INTERPRETING AND USING DMA DATA

DRAFT V01

WATER LOSS SPECIALIST GROUP

APRIL 2026

EDITED BY STUART TROW, MIKAL WILLMOTT, FABIO GARZÓN AND ANNA BOJKO

CONTENT

List of Figures

List of Tables

FOREWORD

The IWA Water Loss Specialist Group (WLSG) has, for more than two decades, been at the forefront of advancing global knowledge and best practice in water loss management. Bringing together practitioners, researchers, and utility leaders from around the world, the Group represents a unique, collaborative network dedicated to reducing non-revenue water and improving the efficiency and sustainability of water distribution systems.

What defines the WLSG is not only its technical expertise, but its ethos of open collaboration. The work presented in this manual reflects a collective effort developed by many active members of the Group where all data, experience, and insights have been freely shared and contributed. This spirit of openness is fundamental to the Group's mission: enabling knowledge transfer across borders, supporting utilities at all stages of maturity, and ensuring that proven methodologies are accessible to all who need them.

This publication is a direct initiative of the WLSG and stands as a testament to the strength of its global community. It builds upon years of shared learning, discussion, and innovation, transforming practical experience into structured guidance that can be applied in diverse operational contexts. As highlighted in this maual, the value of data, particularly from District Metered Areas, lies not only in its collection, but in its interpretation and use to drive effective decision-making and operational improvement.

In 2026, as this manual is released, the WLSG marks its 25th year. Over this period, the Group has grown into a vibrant and influential community of more than 5,000 active members worldwide. These professionals working across utilities, consultancies, academia, and technology providers form the backbone of global progress in water loss management. This manual is written for them, and for the many more who will join this journey in the years ahead.

The knowledge contained within these pages reflects the dedication and generosity of contributors from across the WLSG. It is intended not as a rigid prescription, but as a practical and adaptable resource supporting both experienced practitioners and those new to the field. In this way, it continues the long-standing tradition of the Group: to provide guidance that is grounded in real-world application, informed by data, and strengthened through collaboration.

As Chair of the IWA Water Loss Specialist Group, I am proud to present this manual as part of our ongoing commitment to advancing science and practice of water loss management. I extend my sincere thanks to all those who have contributed their time, expertise, and experience to this initiative.

Stuart Hamilton

Chair, IWA Water Loss Specialist Group

PREFACE

The IWA Water Loss Specialist Group developed its first DMA Manual in 2007 which was reviewed and updated in 2024. Those Guidance Notes are intended as an introduction for leakage practitioners to the benefits, design, establishment and management of District Metered Areas.

With more and more organizations around the world investing in creating district metered areas within their networks as a key element of their water loss reduction strategies, there is a need for further guidance on how data from DMAs can be used to assess levels of water loss and guide operations. The flow and pressure data from DMAs can provide operators with detailed diagnostic information about network performance and support efficient management decisions.

I have been involved in all aspects of water loss management for almost 50 years and have been a member of the IWA Water Loss Specialist Group for over 20 years. The UK water company I joined in 1979 already had over 90% of its network covered by district meters which were read manually every Wednesday. As well as designing new DMAs, one of my first jobs was to input the readings into our weekly metering database and use the data to plan where to send our leak detection technicians. Since then, the techniques to collect, store and analyze DMA flow data have improved greatly.

My original proposal for this initiative was to include one or two chapters in the updated manual on the use of DMA data. However, it soon became apparent that there was too much information to collate in the time available and so I proposed a separate initiative which was launched at Water Loss 2024 in San Sebastian, Spain. At that conference I called for volunteers to lead the initiative and was delighted that Mikal Willmott and Fabio Garzon came forward and together we agreed on the scope. They have been joined by a wide range of authors from different backgrounds: 16 people from 12 countries have contributed text. Anna Bojko, who as well as contributing text herself, has together with Lisa Brown undertaken the challenging task of collating the various sources and compiling them into a standard format document. My role has been to support, review, edit and add a little to the final document.

As I approach the end of my water loss career, I am reassured that there are so many knowledgeable and enthusiastic people who are as interested in the subject as I have been. I'd like to thank all the contributors for their efforts in producing what I am sure will be a useful reference manual for the global water industry.

Stuart Trow

Initiative Promoter and Advisor

CONTRIBUTORS

Anna Bojko
Independent Water Supply and NRW Consultant
French Guiana

Anna has MSc in Hydroinformatics, and since more than 20 years specialises in optimization of water distribution systems in low- and middle-income countries, including NRW, hydraulic modelling, sectorisation and digitalisation, supporting utilities and donor-funded programs to translate data into measurable reductions in water losses.

Katarzyna Chwastek
Senior Hydraulic Modeller, Jacobs
UK

Katarzyna has over six years of experience in water utilities sector across UK and international projects, specialising in hydraulic modelling. Her work focuses on water loss management and application of data-driven solutions to improve water infrastructure performance and operational efficiency.

Tom Crowder
Director,
Crowder Consulting
UK

Tom is a Chartered Manager and Director at Crowder Consulting with over 25 years' experience in water networks and water loss management. He leads specialist teams, develops new services, delivers consultancy and digital projects, and serves on the International Water Association Water Loss Specialist Group committee.

Igor Dundovic
Water Supply Consultant
Hidromodel
Croatia

Igor is a Water specialist, Chartered engineer and Educator known for his expertise in hydraulic modelling, problem solving and DMA/PMA establishment for NRW reduction projects. He has worked on projects across Europe, Asia, and Africa, collaborating with 50 different water service providers.

Guillaume Féry
Independent Senior Water Sector Specialist / Digital Transformation & Technology, Switzerland

Guillaume is a water utilities specialist, WASH engineer, and cleantech expert with over 20 years of experience in water management and technology. Since 2019, he has advised development banks on smart water and climate resilience initiatives across Africa, the Caribbean, and South Asia, and writes on digitalisation, technology adoption, impact, and project management.

Fabio Garzón-Contreras
Water Loss Specialist,
HydroFlux
Colombia

Fabio is a Hydrotechnical Engineer with 36 years' experience in water resources management. He specializes in performance-based NRW reduction and water utilities efficiency programs for major organizations, including the World Bank, IDB, and Miya, working in over 30 countries. He joined the IWA WLSG Management Committee in 2022.

Claudio Cortés Henríquez
Water Loss Specialist
Aguas Antofagasta
Chile

Claudio has worked for nearly 10 years in water loss control in northern Chile. With a background in continuous improvement and data analysis, he focuses on improving processes for non-revenue water reduction and has led the testing and implementation of technologies to improve leakage management.

Klavs Høgh
Project Director
NIRAS A/S
Denmark

Klavs has worked in the field of Hydroinformatics for more than 30 years specializing in applying smart water systems, hydraulic models and digital twins to support non-revenue water management & water loss control. Klavs has extensive experience in designing smart water systems with online/real-time integration to operational systems.

Frank van der Hulst
Co-founder & CTO
HULO
Netherlands

Frank has a background in water, robotics and real-time data analytics, he has extensive experience turning research into scalable software solutions. Frank has worked closely with utilities on pilots and deployments, bridging advanced hydraulic modelling with practical operational needs.

Thomas Kressin
Global Product Manager
Gutermann
Germany

Thomas holds degrees in telecommunications engineering and marketing and over 20 years of global product management experience across major metering industry players. Since 2023, he has focused on acoustic leak detection, passioned by delivering meaningful, application focused solutions that create value for utilities worldwide.

Metin Misirdali
Water Supply Specialist
Türkiye/UAE

Metin is a Civil Engineer (MSc) with over two decades of experience in hydraulic structures and water infrastructure. In Turkey and the GCC Region, Metin served as a consultant for and in collaboration with Water Utilities to implement digital transformation, hydraulic modelling and NRW Reduction.

Thorkil Neergaard
Freelance Consultant,
Former CEO Brønderslev
Water Company Ltd.
Denmark

Thorkil has been CEO of a Brønderslev Water Company Ltd. for 11 years. He and the water utility are amongst the frontrunners in Europe fully to catch and combine real-time water data from several sources including Smart Meters in an advanced GIS-based Management System.

Mark Nicol
Commercial Director
HWM Global
UK / Malaysia

Mark has over 25 years' experience in water supply management across developed and emerging markets. Specialising in NRW control, leak detection, and pipeline asset management, he has spearheaded innovative, technology-driven solutions for utilities worldwide.

Julian Sepulveda
Water Supply Specialist
Colombia

Julian is a Water Engineer with a specialization in Finance and an MBA, bringing 28 years of international experience in potable water distribution. Expert in network operations and NRW reduction, combining hydraulic modelling, asset management, and district metering strategies.

Stuart Trow
HWM Global
UK

Stuart has dedicated nearly 50 years to water loss management and has been an active member of the IWA Water Loss Specialist Group for over two decades. Beginning his career in 1979, he has helped advance DMA design, data collection and analysis, and leakage strategy.

Graham Waley
Asset Management
Principal Consultant
Stantec
UK & Ireland

Graham is an asset management professional and water loss management practitioner with over 20 years working in the water sector. Based in the UK presently he has worked in Europe and North America across water loss topics using DMAs. He is passionate about delivering efficient water services through effective network management.

Mikal Willmott
Leakage Performance &
Strategy Manager
Severn Trent
UK

Mikal is a Chartered Water and Environmental Manager, who has worked in water loss management for over 20 years. Mikal has focussed on understanding water demand, improving flow monitoring, enhancing innovation and bringing leakage best practice to a worldwide audience.

LIST OF ACRONYMS

AL	Apparent Losses
ALC	Active Leakage Control
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
AOI	Area of Interest
AOP	Average Operating Pressure
AV	Air Valve
AZNP	Average Zone Night Pressure
AZP	Average Zone Point
BABE	Burst and Background Estimation
BU	Bottom-Up Leakage Assessment
CAL	Correlating Acoustic Loggers
CAPEX	Capital Expenditure
CARL	Current Annual Real Losses
CLM	Component Loss Model
CLU	Continuous Logged User
CP	Critical Point
DCF	Discounted Cash Flow
DMA	District Metered Area
DPA	Discrete Pressure Area
ELAL	Economic Level of Apparent Losses
ELL	Economic Level of Leakage
EM	Electromagnetic Meter
EoS	Edge of Street
ESPB	Equivalent Service Pipe Burst
FAVAD	Fixed and Variable Area Discharge
FH	Fire Hydrant
GIS	Geographical Information System
GPR	Ground Penetrating Radar
HDF	Hour to Day Factor
ICF	Infrastructure Condition Factor
IHM	Individual Household Monitor
ILI	Infrastructure Leakage Index
IWS	Intermittent Water Supply
LCA	Leakage Control Area
LDNC	Legitimate Domestic Night Consumption
LMS	Leakage Management System
LNC	Leak Noise Correlator
LNC	Legitimate Night Consumption
LNHHNC	Legitimate Non-household Night Consumption
MABL	Minimum Achievable Night Flow
MCR	Marginal Cost of Revenue
MCW	Marginal Cost of Water
MF	Minimum Flow
MinHist	Minimum Historic Night Flow
MNF	Minimum Night Flow Method
MUR	Meter Under-Registration
MVW	Marginal Value of Water
NDF	Night Day Factor
NF	Net Flow
NMUAF	Non-Metered Use Adjustment Factor
NPV	Net Present Value
NRR	Natural Rate of Rise of Leakage
NRW	Non-Revenue Water
OPEX	Operational Expenditure
PCC	Per Capita Consumption
PHC	Per Household Consumption
PIM	Pipeline Insertion Method
PLC	Programmable Logic Controller
PIs	Performance Indicators
PM	Pressure Management
PMA	Pressure Managed Area
PMI	Pressure Management Index
PRV	Pressure Reducing Valve
PSV	Pressure Sustaining Valve
PZT	Pressure Zero Test
RL	Real Losses
SAM	Small Area Monitor
SCF	System Correction Factor
SR	Service Reservoir
ST	Supply Time
SV	Sluice Valve
TD	Top-Down Leakage Assessment
TIF Method	Total Integrated Flow Method
UARL	Unavoidable Annual Real Losses
UBL	Unavoidable Background Leakage
UFW	Unaccounted for Water
WMS	Work Management System
WO	Wash Out
WRZ	Water Resource Zone
WSZ	Water Supply Zon

1 INTRODUCTION

F. Garzón-Contreras[1] and M. Willmot[2]

[1] *HydroFlux, Cali, Colombia*
[2] *Severn Trent Water, UK*

1.1 BACKGROUND AND RATIONALE

In March 2024, the IWA Water Loss Specialist Group updated its 2007 guidance notes for District Metered Areas (DMA)[1]. That benchmark document focuses on the foundational concepts of leakage control through DMA management and the best practices for designing and establishing DMAs. However, establishing a DMA is only the first step; the true value of the investment lies in the data it generates.

While zoning networks remain a common practice for reducing and controlling leakage, the global landscape has changed fundamentally since the first IWA guidance was published in 2007. Two primary drivers have created an urgent need for this new publication:

- The Digital Catalyst (Post-COVID-19): The COVID-19 pandemic acted as a global accelerant for the digitalization of utility processes. Remote network management shifted from an innovative "pilot" phase to an operational necessity. Utilities are now collecting more data, at higher frequencies, than ever before.
- The Age of Artificial Intelligence and Decision Intelligence: The emergence of Generative AI and advanced machine learning has shifted the industry's challenge. We are no longer data-poor; we are information-overwhelmed. The question for the modern water professional is no longer "how do I get data?" but "what do I do with this data to make better decisions?"

To answer that question, this manual provides a rigorous framework for navigating the digital DMA. It focuses on four critical pillars of data maturity:

- Data Quality: Moving beyond raw collection to ensure data is accurate and validated.
- Data Utilization: Providing specific methodologies to transform consumption data and flow and pressure readings into actionable operational insights.
- Sustainability: Establishing protocols to ensure that data remains "fit for purpose" throughout the life of the asset.
- Confidence Assessment: Implementing a structured approach to assessing the level of confidence practitioners should have in their data before committing resources to field interventions.

---

[1] ISO 24528:2021 (Section3.9) defines the term DMA as "district metering area" (using metering rather than metered), this document maintains the traditional term, "metered."

1.2 DEFINING THE DMA AS A DATA BOUNDARY

In the context of data interpretation, a DMA is defined not only by its physical pipes, but also as a discrete water balance zone. To accurately interpret data, we must account for the various hydraulic configurations found in modern networks:

- **Single-Inlet DMA**: The simplest form, where all water enters through one metered point and there are no metered exits.
- **Multi-Inlet DMA**: Areas fed by two or more meters. Here, data synchronization is critical; if the clocks on the loggers are not perfectly aligned, the combined flow data will lead to errors in Minimum Night Flow (MNF) analysis.
- **Cascaded (Transfer) DMA**: An area where water enters through an inlet, but a portion is "transferred" out through a secondary meter to supply a downstream zone. In this case, the "Net Flow" (Inlet minus Outlet) is the only valid data set for leakage calculation.
- **Open vs. Closed DMAs**: While the 2024 benchmark guidance promotes "closed" DMAs, many utilities operate "virtual" or "monitored" DMAs where boundaries are defined by data points rather than physical valves.

For the purposes of this manual, a DMA is any discrete area where net flow can be calculated with a known level of confidence.

1.3 STRUCTURE OF THIS BOOK

To guide the reader through the journey from raw data collection to sophisticated operational analysis, the manual is structured into five logical chapters and a series of technical appendices:

- **Chapter 2: DMA Sensor Data** – Establishes the technical foundation by exploring the types of flow meters and pressure sensors used in DMAs, focusing on their digital capabilities and data output requirements.
- **Chapter 3: Uncertainty and Data Quality** – Addresses the critical step of validation. It provides a framework for calibration, uncertainty assessment, and data quality management to ensure the information is "fit for purpose".
- **Chapter 4: Estimating DMA Leakage Levels** – Moves into the analysis phase, detailing methodologies for interpreting flow data and estimating leakage, including specialized approaches for complex or "special case" DMAs.
- **Chapter 5: Interpreting and Using DMA Data to Plan Actions** – The core operational chapter. It focuses on using data to drive decisions, from component loss modeling and pressure analysis to setting leakage targets and prioritizing field interventions.
- **Chapter 6: DMA Data Management Systems** – Reviews the digital infrastructure required to support these analyses, including Data Management Systems (DMS) and Event Management Systems (EMS).
- **Appendices** – Provide deep-dive technical resources, including a DMA Maturity Matrix (Appendix A), data loggers, assessment of uncertainty budgets, DMA pressure analysis, practical case studies on data issues and data-driven leakage estimation methods.

1.4 USING THIS BOOK

This book has been developed by a specialist team of leakage and network practitioners from around the world. As they developed this document, it was clear that the complexity and the data available from DMAs across different countries varied significantly. Therefore, not every concept, tip or recommendation will be beneficial for every DMA or distribution system. No universal method exists. What works for one system will not necessarily apply to another. The book should be seen as a toolbox rather than a universal methodology to be applied.

Our aim is for this book to be helpful to practitioners working in distribution systems with only a few sensors, as well as those working in complex distribution systems with many sensors. Before reading this document, practitioners may find it helpful to assess the maturity of their DMAs. To this end, we have created a DMA Maturity Matrix, which is available in Appendix A.

We hope this book will benefit both the newest water practitioner as well as the practitioner who has worked in the industry for many years. The document can be read from start to finish; for this purpose, we have arranged the chapters in a logical sequence. Although chapters were authored by different specialists, a consistent editorial standard has been applied throughout.

1.5 INTERACTION WITH OTHER PUBLICATIONS

This book is not expected to be a fully exhaustive document regarding DMA leakage control. It is expected that this book will work alongside other documents, guides and manuals created by the IWA Water Loss Specialist Group. Many of these guides can be found at IWA eBooks collection (https://iwaponline.com/search-results?page=1&f_ContentType=Book) or in the Knowledge Web Hub on Non-Revenue Water (https://globalnrw.com/free-downloads/books/).

1.6 ACKNOWLEDGMENTS

As editors, we would like to thank the many dedicated subject matter experts who have helped create this book. Those who have sacrificed much time and liberally shared their knowledge so that this document can be freely available around the globe. They, like us, are dedicated to reducing water loss so that water will be available not just for this generation, but for many more generations to come.

2 DMA SENSOR DATA

C. Henriquez[1], F. van de Hulst[2], T. Kressin[3], M. Nicol[4], J. Sepulveda[5], G. Waley[6]

[1]Aguas Antofagasta, Chile; [2]HULO, Netherlands; [3]Gutermann, Germany; [4]HWM Global, UK;
[5]Independent, Colombia; [6]Stantec, UK & Ireland

ABSTRACT

This chapter provides essential guidance on managing DMA sensor data, focusing on accurate flow and pressure monitoring as the foundation for reducing leakage and Non-Revenue Water (NRW). It explores the principles of sensor selection, strategic placement, and maintenance practices required to ensure long-term accuracy and data integrity. It also examines the critical role of data loggers in capturing the high-resolution data necessary for transient detection and actionable operational insights.

DMA Inlet Chamber in UAE with additional water quality monitoring and Online data communication

2.1 DMA FLOW METERS

To effectively reduce real losses, utilities must deploy accurate flow metering at every inlet and outlet point of the DMA, including internal reservoirs, wells, or sources. This section details the unique metrological challenges of DMA monitoring—such as bidirectional flow and low-flow sensitivity—and provides a framework for selecting, deploying, and maintaining meters that remain fit for purpose.

2.1.1 FLOW METER TECHNOLOGY

To select the correct sensor, it is necessary to understand the mechanical and electronic principles of the primary meter types used in DMA monitoring:

- In-Line Meters (Permanent Installations):
  - Electromagnetic (Mag-flow) Meters: These operate on Faraday’s Law of Induction. They have no moving parts and present virtually no head loss, making them the preferred technology for large DMA inlets. They excel in bidirectional flow and maintain high accuracy over long periods.
  - Ultrasonic In-Line Meters: These use transit-time technology, where acoustic signals are sent across the flow. Like mag-meters, they have no moving parts and are highly accurate at low flows, which is critical for MNF analysis.
  - Woltman Turbine Meters: These are mechanical meters where water flow rotates a helical turbine. While cost-effective and easy to maintain, they are prone to mechanical wear over time and have a limited "low flow" range compared to static meters.

- Non-Invasive and Specialized Sensors:
  - Clamp-On Ultrasonic Meters: These are strapped to the outside of an existing pipe. They are ideal for temporary "proving" of a DMA or for verifying the accuracy of an older in-line meter without cutting the pipe.
  - Insertion Probes: These are sensors (often electromagnetic) inserted through a small tapping into the water column. They are highly portable and useful for temporary flow surveys but are generally less accurate than full-bore meters because they measure velocity at a single point.

2.1.2 SELECTION CRITERIA

For optimal performance, the meter’s dynamic range and low-flow sensitivity must be matched to the specific consumption profile and size of the DMA. Selection should be based on the following qualitative and quantitative characteristics:

Overload Robustness
Indicates how well the meter type can measure flow beyond its normal operational flow rate without being damaged. Meters without moving parts are, by nature, better at withstanding this.

Head Loss

The pressure loss (drop) across a meter should be minimized. Under normal operating conditions, including operation at the maximum permissible flow rate, both inline ultrasonic and mechanical Woltman meters typically exhibit comparable performance, with head losses in the order of 0.25 bar. Electromagnetic meters, by contrast, inherently present the lowest head loss due to their construction, which from a hydraulic perspective is essentially equivalent to a straight section of pipe (Godley A. & Willmott M., 2020).

Dynamic Range / Turndown Ratio

Dynamic range specifies the ratio between the maximum and minimum flow rates at which the meter meets its defined accuracy performance. According to OIML R 49 and EN 14154, this ratio is defined as Q3/Q1 (permanent flow rate divided by minimum flow rate). Under these standards, the meter must comply with a maximum permissible error (MPE) of ±2% in the upper flow zone and ±5% in the lower flow zone. This classification framework is intended primarily for water meters used for billing and legal metrology purposes.

For bulk flow meters used to measure DMA inlet volumes, including full-bore electromagnetic meters, insertion electromagnetic meters, in-line ultrasonic meters, and clamp-on ultrasonic meters, performance is typically specified differently. These instruments usually define accuracy as a percentage of reading (e.g., ±0.2% of measured value) over a stated velocity range, rather than by discrete metrological zones (Q1, Q2, Q3). Their effective turndown ratio is therefore governed by minimum measurable velocity, signal stability, installation conditions, hydraulic profile, and repeatability performance.

Accordingly, while the OIML Q3/Q1 ratio provides a useful classification framework for custody-transfer meters, it does not necessarily define the operational performance limits of bulk meters used for DMA monitoring, where low-flow stability, repeatability, and accuracy at MNF are the primary technical criteria.

Low-Flow Capabilities

Low-flow capability refers to the meter’s ability to measure very small flow rates with acceptable accuracy and stability. While OIML R 49 and EN 14154 define low-flow performance using metrological zones (Q1–Q2) for billing meters, this framework does not directly apply to bulk meters used at DMA inlets.

For electromagnetic and ultrasonic meters (in-line, insertion, or clamp-on), low-flow performance is typically specified by minimum measurable velocity, accuracy expressed as a percentage of reading, zero stability, and repeatability. Proper meter selection therefore requires matching these parameters to the DMA’s MNF and operating profile.

Oversizing the meter can reduce velocity during low-demand periods, increasing measurement uncertainty and compromising leakage assessment.

Due to reduced demand, leakage, or a DMA configuration, a meter that was once optimally sized may be oversized. A periodical review of meter sizing can be a useful exercise with oversized meters exchanged for optimally sized meters.

Installation Position Sensitivity

Indicates whether the meter must comply with specific mounting criteria to maintain its stated accuracy and low-flow performance. For example, most single-jet meters (type of mechanical meters) must not exceed approximately 10° of inclination in any direction to preserve their metrological characteristics at low flow rates. Similarly, bulk meters such as electromagnetic and ultrasonic devices may require full-pipe conditions, proper electrode orientation, adequate upstream and downstream straight lengths, correct grounding, and avoidance of air accumulation. Deviation from recommended installation practices can introduce profile distortion, signal instability, or systematic measurement errors, particularly at low velocities.

Flow Profile Disturbances U0D0

U0D0 is a standard acronym indicating Upstream 0 DN and Downstream 0 DN. It signifies that the meter can maintain its measurement accuracy despite the presence of flow disturbances located immediately upstream or downstream (0 nominal diameters) of the meter. This feature is particularly important when installation is required directly before or after components such as pressure-reducing valves (PRVs), elbows, filters, or pipe diameter reductions. Compliance with this criterion should be verified for each meter model, as performance may vary between manufacturers and product lines.

Strainer / Filter Requirements

For certain meter types, an upstream strainer or filter is recommended to protect the meter from debris and to help stabilize the flow profile, both of which can affect measurement accuracy. This is particularly important for mechanical meters with moving parts that are susceptible to wear or blockage.

Although electromagnetic and ultrasonic meters have no moving components, upstream screening may still be advisable in networks with high solid loads to prevent sensor fouling, liner damage, or signal degradation. Strainer selection should consider mesh size, headloss, and maintenance accessibility.

Bidirectional Flow Measurement

Indicates whether the meter type can maintain measurement accuracy in both flow directions. This characteristic is particularly relevant in cascading DMAs. While most mechanical meters are physically capable of registering reverse flow, their accuracy in this mode is typically undefined, and operation under such conditions can accelerate wear. Therefore, mechanical meters should be avoided in installations where reverse flow is expected.

MID / ISO / OIML Compliance

Indicates whether the meter type is available with recognized metrological approvals. While such certification is mandatory for billing and custody-transfer applications, it is generally not required for bulk meters used in DMA monitoring or operational control.

For bulk electromagnetic and ultrasonic meters, compliance with standards such as OIML R 49, EN 14154, or the Measuring Instruments Directive (MID) may nevertheless provide assurance of validated accuracy, repeatability, and traceable calibration under defined test conditions. However, for DMA applications, operational performance at low velocities, installation sensitivity, and long-term stability are typically more critical than formal legal-metrology approval.

