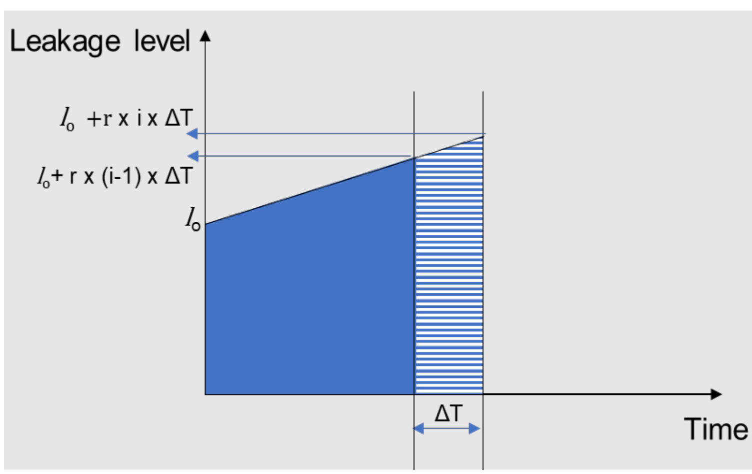

Figure 4. Increasing leakage through time before surveying

Leakage without intervention for each part from 2022 and beyond assumes that the leakage occurring each month is equal to the leakage that occurred during the first month because suppliers will be maintaining that level of leakage (demonstrated in

Figure 5). The following equation can be used to calculate the leakage without intervention, given that the month of implementation will always equal 1:

$$\text{Months taken to survey whole system} \times \Delta\mathrm{T} \times \begin{pmatrix} \mathit{Unreported\ leakage\ per\ month} + \mathit{Rate\ of\ rise\ of\ leakage\ per\ month} \times \\ (\mathit{month\ of\ implementation} - 0.5) \times \Delta\mathrm{T} \end{pmatrix}$$

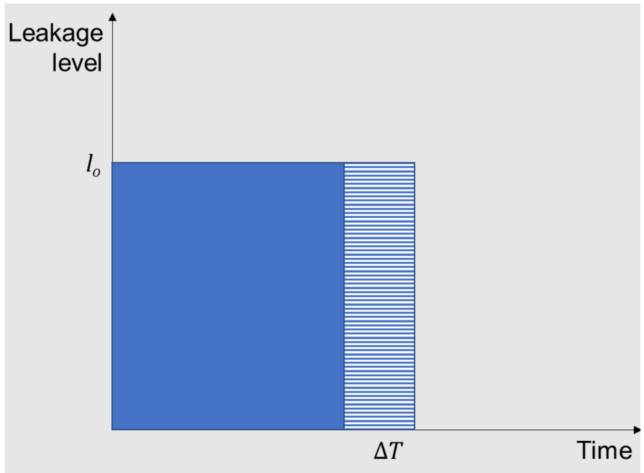

Figure 5. Leakage without intervention

SECTION 5: Benefit-cost analysis for water loss control actions

Water saved due to water loss control in each month with intervention actions (Column 9)

The water lost in each month with intervention is calculated by adding the three following components together: water lost due to backlog of unreported leakage, water loss due to natural rise in leakage in parts of the system never surveyed, and water lost due to natural rise in leakage in parts of the system surveyed previously (Column 5). This sum is subtracted from the water lost without any water loss control actions (Column 7) to calculate the water saved due to water loss control actions (active leak detection and repair) (Column 9).

Unreported leakage level for parts surveyed each month; Leaks found per part of the system with intervention; and efficiency of leak detection equipment (Columns 11 and 12)

The initial unreported leakage occurring in a month is used to determine the number of leaks that would need to be repaired in that month. The unreported leakage occurring in a month is calculated as the sum of the backlog and natural rise in leakage that has occurred since the last survey. Once the backlog is reduced to zero, the leakage per part of the system is reduced to just the natural rise in leakage since the last survey.

The number of leaks repaired each month is calculated as the total number of leaks occurring annually multiplied by the proportion of leakage occurring in that month. The number of unreported leaks is calculated per the AWWA M36 manual by summing the unreported leaks on mains and unreported leaks on service lines or laterals.

Cost associated with water loss control actions (Columns 10, 13, 14, 15)

The cost of leak detection per mile is multiplied by the number of miles surveyed over the time horizon of 30 years. The cost of repairing each unreported leak is multiplied by the number of unreported leaks detected divided by the leak detection efficiency to account for false positives. The sum of cost of leak detection and repair is calculated over the time horizon. The present value of costs is also calculated for reference using a discount rate of 3.5%.

Benefit associated with water loss control actions (Columns 16, 17, 18)

The benefit is calculated by multiplying the higher value of the avoided cost of water and the variable production cost of water by the water saved due to water loss control every month. The real annual rise in price of water is applied to this product. The present value of benefits is also calculated for reference using a discount rate of 3.5%.

Water loss over the year 2027 (Columns 19 and 20)

In the model the net benefit is calculated by deducting the total cost for each month from the value of water lost for each month, without applying the discount rate. The discount rate is then applied to the net benefit to calculate its present value. This present value of the net benefit over 30 years is used to assess the benefit cost.

Correlation of leakage reduction with unreported leakage

The model calculates a performance standard based on water system and leakage characteristics. The calculated percent reduction is strongly correlated with unreported leakage. The benefits associated with water loss reduction for suppliers with a high unreported leakage are high, whereas the benefits for suppliers with low unreported leakage are low (Figure 6).

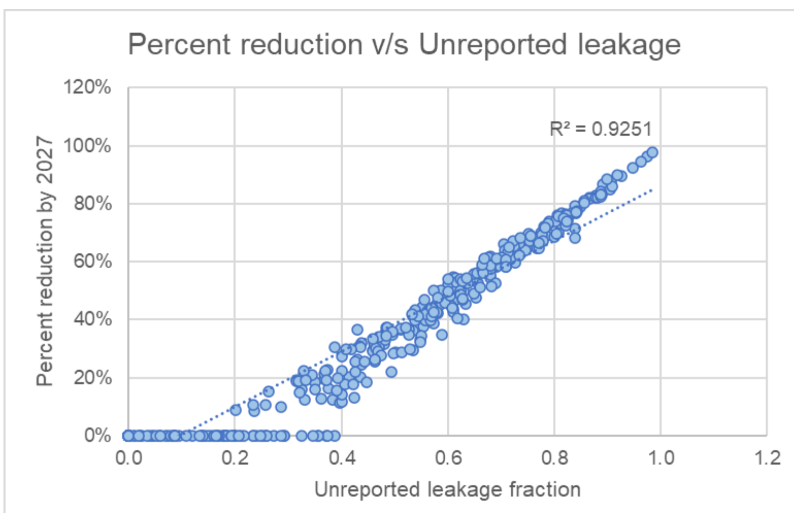

Figure 6. Correlation of percent leakage reduction with unreported leakage fraction

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