Option to Bury the Meter

Certain meter types can be installed without chambers (buried installation), with only the electronic register and communication components positioned in a protected, accessible location. This can significantly reduce the installation footprint and associated costs. However, it should be noted that such configurations may lead to higher replacement or maintenance costs due to more complex access to the buried components.

In Situ Verification

Indicates whether the meter allows field verification of its performance without removal from service. This typically involves diagnostic checks, zero verification, comparison against reference measurements, or validation of internal parameters rather than full recalibration against a traceable standard.

While the absolute accuracy of such verification is limited compared to laboratory calibration, the ability to confirm performance and, where permitted, adjust configuration parameters in the field provides a significant operational advantage by minimizing downtime and maintenance costs.

HELPFUL TIPS

The UKWIR (2015) study into The Accuracy of District Meters provides further guidance on DMA metering accuracy (UKWIR, 2015).

Power Supply

Indicates the type of power source required (internal battery, replaceable battery pack, mains power, or external DC supply) and the expected operational lifetime or consumption. For battery-powered meters, service life depends on sampling interval, data logging, communication frequency, and environmental conditions; reducing measurement or transmission frequency can significantly extend autonomy. For externally powered bulk meters, supply stability and backup provisions (e.g., battery or capacitor for data retention) are key considerations. Power strategy should match site accessibility, reliability requirements, and maintenance policy.

2.1.3 RECOMMENDATIONS FOR METER SELECTION

Based on the criteria established in Section 2.1.2, the following selection logic is recommended for different DMA scenarios and summarized in Table 2-1:

- For High-Priority Large DMA Inlets:
  - Recommendation: Electromagnetic (Full-Bore).
  - Rationale: These provide the best overall performance with minimal head loss and superior low-flow sensitivity. Their lack of moving parts ensures the data remains stable for AI-driven trend analysis over 10–15 years.

- For DMAs with Multi-Inlets or Potential Backflow:
  - Recommendation: Ultrasonic (Inline) or Electromagnetic.
  - Rationale: These technologies are inherently bidirectional. Mechanical Woltman meters must be avoided here, as they do not accurately register reverse flow and can suffer accelerated wear.

- For Small Residential DMAs (Focus on MNF):
  - Recommendation: Single-Jet or Ultrasonic.
  - Rationale: These offer a high Dynamic Range (Q3/Q1) which is necessary to capture the very low flows of a small residential area at night.

- For Temporary "Proving" or Verification of Existing Meters:
  - Recommendation: Clamp-On Ultrasonic.
  - Rationale: These allow for field verification without interrupting service or cutting pipes.

2.1.4 MAINTAINING FLOW METER PERFORMANCE

Meter performance inevitably changes over time, making it necessary to verify accuracy regularly through a structured maintenance program that reflects the specific network conditions and the types of flow meters in use. For mechanical meters, performance degradation is generally easier to identify and is heavily influenced by operational circumstances. Factors such as water quality, physical damage from debris like stones, exposure to flows exceeding the meter's maximum permissible capacity, and frequent operation at very low flows—often the result of oversizing—can all lead to reduced measurement accuracy.

Mechanical bulk (turbine) meters experience progressive accuracy deterioration due to wear of internal moving parts. The rate of degradation depends primarily on operating conditions, particularly sustained high flow rates, total passed volume, and water quality. Continuous operation at high flows can accelerate wear and increase measurement error. Therefore, the appropriate replacement interval should be determined by the expected deterioration rate under actual hydraulic conditions rather than by a fixed time period alone.

Static meters, including ultrasonic and magnetic inductive types, are less susceptible to mechanical wear but still require periodic performance assessment. These meters may fail due to issues with electronic components, depleted batteries, or incorrect configuration settings. Such systematic failures are often detectable by the utility's data collection systems. However, static meters can also experience accuracy drift that is not always immediately apparent from system alerts. For example, deposits accumulating inside the flow tube can increase water velocity at a constant flow rate, leading to over-registration, while contamination of the sensors themselves can also reduce measurement precision.

In many operational contexts, removing a DMA meter and sending it to a certified test bench for metrological verification is a significant logistical challenge, often requiring considerable downtime and cost. For this reason, one of the most practical alternatives is to install a temporary reference flow meter in series with the DMA meter to compare measurements directly. This can be done in an OXO configuration—where a reference meter is placed between two hydrants with a closed valve in between—or through a so called "flush test" setup (Figure 2-2), or through a so called "flush test setup in which incremental water consumption inside the DMA is measured by the reference device while the corresponding increase in net flow is compared to the readings of the DMA meter.

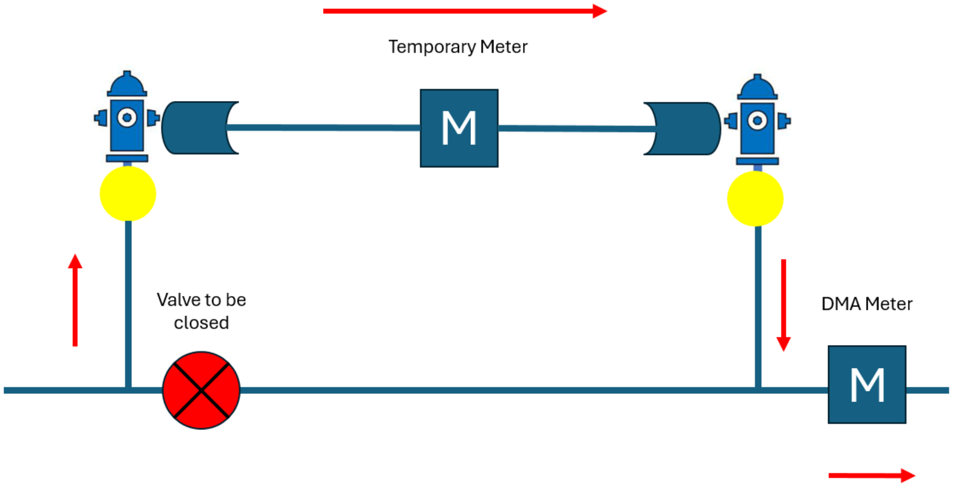


Figure 2-1 *OXO setup (Crowder Consulting, 2022)*

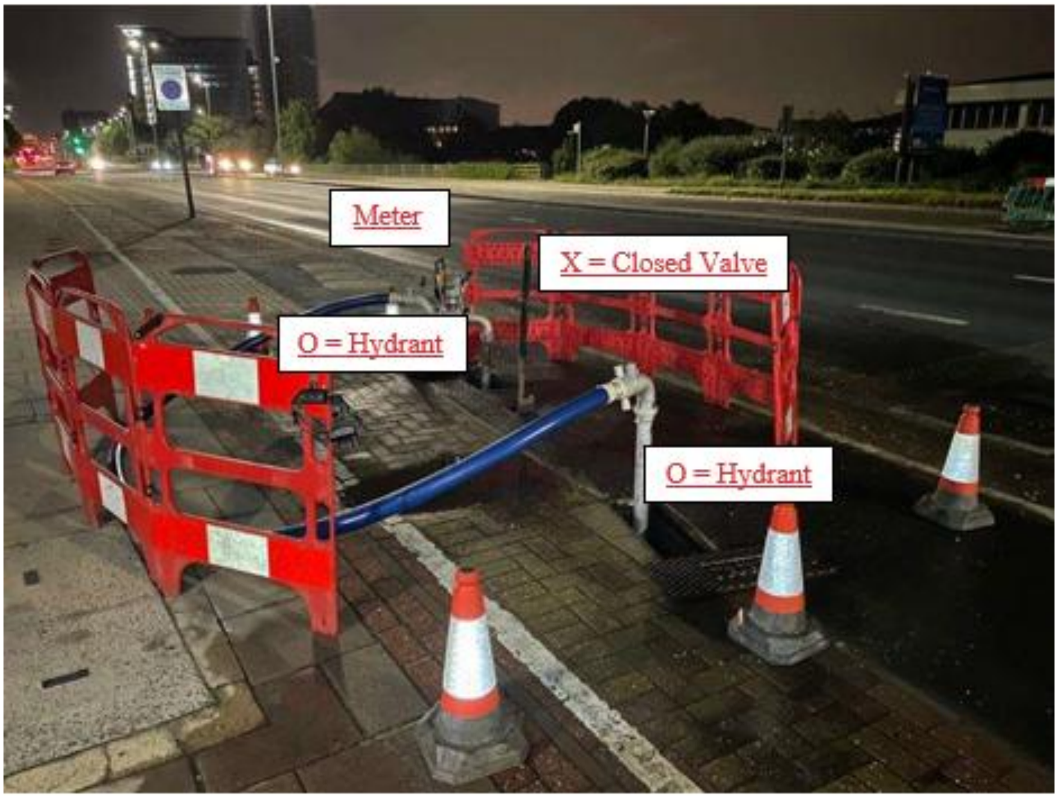


Figure 2-2 *OXO setup (Crowder Consulting, 2022)*

While these methods are often the only realistic options for field verification, they do have limitations. The flush test method, for example, is not well suited for assessing low-flow performance, which is especially important for accurate nightline measurements. Moreover, results obtained from portable reference meters must be interpreted with caution. Even MID-approved meter test benches can exhibit variations of up to ±0.5%, and portable reference meters themselves must be periodically reverified to maintain reliability. Equally important, the procedures used to collect and analyze the data must be clearly defined and strictly followed; otherwise, the results may not be valid for decision-making purposes.

Table 2-1 DMA Flow Meters Selection Overview

Installation Type	In-Line Meters					Clamp On	Insertion probe
Meter type	**Electromagnetic**	**Ultrasonic**	**Woltman Turbine**	**Single Jet Turbine**	**Pressure differential**	**Ultrasonic**	**Electro magnetic**
Overload robustness	+++	++	+	0	++	+++	++
Head loss	+++	++	++	0	0	+++	++
Dynamic Range	50-125	200-800	50-100	100-300	10-20	20-100	20-100
Low Flow	+++	+++	0	++	--	-	-
Sensitive to position	+++	+++	+++	0	+++	0	0
U0D0 capable	Y	Y	Y	Y	0	No	No
Strainer / filter	N	N	R	R	N	NA	NA
Bidirectional flow	Y	Y	N	N	N	Y	N
MID/ISO/OIML	Y	Y	Y	Y	N	N	N
DN mm	50 - >1000	50 - 300	50 - 500	50 -150	50 - 600	50 - 1000	>200
Meter cost	--	+	+++	++		--	--
Bury option	Y	N	N	N	?	Y	N
Long term reliability	+++	++	0	0	++	+++	+
In situ calibration	Y	N	N	N	N	Y	Y
Battery life Years	5-15	5-20	NA	NA	NA	< 1y	N (mains)

N = No; Y = Yes; NA = not applicable; R = Recommended; Relative Performance +++ = Best; 0 = medium; --- least good

**Table 2-1 reflects the understanding of the chapter's authors.*

2.2 DMA PRESSURE SENSORS

Pressure sensors are a fundamental component of effective DMA monitoring. Unfortunately, their importance is often underestimated: sensors of questionable accuracy are sometimes deployed, or calculations are based on rough estimates instead of reliable field measurements. This can lead to inaccurate assessments of system performance and undermine pressure management strategies.

2.2.1 PRESSURE SENSOR TECHNOLOGIES

For DMA monitoring, pressure sensors are typically one of three core technologies:

- Piezoresistive pressure sensors use silicon diaphragms with integrated resistors whose resistance varies under stress; they offer high sensitivity and compact designs, making them common in modern potable water pressure transmitters. While cost-effective, they are prone to zero-offset drift over time and must be sufficiently temperature-compensated; otherwise, the resulting error can render digital measurements unusable.
- Strain gauge pressure sensors use metallic foil gauges bonded to a diaphragm; applied pressure causes mechanical strain that changes resistance, providing a robust solution for medium-to-high pressure water applications, although they may have lower resolution than other types.
- Capacitive pressure sensors measure changes in capacitance between a diaphragm and a fixed electrode; their high resolution makes them suitable for low-pressure and hydrostatic level measurements in clean water systems, though they can be more sensitive to electromagnetic interference.

2.2.2 SELECTION CRITERIA

When selecting a sensor, the key factors are:

- Required pressure range: Typically, 0–10 to 0-20 bar for DMA applications

HELPFUL TIPS

Match the sensor range as closely as possible to the expected operating pressure. Since accuracy is often specified as a percentage of Full Scale (FS), using a high-range sensor in a low-pressure zone creates proportionally higher relative uncertainty.

- Accuracy and linearity: Standard accuracy should be better than 0.5% within the expected temperature range.
- Resolution: Should be better than 0.01 bar to capture subtle diurnal changes in the DMA profile.
- Resistance to physical overload: ≥ 4 times max pressure is recommended.
- Sampling frequency: : Typically pressures are sampled every second (1Hz). For enhanced monitoring and detection of rapid transients (surges), the sensor must be capable of fast sampling (>25Hz or 25 times per second).

- Logging frequency: Loggers typically save pressure data intervals of 1 minute, 5 minutes, or 15 minutes, based on either one or more of the minimum, maximum, or average of samples collected during this period. The ability to have a secondary channel capturing higher frequency transients offers enhanced monitoring.

Table 2-2 Qualitative assessments of sensor technologies*

Criteria	Piezoresistive	Capacitive	Strain Gauge
Range (0–20 bar)	++	++	++
Resolution (≤0.01 bar)	+	++	o
Accuracy (of Full Scale)	+	++	+
Stability Over Time	+	++	+
Power Consumption	+	o	+
Cost	++	o	+
Overload Resistance	o	o	++
Stability vs. Temperature Variations (night – day / sunlight)	O (+**)	O (+**)	+

**Table 2-2 reflects the understanding of the chapter's authors*
***With appropriate temperature compensation*

2.2.3 LOCATION OF PRESSURE SENSORS

Pressure sensors must be strategically positioned to capture both representative and critical conditions across the DMA. Pressure is a fundamental factor in leakage calculations; because leakage is highly pressure-dependent, higher network pressures directly increase the force exerted on pipe walls, leading to greater water loss and faster degradation of pipe integrity.

Recommended Monitoring Points
To ensure pressure remains within required standards and to obtain the parameters necessary for leakage analyses, sensors should be placed at the following locations:

- **DMA Boundary Monitoring (Internal vs. External):** Placing pressure sensors both inside and outside DMA boundaries is essential for verifying hydraulic isolation and system integrity. This configuration allows utilities to perform Zero Pressure Tests (ZPT) to ensure boundary valves are fully closed and not passing flow, ensuring that leakage calculations are based on a truly contained system.
- **DMA Entry Points:** Used to monitor upstream and/or downstream pressures at boundaries between DMAs. These pressure monitoring points may be located on assets such as meters, pressure control valves, pumps, storage tanks, etc.
- **Pressure Reduction Valves (PRVs):** Monitoring upstream and downstream of PRVs focuses on the mechanical health and regulatory performance of these specific assets. This dual-point sensing tracks the pressure differential (ΔP) to verify that control setpoints are maintained and to detect "drift" or internal diaphragm failure before it leads to downstream pipe bursts. Monitoring a third pressure channel in the 'top chamber' of a PRV also enables remote condition monitoring of the valves to ensure optimal performance.

- **Average Zone Pressure (AZP):** The AZP is a field measurement location where pressure variations are approximately equal to the mean hydraulic conditions across an entire DMA.

  Defining the AZP is vital because the relationship between pressure and leakage (the N1 leakage exponent) relies on the average zone pressure, not the inlet pressure. Using the inlet pressure as a proxy can lead to significant errors in estimating real losses. Furthermore, the AZP is the essential variable for calculating the Night-Day Factor (NDF), which is used to accurately convert MNF measurements into total daily leakage volumes.

  Defining this point involves three primary methods (Lambert, 2022):

  - ***Weighted Average Ground Level (WAGL)***: This is the most robust and auditable method. It involves calculating the mean elevation of all assets—typically service connections or hydrants—within the DMA. A physical point (such as a hydrant) with an elevation closest to the average connection height is then selected for permanent or portable pressure sensing.
  - ***Distributed Internal Measurements***: Multiple loggers are temporarily deployed across the zone to identify which specific location most closely reflects the average pressure fluctuations of the entire sample group over a 7-day period.
  - ***Network Analysis Modeling (NAM)***: A calibrated hydraulic model is used to identify the specific node whose pressure profile correlates best with the average of all nodes across various demand scenarios.

- **Critical Point (CP):** The hydraulically most disadvantaged location, typically the point with the lowest pressure during peak demand. The primary objective of monitoring the CP is based on the premise that if pressure at this point is maintained above the required service threshold, it can be assumed with reasonable confidence that all other points in the DMA are adequately supplied.

  Consequently, CP monitoring supports the following key operational functions:

  - ***Regulatory Compliance***: Ensuring minimum service thresholds are consistently met, especially during high-demand periods or operational disturbances.
  - ***Validation of Strategies***: Serving as the primary metric for validating the effectiveness of pressure management strategies.
  - ***Dynamic Control Feedback***: In advanced systems, the CP is used as a real-time control feedback point to dynamically adjust Pressure Reducing Valve (PRV) outlet pressures based on actual network needs.

- **Other Relevant Infrastructure:** Pressure sensors can also be installed at key operational assets within or adjacent to the DMA, such as service reservoirs, pumping stations, and booster sets for verifying pump performance, detecting suction side restrictions, and ensuring that pump curves match operational requirements.

- **Throughout the DMA:** For utilities pursuing a digital-first approach leveraging digital twins, hydraulic models, or AI-driven analytics, distributed pressure sensing throughout the DMA is the most strategically important investment. The primary objective of these sensors is not simply to monitor pressure at individual points, but to maximize the observability of the network as a whole.

  From a control-systems perspective, observability determines how well a model can reconstruct the full internal state of the network, pressure and flow at each junction and pipe, from a limited set of measurements. When sensors are placed at locations that maximize observability, the digital twin can infer pressures, flows, and anomalies across every pipe in the network including at the CP and AZP without requiring dedicated sensors at those specific points. In contrast, a sensor at the CP tells you about one point only; it provides no insight into conditions elsewhere in the network.

  Optimal sensor placement for observability can be determined through methods such as sensitivity analysis of the hydraulic model, information-theoretic approaches, or greedy optimization algorithms that select the set of nodes contributing most to overall network state estimation accuracy.

2.2.4 PRESSURE MONITORING FOR ADDITIONAL PURPOSES

Pressure data contains much more insights into the network than only leak or legal requirements towards consumers. Some additional uses of pressure data are outlined below:

Anomaly Detection

Apart from common detection of leak anomalies, other types of anomalies can be spotted using pressure data and they help gain insights into day-to-day operations. The effectiveness of anomaly detection depends on the sampling frequency of the loggers. Many utilities have high frequency loggers at critical points to control pumps and valves in real-time and low frequency (>15 minutes logging rate) on other areas in the network as these are less suitable for anomaly detection. For good anomaly detection it is recommended to use a shorter logging rate, which is a good trade-off between battery lifetime and insights.

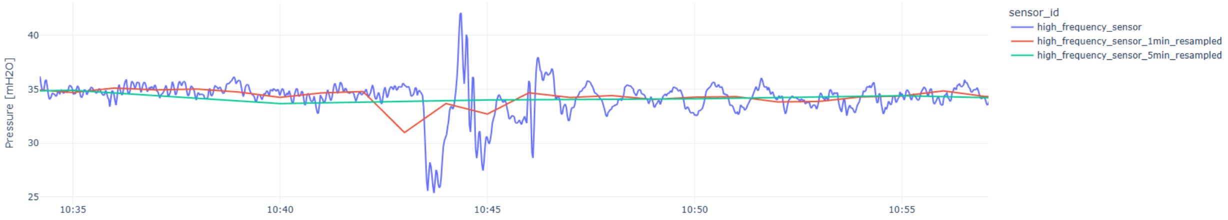


Figure 2-3: *Pressure transient captured by high frequency loggers (1 second sample rate) (source: HULO)*

Anomaly detection can give insight into malfunctioning pumps and valves; operational activities which are not registered in the system, such as opening and closing valves; or large consumers taking drawing large volumes and suddenly closing a float valve which can introduce pressure transients in the upstream network.

Energy Optimization

To optimize water supply, advanced pressure controllers are often installed on critical valves, such as PRVs, or variable speed pumps. These control systems often require high frequency logging (1 second sample rates) to detect changes in real-time. Dynamic pressure management through real-time pressure data enables automatic adjustment of pressure reducing valves (PRVs) and pump operations to maintain optimal pressure levels throughout the network. Precise pressure management significantly reduces energy consumption by avoiding over-pressurization and optimizing pump scheduling based on actual demand patterns.

Supply Assurance

Continuous pressure monitoring ensures that customers receive adequate water supply regardless of demand fluctuations or network events, enabling utilities to meet contractual service commitments.

Many regulatory frameworks specify minimum and maximum pressure requirements for water distribution systems, making pressure monitoring essential for legal compliance. Maintaining consistent pressure prevents service complaints related to low water pressure, particularly at critical points like highest elevations or remote endpoints.

2.3 DATA LOGGING AND RESOLUTION

To ensure technical clarity and avoid redundancy, this book distinguishes between data resolution requirements and the physical capabilities of the hardware. This section focuses on the data-centric requirements for DMA monitoring, specifically how logging intervals and pulse weights impact the accuracy of MNF analysis and transient detection. Conversely, Appendix B provides a detailed engineering reference for the physical hardware, covering environmental durability (IP68), communication protocols like NB-IoT and LTE-M, battery management, and the technical interfaces between meters and loggers.

Once installed, a data logger can be configured to record measurements at different time intervals. A 15-minute interval is commonly used; however, shorter intervals (e.g., 5-minute or 1-minute) provide greater resolution and allow more accurate assessment of MNF, since longer intervals can mask short-term variations as shown in Figure 2-4.

An alternative to timed logging intervals, a different way of measuring flow is to use Pulse Interval Timing. Pulse Interval Timing is a measurement method in which the flow rate is calculated by recording the time between successive pulses generated by a flow sensor and using this information to derive a continuous flow value. Each pulse represents a discrete volume, and at low flow rates these pulses may occur infrequently, leading to long gaps between them. If interpreted instantaneously, this can appear as alternating periods of flow and no flow. To overcome this, the measured time intervals between pulses are recorded, allowing the total measured volume to be evenly distributed across time. This averaging process smooths out the natural irregularity of pulse generation at low flows, converting sporadic pulse data into a stable and accurate representation of true flow. As a result, pulse interval timing with averaging provides improved resolution and reliability at low flow conditions compared with simple pulse counting methods.

Figure 2-5 shows how different logging intervals (15, 5, and 1 minute) affect recorded flow when the pulse weight is 1 m³ per pulse. At a flow of about 100 m³/h, a 15-minute interval records many pulses (around 25), resulting in a smooth and stable flow profile. With a 5-minute interval, only 8–9 pulses are counted and rounding effects begin to introduce visible fluctuations. At a 1-minute interval, just 1–2 pulses are recorded per minute, causing large apparent variations that do not reflect real hydraulic changes but rather the discrete nature of the pulse signal. The figure demonstrates that short logging intervals require a smaller pulse weight to avoid artificial variability and accurately represent actual flow conditions.

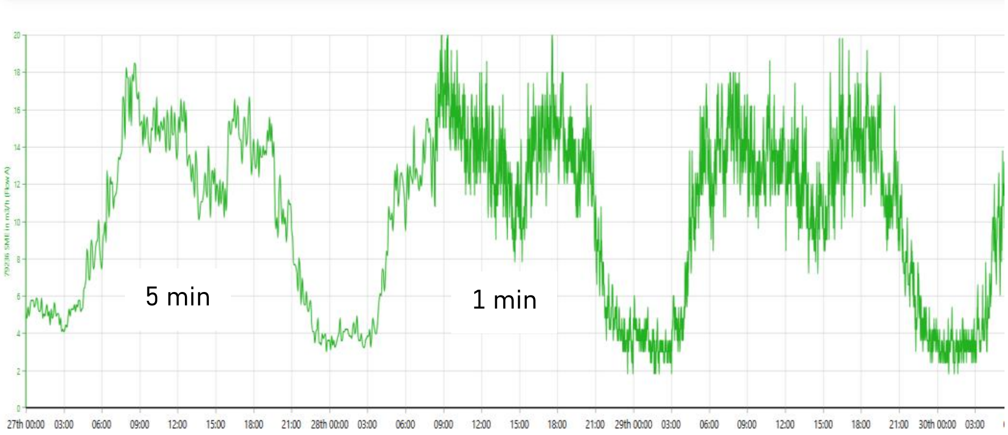


Figure 2-4 *Impact of logging frequency on the capture of hydraulic variability (source: Gutermann AG, 2025).*

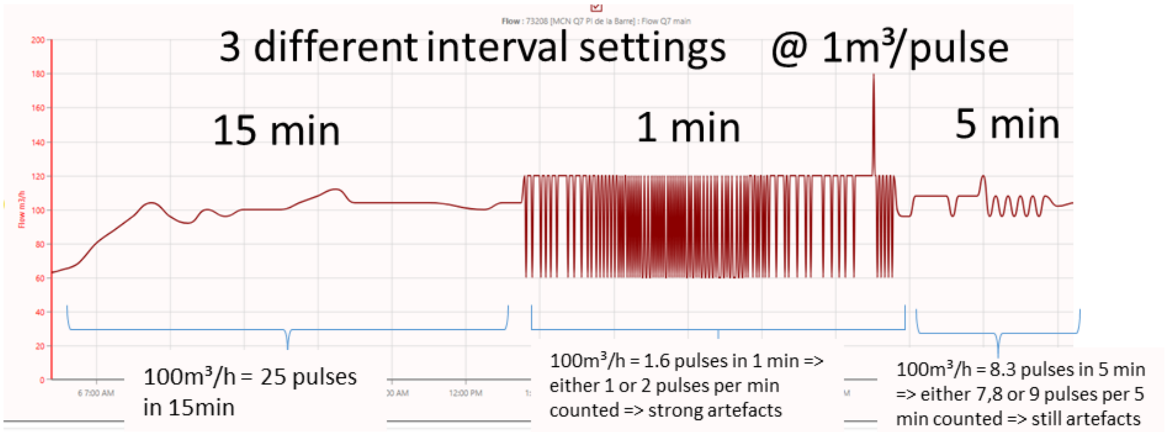


Figure 2-5 *Influence of logging intervals on discretization artefacts (source: Gutermann AG, 2025).*

HELPFUL TIPS

Select the logging interval carefully in relation to the meter's pulse weight. If the pulse volume is too large for the chosen interval, the recorded data may show artificial fluctuations that do not represent real flow variations.

Pressure can fluctuate even more rapidly than flow and may vary significantly within a standard 15-minute period. Therefore, pressure loggers should record not only the average value for each interval, but also the minimum and maximum pressures observed. Capturing these extremes allows detection of short-duration pressure drops or spikes that would otherwise remain unnoticed, improving operational insight and response capability.

Figure 2-6 illustrates this approach where the shaded area represents the minimum and maximum pressures recorded during each 15-minute interval. Without these values, short-duration pressure drops or spikes may be missed entirely, delaying operational response.

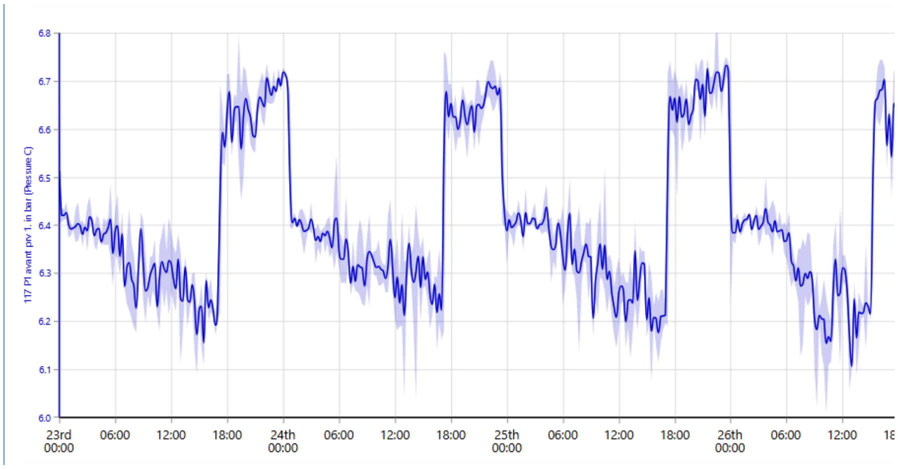


Figure 2-6 *Difference in pressure measurements between average (solid) and max/min (shaded) values (source: Gutermann AG, 2025).*

When choosing the resolution of measured data for DMA flow monitoring, consider the trade-off between data granularity and operational constraints such as battery life of measuring equipment, energy consumption, frequency of signal transmission, and data storage volume.

For greater diagnostic resolution, high-frequency pressure loggers — sampling at more than 100 Hz — can be deployed across the DMA. The resulting data enables accurate detection of pressure transients: rapid, significant pressure changes that standard logging intervals would not capture.

Figure 2-7 shows is a single transient logged at 100Hz (10Hz before the transient hit). The yellow line is the transient, red is average, green is maximum and blue is minimum pressures at 1 sec sampling. It can be clearly seen that without high frequency logging the transient would have been missed.

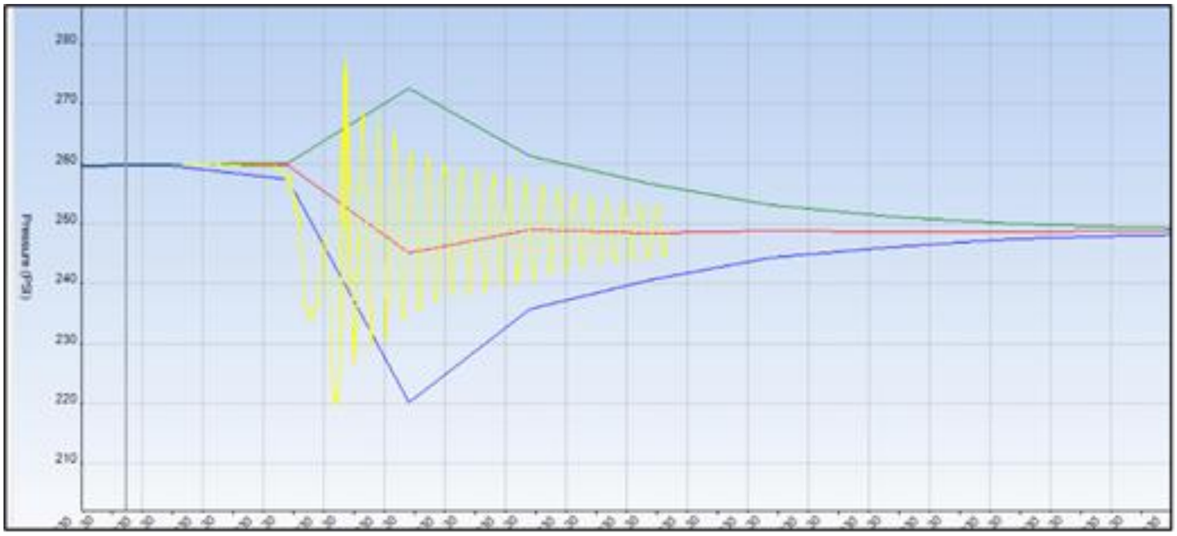


Figure 2-7 *High Frequency Transient Logging (source: Mobiltex FloPath)*

REFERENCES

Godley A. & Willmott M. (2020). *DMA and Large Diameter Metering – Some Guiding Principles*. Water Loss Specialist Group YouTube Channel.

Lambert, A. (2022). *Good leakage calculations need AZP pressures. Why are AZPs needed, and how to establish them*. https://www.leakssuitelibrary.com/average-zone-point/

UKWIR (2015). *The Accuracy of District Meters*. UK Water Industry Research, London, UK.

Telemetry and control module of DMA Pressure Control and Meter Station, Colombia

3 UNCERTAINTY AND DATA QUALITY IN DMA-BASED WATER LOSS ANALYSIS

C. Henriquez[1], T. Kressin[2], J. Sepulveda[3], G. Waley[4]

[1]Aguas Antofagasta , Chile; [2]Gutermann, Germany; [3]Independent, Colombia; [4] Stantec, UK & Ireland

ABSTRACT

This chapter presents a structured framework for managing uncertainty and data quality in DMA-based water loss analysis, covering the complete analytical chain from raw sensor data to auditable, decision-ready outputs. Calibration correction addresses systematic and random errors in flow meters and pressure transducers through laboratory and field verification methods, temperature compensation, and correction of legacy data. Uncertainty assessment follows the GUM methodology (JCGM, 2008), providing a five-step framework for developing uncertainty budgets and communicating confidence intervals on key indicators such as MNF and water balance components; detailed uncertainty equations for specific meter types are provided in Appendix C.

Data validation covers plausibility tests, internal consistency checks, and statistical outlier detection. The chapter concludes with data quality management — classifying data by reliability, visualizing quality indicators, and imputing missing values — ensuring DMA analyses are founded on measurements of known and documented reliability.

3.1 DATA QUALITY WORKFLOW

Effective management of the availability, accuracy, and reliability of DMA measurements—particularly pressure and flow—is vital for robust monitoring and leak detection. High-quality data enables practitioners to trust their analyses, make informed decisions, and optimize water management, especially when evaluating critical metrics such as MNF.

Figure 3-1 presents the foundational data quality workflow necessary for converting raw sensor measurements into reliable, actionable insights within water distribution networks, with a focus on DMA management. This sequential process ensures the integrity and usability of data collected from flow meters and pressure sensors, establishing a structured approach for managing metrology in DMAs.

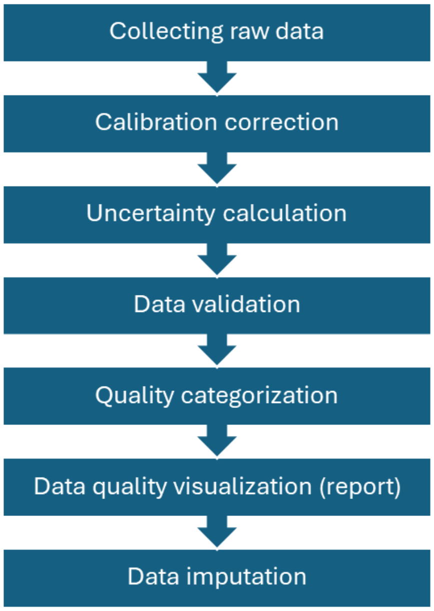


Figure 3-1 *Data Workflow.*

The workflow begins with the "Collecting raw data" phase, which involves gathering measurements from field equipment and which is described in Section 2 and Appendix B. These initial data are subject to various systematic and random errors, making the subsequent step—"Calibration correction"—essential. During calibration correction, predetermined factors and adjustments are applied to mitigate instrument bias and systematic errors, thereby aligning the raw output with traceable metrological standards.

Next, the "Uncertainty calculation" phase quantifies the range within which the true measurement value lies. This step establishes the confidence level of the data and provides the basis for further quality checks. The following "Data validation" phase subjects the corrected and quantified data to rigorous plausibility and consistency tests to identify errors, inconsistencies, or anomalies.

Validated data then advances to "Quality categorization," where each data point is assigned a quality flag (e.g., Good, Doubtful, Unreliable) based on its performance in validation tests. This categorization informs subsequent stages, including "Data quality visualization (report)," which communicates the overall quality and distribution of reliable data to stakeholders via interactive dashboards or summary reports.

The final step, "Data imputation," addresses missing or unreliable data points by filling gaps using verified techniques such as interpolation or predictive modeling. This ensures the continuity and completeness of the time series required for hydraulic modeling and dependable DMA analysis.

This systematic progression from raw data to curated outputs provides an essential framework for reliable DMA data analysis and supports effective leakage detection and pressure management strategies.

3.2 CALIBRATION CORRECTION

Calibration correction represents a critical stage in the data analysis workflow for DMAs, positioned between raw data collection and uncertainty assessment. The accuracy of subsequent analytical steps, including leakage estimation, water balance calculations, and performance indicator derivation, depends fundamentally upon the quality of calibrated measurements.

Electromagnetic and ultrasonic flow meters can exhibit zero drift, span errors, and velocity profile sensitivity. Transit-time ultrasonic meters are particularly susceptible to signal degradation from pipe wall deposits and changes in water quality parameters. Mechanical meters experience wear on moving parts, leading to under-registration, particularly at low flow rates.

Pressure sensors exhibit zero-offset drift, span errors, temperature dependence, and long-term stability issues. Piezoresistive transducers demonstrate notable temperature coefficients that require compensation, while membrane-based sensors may experience hysteresis effects under cyclic loading conditions.

3.2.1 PRE-CORRECTION ASSESSMENT

Prior to implementing correction procedures, a comprehensive assessment of the monitoring infrastructure must be conducted. This assessment should document:

- Meter type, manufacturer, model, and installation date
- Previous calibration dates and certificates
- Installation conditions and compliance with manufacturer specifications
- Historical performance data and known issues
- Operating range relative to rated capacity

Equipment operating consistently outside recommended ranges or exhibiting erratic behavior may require replacement rather than correction.

3.2.2 LABORATORY CALIBRATION-BASED CORRECTION

When laboratory calibration certificates are available, correction functions can be derived directly from certified reference measurements. The standard approach involves:

- Linear Correction Model: For equipment demonstrating predominantly linear errors. This model addresses both span error (coefficient a) and zero-offset (coefficient b).
- Piecewise Linear Correction: Flow meters often exhibit different error characteristics across their operating range. A piecewise approach divides the measurement range into segments, applying distinct correction parameters to each.
- Polynomial Correction: Higher-order corrections may be warranted for equipment with pronounced nonlinear characteristics. Polynomial order should be determined through statistical model selection criteria, balancing fit quality against overfitting risk. Orders exceeding three are rarely justified for DMA applications.

3.2.3 TIME-INTERPOLATED CORRECTION

When multiple calibration events span the data collection period, correction parameters must be interpolated temporally. Linear interpolation provides a reasonable approximation for gradual drift. This approach assumes one-directional change in a sensor's measurement error over time between two calibration events, which should be verified through residual analysis.

3.2.4 FIELD VERIFICATION-BASED CORRECTION

In the absence of laboratory calibration data, field verification methods provide alternative correction pathways:

- **Clamp-On Verification for Flow**: Portable ultrasonic flow meters can be temporarily installed to provide reference measurements. Correction factors are derived by comparing simultaneous readings over representative operating conditions spanning MNF to peak demand periods. A minimum of 24 hours of concurrent measurement is recommended to capture diurnal variation.
- **Portable Gauge Verification for Pressure**: Calibrated portable pressure gauges installed at test points adjacent to permanent transducers enable direct comparison. Measurements should be recorded at stable pressure conditions, avoiding transient events. Multiple verification points across the expected pressure range improve correction reliability.
- **Hydraulic Model Verification**: Where calibrated hydraulic models exist, predicted pressures and flows can serve as reference values. This approach requires high-confidence model calibration and should be reserved for situations where direct measurement verification is impractical. Model-based corrections carry greater uncertainty and should be clearly documented as such.

3.2.5 TEMPERATURE COMPENSATION

Pressure transducers with significant temperature coefficients require explicit temperature compensation. These correction equations are typically provided in manufacturer specifications or determined through temperature-controlled calibration.

3.2.6 IMPLEMENTATION CONSIDERATIONS

Application Sequence and Data Integrity

Calibration corrections must be applied systematically to raw data prior to any aggregation or statistical analysis. The recommended sequence involves:

- Import raw data maintaining full temporal resolution
- Apply instrument-specific correction functions
- Document correction parameters and sources
- Flag corrected data points for traceability
- Proceed to uncertainty assessment using corrected values.

Original raw data should be preserved in archival form to enable reprocessing if improved correction parameters become available.

Bounds Checking and Physical Constraints

Corrected values must be evaluated against physical constraints. Flow rates must be non-negative (except where bidirectional flow is expected), and pressure measurements must remain positive gauge values. Corrected values violating physical constraints indicate either measurement failure or inappropriate correction functions. Such data points should be flagged for quality categorization rather than forced to constraint boundaries.

Correction Uncertainty Propagation

Calibration correction introduces additional uncertainty that must be quantified and propagated through subsequent analyses. The combined standard uncertainty of corrected measurements includes contributions from:

- Calibration reference uncertainty
- Calibration function fitting uncertainty
- Temporal interpolation uncertainty
- Resolution and digitization uncertainty

3.2.7 SOFTWARE IMPLEMENTATION

Automated calibration correction should be implemented within data processing pipelines with appropriate version control and audit trails. Key software design considerations include:

- **Lookup Tables**: Correction parameters organized by meter identifier, calibration date, and applicable date ranges enable efficient retrieval and application.
- **Exception Handling**: Robust error handling for missing calibration data, extrapolation beyond calibrated ranges, and computational anomalies prevent silent failures.
- **Validation Checks**: Automated comparison of pre- and post-correction statistics identifies unexpectedly large corrections that may indicate data entry errors or incorrect parameter assignment.
- **Documentation Generation**: Automated generation of correction reports documenting applied corrections, parameter sources, and affected data ranges facilitates audit and quality assurance.

3.2.8 SPECIAL CASES AND PRACTICAL CHALLENGES

Meter Replacement and Data Continuity
When monitoring equipment is replaced mid-period, distinct correction functions must be applied to data segments corresponding to each instrument. Abrupt changes in corrected values at replacement boundaries should be anticipated and documented. In cases where replacement is prompted by meter failure, data immediately preceding replacement may require retroactive invalidation if deteriorating performance is evident.

Low Flow Measurement Accuracy
Flow meters typically exhibit degraded accuracy below 10-20% of full scale. For DMAs where MNF represents a small fraction of meter capacity, consideration should be given to:

- Installation of dual-range meters or parallel small-diameter meters
- Enhanced uncertainty quantification at low flows
- Alternative measurement techniques (pressure-based inference) during low-flow periods.

Fouling and In-Situ Performance Degradation
Biological fouling, scale accumulation, and sediment deposition cause progressive in-situ degradation not captured by laboratory calibration. Divergence between corrected data and independent verification suggests fouling-related drift. Remedial options include increased calibration frequency, installation of automatic cleaning systems, or statistical correction based on performance degradation models.

Legacy Data and Retrospective Correction
Application of calibration corrections to historical data presents challenges when calibration records are incomplete or absent. Retrospective correction approaches include:

- Extrapolation from earliest available calibration using assumed drift rates
- Inference from system-level water balance checks

- Application of manufacturer-specified typical drift characteristics
- Explicit acknowledgment of uncorrected status with elevated uncertainty.

Conservative practice mandates clear documentation of assumptions and elevated uncertainty estimates for retrospectively corrected legacy data.

3.2.9 QUALITY ASSURANCE AND VERIFICATION

Correction Validation Procedures
Systematic validation ensures correct implementation of calibration corrections:

- **Mass Balance Verification**: For DMAs with multiple inflow/outflow meters, summation of corrected flows should satisfy continuity. Persistent imbalances exceeding combined measurement uncertainty indicate correction errors or unaccounted flows.
- **Temporal Consistency Checks**: Corrected time series should exhibit expected diurnal patterns and respond appropriately to known system events (valve operations, pump starts, main breaks). Anomalous patterns post-correction suggest parameter errors.
- **Peer Comparison**: Where multiple similar meters operate in comparable conditions, corrected measurements should demonstrate statistical similarity. Outliers warrant investigation of correction parameter assignment.

Documentation Requirements
Comprehensive documentation of calibration correction procedures must include:

- Correction function type and parameters for each instrument
- Calibration data sources (certificate numbers, field verification dates)
- Temporal applicability ranges for each parameter set
- Software version and implementation verification results
- Known limitations and elevated uncertainty periods
- Responsible personnel and approval signatures

This documentation forms an essential component of quality assurance and enables independent verification of analytical results.

3.3 UNCERTAINTY CALCULATION

Uncertainty assessment is fundamental to rigorous DMA data analysis. It provides quantitative characterization of confidence intervals for both measured data and derived performance indicators. Following calibration correction in the analytical workflow, systematic uncertainty quantification enables informed decision-making by distinguishing statistically significant changes from measurement variability, establishing detection limits for leakage identification, and supporting risk-based prioritization of interventions.

This section provides guidance for assessing and propagating uncertainties through the complete chain of DMA analyses, from primary measurements through complex derived indicators including water balance components, MNF, day-night factors, and infrastructure condition indices.

The framework presented adheres to the Guide to the Expression of Uncertainty in Measurement (GUM) methodology (JCGM, 2008), adapted specifically for water distribution system monitoring applications. It emphasizes practical implementation considerations for operational DMA management while maintaining statistical rigor.

3.3.1 FUNDAMENTAL PRINCIPLES OF UNCERTAINTY ASSESSMENT

Uncertainty assessment is essential professional practice in leakage management. Because measurements are never perfect and cannot be conducted under ideal conditions, a measurement result is only a quantitative estimate of the "true" value. To ensure that results are reliable and can be compared with reference values or standards, they must be accompanied by a quantitative indication of their quality.

The assessment process follows the framework established by international standards in the Guide to the Expression of Uncertainty in Measurement (JCGM, 2008). These standards distinguish between three primary methods of evaluation:

- ***Type A Evaluation***: Based on the statistical analysis of a series of repeated measurements. It characterizes the dispersion of values—often expressed as a standard deviation—to quantify the measurement precision under defined conditions.
- ***Type B Evaluation***: Based on a mathematical measurement model (Law of Propagation of Uncertainties) that determines the uncertainty of a calculated result from the known uncertainties of its individual input quantities. This method utilizes prior information from calibration certificates, expertise, or scientific literature.
- ***Monte Carlo Method (MCM)***: A numerical approach that uses stochastic simulations of a measurement model. It is particularly effective for non-linear models or when dealing with non-symmetric probability distributions.
- **Expanded Uncertainty** provides an interval within which the true value is expected to lie with specified confidence, calculated as the combined standard uncertainty multiplied by a coverage factor (typically $k = 2$ for 95% confidence).

Effective uncertainty assessment requires a clear distinction between sensor uncertainty (errors inherent to the device and the entire measuring chain) and in-situ measurement uncertainty (errors caused by field conditions, such as surface waves or turbulence). By quantifying these components, operators can establish a coverage interval that represents the range within which the true value is expected to lie with a specific probability level, typically 95%.

The quantitative application of these principles to DMA instrumentation — including specific uncertainty equations for electromagnetic, ultrasonic, and mechanical flow meters, pressure transducers, and temporal integration — is presented in Appendix C. Practitioners performing formal uncertainty budgets should consult Appendix C for the relevant equations and worked examples. The sections that follow present the operational framework for managing and communicating uncertainty at the DMA level.

3.3.2 PRACTICAL IMPLEMENTATION FRAMEWORK

Uncertainty Budget Development

A systematic uncertainty budget enumerates all significant uncertainty sources, quantifies their magnitude, and documents combination methodology. For DMA applications, uncertainty budgets must address:

- **Measurement Uncertainty**: Intrinsic to instrumentation and data acquisition
- **Calibration Uncertainty**: Arising from reference standards and correction procedures
- **Installation Uncertainty**: Due to non-ideal mounting conditions and flow disturbances
- **Temporal Uncertainty**: From sampling intervals and interpolation
- **Model Uncertainty**: Inherent in empirical relationships and assumptions
- **Operational Uncertainty**: Related to system state variability and boundary condition definition.

The practitioner should consider the overall impact that age has towards the uncertainty factors in the budget. Increased age of infrastructure, instruments and computation devices can affect the measurement / calibration / installation and operational uncertainty. Across a group of DMAs some uncertainty effects will be randomized but with age there is typically, but not always, a bias towards degradation across metrology and data workflow which can lead to systematic volume under-registration known broadly as apparent loss meter under-registration.

Systematic uncertainty budget development follows a structured process:

Step 1: Component Identification: Enumerate all measurement, model, and operational components contributing to the final calculated quantity.

Step 2: Uncertainty Quantification: For each component, assign Type A (statistical) or Type B (systematic) uncertainty based on available information sources.

Step 3: Probability Distribution Assignment: Characterize each uncertainty component with appropriate probability distribution (normal, rectangular, triangular) based on underlying physics and information quality.

Step 4: Sensitivity Analysis: Determine sensitivity coefficients relating component uncertainties to combined output uncertainty through analytical derivatives or numerical perturbation.

Step 5: Combination and Reporting: Combine component uncertainties according to GUM methodology and report as standard and expanded uncertainties.

While the example below illustrates the estimation of the uncertainty budget for a DMA flow meter, Appendix C of this document provides a more detailed assessment of uncertainty budgets associated with primary measured data (electromagnetic, ultrasonic and mechanical flow meters, and pressure measurements), as well as with derived parameters such as water balance calculations and MNF estimation methods.

Worked Example: Uncertainty Budget for a DMA Inlet Flow Meter

The following example illustrates the five-step process applied to a single electromagnetic flow meter at a DMA inlet, operating at a measured flow of Q = 25 m^3/h during the minimum night flow period. The meter has a manufacturer accuracy specification of ±0.5% of reading (at k = 2, 95% confidence), a zero-stability specification of 1 mm/s velocity equivalent, a pipe diameter of DN150, and was installed 18 months ago under partially compliant conditions (insufficient upstream straight length).

Step 1 — Component Identification. Four uncertainty sources are identified: (i) meter accuracy, (ii) zero-stability drift at low flow, (iii) installation effects from non-ideal mounting, and (iv) calibration uncertainty from the last verification certificate.

Step 2 — Uncertainty Quantification. Each component is classified and quantified:

Table 3-1 Uncertainty Quantification

Component	Type	Source	Value
Meter accuracy	B	Manufacturer datasheet	±0.5% of Q at k = 2
Zero stability	B	Manufacturer datasheet	1 mm/s velocity equivalent
Installation effects	B	Engineering judgment	1.5% of Q (partially compliant)
Calibration certificate	B	Last verification record	±0.3% of Q at k = 2

For the equations used to convert these specifications into standard uncertainty values (u), refer to Appendix C.

Step 3 — Probability Distribution Assignment. Meter accuracy and calibration certificate uncertainties are assumed normally distributed (divisor = 2, since k = 2 is stated). Zero-stability and installation effects are assumed rectangular distributions (divisor = √3), reflecting bounded but uncharacterized variation.

Converting to standard uncertainties at Q = 25 m³/h:

Table 3-2 Standard Uncertainty

Component	Standard Uncertainty u (m³/h)
Meter accuracy	0.005 × 25 / 2 = **0.063**
Zero stability	1 mm/s × 0.01767 m² / √3 = **0.010**
Installation effects	0.015 × 25 / √3 = **0.217**
Calibration certificate	0.003 × 25 / 2 = **0.038**

Step 4 — Sensitivity Analysis. All four components feed directly into the flow measurement result with a sensitivity coefficient of 1. Installation effects dominate, contributing approximately 89% of the combined variance. This identifies non-ideal mounting as the primary target for uncertainty reduction.

Step 5 — Combination and Reporting. Assuming independence between components, the combined standard uncertainty is:

$$u\_c = \sqrt{(0.063^2 + 0.010^2 + 0.217^2 + 0.038^2)} = \mathbf{0.226\ m^3/h}$$

The expanded uncertainty at 95% confidence (k = 2) is:

$$U = 2 \times 0.226 = \mathbf{0.45\ m^3/h}, \text{ equivalent to } \mathbf{\pm 1.8\%\ of\ the\ measured\ flow}$$

This means that a reported MNF of 25.0 m³/h carries a 95% confidence interval of approximately 24.6 to 25.5 m³/h. Any apparent change in MNF smaller than 0.45 m³/h cannot be distinguished from measurement uncertainty alone and should not be interpreted as a real operational change without corroborating evidence.

The dominant uncertainty source — installation effects — should be addressed first. Correcting the upstream straight length to comply with manufacturer requirements could reduce installation uncertainty from 1.5% to approximately 0.3% of reading, reducing the expanded uncertainty to approximately ±0.5% — a fourfold improvement achievable without changing the meter itself.

Uncertainty Reduction Strategies

Strategic interventions target dominant uncertainty contributors identified through sensitivity analysis:

- **Measurement System Enhancement**: Upgrading to higher-accuracy instrumentation, improving installation compliance, and implementing redundant measurement reduce primary uncertainty.
- **Calibration Frequency Optimization**: More frequent calibration reduces temporal drift uncertainty but increases operational costs. Optimal intervals balance uncertainty reduction against resource constraints.

- **Data Resolution Improvement**: Higher sampling frequencies reduce integration and interpolation uncertainties but increase data storage and processing requirements.
- **Infrastructure Data Quality**: Systematic GIS audits, field verification campaigns, and asset register enhancement reduce model input uncertainties.
- **Consumption Estimation Refinement**: Expanded night consumption surveys, AMR/AMI deployment, and improved customer classification reduce authorized consumption uncertainty.

Adaptive Uncertainty Assessment

Uncertainty characteristics evolve with system conditions, requiring adaptive assessment strategies:

- **Flow-Dependent Uncertainty Functions**: Implement lookup tables or continuous functions relating measurement uncertainty to operating point, automatically adjusting estimates based on real-time conditions.
- **Time-Varying Uncertainty**: Track calibration age, seasonal temperature effects, and known equipment degradation to continuously update uncertainty estimates.
- **Condition-Triggered Reassessment**: Significant system events (meter replacement, pressure regime changes, infrastructure upgrades) trigger comprehensive uncertainty reassessment.

Uncertainty Communication and Decision Support

Effective communication of uncertainty to decision-makers requires appropriate visualization and interpretation:

- **Confidence Intervals**: Present key performance indicators with explicit confidence intervals at standard levels (90%, 95%, 99%).
- **Uncertainty Bands on Time Series**: Graphical presentation of flow and pressure data with shaded uncertainty envelopes enables visual assessment of measurement confidence.
- **Detection Limits**: Establish minimum detectable changes for leakage indicators, consumption anomalies, and performance trends based on combined uncertainties.
- **Risk-Based Classification**: Categorize DMA performance accounting for uncertainty, distinguishing high-confidence conclusions from uncertain interpretations requiring additional investigation.

3.3.3 QUALITY ASSURANCE AND DOCUMENTATION

Uncertainty Budget Documentation

Comprehensive uncertainty documentation includes:

- **Component Tables**: Tabular presentation of all uncertainty sources, magnitudes, probability distributions, and combination methodology.
- **Sensitivity Analysis Results**: Quantitative identification of dominant uncertainty contributors guiding improvement priorities.

- **Calculation Worksheets**: Detailed uncertainty propagation calculations enabling independent verification.
- **Assumptions Register**: Explicit documentation of simplifying assumptions, their justification, and potential impact on results.
- **Update History**: Version-controlled record of uncertainty budget revisions reflecting equipment changes, methodology improvements, and updated information.

Independent Verification

Quality assurance requires independent verification of uncertainty assessments:

- **Cross-Check Calculations**: Independent recalculation using alternative methods or software tools.
- **Benchmark Comparisons**: Comparison of uncertainty estimates against published values for similar systems and applications.
- **Peer Review**: Expert review of methodology, assumptions, and calculations by personnel independent of the original analysis.
- **Field Validation**: Where feasible, comparison of uncertainty predictions against repeated measurements or reference standard campaigns.

Continuous Improvement Process

Uncertainty assessment methodologies evolve through systematic learning:

- **Residual Analysis**: Comparison of predicted uncertainties against observed variation in repeated measurements or cross-checks identifies systematic under- or over-estimation.
- **Root Cause Investigation**: Unexpectedly large uncertainties or discrepancies trigger investigation of underlying causes and potential systematic errors.
- **Methodology Updates**: Incorporating improved understanding, new measurement technologies, and lessons learned into updated uncertainty assessment procedures.
- **Knowledge Management**: Systematic capture and dissemination of uncertainty-related insights across organizational units and projects.

3.4 DATA VALIDATION

Data validation determines whether available data meet predefined quality objectives for their intended use. It assigns a quality indicator to each data point using objective criteria, reflecting both its correctness and relevance. While correctness is based on physical meaning, data quality is also influenced by its suitability for the specific application.

For DMAs, the main goal of data validation is to ensure that flow and pressure records are reliable, consistent, and accurately represent actual hydraulic behavior. Reliable records are essential for sound operational decisions, historical analysis, and modeling. Errors, inconsistencies, or gaps can lead to incorrect leakage estimates, unnecessary inspections, and poor operational choices regarding valves, pumps, and pressure management.

Appendix F provides examples of the most common issues encountered in DMA data analysis by Water Utilities.

3.4.1 BASIC CHECKS

Plausibility Test
Plausibility Tests are procedures that check whether the data are logical and reasonable. They focus on:

- Physical range: Ensures that the values are physically possible, e.g. pressure within operational limits, positive flow only, and flags very low or zero flow readings for review.
- Sensor measuring range: Verifies that the data is within the sensor's measurement range.
- Calibration range: This test verifies that each measurement falls within the sensor's calibrated range.
- Maximum gradients: Detects abrupt changes in the data, such as excessive variations over a short period.

These tests help identify erroneous data and ensure its reliability for decision-making. For example:

- **Physical Range**
  Flow > 0 (if DMA supply meter), above realistic minimum and below unrealistic maximum (e.g. < max flow of meter or burst flow rate); Pressure within the operational limits of the system (e.g., 0 to 80 mH_2O).

- **Sensor Measuring Range**
  The pressure recorded by a pressure sensor has a measuring range between 0 and 100 mH_2O. If a recorded value is lower than 0 (i.e. negative) or higher than 100 mH_2O then this value is flagged as invalid.

- **Calibration Range**
  In the previous example the sensor was calibrated from 0.3 mcw to 100 mcw. If the recorded values is outside those boundaries, then this value is a not good data for this test.

- **Maximum Gradients**
  Set variation thresholds between intervals. Example: $\Delta Q > 20$ m^3/h within 5 minutes, flag as suspicious.

Internal Consistency
Internal consistency refers to the alignment and coherence of related data within a system. It ensures that measurements, such as those from redundant sensors or hydraulic parameters,

are logically consistent with each other. This helps verify that the data is reliable and reduces errors in decision-making.

Sensor Redundancy

If two flow meters are installed in parallel, readings can be cross-compared to identify outlying values. (Example recommended threshold: difference ≤5%).

Hydraulic Relationships

The dynamic behavior of the water distribution system should be consistent: under standard conditions, if water consumption increases, the flow increases and the pressure decreases.

- High pressure + sustained low flow → Possible leak.
- Pressure drop + flow increase → Valve opening or pipe burst.
- The measured flow at any DMA outlet (into a neighboring DMA) cannot exceed the total DMA inflow.

Time Stamp Consistency

Measurement data always carry a time reference. If measurement data are recorded at a regular time interval (e.g. each 15 minutes), the distance between two consecutive time stamps is equal. Irregular time series exhibit unexpected gaps or duplicate entries sharing an identical time index.

Data Accuracy

A measurement is considered sufficiently accurate for use when its standard uncertainty falls within a threshold appropriate for its intended application. If this threshold is exceeded, the data point should be flagged for review or discarded, depending on the severity of the exceedance and the sensitivity of the downstream analysis.

Accuracy thresholds are not universal — they depend on the purpose for which the data will be used. For MNF analysis, where small flow variations are operationally significant, tighter thresholds are required than for daily volume totalization. As a general orientation:

- Flow measurements used for MNF analysis: standard uncertainty should not exceed ±2–5% of the measured value.
- Pressure measurements used for AZP or N1 calculations: standard uncertainty should not exceed ±0.5% of full scale.

These values are indicative. Each utility should define its own thresholds based on its metrological infrastructure, the sensitivity of its leakage indicators, and any applicable regulatory requirements.

The standard uncertainty values required to apply this criterion are derived using the GUM-based framework presented in Section 3.3. Data points for which uncertainty cannot be quantified — for example, due to absent calibration records — should be treated as potentially unreliable and flagged accordingly, as described in Section 3.2.9 Quality Assurance and Verification.

Data Auditability

To ensure the integrity of data in a monitoring project, a framework for auditability is essential. This allows for tracking the complete journey of a measured value and understanding any modifications it underwent, with particular attention to calibration and maintenance events. Data recorded during these events should be treated as potentially unreliable. It is also important to verify that calibration and maintenance were performed at the frequencies specified in utility protocols.

Data Completeness

Completeness refers to how fully and consistently data is recorded, ensuring that all expected values are present with minimal gaps or missing entries. This is essential for maintaining the integrity of the data, which is crucial for accurate analysis, reliable predictions, and sound decision-making. In practice, completeness can be assessed by evaluating the coverage of records over time.

For example, at least 95% of the expected interval data should be recorded each month. To effectively monitor data completeness, conditional formatting and user-friendly visualization and heat maps can be used to highlight gaps or recurring data losses, helping identify patterns and areas that require attention. Ensuring high data completeness minimizes the risk of inaccuracies in system analysis.

3.4.2 APPLIED CLASSICAL METHODS

Detecting Outliers

Outlier Detection is a critical process for identifying data points that deviate significantly from expected values. These outliers can indicate errors in measurement, faulty sensors, or unusual system events, all of which warrant further investigation.

Common methods for outlier detection include (Barnett and Lewis, 1996, Iglewicz and Hoaglin, 1993, Choi, 1992):

- Z-test or Grubbs' Test: These statistical tests are used to detect values that are significantly different from the mean. For instance, if a night-time flow value exceeds three standard deviations from the historical average, it is flagged as "suspicious." This helps identify values that are statistically unusual and may need to be verified or corrected.
- ARMA (Auto-Regressive Moving Average) or LSTM (Long Short-Term Memory) Models: These models are particularly useful for analyzing time series. ARMA models predict values using past observations (AR) and past prediction errors (MA), enabling pattern recognition in time series data. Outliers are identified by the size of the residuals — the discrepancies between observed and predicted values.
- LSTM networks are a deep learning approach trained either to reconstruct or to predict normal time series data, capturing long-term temporal dependencies. Data

points are flagged as anomalies when actual values deviate significantly from predicted values or when reconstruction error exceeds a predefined threshold. While a 15% deviation is sometimes used as a domain-specific heuristic, advanced water distribution monitoring often employs adaptive thresholds — such as the maximum reconstruction error observed during a sufficiently clean training period — to account for the natural hydraulic variability and noise inherent in flow and pressure data. This makes LSTM particularly effective in complex, dynamic systems where traditional methods may miss subtle trends.

By using these methods, data analysts can identify and address potential issues early, ensuring the data quality is maintained and any operational abnormalities are addressed promptly.

Drift or Undesired Trend Detection

Drift or Undesired Trend Detection helps identify gradual changes in data that may indicate sensor issues or external factors, affecting measurement accuracy.

Linear Regression is used to detect slow, consistent changes, such as sensor drift caused by sediment buildup or wear. It fits a straight line to the data and identifies deviations from expected patterns.

Spearman’s Coefficient evaluates non-linear relationships, such as pressure vs. temperature or flow vs. consumption, by measuring monotonic correlations. If these relationships break down over time, this signals potential sensor or system issues that should be investigated to maintain data accuracy.

3.5 QUALITY CATEGORIZATION

Data quality management in the context of leakage control is a critical, goal-driven process that ensures measurements are fit for their intended purpose. Raw data acquired from DMAs are rarely flawless; they are frequently subject to systematic and random errors caused by instrumental failures, human error, environmental interference, or discontinuities in power and communication. The primary objective of data quality management is to assign a reliable quality flag to each data point through systematic validation. This prevents misleading decisions based on faulty information and helps maintain the integrity of the entire monitoring system.

Data quality classification is essential to ensure that analytical results are accurate and reliable. Systematic categorization based on reliability allows operators to prioritize corrective actions for sensor malfunctions or physical inconsistencies.

Table 3-3 illustrates a standard framework for labeling data to indicate its technical validity and fitness for use and suggested actions.

Table 3-3 Example of data quality classification

Category	Description	Suggested Action
G	Good	Data point passed all validation tests
U	Unreliable/Unsuitable (invalid physical range, sensor failure)	Data point is physically invalid or is definable erroneous so that it cannot be used.
D	Doubtful (outliers without clear explanation)	Data point is physically valid but somewhat questionable when evaluated in a wider context.
I	Imputed (filled with model or interpolation) Label as imputed	Maybe replaced with real sensor data once available (e.g. after LPWAN outage the logger sends data later
M	Missing	Missing data point

3.6 DATA QUALITY VISUALIZATION

Effective data management relies on the real-time or frequent visualization of data quality indicators. Utilizing heatmaps and interactive dashboards categorized by a traffic-light system enables a rapid assessment of sensor performance, technical reliability, and fitness for use. This systematic visualization facilitates the early detection of persistent failures and anomalous trends within the monitoring network.

Key indicators include (Table 3-4)

- ***% Valid Data***: Total usable data over the expected number of recordings.
- ***Outliers % per day***: Helps identify intermittent interference or malfunctioning equipment.
- ***Weekly/Monthly Drift***: Tracks changes in sensor performance over time relative to maintenance and calibration logs.

Table 3-4 Example of data quality visualization

Indicator	Traffic Light	Thresholds
% valid data	🟢 >95%, 🟡 80–95%, 🔴 <80%	To alert persistent failures
Outliers % per day	🟢 <1, 🟡 1–5, 🔴 >5	
Weekly drift	🟢 Stable, 🟡 Slight, 🔴 Critical	

3.7 DATA IMPUTATION

Data imputation maintains the continuity and reliability of time series datasets by estimating missing or invalid measurements.

- For Short Gaps (<2 hours): Apply linear interpolation or a moving average method to estimate missing values based on surrounding data points. These approaches are simple yet effective for small data gaps (Lepot et al., 2017).
- For Long Gaps: Use more advanced techniques such as hydraulic simulations, historical regression models, or machine learning-based predictive models (e.g., ARIMA, LSTM) to reconstruct plausible values (Pratama et al., 2016; Wongoutong, 2020).

To ensure data transparency, it is essential to maintain two distinct datasets: the original "raw" series containing gaps and the "gap-fillet" series with imputed values. All processed entries must be explicitly labeled as "imputed" to distinguish them from direct measurements.

Temporary Pressure Logging inside a DMA in UAE

REFERENCES

Barnett V. & Lewis T. (1996). *Outliers in Statistical Data*, *3rd edn*. John Wiley & Sons, Chichester (UK), 604 p. ISBN 978-0471930945.

Choi B. (1992). *ARMA Model Identification*. Springer, New York (USA), 212 p. ISBN 978-1461397472.

Iglewicz B. & Hoaglin D. C. (1993). *How to Detect and Handle Outliers*. American Society for Quality Control, Milwaukee (USA), 87 p. ISBN 9780873892476.

Joint Committee for Guides in Metrology. (2008). *Evaluation of measurement data — Guide to the expression of uncertainty in measurement* (JCGM 100:2008). Bureau International des Poids et Mesures. http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Lepot M., Aubin J.-B. & Clemens F. H. L. R. (2017). *Interpolation in timeseries: an introductive overview of existing methods, their performance criteria and uncertainty assessment*. Water, 9(10), 796, 20 p. doi: 10.3390/w9100796.

Pratama I., Erna Permansari A., Ardiyanto I. & Indrayani R. (2016). A review of missing values handling methods on time-series data. *Proceedings of the 2016 International Conference on Information Technology Systems and Innovation (ICITSI)*, 24–27 Oct., Bandung, Bali (Indonesia), 1–6. doi: 10.1109/ICITSI.2016.7858189.

Wongoutong C. (2020). *Imputation for consecutive missing values in non-stationary time series data*. Advances and Applications in Statistics, 64(1), 87–102. doi: 10.17654/AS064010087.

4 ESTIMATING DMA LEAKAGE LEVELS

A. Bojko[1], T. Crowder[2], I. Dundovic[3], K. Høgh[4], T. Kressin[5], M. Misirdali[6], T. Nergaard[7], J. Sepulveda[8], G. Waley[9]

[1] Independent, French Guyana; [2]Crowder Consulting, UK, [3] Hidromodel, Croatia; [4]Niras A/S, Denmark; [5]Gutermann, Germany; [6]Independet, Türkiye/UAE; [7]Independent, Denmark; [8]Independent, Colombia; [9]Stantec, UK&Ireland.

ABSTRACT

This chapter provides a detailed guide to estimating leakage levels in District Metered Areas (DMAs), a critical step in managing Non-Revenue Water (NRW) and improving operational efficiency. It begins by emphasizing the importance of accurate, validated flow data, including recommended resolution, minimum data duration, and long-term records for trend analysis. Key parameters such as Net Flow, Average Flow, MNF, and flow patterns are introduced as foundational elements for leakage assessment. Existing methods of estimating DMA leakage levels are presented, including detailed description of Ratio Method, Water Balance and Minimum Night Flow, and their applicability for special cases, such as DMA with customer storage tanks, intermittent supply and pressure control.

Additionally, Appendix D describes application of Hydraulic Modelling for validating and locating leakages in DMA, and Appendix E contains detailed information about DMA pressure analysis and its application for calculating DMA leakage levels.

4.1 UNDERSTANDING DMA FLOW DATA

Data quality, validation, and accuracy are prerequisites for any leakage analysis and are addressed in Chapters 2 and 3 respectively. This section focuses on what a practitioner needs to understand about the flow patterns visible in DMA data: what drives their shape, how that shape changes with supply configuration and pressure regime, and how to confirm that the flow trace reliably reflects conditions inside the DMA before any estimation method is applied.

4.1.1 DMA BOUNDARY VALIDATION

Confirming the integrity of a DMA boundary is a prerequisite for reliable leakage analysis. A well-defined boundary exhibits minimal hydraulic interaction with adjacent DMAs, meaning that the flow and pressure data recorded at the inlet meters accurately reflect conditions inside the DMA rather than external influences. Where boundary integrity is compromised — through leaking or partially open valves, unauthorized connections, or meter inaccuracies — leakage estimates will be distorted regardless of the method applied.

Pattern-Based Boundary Indicators

Unusual pressure or flow patterns are often the first sign of a boundary breach. Sudden spikes or drops that cannot be attributed to known events such as bursts or valve operations should be treated as potential integrity indicators. Over time, monitoring these patterns and setting threshold-based alarms allows breaches to be detected systematically rather than through manual inspection. Corroborating the flow and pressure signal with other operational data — pressure complaints, repair records, burst history, and water quality observations — helps narrow the location of a suspected breach.

Pressure Differential Analysis

A functioning boundary valve maintains a measurable pressure difference between its two sides. Where pressure patterns on either side of a boundary valve are identical or closely correlated, the valve may be malfunctioning or partially open, allowing unmonitored flow across the boundary. Conversely, a low correlation between pressure and flow data in adjacent DMAs indicates effective separation. Systematic comparison of diurnal pressure profiles across boundary valves is therefore one of the most reliable diagnostic tools for boundary validation.

Logger Deployment for Breach Detection

Where pattern analysis suggests a potential breach, targeted deployment of pressure, flow, and acoustic loggers can locate it precisely. Pressure loggers identify localized fluctuations consistent with unmonitored flow; flow loggers trace irregular movement patterns within the DMA; acoustic loggers detect the characteristic sound signature of flow passing through a compromised valve. Triangulating data from multiple logger types improves the accuracy of breach localization and ensures that corrective action is directed at the right point in the network.

Advanced Analytical Methods
Regression models can validate whether observed pressure differentials across boundary valves are consistent with expected isolation patterns, flagging statistical anomalies that visual inspection might miss. Where larger datasets are available, machine learning techniques extend this capability by identifying complex multi-variable patterns indicative of boundary compromise. These methods are particularly valuable in large networks where manual review of individual DMA boundaries is impractical.

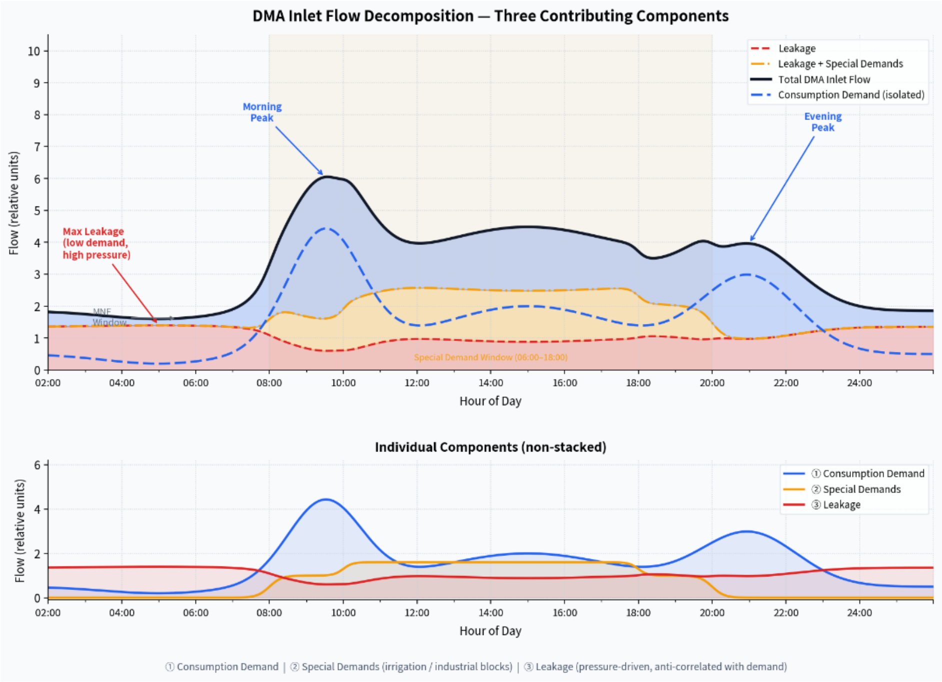
4.1.2 THE DIURNAL FLOW PATTERN AND ITS COMPONENTS

The flow measured at a DMA inlet is not a single signal — it is the superposition of three distinct contributions that combine differently depending on the time of day as shown in the Figure 4-1:

- **Consumption Demand** follows a characteristic diurnal shape driven by human behavior. In residential DMAs this typically produces two peaks — a morning peak between 06:00 and 09:00 as households begin their day, and a smaller evening peak between 17:00 and 21:00. Between these peaks, demand falls to a mid-day plateau, then drops sharply after midnight to its daily minimum. Industrial and commercial DMAs produce flatter profiles with daytime-dominated demand and little evening peak. The shape varies with culture, climate, and customer mix, but the underlying behavioral driver is consistent across systems.

- **Special Demands** — irrigation, industrial processes, and institutional storage are superimposed on the domestic base pattern and can distort it significantly. A large irrigator or industrial consumer can add a flat or block-shaped demand component that masks the residential diurnal shape entirely during its operating period.

- **Leakage** contributes to a continuous, pressure-dependent flow that does not follow the consumption rhythm. Because pressure in an uncontrolled DMA is highest when demand is lowest — typically between 01:00 and 05:00 — leakage is also highest during this period. This is the physical basis of MNF analysis: at the hour of minimum demand, the flow remaining in the trace after subtracting legitimate night consumption is predominantly leakage.


DMA Inlet Flow Decomposition — Three Contributing Components

Individual Components (non-stacked)

① Consumption Demand | ② Special Demands (irrigation / industrial blocks) | ③ Leakage (pressure-driven, anti-correlated with demand)

Figure 4-1 *Diurnal flow pattern and its components (source: Fabio Garzón-Contreras).*

Understanding which of these three components is dominant at any given hour is the foundation of leakage estimation. A practitioner reading a DMA flow trace should be able to identify the consumption shape, locate the night minimum, and assess whether the night floor is elevated relative to what the consumption pattern would predict.

4.1.3 INFLUENCE OF SUPPLY CONFIGURATION AND PRESSURE REGIME

The shape of the diurnal flow trace changes substantially depending on how the DMA is fed and whether pressure is actively managed. Recognizing these configurations is essential before interpreting any flow data for leakage purposes.

Gravity-fed DMA

Gravity-fed DMAs without pressure control produce the clearest and most interpretable flow traces. Pressure varies naturally and inversely with demand: it is highest at night when flow is low and falls during peak demand periods as friction losses increase with flow. Figure 4-2 illustrates this normal pressure-flow relationship. Because pressure is highest precisely when consumption is at its minimum, the leakage contribution to MNF is also at its highest, making MNF analysis reliable and sensitive. This is the configuration for which standard MNF analysis was originally designed (UK Report 26, 1980).

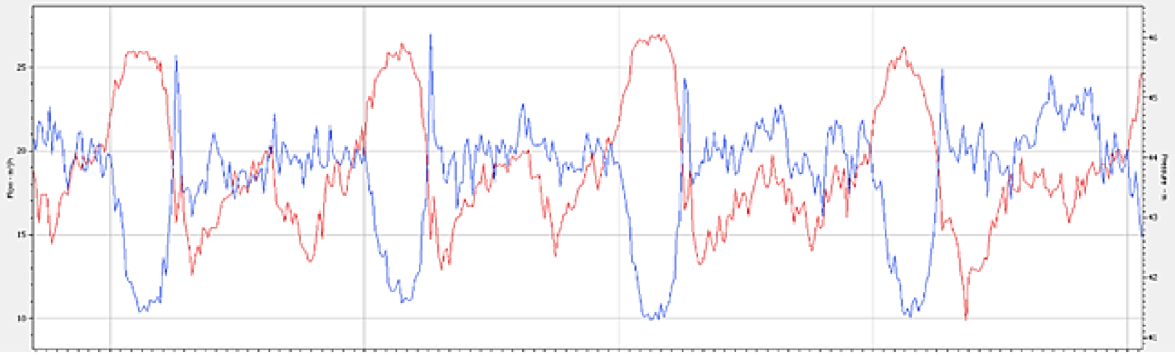


Figure 4-2 *Gravity-feed flow and pressure pattern (source: Crowder Consulting, 2025)*

Pump-fed DMA

Pump-fed DMAs introduce a supply-side signal into the flow trace. Pump start and stop cycles create step changes in flow that are unrelated to customer demand and can be mistaken for demand events or pressure transients. Where pump operation is time-controlled rather than pressure-controlled, the diurnal flow pattern may reflect pump scheduling as much as actual consumption. Analysts should obtain pump operating schedules before interpreting flow data in pump-fed systems.

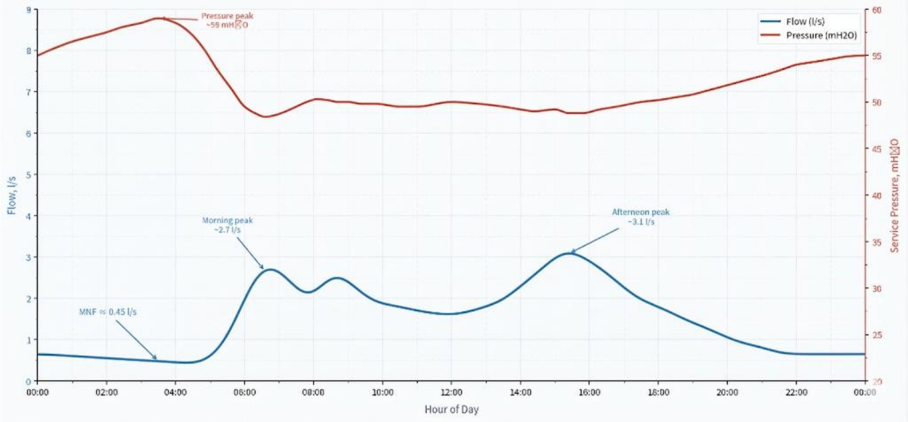


Figure 4-3 *Pumping-feed DMA - flow and pressure pattern (UKWIR, 2015)*

DMA with Pressure Control

DMAs with pressure control — typically equipped with Pressure Reducing Valves (PRVs) or active control systems — require particular care. When pressure is actively reduced during low-demand periods, the inverse pressure-flow relationship no longer holds. Instead, both pressure and flow follow a similar pattern, as the PRV suppresses pressure precisely when leakage would otherwise be highest. Figure 4-4 illustrates this controlled pressure-flow relationship. The practical consequence is that MNF in a pressure-managed DMA is artificially lower than it would be under unmanaged conditions. A low MNF reading does not necessarily indicate low leakage — it may simply reflect effective pressure reduction. Any comparison of MNF values between pressure-managed and unmanaged DMAs must account for this difference.

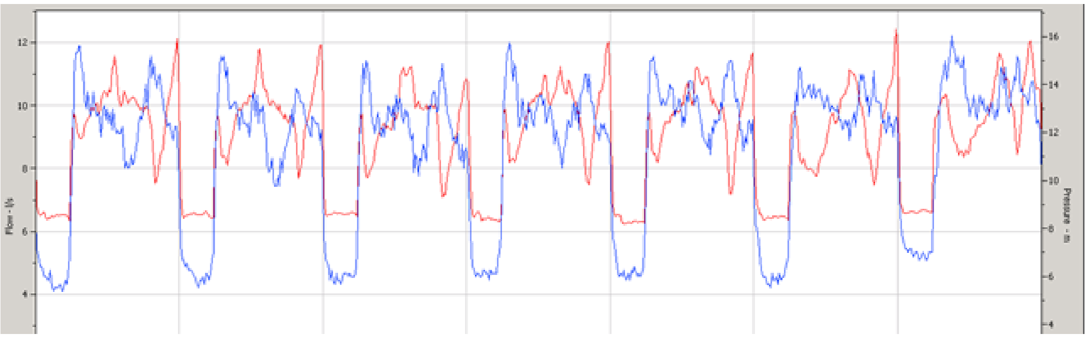


Figure 4-4 *Pressure controlled DMA - flow and pressure pattern (source: Crowder Consulting, 2025)*

DMA with Intermittent Supply

DMAs with intermittent supply produce fundamentally different flow patterns (Figure 4-5). Supply periods are characterized by high initial inflows as the network re-pressurizes and customer storage tanks fill, followed by declining flows as tanks reach capacity. During non-supply hours the DMA flow drops to zero regardless of leakage level, since the system is depressurized. Standard MNF analysis cannot be applied directly.

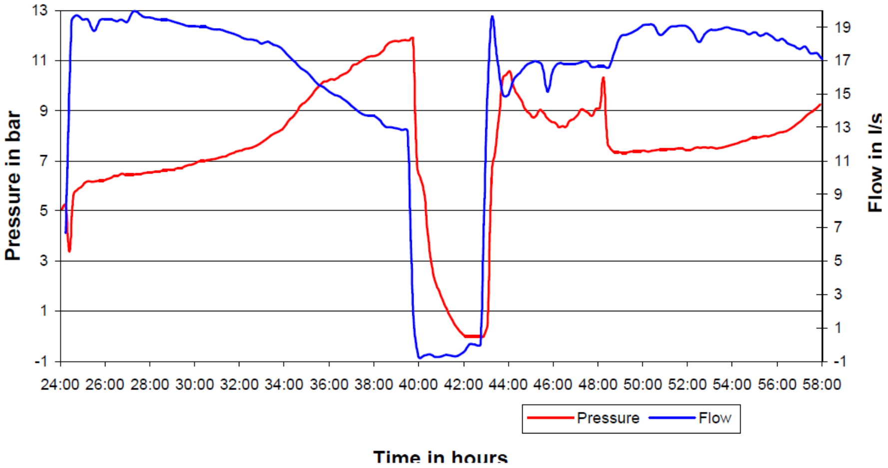


Figure 4-5 *Intermittent water supply DMA - flow and pressure pattern (source: Battermann & Macke, 2001).*

DMA with Customer Storage

DMAs with significant customer storage — particularly those serving high-rise buildings, hotels, or large commercial premises — exhibit smoothed and time-shifted flow patterns. Storage tanks decouple customer consumption from the network supply signal: tanks fill when network pressure is available, not necessarily when customers are using water. The morning peak is delayed and flattened, and tank filling activity during or after the evening peak can inflate the apparent MNF, mimicking leakage. Figure 4-6 illustrates the contrast between a high-rise DMA with storage and a conventional low-rise residential.

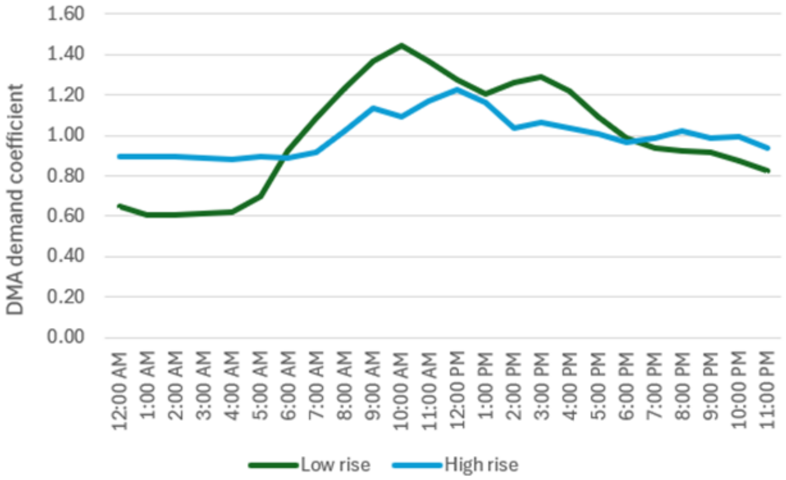


Figure 4-6 *Difference in flow pattern due to presence of storage tanks (source: WMI, 2019)*

4.1.4 WEEKLY, MONTHLY, AND SEASONAL VARIATION

The diurnal pattern described above repeats daily but is not identical every day. Recognizing the sources of day-to-day and season-to-season variation is essential for distinguishing genuine changes in leakage from predictable fluctuations in consumption.

Weekly variation is consistent and predictable in most systems. Weekday patterns (typically Monday to Thursday) are usually similar to each other. Friday may differ depending on cultural and religious context — in many regions it carries a weekend-type pattern. Saturday and Sunday typically have their own distinct profiles with later morning peaks and higher daytime residential demand, reflecting time spent at home. Industrial and commercial DMAs show the reverse: lower weekend demand as businesses are closed. Figure 4-7 illustrates weekday versus weekend flow profiles derived from a week of high-resolution DMA data.

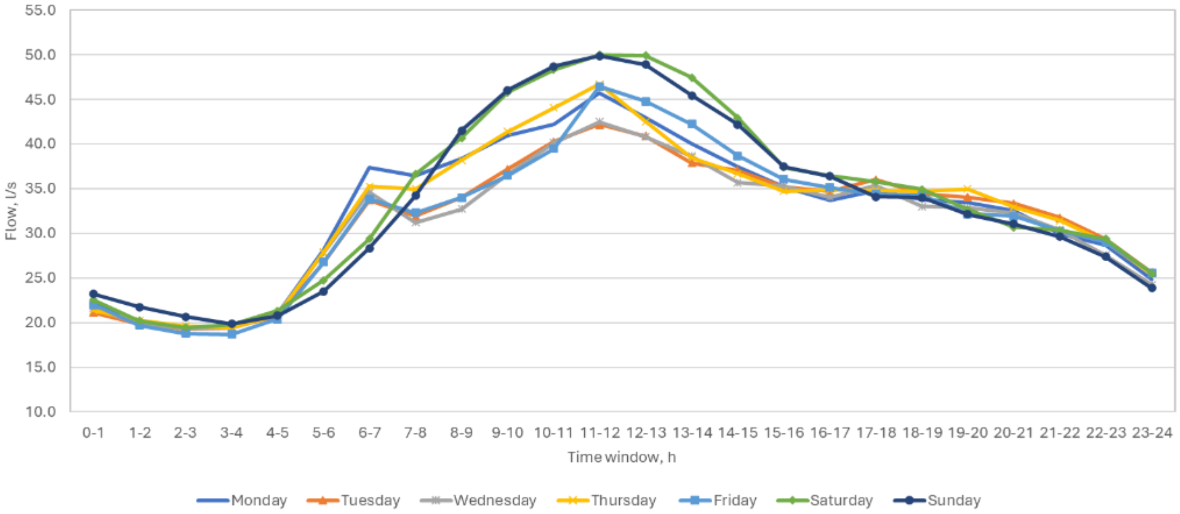


Figure 4-7 *Weekly flow pattern*

Monthly and seasonal variation is driven primarily by temperature and outdoor water use (Figure 4-8). Summer months typically show elevated average flows due to garden irrigation, cooling systems, and tourism demand. Winter months may show lower average consumption, but higher MNF if cold temperatures increase burst frequency and background leakage rates. For leakage analysis, it is important to select a representative baseline period that excludes atypical seasonal events — drought restrictions, heat emergencies, or periods of unusually high precipitation — that would distort the estimate. A minimum of two weeks of stable data under normal operating conditions is recommended before applying any estimation method.

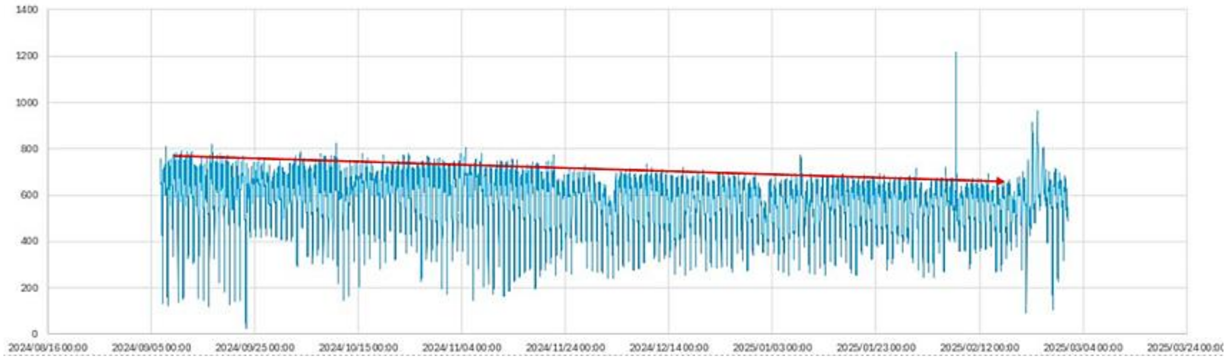


__Figure 4-8__ Monthly flow pattern (source: NIRAS, 2025)

Multi-year trends are the most important signal for strategic leakage management. A gradual year-on-year increase in the baseline MNF — visible only when records extend over twelve months or more — is the characteristic signature of progressive background leakage growth, typically driven by infrastructure ageing and pipe deterioration. A sudden increase in MNF against a stable background indicates a discrete burst event. Distinguishing between these two patterns requires long-term records: a one-year dataset reveals seasonal fluctuations; a five-year dataset begins to reveal infrastructure trends.

4.1.5 DMA PATTERN ANALYSIS FOR DEMAND MANAGEMENT & FORECASTING

A utility can use data from a DMA to forecast water demand by analyzing patterns in historical consumption, time-of-day usage, weather conditions, and seasonal fluctuations. Forecasting at the DMA level enables the utility to estimate total demand for that zone and manage bulk water supply accordingly. This supports operational planning, such as optimizing pump and valve operations, scheduling reservoir refills, and detecting deviations from expected patterns that might indicate leaks or unauthorized use.

Demand Profiling

For more detailed forecasting, demand can be broken down by customer category through demand profiling—residential, industrial, and commercial segments —each of which has distinct usage patterns. These profiles can be integrated with a hydraulic model to simulate how different demand scenarios affect network behavior, supporting both planning and real-time decision-making. This level of detail helps utilities better align supply with demand, implement targeted pressure management, and plan for zone-specific upgrades.

Time-Horizons

Forecasts can be developed over different time horizons. Short-term forecasts, such as next-day predictions, can often be performed reliably by applying the diurnal pattern of the previous day with minor adjustments for temperature or known events. In contrast, long-term forecasts, which may span months or years, carry more uncertainty and require consideration of broader factors such as demographic trends, policy changes, economic activity, and climate change. These longer-term forecasts are essential for strategic infrastructure planning, ensuring system resilience and future-readiness while avoiding overinvestment.

DMA Forecasts in Relation to Supply Zone

A utility can extend DMA-level forecasts to supply zones by aggregating the demand predictions from each constituent DMA and comparing them with the measured inflow to the zone. This creates a bottom-up view of demand that connects local consumption patterns to higher-level supply planning. When differences arise between the aggregated DMA forecasts and the actual inflows, they often point to systemic issues such as leakage outside DMA boundaries, hidden connections, or operational misconfigurations. At a strategic level, this approach not only strengthens production and pumping planning but also gives management visibility into inefficiencies that would otherwise remain hidden in the broader network.

Strategic steps to implement this:

- **Establish forecasting at the DMA level:** build consistent forecasting capability within each district.
- **Aggregate into supply zones:** roll up DMA forecasts to align with operational supply areas, line-up on timestamps on different time-horizons.
- **Benchmark against zone inflows:** compare forecasts with measured inflows into the supply zone to assess performance.
- **Identify systemic discrepancies:** treat persistent gaps as indicators of leakage outside DMAs, boundary valve errors, or planning blind spots.

This strategic use of DMA forecasting elevates it from an operational leakage tool to a framework for long-term resource planning and network efficiency.

4.1.6 KEY FLOW PARAMETERS

The flow parameters used in leakage estimation are derived directly from the patterns described above. Their definitions, calculation methods, and practical considerations are set out in the sub-sections that follow.

Net Flow

If a DMA has several inlets and outlets, the Net Flow — also referred to as DMA Total Demand or, in the IWA Water Balance framework, System Input Volume (Pearson, 2019) is the total flow into the area calculated by summing all inlet and outlet meter readings with their appropriate signs:

$$\textit{Net Flow} = \textit{Total Inflow} - \textit{Total Outflow}$$

In multi-inlet DMAs, flow direction can vary from hour to hour and differ between peak and low-demand periods, depending on available supply sources and network pressures. The net flow is therefore calculated as the algebraic sum of all boundary meter readings, with inflow defined as positive and outflow as negative. It is essential that all meters contributing to this calculation are synchronized to the same time resolution, and that the sign convention for each meter is verified against actual field conditions rather than assumed from drawings alone.

Where the DMA contains continuously metered users whose consumption is recorded separately, the Net Flow is determined by subtracting both the total outflows and the logged user consumption from the total inflows.

HELPFUL TIPS

Always verify the flow direction of every boundary meter installed in the field — ideally with photographic records — as incorrect flow direction assignment is one of the most frequently encountered errors in DMA data. It typically arises from discrepancies between design drawings and actual site conditions, poorly georeferenced network plans, or ambiguous pipe

Average Flow

The Average Flow (AF) represents the total net water inflow to the DMA averaged over a defined period — daily, weekly, or monthly. It encompasses both authorized consumption (billed and unbilled) and losses (real and apparent) and is used as the denominator in the Ratio Method and as the System Input Volume in the Water Balance Method.

When calculating AF, apply the following:

- Exclude error values and outliers identified during data validation (Chapter 3).
- Exclude zero-flow values recorded during non-supply hours in intermittent supply systems (Section 4.3.2).
- Use a minimum of 7–14 days of data under stable operating conditions to ensure a representative result.

Minimum Night Flow

The Minimum Night Flow (MNF) is the lowest 1-hour average flow rate recorded at the DMA boundary during the night period, normally defined as midnight to 06:00. In urban systems the MNF typically occurs within a two-hour window in the early morning, though the exact timing varies by region and customer mix (Pearson, 2019).

In a stable DMA, the majority of the MNF is attributable to leakage, since customer consumption reaches its daily minimum during this period. The MNF is therefore the primary input to the MNF Analysis method described in Section 4.2.3.

In DMAs with multiple inlets or outlets, the MNF is the minimum of the aggregated net flow across all boundary meters — not the sum of the individual minimum flows recorded at each meter separately (IWA, 2024). This distinction is important: summing individual meter minima, which may occur at different times, will underestimate the true MNF.

Where the highest measurement precision is required, fast logging at intervals of one second or less can be applied without interfering with the standard logging configuration. This enables the detection of pressure transients and more accurate MNF determination using Pulse Interval Timing (PIT), which is described in Section 2.3.

Table 4-1summarizes the three principal MNF calculation methods — Fixed, Rolling, and Actual — and Figure 4-9 illustrates their application to a typical DMA flow trace.

Table 4-1 DMA MNF calculation methods

Method	Calculation	Notes	Value from the example
Actual	Actual lowest value during the night period	Can be affected by data quality	0.48 m³/h
Fixed	Average value of readings over the fixed night period (usually one hour)	Actual minimum flow can occur outside fixed period	0.59 m³/h
Rolling	A rolling average of the lowest flows during rolling time window across multiple nights	Smoothing out anomalies and data quality issues	0.54 m³/h

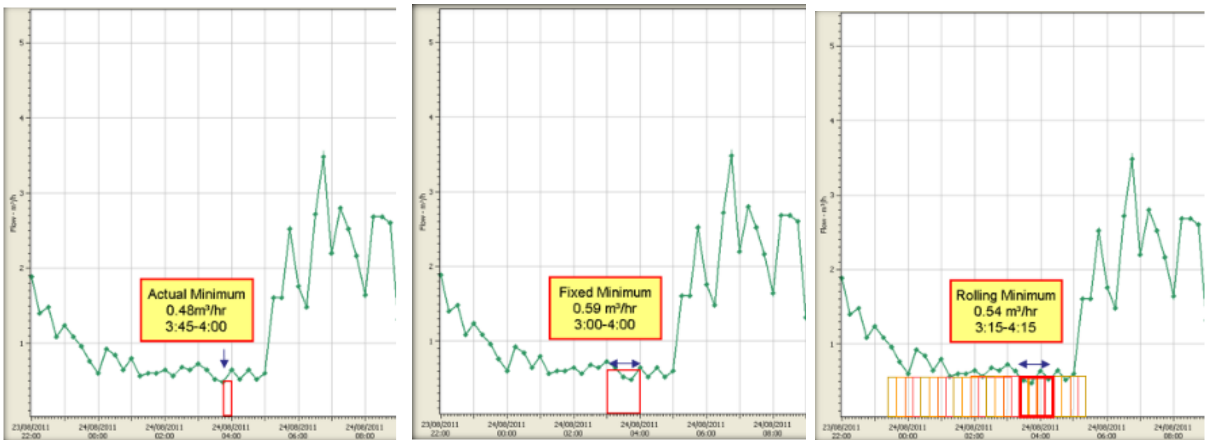


Figure 4-9 Example of DMA MNF calculation methods (source: Crowder Consulting, 2025).

The choice of MNF calculation method should be guided by the analytical objective. For routine monitoring and reported leakage estimates, a rolling 7-day percentile of the minimum rolling hour is recommended (UKWIR, 2017). The minimum rolling hour is calculated by averaging four consecutive 15-minute flow values, producing an hourly average every 15 minutes; the minimum of these rolling hourly averages within the 00:00–06:00 window is then determined for each night. The 7-day percentile is calculated daily by ordering the minimum rolling hours from the current day, the three preceding days, and the three following days, and calculating the percentile of these seven values.

The 20th percentile provides the best estimate of the underlying leakage trend. By returning a value between the second and third lowest of the seven daily values, it allows isolated low readings — caused by unusually low night consumption on a single night — to be disregarded while remaining sensitive to genuine leakage increases. Where consistent night use allowances at the 20th percentile level are difficult to determine, the 50th percentile is an acceptable practical alternative; it corresponds more closely to average night conditions and simplifies the night use estimation. The period over which the percentile is applied should be short enough to detect sudden changes such as burst events, but long enough to smooth day-to-day variation in night use — 7 days represents a well-supported compromise.

The fixed hour method — the minimum flow within a fixed nightly window — gives results similar to the minimum rolling hour and may be preferred where operational systems are not configured for rolling average calculations. It is appropriate for daily alerting and automated monitoring where computational simplicity is valued over precision.

The Actual MNF — the unconstrained minimum flow across the full 24-hour period — is appropriate for one-off leakage assessments, formal MNF Analysis calculations (Section 4.2.2), and BABE applications, but should not be used for routine monitoring or reported leakage estimates.

For monthly and annual leakage estimates, the daily 7-day percentile values should be averaged over the reporting period. Where data gaps occur, the percentile can be calculated with fewer than 7 days of data, but reliability decreases progressively. The percentile should not be calculated when fewer than 4 daily values are available; gaps below this threshold should be filled using the average of the 7-day percentile values from the months immediately before and after the gap.

Regardless of which method is used, the night use allowance applied must be consistent with the leakage estimation method chosen. Mixing a 20th percentile nightline with a night use allowance derived from average night conditions, for example, will systematically underestimate leakage.

4.2 LEAKAGE ESTIMATION METHODS

Leakage in a DMA cannot be measured directly — it must be estimated by analyzing the flow and pressure data collected at the DMA boundary and combining it with knowledge of legitimate consumption. The reliability of any estimate depends on the quality of that data, the validity of the assumptions applied, and the degree to which the chosen method is appropriate for the specific characteristics of the system being analyzed.

No single method is universally optimal. Each of the methods presented in this section makes different demands on data availability and quality, operates at different levels of spatial resolution, and carries a different degree of inherent uncertainty. The choice of method should therefore be driven by the analytical objective — whether the goal is a rapid screening of multiple DMAs, a precise quantification of total losses in a single DMA, or the identification of likely leak locations within the network — as well as by the data and resources available to the analyst.

The methods presented here span this range of objectives and data requirements. At one end, the Ratio Method requires only flow data and provides a quick comparative indicator suitable for initial screening. MNF Analysis and the Water Balance Methods are the workhorses of operational leakage management, each approaching the total leakage estimate from a different direction — one from the bottom using night flow minimum, the other from the top using supply-consumption balance. Table 4-2 summarizes the key characteristics, data requirements, and appropriate applications of each method.

Table 4-2 DMA leakage level estimation methods.

Method	Best for…	Requires	Main Challenges
Ratio Method	To estimate order of magnitude of leakage level, and compare them between DMAs	DMAs with little available data (flow only)	Very approximative
DMA Water Balance (top-down)	Estimation of NRW	DMA in and out flow meters, high ratio of metered customers with regular readings	Estimation of Apparent Losses
DMA MNF Analysis (bottom-up)	Estimation of real losses (leaks)	DMA in and out flow meters and average zone pressure with high frequency, legitimate night use, stable diurnal pattern	Legitimate night use estimation

Every leakage estimate carries uncertainty. The magnitude of that uncertainty depends on the accuracy of the input data, the validity of the assumptions embedded in the method, and the stability of the operating conditions during the measurement period. Quantifying this uncertainty — rather than treating the estimate as a precise figure — is essential for sound decision-making. The uncertainty estimation framework presented in Chapter 3 applies directly to leakage estimates derived by any of the methods below; practitioners are encouraged to document the uncertainty associated with each estimate and to communicate it alongside the result.

The example of real case data-driven DMA leakage estimation used by Brønderslev Water Company in Denmark is presented in Appendix G.

4.2.1 RATIO METHOD

The Ratio Method is a simple, effective screening tool for initial estimation of leakage levels and for detecting new leakage events in a DMA. It is especially useful when:

- Only flow data is available - no pressure or customer metering data is required.
- Rapid comparative screening across multiple DMAs is required to identify those with the highest leakage levels.
- The DMA operates without active pressure control.

This method is based on the ratio of MNF to Average Flow (AF), which serves as an indicator of the relative magnitude of real losses within the DMA. A higher ratio indicates a greater level of real losses in the DMA.

$$Ratio = \frac{\mathrm{MNF}}{\mathrm{AF}}$$

Monitored over time, a sudden increase in the MNF/AF ratio relative to historical values is a reliable indicator of a new leakage event.

Figure 4-10 shows the measured inlet flow for two residential DMAs of different sizes. The substantially higher MNF/AF ratio in the left DMA indicates a significantly higher leakage level.

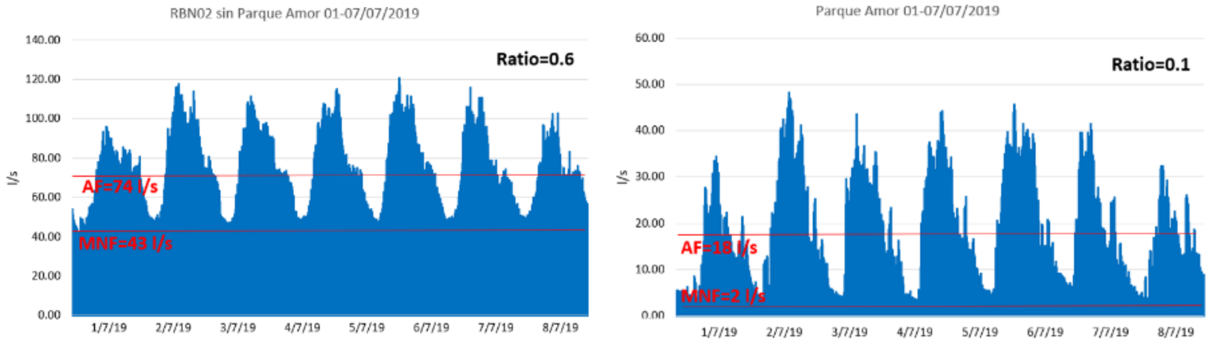


Figure 4-10 *Cross-DMA Comparison using MNF/AF Ratio (source: WMI, 2020).*

Typical classification thresholds (subject to local context and seasonal demand):

- Ratio < 0.30: Low leakage
- 0.30 ≤ Ratio ≤ 0.50: Medium leakage
- Ratio > 0.50: High leakage.

Where a utility defines a target MNF/AF ratio, the difference between the actual MNF and the MNF implied by that target ratio at the current AF provides an approximate indication of recoverable leakage, subject to the pressure-dependence limitations of this method.

4.2.2 WATER BALANCE

The IWA Water Balance is a widely applied framework for quantifying Non-Revenue Water at the level of a water utility or supply zone. At DMA level, the same accounting structure applies — System Input Volume minus Authorized Consumption equals NRW — but the practical context is fundamentally different, and several assumptions that are acceptable at utility level require careful reconsideration when applied to a DMA.

At utility level, the System Input Volume is typically derived from production meters at treatment works or bulk import points, which are large, well-maintained instruments operating within their designed flow range and calibrated to a high standard. At DMA level, the equivalent measurement is the Net Flow calculated from boundary meters that may be smaller, older, operating near the limits of their measurement range during low-demand periods, and subject to the installation effects discussed in Chapter 2. The metering uncertainty at DMA level is therefore structurally higher than at utility level, and this propagates directly into the uncertainty on the Real Losses estimate.

At utility level, customer consumption is known from billing records that cover the entire customer base with reasonable completeness. At DMA level, the spatial boundary of the DMA and the spatial boundary of the billing database are frequently misaligned and before any Water Balance calculation is attempted, the analyst should verify that the customer register used for consumption estimation corresponds to the physical DMA boundary as currently configured, not to a historic or administrative boundary that may have drifted from it.

The time dimension presents a further DMA-specific challenge. At utility level, production volumes and billing data are typically aggregated to the same monthly or annual reporting cycle. At DMA level, the Net Flow is recorded continuously at 15-minute intervals while customer meter readings are collected on rolling routes that may take one to two weeks to complete for a single DMA. Failing to account for this misalignment can introduce systematic errors in the Real Losses estimate, particularly in periods of rapidly changing consumption such as the transition between summer and winter demand.

Finally, DMAs are small enough that a single large customer — a hospital, an industrial facility, a hotel with significant storage — can represent a material fraction of total authorized consumption. At utility level, individual large consumers are smoothed into a population average. At DMA level they are not, and their consumption patterns, meter sizes, and billing cycles warrant individual attention rather than treatment as part of a homogeneous customer base.

These considerations do not make the Water Balance inapplicable at DMA level — they make it more demanding to apply correctly. The procedure that follows addresses each of these challenges in turn.

Constructing a DMA Water Balance: Step-by-Step Procedure

The IWA Water Balance framework (Pearson, 2019) provides the standard structure for quantifying NRW at any level of the distribution system (Figure 4-11). At DMA level, the same framework applies, but the data sources and practical challenges differ from utility-level calculations. The following procedure guides the analyst through a complete DMA Water Balance under typical operational conditions.

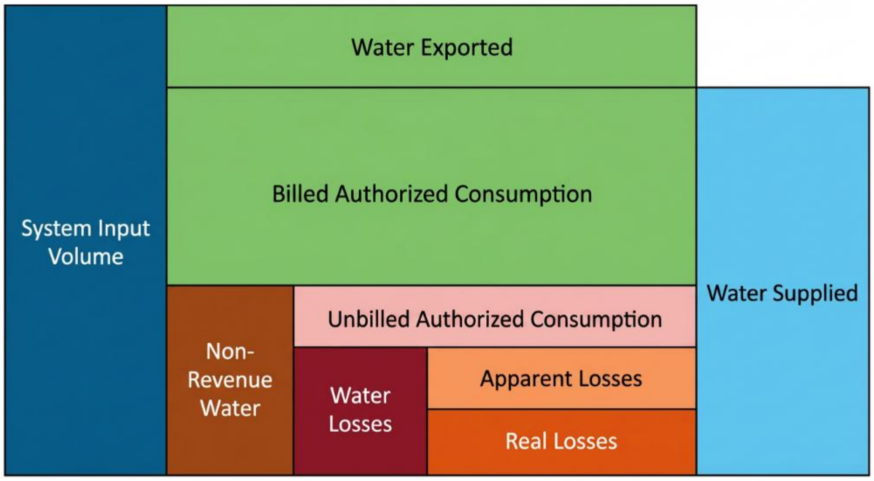


Figure 4-11 *IWA Water Balance*

Step 1 — Define the Analysis Period

Select a period that is representative of normal operating conditions and for which complete data is available across all components. Avoid periods affected by network interventions, pressure regime changes, meter replacements, or atypical demand events such as droughts or public holidays. For a first assessment, a calendar month is a practical starting point; for active leak management, weekly or daily periods are preferable. All subsequent steps must use data covering exactly this period — temporal alignment across components is the single most important quality requirement of the Water Balance calculation.

Step 2 — Calculate the System Input Volume

The System Input Volume (SIV) is the total volume of water entering the DMA during the analysis period, calculated by integrating the Net Flow (Section 4.1.5) over time. Where the DMA contains distribution tanks, the volume changes in tank storage must be accounted for: water drawn from a tank during the period must be added to the metered inflow, and water used to fill a tank must be subtracted. Direct pumping from boreholes or other sources within the DMA boundary must also be included.

Step 3 — Determine Billed Authorized Consumption

Billed Authorized Consumption is the total volume invoiced to registered customers during the analysis period. Before extracting consumption data, two alignment checks must be performed — one spatial and one temporal — and, where unmetered accounts are present, the supply and payment arrangements for those accounts must be confirmed. All three are sources of systematic error specific to DMA-level analysis that do not arise in the same way at utility level.

Spatial alignment — verify the customer register against the physical DMA boundary

The customer register used to extract consumption data must correspond to the physical DMA boundary as currently configured. Spatial misalignment between billing zones and DMA boundaries is common and arises from several causes: customers near a DMA boundary may be assigned to a different billing zone than the DMA from which they are physically supplied; properties may have been transferred between DMAs following network reconfigurations without the billing system being updated; and bulk meter connections or wholesale customers may not appear in the standard residential billing extract. Any of these conditions introduces a systematic error into the Billed Authorized Consumption figure that carries through directly into the Real Losses residual.

Before the consumption extraction is run, the analyst should cross-check the customer register against the current DMA boundary using the GIS or network model, identify any accounts spatially inside the DMA boundary but assigned to a different billing zone, and confirm that all bulk and wholesale meters within the boundary are included. This check is a one-off investment per DMA that significantly improves the reliability of all subsequent Water Balance calculations.

Temporal alignment — match billing data to the analysis period

Billing cycles and DMA flow monitoring periods are rarely aligned: meter reading routes typically take one to two weeks to complete, and billing records are aggregated by invoice cycle rather than by calendar period. To align billed consumption with the analysis period, one of the following approaches should be applied:

- Where static meters are installed, extract hourly or daily consumption records for all meters within the DMA boundary and sum them directly over the analysis period. A representative sample of 30% is considered acceptable where full coverage is not available (UKWIR, 2024).
- Where manual meter reads are used, prorate the billed consumption to the analysis period using daily average consumption rates derived from the billing cycle volume and its duration.
- Where consumption is unmetered and billed at a flat rate, apply the appropriate consumption rate per property type from published reference values appropriate to the local context or from local field measurements.

Large consumers

Regardless of the temporal alignment method applied, large non-domestic consumers within the DMA should be treated individually rather than as part of the general consumption extraction. A single hospital, hotel, industrial facility, or commercial premises can represent a material fraction of total DMA consumption, and errors in their billing data — misread meters, incorrect tariff assignments, estimated reads not reconciled against actuals — have a disproportionate effect on the Billed Authorized Consumption figure. Where a large consumer's most recent meter read falls outside the analysis period, consumption should be estimated from daily average rates derived from surrounding reads rather than carried forward from a stale reading.

Unmetered consumption

Step 3a — Identify Supply Arrangement and Payment Classification

Before applying any estimation method, confirm two characteristics of each group of unmetered accounts: the supply arrangement — whether supply is bulk-metered or individually unmetered — and the payment arrangement — whether an invoice is issued and by whom.

Where a bulk meter is installed at the supply area boundary, the entire metered volume is Billed Authorized Consumption. The utility's Water Balance ends at the meter: leakage on internal distribution pipes downstream is outside the utility's asset boundary and falls within the internal operator's own loss accounting. The Non-Metered Use Adjustment Factor (NMUAF) procedure below does not apply.

Where no bulk meter exists and properties are supplied without individual meters, the Water Balance classification depends on the payment arrangement:

- Where the community or municipality pays an invoice at any applicable tariff — including a social tariff — the consumption is Billed Authorized Consumption. Where a social tariff applies, this rate should be used as the conversion denominator in Step 3b rather than the residential tariff.
- Where no invoice is issued but the supply is authorized, the consumption is Unbilled Authorized Consumption and should be estimated in Step 4.
- Where no invoice is issued and no authorization exists, the supply is Unauthorized Consumption and belongs in Step 5, subject to the policy classification decision in Step 4.

Step 3b — Convert Flat-rate Charge to Baseline Volume

Divide the flat-rate charge by the applicable volumetric unit charge to produce a baseline consumption volume per household, expressed over the same billing period as the flat-rate charge and then scaled to the analysis period. Where a single volumetric rate applies, this conversion is direct. Where an increasing block tariff is in effect, use the average revenue per cubic meter across metered customers of the same property type within the DMA, calculated from billing records. This avoids the circularity of using a block rate that depends on the consumption volume being estimated. Where billing data is insufficient to calculate this average, the first block rate may be used as a fallback, noting that this will tend to produce a higher baseline volume.

Step 3c — Estimate Unmetered Consumption

Two approaches are available depending on whether sub-DMA measurement infrastructure exists.

- NMUAF approach — where sub-DMA direct measurement is not available:

  Unmetered consumers systematically use more water than metered consumers of equivalent property types due to the absence of a financial disincentive for excessive use — the metering elasticity gap. The flat-rate baseline from Step 3b underestimates physical consumption and must be adjusted upward:

Estimated unmetered consumption = Baseline volume × NMUAF

The NMUAF should be derived from local field measurement — paired comparisons of consumption before and after meter installation or monitoring of a sample of newly metered previously-unmetered connections. Where local data is not available, the reference ranges in Table 4-3 may be used as a starting point. These ranges are based on practitioner experience and should be replaced by locally calibrated values as field data becomes available.

Table 4-3 Unmetered consumption estimation methods.

Development type	NMUAF range	Primary driver
High-density residential	1.20–1.25	Predominantly indoor use
Standard urban / middle-income	1.25–1.30	Discretionary outdoor use; small gardens
Low-density / suburban	1.30–1.40	Irrigation; larger property footprints
Informal settlements — communal tap, no bulk meter	1.25–1.35	Waste downstream of tap outlet only — see boundary conditions below
Modern eco-districts	1.00–1.10	Low-flow fixtures; water-efficient infrastructure

Where a DMA contains a mix of development types, apply a weighted average NMUAF based on the proportion of unmetered accounts in each category.

- Area monitor approach — where sub-DMA measurement is available:

  Where a flow logger can be installed at the inlet to a discrete unmetered sub-area, unmetered consumption can be estimated directly: measure total inlet flow over the analysis period, subtract estimated network leakage derived from night flow analysis at the sub-area inlet, and subtract the metered consumption of any metered customers within the sub-area. The residual is the unmetered consumption for that area and period. This is the most direct available method and its results should be used to calibrate the NMUAF for similar development types elsewhere in the portfolio.

The output of Steps 3b and 3c is consumption per household per analysis period. This is the figure that enters the Water Balance. Conversion to per-capita consumption is not required for Water Balance purposes, since property counts from the asset register are more reliable than occupancy estimates, which are typically less current and carry higher uncertainty — particularly in areas of rapid urban change.

Calibrating the NMUAF

Where locally calibrated NMUAF values are to be derived, the calibration target is consumption per household per day by development type, using property counts from the asset register as the denominator. Individual household monitors — with data logging at 15-minute intervals for flow profile analysis, or with manual reads for average consumption only — and area monitors as described above are the primary field methods. Where multiple DMAs with similar characteristics are available, pooling results across DMAs produce more robust estimates and is particularly valuable for smaller utilities that cannot sustain a large individual monitoring program. Calibrated NMUAF values should be reviewed every three to five years as metering penetration, tariff structure, and urban development patterns change.

Boundary Conditions to Prevent Double Counting

Three boundaries apply to all unmetered consumption estimates regardless of the approach used.

The estimate covers legitimate consumption waste downstream of the last pressurized point of the utility's system — the tap outlet or connection point. Leakage on utility-owned pipes upstream of that point is Real Loss and is estimated in Step 6. In informal settlements supplied through communal taps, this boundary is the tap outlet: leakage upstream is Real Loss; waste after water exits the tap is consumption. Where upstream leakage is material, its volume should be estimated from night flow measurements at the settlement supply point and recorded as Real Loss in Step 6, not included in the consumption estimate.

The estimate does not include unauthorized consumption — water taken without the utility's authorization — which is estimated in Step 5. Where unauthorized consumption is present in unmetered areas it must be excluded from the consumption estimate.

The informal settlement NMUAF includes communal tap waste only where the utility has classified that supply as Authorized Consumption in Step 4. Where it has been classified as Unauthorized Consumption it must be excluded here and estimated in Step 5 instead.

Step 4 — Estimate Unbilled Authorized Consumption

Unbilled Authorized Consumption (UAC) comprises two distinct categories: servicing water — volumes used by the utility for its own operational purposes — and free water supply — volumes provided without charge to specific consumer categories by legal obligation, contractual arrangement, or utility policy (Vermersch et al., 2016). Although UAC is not a water loss, it is a component of NRW, and underestimating or neglecting it will lead to systematic overestimation of Real Losses and Apparent Losses, and consequently to misdirected action planning.

Before any quantification is attempted, the first task is to establish an inventory of all UAC categories present within the DMA during the analysis period. Servicing water typically includes tank cleaning, pipe flushing, network discharge for water quality maintenance, hydrant flow and pressure tests, and backwashing of treatment devices. Free water supply may include water provided to municipal premises, public fountains, street cleaning operations, firefighting, frost protection, and utility staff — the exact categories depend on local legal and contractual arrangements.

A category of UAC that warrants explicit recognition, particularly in low- and middle-income country contexts, is water supplied to informal settlements or communities located in disaster risk zones. Where such supply is provided under a legal obligation, constitutional human right mandate, or explicit regulatory directive, it is unambiguously UAC and must be estimated and included in the Water Balance accordingly. Where it is provided on a tolerated but informally authorized basis — a common situation in rapidly urbanizing systems — the utility should make a formal policy decision on classification and document it: treating this water as Unauthorized Consumption or leaving it unclassified will systematically inflate both Apparent Losses and Real Losses estimates. In either case, the volume should be estimated using community population counts, representative per-capita consumption rates for the supply type, and the duration of supply during the analysis period. Only where connections have been made entirely without utility knowledge or tolerance should the supply be classified as Unauthorized Consumption within Apparent Losses.

Where UAC is metered, the recorded volumes for the analysis period should be extracted directly. Where it is unmetered — which is the case for the majority of servicing activities — volumes should be estimated using, in order of preference: operational records of known activities during the period such as pipe flushing events, reservoir cleaning, and fire incidents; technical standards appropriate to the local context, such as the Astee (2011) framework which provides standard volumes per activity type; or default percentage values as a last resort.

Where default values are applied, the following internationally referenced figures provide a basis for assessment. No single default is universally applicable — each reflects different national circumstances, objectives, and definitions of what constitutes authorized consumption (Vermersch et al., 2016):

- 1.25% of Water Supplied: median of 23 England and Wales utilities (OFWAT, 2002–03); also the AWWA M36 default for unmetered UAC (AWWA, 2016).
- 0.5% of Water Supplied: default adopted by the Water Services Association of Australia and the New Zealand Water & Wastes Association (2010).
- 0.5% of Billed Metered Consumption excluding water exported: recommended maximum default for initial overview assessments by the EU Good Practices on Leakage Management reference document (2015).

Of these, expressing UAC as a percentage of Billed Metered Consumption excluding water exported is preferable to a percentage of System Input Volume or Water Supplied. Once UAC is reduced through operational improvement, the volume reduction transfers directly into Billed Authorized Consumption, keeping the denominator stable and making comparisons over time more meaningful (Vermersch et al., 2016).

This general limitation is particularly acute at DMA level. A single large UAC source — an informal settlement, a municipal facility, or a public fountain — can account for a disproportionate share of total UAC relative to the DMA System Input Volume, meaning a blanket percentage default will produce a materially incorrect estimate regardless of which reference value is chosen. The UAC inventory, the chosen estimation method, the assumed values, and their basis must all be documented explicitly as part of the uncertainty record for the Water Balance.

Step 5 — Estimate Apparent Losses

Apparent Losses comprise three distinct sub-components: unauthorized consumption, customer meter inaccuracies, and data handling errors. Although these are often aggregated into a single percentage default at utility level, this approach is unreliable at DMA level and should be avoided as the primary estimation method. A DMA is small enough that a single unauthorized connection serving a commercial or industrial consumer, or a cluster of tampered meters, can represent a material fraction of total System Input Volume — far exceeding any standard default percentage. Equally, a well-managed DMA with smart metering and no known integrity issues may have near-zero apparent losses in one or more sub-components. Estimation at DMA level should therefore be based on direct investigation wherever possible, with percentage defaults reserved for sub-components where no better information is available.

In a network of multiple DMAs, it is neither necessary nor practical to conduct a detailed apparent losses investigation for every DMA simultaneously. A portfolio-level screening should first be applied using readily available indicators — the MNF/AF ratio (Section 4.2.1), the NRW percentage from a preliminary Water Balance using default assumptions, or trend analysis of inlet flow over time — to identify the DMAs with the highest apparent loss risk or the most significant deteriorating trends. Detailed investigation using the methods described below should be concentrated on this priority subset. In a typical network, a minority of DMAs account for the majority of total NRW, and directing investigative resources accordingly will produce more reliable Water Balance estimates across the portfolio than applying weak methods uniformly to every DMA. As each priority DMA is investigated, its DMA-specific apparent loss estimate replaces the default assumption in subsequent portfolio-level calculations, progressively improving the accuracy of the overall Water Balance without requiring a simultaneous network-wide investigation.

Unauthorized Consumption

Unauthorized consumption falls into three categories, each requiring a different detection approach (Carteado & Vermersch, 2016):

- Consumption by unregistered consumers — those who have made connections without appearing in the utility's customer database.
- Consumption by registered consumers committing fraud through meter tampering, bypasses, or unauthorized reconnection after disconnection.

- Theft from network equipment such as hydrants and discharge valves.

Portfolio screening level

Across a DMA portfolio, the first step is a batch analysis of the billing and customer database, which can be run simultaneously across all DMAs at low cost and without field work. For each DMA, the analyst should extract:

- Number of accounts without meters.
- Number of accounts showing zero or abnormally low consumption for two or more consecutive billing periods.
- Number of accounts registered as disconnected for non-payment that have not requested formal reconnection.
- Number of accounts whose consumption shows no seasonal variation over a twelve-month period.

These indicators do not quantify unauthorized consumption directly — they identify DMAs where the risk is elevated and where detailed investigation is likely to be productive. DMAs where these indicators cluster geographically, exceed locally defined threshold rates, or show a deteriorating trend over successive periods should be added to the priority investigation list. For non-priority DMAs, a default assumption of 0.1% of Water Supplied (Lambert & Taylor, 2010; Vermersch et al., 2016) or the locally applicable reference value may be applied, with the explicit understanding that this figure will be replaced by a direct estimate once the DMA is investigated.

Priority DMA investigation

For DMAs identified as priorities, assessment follows a two-stage sequence. The first stage extends the screening indicators into a systematic database review: flagged account categories — zero-consumption accounts, disconnected accounts without reconnection requests, accounts with implausibly stable consumption — are extracted and counted, and their geographic distribution within the DMA is mapped to identify spatial concentrations of risk.

The second stage is a field campaign designed to establish anomaly rates across both the flagged categories and the general DMA population. The campaign should cover 3–5% of customers, structured so that flagged account categories are sampled at higher intensity than their proportion in the DMA population warrants, while the remainder of the sample is selected to represent the full range of property types, geographic zones, and social conditions within the DMA (Carteado & Vermersch, 2016). For each visited account the survey records:

- Presence and condition of meter.
- Evidence of bypasses, tampered seals, or reversed meters.
- Unregistered connections.
- Discrepancies between the field situation and the customer database.

From this stratified sample, two extrapolations are made: the anomaly rate within each flagged category, applied to the full count of flagged accounts; and the background anomaly rate in the general population, applied to the non-flagged accounts. The sum of these two extrapolations gives the estimated unauthorized consumption volume for the DMA, together with an indication of whether a more comprehensive census is warranted.

In DMAs containing informal settlements or very low-income areas, standard detection methods are generally not applicable. The technical and administrative conditions that make database analysis and field surveys tractable — a maintained customer register, accessible meter installations, safe operating conditions for field staff — are frequently absent. In these areas the assessment requires a sociological as well as a technical approach, with community participation and engagement with local associations forming an essential part of any investigation (Carteado & Vermersch, 2016). The classification of supply in these areas as unauthorized consumption or UAC should follow the policy decision made in Step 4.

Where direct estimation remains unfeasible after screening and investigation, the following reference values may be applied as a last resort. No single value is appropriate for uniform application across a DMA portfolio, and in developing country contexts in particular, unauthorized consumption is typically concentrated in specific DMAs rather than uniformly distributed — applying a portfolio-wide average to individual DMAs will underestimate losses in high-risk areas and overestimate them in well-managed ones:

- 0.1% of Water Supplied for systems with robust metering and enforcement (Lambert & Taylor, 2010; Vermersch et al., 2016).
- 0.25% of Water Supplied where AWWA audit methodology is applied (AWWA, 2016).
- 10% of NRW has been cited for developing country contexts at utility level (Mutikanga et al., 2011; Seago et al., 2004), but this figure should not be applied at DMA level without field verification, as unauthorized consumption in these contexts is typically concentrated in specific DMAs rather than uniformly distributed.

Customer Meter Inaccuracies

Customer meters systematically under-register at low flow rates and, depending on age and technology, may also under-register at high flows. At DMA level, the estimation of meter inaccuracy requires a different approach from utility-level practice because the small number of accounts means that a single poorly performing meter — particularly a large non-domestic meter — can dominate the sub-component estimate in a way that a utility-wide average would never reveal.

Portfolio screening level

For non-priority DMAs, meter inaccuracy may be estimated using a default percentage applied differentially by meter technology and age band, derived from the utility's asset register and meter test program results. Applying a single undifferentiated default across all meter types is not recommended even at screening level, because the range of inaccuracy between a new static meter and an aged velocity meter at the same flow rate can span an order of magnitude. Where the asset register holds sufficient information to stratify meters by technology and approximate age and accumulated volume, a weighted average inaccuracy can be calculated for each DMA from the portfolio-level test results without requiring DMA-specific testing.

The exception at screening level is large non-domestic meters. Even in a portfolio-level calculation, large non-domestic meters within each DMA should not be folded into the default percentage assumption. Their volume weighting is too great for the resulting error to be acceptable: a single oversized or ageing large meter can represent a substantial fraction of total billed consumption in the DMA, and its inaccuracy has an outsized effect on the Real Losses residual. Non-domestic meters should therefore be individually identified in every DMA and their inaccuracy estimated separately — from asset register data, recent test results, or consumption pattern analysis — regardless of whether the DMA is on the priority investigation list.

Priority DMA investigation

For priority DMAs, the estimation of meter inaccuracy should be built from DMA-specific data rather than portfolio defaults. The first step is to identify the dominant meter groups within the DMA — by technology, nominal diameter, brand and model, and approximate age band or accumulated volume as a proxy — and test a representative sample within each. Generic accuracy curves from manufacturer data or national standards should not be substituted for DMA-specific test results, since meter performance depends on the actual flow regime, water quality, and operating pressure of the specific DMA, none of which are captured in generic profiles. DMA-specific data logging is strongly recommended for domestic consumption profiles, as demand patterns at DMA level can differ significantly from utility-wide averages depending on property type, occupancy rates, and local demand characteristics.

Non-domestic meters must be studied individually. A single large commercial or industrial meter can represent a substantial fraction of total billed consumption, and its inaccuracy profile — typically different from domestic meters in both direction and magnitude and often involving systematic under-registration at partial load — has an outsized effect on the overall estimate. Identifying and individually characterizing even one large non-domestic meter can materially change the meter inaccuracy estimate in a way that correctly reflects where metering loss is actually occurring (Carteado & Vermersch, 2016). Where smart meter data is available, comparison of individual meter readings against expected consumption profiles can identify under-registering meters without requiring physical testing (UKWIR, 2024).

Because the sample of meters tested at DMA level is necessarily small, the resulting estimate carries higher relative uncertainty than a utility-level figure. The result should be expressed as a range rather than a point estimate, and the uncertainty documented as part of the Water Balance uncertainty record (Chapter 3, Section 3.3).

As a cross-check, the meter inaccuracy estimate should be validated against DMA night flow analysis: where the implied apparent loss volume from meter inaccuracy is large relative to the MNF-derived leakage estimate, or vice versa, the inconsistency should be investigated before the Water Balance is finalized. Any meter audit campaign should simultaneously include a diagnostic check of meter size and condition, since oversized meters are a common source of significant under-registration that is technically a metering error rather than fraud (Carteado & Vermersch, 2016).

Step 6 — Calculate Real Losses

Real Losses are calculated as the residual of the Water Balance:

$$\text{Real Losses} = \text{SIV} - \text{Billed Authorized Consumption} - \text{Unbilled Authorized Consumption} - \text{Apparent Losses}$$

Alternatively, where only a top-level NRW figure is required:

$$\text{NRW} = \text{SIV} - \text{Billed Authorized Consumption}$$

where NRW = Real Losses + Apparent Losses + Unbilled Authorized Consumption.

The first equation isolates Real Losses but requires Steps 4 and 5 to have been completed with sufficient confidence. The second equation is always calculable but leaves the three NRW components undifferentiated. Moving from the second to the first requires the independent estimation of Unbilled Authorized Consumption and Apparent Losses as described in Steps 4 and 5.

Step 7 — Assess and Document Uncertainty

Every component of the Water Balance carries uncertainty. The System Input Volume carries metering uncertainty quantified using the framework in Chapter 3. Billed Authorized Consumption carries uncertainty from meter inaccuracies, proration assumptions, and spatial boundary mismatches between billing zones and DMA boundaries. Unbilled Authorized Consumption and Apparent Losses are frequently estimated from default values and carry the highest relative uncertainty of any component. The combined uncertainty on the Real Losses estimate should be calculated using error propagation or Monte Carlo simulation (Chapter 3, Section 3.2.9) and reported alongside the result. A Real Losses estimate presented without an uncertainty range should be treated as approximate.

4.2.3 MINIMUM NIGHT FLOW ANALYSIS

Leakage is most accurately determined when customer consumption is at its minimum, which normally occurs at night. This is the principle of Minimum Night Flow (MNF) Analysis, originally recommended in Report 26 (UKWIR, 1980) and now applied worldwide. The method rests on the observation that DMA night flow at its lowest point consists predominantly of network leakage, with customer consumption reduced to a small and estimable residual.

MNF Trend Monitoring

MNF monitoring over time provides a continuous indicator of leakage level and an early warning of new bursts. In a stable, well-defined DMA the MNF hour consumption is expected to be approximately constant, so any sustained upward shift signals either a new burst (rapid step change) or growing background leakage (gradual creep). Figure 4-12 illustrates this from operational practice.

The figure shows three phases. In the initial period, highly stochastic behavior resulted from valves on larger pipes that were not fully closed or were leaking; following valve replacement the MNF stabilized at a high level with moderate day-to-day variation. A subsequent survey and repair program progressively reduced the baseline. After eight months of intervention in this zone reached stable operation with MNF confined within a narrow, consistent range.

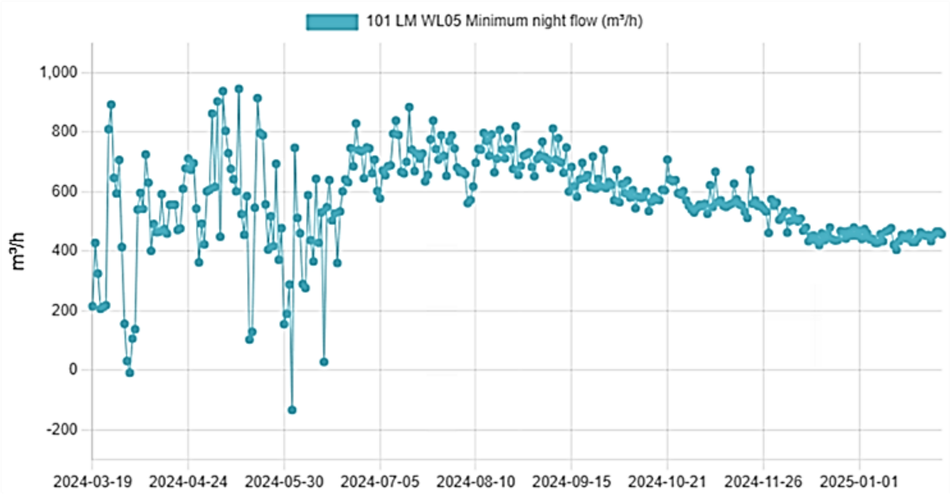


Figure 4-12 *MNF trend monitoring*

Day-to-day variability in the MNF record is normal and should be expected. Empirical studies across England and Wales found that night use varies by ±60–70% from day to day — three to four times more variable than daily consumption — as a direct consequence of the stochastic nature of water use events during the night period (UKWIR, 2008a). A single night's reading is therefore an unreliable basis for leakage estimation; only a sustained shift sustained over multiple consecutive nights warrants an operational response.

HELPFUL TIPS

Operational alert thresholds should be set relative to the established MNF baseline and evaluated over a minimum of three to five consecutive nights before triggering a field response, to avoid false positive alarms arising from normal night-to-night variability.

The MNF record shown above tracks the *total* flow entering the DMA at its lowest point each night— it is what the meter measures. It does not, however, directly measure leakage. The recorded MNF is the sum of several distinct components with different physical origins and different degrees of controllability, and only one of those components — Utility Night Leakage — is the target quantity of the analysis. Estimating it requires the others to be identified and subtracted. Figure 4-13 disaggregates the recorded MNF into its four constituent components for a sequence of weekday nights, illustrating both the structure of the signal and the day-to-day variability that makes the estimation problem non-trivial.

Decomposing the MNF Signal

The base of the signal — the component that remains when all customer activity ceases— is Utility Night Leakage (UNL), the network leakage from mains, service connections and fittings up to the customer meter. UNL is continuous, pressure-dependent, and persistent until a repair is made. The portion of the MNF attributable to UNL— that is, the MNF after Night Consumption (NC) has been subtracted— is termed the Leakage during the MNF hour (LMNF), and it is the primary output of the analysis.

Immediately above it sits Customer Night Leakage (CNL): persistent low-level continuous flows on the customer side of the meter— float valve tails refilling header tanks, internal drips, and small plumbing losses such as dripping taps. These flows are indistinguishable from network leakage in the DMA flow signal; they are real losses, but they lie beyond the utility's meter and must be subtracted from the MNF as part of the Night Consumption allowance rather than counted as network leakage (UKWIR, 2008b).

Figure 4-13 *MNF Component Decomposition*

Together, UNL and CNL form the continuous baseline of the night flow — the level to which the DMA signal would settle if all deliberate water use stopped. Superimposed on this baseline is

Night Use (NU): the intermittent flows from household water use events such as toilet flushing, taps, appliances, and baths or showers.

Unlike UNL and CNL, NU does not flow continuously. It arrives as discrete pulses, separated by periods of silence. This pulse structure is what makes NU estimable— but also what makes the estimation sensitive to DMA size and logging interval.

In a small DMA recorded at fine resolution, the gaps between pulses are wide enough to be visible in the data. At those moments the flow drops to the true continuous baseline— UNL plus CNL —and the minimum can be read directly. This is the visible component of NU: it is effectively transparent at the MNF hour.

As the DMA grows larger, more households are active and the pulses arrive more frequently. Eventually the gaps close and the flow never returns to the true baseline during the night. A residual from overlapping events is always present, no matter how carefully the MNF hour is selected. This overlapping component cannot be observed away — it must be estimated as a fixed allowance (UKWIR, 2008b).

Both DMA size and logging interval determine how much NU falls into each category. The practical consequences for measurement period and data resolution are discussed in Section 2.3.

Night Consumption (NC) is the sum of NU and CNL. The leakage during the MNF hour (LMNF) is therefore:

$$\mathrm{L\_MNF} = \mathrm{MNF} - \mathrm{NC} = \mathrm{MNF} - \mathrm{NU} - \mathrm{CNL}$$

For non-household or mixed DMAs, two additional components must be considered: intermittent non-household use, which cannot be modelled statistically and requires local investigation; and continuous non-household use (cooling systems, hospitals, industrial processes), which is persistent, difficult to separate from leakage, and requires specific field tests or metering to quantify (UKWIR, 2008b). The remainder of this section addresses household-only DMAs.

Data Selection and MNF Calculation

Seasonal window of opportunity

The MNF hour — and therefore the period of minimum consumption — is not fixed universally and must be identified from local data. Seasonal patterns in consumption shift the timing and depth of the night minimum, and the most reliable leakage estimates are obtained when consumption is at its annual lowest (Fantozzi & Lambert, 2011). In Mediterranean climates this typically corresponds to the cooler months (October to April); in southern hemisphere temperate zones the equivalent period is June to September; in northern European climates the seasonal variation is smaller, and monitoring can be conducted year-round. In all cases the optimal window should be confirmed by inspecting at least one full year of logged flow data before a measurement campaign is designed.

Weekday selection and minimum period

Weekday and weekend night flows differ systematically. The dominant hour of minimum night consumption in Denmark was found to be 03:00–04:00 on working days and 04:00–05:00 at weekends, with weekend MNF consistently lower than weekday MNF (Kirstein et al., 2022); similar patterns were found in the Mediterranean, where 03:00–05:00 defined the MNF window (Estrada et al., 2022). For trend monitoring purposes, weekday MNFs should be used exclusively to avoid weekend effects, and the median of the daily values should be used rather than the arithmetic mean, which is sensitive to the outliers produced by the non-normal distribution of night consumption (Fantozzi & Lambert, 2011).

A minimum measurement period of two weeks of stable data is required before an MNF-based leakage estimate is used for operational decisions. This window is long enough for large-scale non-persistent continuous uses — garden watering, cistern overflows — to complete and be excluded from the minimum, while being short enough that a new burst is unlikely to have arisen and been repaired within the period (UKWIR, 2008b). Repair records should be checked to confirm that no new leaks were detected and fixed during the measurement window.

HELPFUL TIPS

For DMAs serving Muslim-majority communities, nights during Ramadan should be excluded from MNF analysis or analyzed separately. Pre-dawn water use for the Suhoor meal significantly increases night flow, the effect varies year-to-year with the timing of sunrise, and standard socio-demographic indicators are unreliable predictors of its magnitude (UKWIR, 2008a). The MNF window may be shifted to an hour before the pre-dawn period for affected DMAs during Ramadan.

logging intervals.

Typical SCADA systems log averaged flows at 10, 15, or 60-minute intervals. In a small DMA, individual consumption events may be separated by true zero-flow periods that last only seconds or minutes. A 15-minute average spans multiple such events and their intervening gaps, producing an apparent minimum that is higher than the true leakage baseline. The result is that the MNF value extracted from standard SCADA data overestimates the true minimum flow, and changes in consumption density or timing can shift the logged MNF without any change in leakage — creating false positive alarms or masking genuine leakage increases (Bruns et al., 2026; UKWIR, 2008b). Where high-resolution data stored on the flow meter device is accessible — for example via mobile application or near-field communication — it should be used in preference to SCADA-averaged records for MNF determination in small DMAs.

Estimating Night Consumption

Estimating NC is the most susceptible step to error in MNF Analysis, and the quality of the NC estimate directly determines the quality of the leakage estimate. Three approaches are available, in decreasing order of reliability:

Approach 1 — Direct measurement from smart meter or AMR data (preferred)

Where individual customer meters record consumption at hourly or finer intervals, NC can be disaggregated directly into its components using algorithmic methods. The PROFUGA methodology (Estrada et al., 2022) applies a median-based threshold algorithm to hourly smart meter data to separate continuous baseline flows — corresponding to CNL — from intermittent use events corresponding to NU. Applied to approximately 20,000 residential customers in a Mediterranean city, this approach identified a mean CNL of 0.53 L/h/customer and a mean NU of 0.92 L/h/customer, with the 03:00–04:00 window providing the clearest separation. The disaggregation was consistent across five sub-sectors, supporting its use at portfolio scale.

Even with smart meter data, the logging interval affects the measured NC. Studies in northern China found that 30-minute data produced MNC estimates approximately 14% lower than 60-minute data, because finer intervals capture more of the true inter-event gaps that coarser averaging obscures (Xu et al., 2024). NC reference values and MNF measurements must therefore use matched logging intervals to produce consistent LMNF estimates.

Approach 2 — Field survey using fast-flow logging

Where smart meter data is unavailable, a sample of customer meters within the DMA can be fast-logged at short intervals (one to five minutes) during the MNF window. This allows individual consumption events to be identified, and the overlapping component estimated from the statistical distribution of the sample. The sample should be stratified by demand type (residential, commercial, institutional) and should be sufficiently large to capture the range of behaviors present. This approach also provides DMA-specific Customer Night Consumption (CNC) reference values.

Approach 3 — Reference values (use with caution)

Where neither direct measurement nor field survey is practicable, NC may be estimated using published reference values for Customer Night Consumption (CNC) applied to the known customer composition of the DMA. Table 4-4 provides reference values from literature. These values are not interchangeable: they were derived at different scales, with different logging intervals, in different climatic and cultural contexts, and using different component definitions. Before applying any reference value, the practitioner must verify that the logging interval used to derive the reference matches the interval used to measure MNF, and that the component definition (total NC, NU only, or CNL only) matches what is required for the analysis.

Table 4-4 Customer Night Consumption estimation methods.

Context / geography	CNC value	Component	Logging interval	Scale	Source
UK — residential	1.7 L/h/household	Total NC (intermittent + continuous)	60 min	Large	UK Managing Leakage Report E (1994) via Fantozzi & Lambert (2011)
UK — non-residential	7.4 L/h/property (weighted avg)	Total NC	60 min	Large	UK Managing Leakage Report E (1994) via Fantozzi & Lambert (2011)
UK — internal plumbing losses	1.4 L/h/household	CNL inside buildings (persistent continuous)	—	Company surveys	UKWIR (2018a)
Malaysia — residential	5.0 L/h/property	Total NC	60 min	Not stated	Fantozzi & Lambert (2011)
Germany / Austria — residential	0.4–0.8 L/h/person	Total NC	60 min	Large	DVGW (2003); ÖVGW (2009) via Fantozzi & Lambert (2011)
Denmark — residential	See Kirstein et al. (2022) Table 4-3a	Total NC	60 min	~6,000 meters	Kirstein et al. (2022)
Mediterranean — residential (intentional use only)	0.92 L/h/customer	Assessed Night Use (NU) only	60 min	~20,000 customers	Estrada et al. (2022)
Mediterranean — residential (customer-side leakage only)	0.53 L/h/customer	CNL inside buildings only	60 min	~20,000 customers	Estrada et al. (2022)
Northern China — residential	~0.70 L/h/household	Total NC	30 min	≥4,000 household-days	Xu et al. (2024)

Notes on Table 4-4:

- No universal standard value for CNC exists and none is likely to exist, given the sensitivity of night use to climate, culture, property type, occupancy, and appliance stock (Fantozzi & Lambert, 2011).
- The 17% of average daily consumption benchmark (UKWIR, 2008a) is a normalization tool for adjusting NC spatially across DMAs within a company that has already calibrated its base NC from measurement. It is not a substitute for measurement and should not be used as a primary NC estimate for an individual DMA.
- The Estrada et al. (2022) values of 0.53 and 0.92 L/h/customer represent customer-side CNL and NU respectively — not network leakage. Applying them without this distinction will underestimate total NC.

Approach 4 — ARNC: analytical benchmark from population and property data

The Average Residential Night Consumption (ARNC) method (Fantozzi & Lambert, 2011) constructs an expected night consumption benchmark analytically, without requiring smart meter data or a field survey. It separates NC into two categories of input available from standard customer records.

People-based components cover uses that require a resident to be awake — toilet flushing, taps, showers. At the MNF hour only a small fraction of residents is active; empirical studies suggest approximately 3% during the 02:00–04:00 window (Fantozzi & Lambert, 2011). The Binomial distribution is used to model this, treating each resident as independently active with a small probability rather than assuming uniform contribution across all occupants.

Property-based components are occupancy-independent — storage tank refilling, timer-controlled appliances, and persistent low-level flows from float valve tails. These are estimated per property and correspond to the CNL component in the WLSG framework.

The ARNC benchmark is the sum of both categories across all residents and properties in the DMA. If the recorded MNF is close to the ARNC the system is performing normally; a sustained excess points to leakage beyond the expected baseline. The Binomial model also provides a natural measure of the variability around the benchmark, which is particularly important in small DMAs where night-to-night fluctuations are large relative to the mean — a point discussed further in Section 4.2.4

Approach 5 – Ratio of Night Use to Day Use

Another way of estimating night consumption is to base it on the proportion of daily consumption. Whilst we do not know for sure how much of the night flow is due to real loss (leakage) and how much is due to the customer night consumption, what we do know for sure is that the DMA flow above the minimum night flow must be due to customer consumption.

The ratio of night use to average daily use can typically be 10% to 20%. It should be noted when we talk about night use in this approach, we are talking about intermittent night use, not continuous flows, such as internal plumbing losses. A graphical example of this approach is shown in *Figure 4-14* below.

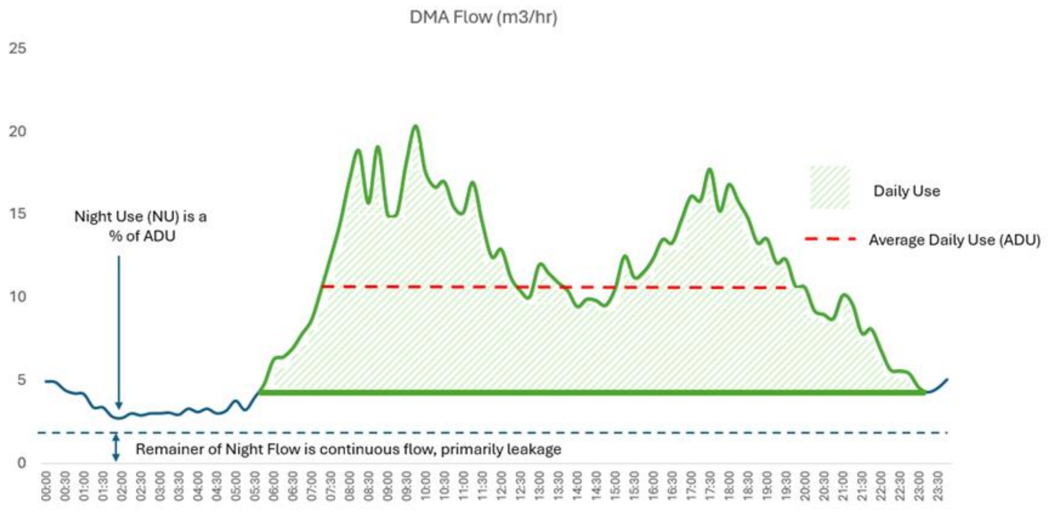


Figure 4-14 *A graphical example of the Ratio of Night Use to Day Use approach (Source: Mikal Willmott and Stuart Trow).*

Non-household Customers

Although this section focuses on household-only DMAs, most operational DMAs contain some non-household customers, and their night flows require separate treatment before the MNF Analysis can proceed. Non-household customers fall into two categories with different implications.

- Intermittent non-household use — from small commercial premises, offices, or retail units — can generally be treated in the same way as household intermittent use, provided the number of such customers is small relative to the total DMA population and their individual night use events are not exceptionally large. Where a single non-household customer generates flows that dominate the DMA night profile, it should be metered individually and its contribution subtracted before analysis.

- Continuous non-household use is the more critical case. Cooling systems, hospitals, hotels, food processing facilities, and similar premises draw water continuously through the night at rates that are indistinguishable from network leakage in the DMA flow signal. Unlike household CNL, these flows cannot be modeled statistically, cannot be eliminated by extending the measurement period, and cannot be estimated from reference tables. They require individual field investigation — either direct sub-metering of the premises, or a controlled test such as temporary isolation combined with flow measurement — before the MNF Analysis is carried out (UKWIR, 2008b). Failing to account for continuous non-household use is one of the most frequent sources of leakage overestimation in operational practice.

Scale-dependence and Required Measurement Period

The most significant limitation of reference-value approaches is scale-dependence. NC estimated from logged DMA flows is not a fixed property of a DMA but increases systematically with the number of household-days of data included in the estimate, because larger samples contain more overlapping consumption events that raise the apparent minimum. Studies in northern China using 2.32 million household-day records found that MNC stabilized only at approximately 4,000 household-days of data, reaching a value of ~0.70 L/h/household at 30-minute logging interval (Xu et al., 2024). Below this threshold, NC is underestimated and consequently leakage is overestimated. Applying a reference value derived from a large dataset to a small DMA measured over a short period introduces a systematic error; the annual leakage underestimation has been quantified at approximately 374 m³ per DMA per year for DMAs below the stability threshold (Xu et al., 2024).

The 4,000 household-day threshold translates to practical measurement periods as follows:

- 500 households → 8 days minimum
- 200 households → 20 days minimum
- 100 households → 40 days minimum

For small DMAs in the range 50–100 households, the required period substantially exceeds the two-week minimum for continuous use elimination and approaches the timescale over which leakage may change. For such DMAs, the leakage estimate carries high inherent uncertainty and should be treated accordingly (see Chapter 3 — Uncertainty and Data Quality in DMA-Based Water Loss Analysis).

This scale-dependence effect is a direct consequence of the visible/overlapping structure of night consumption described in the component framework above: in small DMAs, more of the intermittent consumption is visible and can be resolved at fine logging intervals, but less data is available to characterize the overlapping component reliably. Day-to-day variability in night use — empirically ±60–70% — means that a large number of nights is required before the mean NC converges to a stable value (UKWIR, 2008a).

Large Customers with Booster Pumps

A specific case of continuous non-household use that warrants separate mention is that of large customers— commercial centers, industrial facilities, or multi-unit residential buildings —that operate internal booster pumps to supplement distribution pressure. Booster pumps draw water from the network in short, high-flow bursts when their internal pressure switches activate, producing a characteristic flow signature at the DMA inlet: repeated abrupt peaks of short duration separated by near-zero intervals, superimposed on the underlying DMA flow profile. If not identified and subtracted, these peaks inflate the recorded MNF and produce a systematic overestimate of leakage.

The correction procedure is the same as for any metered large customer: install a dedicated datalogger at the service connection of the premises, synchronized in time with the DMA inlet meter, and subtract the recorded customer flow from the DMA inflow before any MNF analysis is performed. The synchronization requirement is strict— a timing offset of even a few minutes between the customer logger and the DMA inlet meter will prevent accurate subtraction of the sharp pump activation peaks.

From Night Leakage to Daily Volume

The result of the preceding analysis — L_MNF — is an hourly leakage rate (volume/hour) estimated at the MNF hour, under the pressure conditions prevailing at that specific time. To obtain the Average Daily Leakage (volume/day), this hourly rate must be multiplied by the Night Day Factor (NDF), also known in the United Kingdom as the Hour-Day Factor:

$$Daily\ Leakage\ (m^3/day) = L_{MNF}(m^3/h) \times NDF$$

The NDF is necessary because network pressure — and therefore leakage rate — is not constant across the 24-hour period. If the Average Zone Pressure were perfectly stable throughout the day, every hour would contribute to the same leakage rate as the MNF hour, and the NDF would equal exactly 24 hours/day. In practice, pressure varies continuously with the diurnal demand cycle, and the leakage rate at each hour of the day differs from L_MNF in proportion to the pressure ratio between that hour and the MNF reference hour, raised to the power of the pressure-leakage exponent N1. The NDF accumulates these hourly contributions across the full 24-hour period:

$$NDF = \sum_{i=1}^{24} \left(\frac{AZP_i}{AZP_{MNF}} \right)^{N1}$$

where AZP_i is the Average Zone Pressure during hour i and AZP_MNF is the Average Zone Pressure at the MNF hour — the reference condition under which L_MNF was measured.

In a system supplied by gravity without pressure control, the AZP is highest at night when consumption is low, and falls during the morning and afternoon demand peaks as friction losses increase through the network (Figure 4-15). The MNF hour therefore occurs under above-average pressure conditions: L_MNF is measured at a leakage rate that is higher than the average rate sustained across the rest of the day. Multiplying by 24 would overestimate daily leakage. The NDF corrects this by reducing the effective multiplier below 24. For a typical urban gravity system, NDF values lie in the range 20–23. For gravity systems with high frictional losses — where daytime pressures fall substantially relative to the night — NDF values below 12 hours/day are possible.

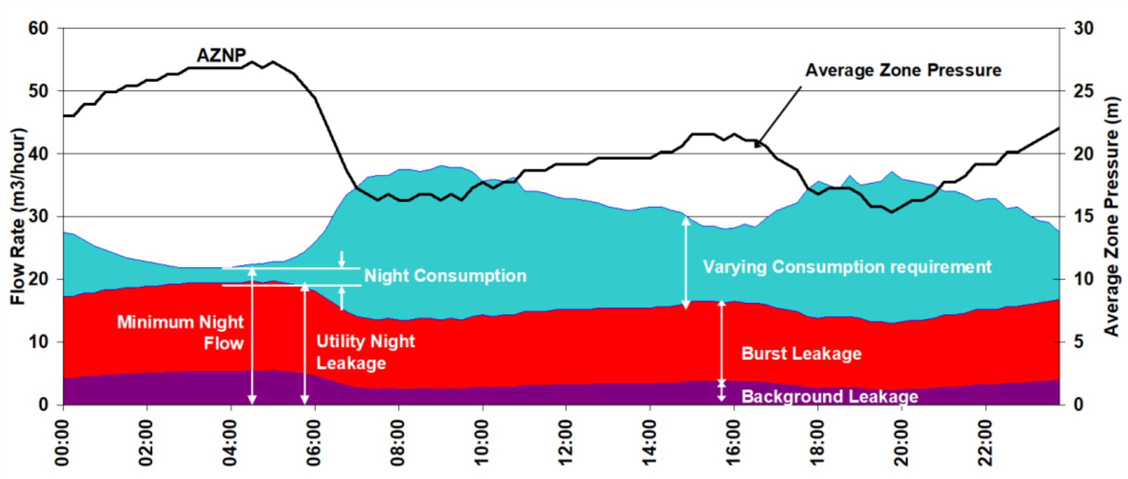


Figure 4-15 *Daily Leakage Variation (Liemberger, 2002)*

In a pressure-managed DMA where a pressure-reducing valve operates with time modulation or flow modulation, or where pump scheduling deliberately reduces night pressure, the situation is reversed: pressure is lower at night than during the day. The MNF hour now occurs under below-average pressure conditions, so L_MNF understates the average hourly leakage rate prevailing through most of the day. Multiplying by 24 would underestimate daily leakage. The NDF corrects this by raising the effective multiplier above 24. In flow-modulated pressure management systems, NDF values exceeding 36 hours/day have been recorded.

The practical range of NDF is therefore wide — from below 12 to above 36 hours/day — and the choice of multiplier has a large effect on the daily leakage estimate. Using the default of 24 without calculating the actual NDF from pressure data can introduce errors that are not marginal: in a high-friction gravity system, multiplying by 24 instead of 12 doubles the estimated daily leakage. Utilities must calculate the DMA-specific NDF from logged AZP data rather than assuming a default.

The NDF calculation requires hourly AZP values for a full representative 24-hour period. Where a pressure logger is installed at the AZP, these values are read directly. Where only boundary pressure is available, the AZP diurnal profile must be derived from a hydraulic model or from a field-measured pressure offset between the boundary and the AZP. Uncertainty in the AZP profile propagates directly into the NDF and into the daily leakage estimate; this should be quantified and reported (see Chapter 3).

The exponent N1 in the NDF formula determines how sensitively leakage responds to pressure variation at each hour of the day. When N1 = 1 the relationship is linear and the NDF reduces to the arithmetic sum of 24 pressure ratios. When N1 > 1 the correction is amplified — further below 24 for gravity systems, further above 24 for pressure-managed systems. When N1 < 1 the correction is attenuated and the NDF clusters closer to 24.

However, N1 is not a fixed physical constant of the DMA. It is a pressure-dependent parameter: as demonstrated by the FAVAD (Fixed and Variable Area Discharges) concept (van Zyl & Lambert, 2017), the apparent N1 of a leakage population varies with the prevailing AZP, because the mix of fixed-area orifice behavior and variable-area crack behavior in the leakage population produces a curved, not linear, relationship between log(leakage) and log(pressure). The step test yields a local estimate of N1 valid only within the pressure range over which the test was conducted. Applying this fixed value across the full diurnal pressure range — as the NDF summation does — is an approximation whose error increases as the daytime AZP departs from the test pressure range. For gravity systems, the fixed-N1 approach over-predicts the leakage sensitivity at lower daytime pressures, causing the NDF to be underestimated and daily leakage to be understated. For pressure-managed systems, the corresponding error runs in the opposite direction.

For most operational DMAs with moderate diurnal pressure variation, this error is limited and the fixed N1 from a step test is an adequate operational approximation. Where the diurnal AZP range is wide — high-elevation gravity systems with large frictional losses, or aggressively flow-modulated pressure management — the uncertainty should be acknowledged. In the absence of a measured N1, N1 = 1 is the recommended default for mixed-pipe DMAs. Full guidance on N1 step testing is provided in Appendix E.

Where a DMA contains multiple Pressure Management Areas or Residual Pressure Areas with distinct pressure profiles, each sub-zone requires its own AZP diurnal series, AZP_MNF, and NDF. The zone-level NDFs are combined as a property-weighted average to produce the DMA-level NDF. More details about DMA pressure analysis can be found in Appendix E.

4.2.4 RECONCILING THE WATER BALANCE AND MNF ANALYSIS

The Water Balance and MNF Analysis are the two principal methods for estimating real losses at DMA level. Applied correctly to the same analysis period, their results should be consistent. The Water Balance works top-down: it derives real losses as the residual of all metered inflows minus authorized consumption and apparent losses, integrating performance over days, weeks, or months. MNF Analysis works bottom-up: it isolates the continuous leakage signal during the night-hour window of minimum consumption and scales it to a daily volume through the Night Day Factor (NDF). Each method has complementary strengths and characteristic blind spots; neither alone is sufficient to guarantee a reliable leakage estimate.

When the two methods diverge significantly, the divergence itself is diagnostic— it indicates a data integrity problem or an unaccounted hydraulic behavior that must be resolved before either estimate can be used with confidence for operational decisions. The reconciliation procedure described here provides a practical daily check on DMA data quality and is the basis for the operability classification developed in Section 5.2.4.4.

Complementary Strengths and Limitations

The Water Balance captures all real losses over the full 24-hour period, including losses that occur during peak demand hours when pressure — and therefore leakage rate — is lower than at night. It is sensitive to apparent losses, which MNF Analysis does not directly measure, and it provides the long-term volumetric accounting required for regulatory reporting. However, its accuracy depends on the completeness and spatial alignment of consumption data. At DMA scale, billing boundaries frequently diverge from hydraulic boundaries, a significant proportion of customers may be unmetered, and temporal misalignment between metering and billing cycles introduces systematic uncertainty (Section 4.2.1, Steps 3–5). These effects accumulate: the combined uncertainty of the Water Balance at DMA level can be substantially larger than at utility level (Chapter 3).

MNF Analysis provides a near-real-time leakage signal, is insensitive to consumption data quality, and can detect new burst events within hours of their occurrence. Its principal limitations are the accuracy of night consumption separation (Section 4.2.2) and the reliability of the NDF calculation (Section 4.2.4). It does not directly capture apparent losses. In DMAs with significant customer storage tanks, MNF-based estimates can be unreliable even in the absence of measurement error (Section 4.3.1). When both methods carry errors that push in the same direction, their apparent agreement may be spurious — reconciliation reduces but does not eliminate this risk.

The Residual as Reconciliation Metric

Reconciliation is achieved by computing the daily Residual (R) that is the difference between Daily Losses from the Water Balance (DL) and Daily Leakage from MNF Analysis (DLeak):

$$R = DL - DLeak$$

$$R = \frac{Real\ Losses}{Assessment\ Period}\left(\frac{m^3}{d}\right) - L_{MNF} \times NDF\left(\frac{m^3}{d}\right)$$

where L_MNF is the hourly leakage rate at the MNF hour (Section 4.2.2), NDF is the Night Day Factor (Section 4.2.4), and Real Losses are the output of Water Balance Step 6 (Section 4.2.1).

The Residual is normalized by the Total Daily Flow (TDF) that is the mean daily System Input Volume over the analysis period— to make it comparable across DMAs of different sizes:

$$\hat{R} = \frac{R}{TDF} \times 100\%$$

A Normalized Residual within ±20% of TDF indicates acceptable consistency between the two methods. This threshold reflects typical combined measurement and estimation uncertainty at DMA scale and is widely adopted in operational practice. A Residual outside ±20% signals that one or both methods are producing an unreliable estimate; the DMA should not be used for leakage analysis until the cause is identified and resolved. The ±20% threshold is an operational guideline derived from field experience, not a formal standard. Utilities with high-quality consumption data and well-characterized measurement uncertainty (Chapter 3) may apply a tighter threshold.

Interpreting the Sign of the Residual

The sign and magnitude of the Residual provide directional guidance for investigation. Table 4-5 summarizes the most common patterns and their likely causes.

A strongly positive Residual — where the Water Balance shows substantially more losses than MNF Analysis — most commonly reflects underestimated apparent losses (see Section 4.2.2, Step 5) or a spatial misalignment between the billing register and the hydraulic boundary. A strongly negative Residual — where MNF Analysis shows more leakage than the Water Balance — most commonly points to a boundary integrity failure such as an open or leaking boundary valve not captured in the flow meters, a night consumption overestimate, or large customers with nocturnal demand that has not been separately logged. The most difficult case is when both methods carry simultaneous errors in the same direction: their apparent agreement is spurious, and an independent check — such as a temporary flow survey or a boundary walk — is required.

Table 4-5 Interpretation of the DMA Residual and recommended actions

Residual pattern	Likely cause	Recommended action
Near zero ($\|R\| \leq$ 20% TDF)	Both methods are consistent; data reliable	Classify DMA as operable. Proceed to leakage decomposition (see Sections 5.1–5.2).
Strongly positive (DL >> DLeak)	Apparent losses underestimated (unregistered use, meter under-reading, data handling errors); billing boundary misalignment; night consumption underestimated in MNF Analysis	Review Step 5 of Water Balance (Section 4.2.2). Verify customer register spatial alignment. Re-examine NC estimate and method.
Strongly negative (DLeak >> DL)	Open or leaking boundary valve not reflected in flow metering; night consumption overestimated; NDF calculation error; large customers with significant nocturnal demand not separately logged; customer storage tanks (Section 4.3.1)	Inspect all boundary valves. Verify DMA hydraulic isolation (Section 4.1.1). Review NC model, NDF inputs, and diurnal pressure data.
Large magnitude, sign varies between periods	Multiple simultaneous data errors; hydraulically unstable DMA; metering anomaly masking true leakage	Classify as non-operable. Systematic data audit required. Consider temporary flow survey and boundary walk before resuming leakage analysis.

Operational Consequences and Forward Link to Chapter 5

A DMA whose Normalized Residual falls outside ±20% should be classified as non-operable (Figure 4-16). Targeting a non-operable DMA for active leakage detection is ineffective and potentially misleading: the calculated leakage figure is unreliable, and field resources may be directed toward a problem that does not exist — or diverted from one that does. Resolving the Residual by identifying and correcting the data issue that causes it is a prerequisite for confident operational use of either method.

Once a DMA is classified as operable, both estimates are available to the analyst. In Chapter 5, the MNF Analysis result provides the operational basis for decomposing total leakage into background and burst components, while the Water Balance result provides the strategic benchmark for recovery targets and long-term performance trends. The DMA operability concept and its daily monitoring workflow are developed further in Section 5.2.4.

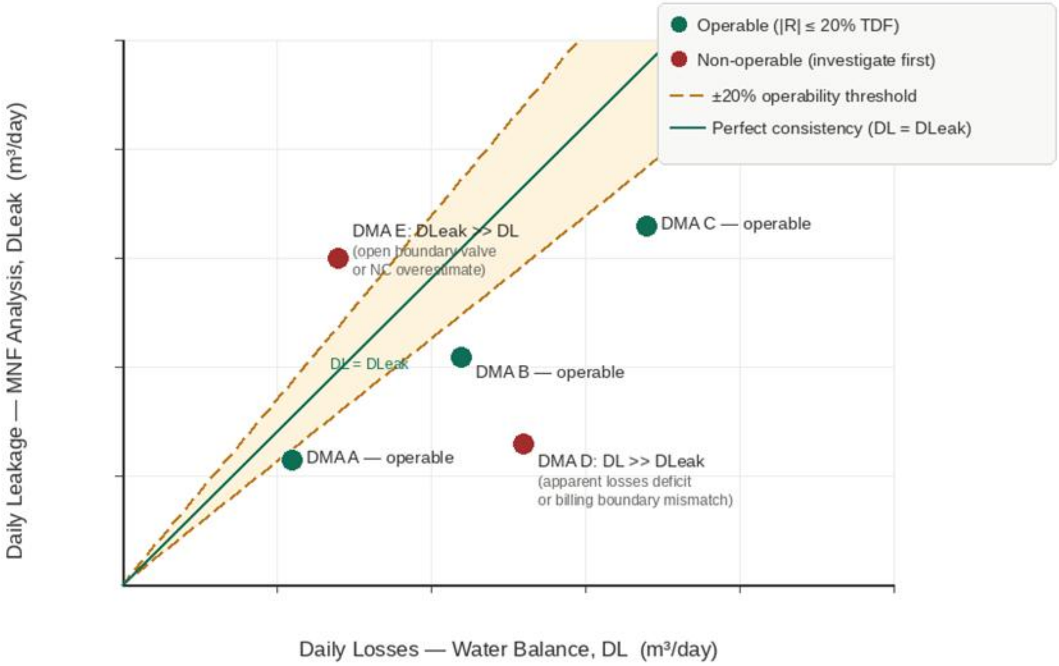


Figure 4-16 *DMA operability scatter plot.*

4.3 LEAKAGE ESTIMATION FOR SPECIAL CASES

4.3.1 DMA WITH CUSTOMER STORAGE TANKS

Customer-side storage tanks — including rooftop cisterns, underground break-pressure tanks, and large institutional reservoirs — alter the diurnal flow profile of a DMA and complicate leakage estimation by decoupling the timing of network inflow from the timing of actual water consumption. As described in Section 4.1.2, tanks fill according to network pressure availability and level-controlled valve behavior, not according to customer demand cycles. The degree of disruption to leakage analysis depends on tank type, size, and the density of storage installations within the DMA.

In a DMA without significant customer storage, the flow trace closely reflects the diurnal consumption pattern of the customer population. In a DMA with a high density of storage tanks, this relationship breaks down. Figure 4-6 illustrates the contrast: the high-rise DMA with roof tanks shows a smooth, time-shifted profile with a delayed consumption peak at approximately 12:00, while the low-rise residential DMA without storage displays the characteristic morning peak at approximately 10:00. Large institutional customers — hotels, hospitals, and shopping centers — introduce additional demand blocks that may be scheduled or pressure-triggered rather than consumption-driven.

Figure 4-17 shows the measured inlet flow profile for a high-rise apartment compound in Istanbul, illustrating the characteristic tank-filling pulses superimposed on the underlying consumption signal. These pulses are controlled by float-operated or level-sensor inlet valves, which open when tank level drops below a set point and close when the tank is full. The timing and flow rate of each filling event depends on tank size, valve type, and the rate of consumption drawing down from the tank — making these flows difficult to predict or subtract analytically without sub-metering.

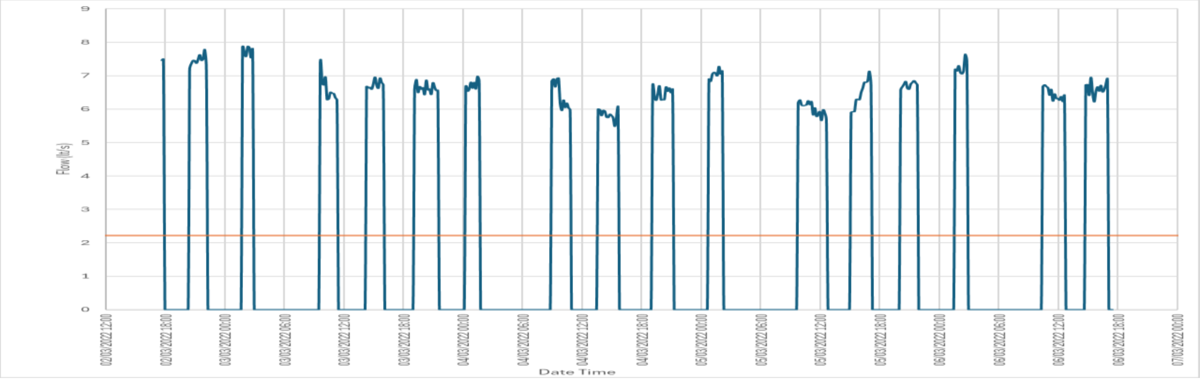


***Figure 4-17** Flow measurement of high-rise apartment building compound in Istanbul (source: DEWA, 2025).*

Effects on MNF Analysis

Standard MNF Analysis relies on the assumption that the night flow minimum reflects a period of near-zero consumption, so that the residual flow after subtracting NC (Section 4.2.3) is attributable to network leakage. Large storage tanks violate this assumption in two ways:

- Tank filling during or after the evening peak elevates the apparent MNF. Tanks whose level-controlled valves open late in the evening or at night add a filling flow to the DMA signal that is indistinguishable from leakage at the boundary meter. This effect is most pronounced for large tanks with slow fill rates controlled by float-operated ball valves, which maintain a near-constant low inflow over extended periods — precisely the signature that MNF Analysis interprets as background leakage.

- Customer-side float valve leakage contributes a continuous low-level flow at the meter, classified as Customer Night Leakage (CNL) within the Night Consumption framework (Section 4.2.3). Small domestic tanks have negligible CNL contributions. Large tanks with float valve defects can produce flows that are material relative to the DMA's network leakage level and must be estimated and subtracted as part of the NC allowance, not treated as network leakage.

The reliability of MNF Analysis in storage-tank DMAs depends on the magnitude of these effects relative to network leakage. Where tank filling flows are small compared to the DMA's MNF — typical for DMAs with predominantly small domestic tanks — standard analysis with an appropriately adjusted NC allowance remains valid. Where large tanks dominate the night flow signal, MNF Analysis may become unreliable as a leakage quantification tool. Operational experience from utilities in high-rise-dominated supply zones confirms this limitation.

Level-controlled inlet valves operating in the near-full condition maintain a very low inflow rate as the float valve throttles toward closure. Flow rates below the minimum registration threshold of the boundary meter will be recorded as zero, causing under-registration of actual consumption. This systematic under-registration reduces the recorded AF and inflates the apparent MNF/AF ratio, potentially misclassifying a low-leakage DMA as a high-leakage one. The apparent loss implications of meter under-registration at low flows are discussed in Section 4.2.2.

Role of Metering Configuration

The analytical treatment of customer storage tanks in both MNF Analysis and the Water Balance depends critically on what is metered and where. Two configurations are common in practice, and they have fundamentally different implications.

Configuration A — Metered tank inlet, no downstream consumption meters

Where the flow entering each large customer storage tank is fully captured by a dedicated inlet meter, the metered inlet volume can be classified as Authorized Consumption within the DMA Water Balance. The tank and all water use downstream of the inlet meter fall outside the DMA's leakage accounting boundary: what happens inside the tank — consumption, internal losses, storage fluctuation — is no longer relevant to the DMA calculation. The correction due to volume change in the storage tanks is not required, because the DMA's accounting boundary ends at the inlet meter. The Water Balance isolates network real losses correctly, provided the inlet meter captures all flow entering the tank without bypassing.

This configuration is the most practical solution for large institutional customers (hotels, hospitals, high-rise compounds) where sub-metering of individual consumption units is impractical. The utility's analytical objective — quantifying network leakage — is fully served by the inlet meter alone.

The remaining limitation is apparent loss: at low inflow rates, when the tank is near full and the inlet valve is throttling, the inlet meter may under-register, causing the recorded Authorized Consumption to fall below the true delivered volume. This under-registration is an apparent loss on the inlet meter, not a real loss, and should be assessed as part of the apparent losses' component of the Water Balance (Section 4.2.2).

Configuration B — Metered tank inlet and individual downstream consumption meters

Where individual consumption units are metered in addition to the tank inlet, the difference between the inlet meter volume and the sum of unit meter volumes over any assessment period represents water that entered the tank but was not recorded as authorized consumption at the unit meters. Over a short period, this difference includes the net tank storage change. Over an extended period — typically one year or more, when seasonal storage fluctuations cancel — the persistent residual represents customer-side real losses: structural leakage from the tank, overflow, and losses from the internal pipework between the tank and the unit meters.

This configuration provides information that Configuration A cannot: it allows customer-side real losses to be separated from network real losses, and the relative responsibility of utility and customer to be quantified. The long-term mean of the inlet-minus-units difference is a direct estimate of customer-side loss rate. The short-term variation around that mean reflects storage cycling and provides — if tank geometry is known — an indirect measure of the tank storage change without requiring direct level measurement.

In the IWA framework, customer-side losses of this type are classified as real losses attributable to customer pipework and fall outside the utility's direct control but within its scope of interest for total NRW accounting. Utilities with a large proportion of Configuration B metering can therefore disaggregate total DMA real losses into network leakage and customer-side losses — a distinction that has direct implications for leakage reduction strategy and for the allocation of intervention responsibility between utility and customer.

Recommended Analytical Approach

The appropriate analytical response depends on the nature and extent of the storage tank effect:

- Where large tanks are individually sub-metered, their filling volumes can be subtracted from the DMA inflow before applying MNF Analysis or Water Balance, restoring the standard analytical framework.
- Where sub-metering is not available, the Water Balance method applied over a full billing cycle is less sensitive to short-term tank filling disturbances than MNF Analysis and is the preferred method for leakage quantification in storage-tank DMAs (Section 4.2.2).
- Where the MNF window can be verified as tank-fill-free — for example, through monitoring of tank levels or pressure signals indicating tanks are full — MNF Analysis can be applied to those nights only, accepting that the available dataset will be smaller than for a standard residential DMA.
- Individual large tanks that generate material night flows should be treated in the same way as continuous non-household use (Section 4.2.3): sub-metered separately, and their contribution subtracted from the MNF before analysis.

Note that Section 4.3.3 addresses the related case of customer booster pumps, which introduce an additional source of flow signal distortion, distinct from the storage tank filling effect described here.

4.3.2 DMAS WITH INTERMITTENT SUPPLY

Intermittent water supply (IWS) — where customers receive water for only a few hours per day or per week — compounds every analytical challenge described in Section 4.3.1 with a further set of IWS-specific phenomena. No single assessment method is sufficient; reliable estimates of real losses in IWS systems require multi-method triangulation.

IWS-specific Phenomena

During each pressurization event, air trapped in the distribution network is forced through boundary meters and customer meters, causing systematic over-registration that must be corrected before any Water Balance or MNF analysis is attempted. In a southern India case study, uncorrected air over-registration inflated measured consumption by 15%; correcting only the boundary meter without also correcting customer meters understates real losses by a corresponding amount (Mastaller & Klingel, 2018). Recharging losses — water that escapes from pipes at the moment of depressurization, and is not recovered on the following supply cycle — add a loss component with no equivalent in continuous supply. Repeated pressurization cycles also accelerate pipe deterioration, progressively increasing background leakage rates in ways that standard BABE component estimates, calibrated on continuous-supply failure data, do not fully capture.

Customer storage tanks, ubiquitous in IWS systems, generate two further complications. First, tank overflow constitutes a substantial wastage component which, where metering is at the service connection inlet, passes through the boundary meter and is counted as authorized supply yet produces no customer benefit. Reported magnitudes range from approximately 10% of SIV in southern India (Mastaller & Klingel, 2018) to 44% of total residential consumption in Trinidad and Tobago (Fanner, 2009); the primary driver is the pressure distribution during the supply period, which causes customers near the source to fill and overflow their tanks before distant customers receive any water. Second, unmetered or flat-rate billed consumption cannot be estimated from meter readings and requires statistical sampling, as described below.

These phenomena interact with DMA design. DMAs delimited using continuous-supply criteria produce large within-DMA pressure disparities during the supply period, which intensify overflow wastage, lengthen the time required to reach supply saturation, and increase variability in the minimum night flow timing. IWS DMAs should therefore be small and hydraulically homogeneous, designed so that pressure differences between the most and least favored nodes during the supply period remain within acceptable equity bounds (Ilaya-Ayza et al., 2017). Such a configuration also shortens saturation time and improves the reliability of MNF analysis.

Supply Cycle as the Unit of Analysis

In IWS, the natural analytical unit is the complete supply cycle, not the calendar day. Water Balance calculations should be accumulated over one or more complete cycles. MNF analysis applies within the pressurized period rather than within a fixed nocturnal window. Storage volume corrections are more tractable when the balance period is aligned with complete supply cycles, since tank levels at cycle boundaries can be more consistently defined.

Adapted Water Balance

The standard IWA Water Balance requires adaptation for IWS contexts. Where customers are metered, a top-down approach using authorized consumption estimated at approximately 10%

of billed consumption provides a workable starting point, with real loss uncertainty typically in the range ±11–21% (Al-Washali et al., 2020). Where customers are unmetered and charged a flat-rate tariff, the meter-based utility/customer boundary collapses entirely. In this case, authorized supply must be disaggregated into its billed and unbilled components, and the billed component must be further separated into actual consumption and wastage (principally tank overflow), following the adapted framework of Mastaller & Klingel (2018). An important consequence of this framework is that NRW may be dominated by an inadequate flat-rate tariff rather than by physical losses: in Tiruvannamalai, India, 44% of a total NRW of 73% was attributable to this cause, a result that would be invisible in a standard Water Balance.

Estimating billed authorized supply in unmetered systems requires a statistically representative consumption monitor — meters installed on a random sample of unmetered customers who continue to be charged the flat-rate tariff. A sample of 6–10% of connections, stratified by household occupancy and supply type, typically achieves a 95% confidence interval of ±7–10% on average consumption (Mastaller & Klingel, 2018; Fanner, 2009). Two practical constraints are important. Meters used for IWS consumption monitoring must not register air and must withstand the mechanical stress of repeated air flow; standard velocity meters are unsuitable, and meters with no moving parts should be specified (Fanner, 2009). Customer address data quality frequently limits the achievable sample size and should be assessed before the monitoring program is designed.

Where centralized sewerage with measured wastewater flows is available, a Water and Wastewater Balance provide an independent estimate of apparent losses that bypasses meter accuracy problems entirely. This method tends to overestimate apparent losses where sewer exfiltration is significant and requires local correction factors for outdoor water use and unbilled consumption, but it provides a valuable cross-check and should be included in the multi-method assessment where data permit. The storage volume correction (ΔV_tanks) applicable to all Water Balance calculations in systems with customer storage tanks is described in Section 4.3.1.

MNF Analysis

MNF analysis can be applied in IWS systems at DMA scale, but only under conditions that may require significant operational preparation. The method is not applicable where the DMA cannot be isolated for a continuous supply period of sufficient duration, or where available water is insufficient to reach customer storage saturation; in a severely stressed system in Sana'a, Yemen, both conditions could not be met and no valid MNF analysis was obtainable (Al-Washali et al., 2020).

Where isolation is achievable, the following guidance applies, based on field experience in Zarqa, Jordan (Al-Washali et al., 2019b). Continuous supply to the DMA should be maintained for a minimum of five days; in the Zarqa experiment, customer storage saturation required approximately 63 hours before flow profiles began to repeat reliably. Saturation can be confirmed in the field when successive daily flow profiles closely reproduce each other, without requiring calculation. Analysis should use only confirmed saturated days, excluding any day affected by identifiable operational disturbances such as pressure collapses or valve changes.

The full 24-hour flow profile must be monitored on each analysis day. In pumped or partially pressurized IWS systems, the MNF may occur at any point in the night or early morning depending on when customer storage tanks reach capacity; assuming a fixed nocturnal window will miss the true minimum in many cases. Results should be averaged across multiple valid days, since day-to-day variation in the MNF estimate contributes greater uncertainty than refinements to the leakage night component (LNC) assumption. The NDF should be calculated from measured pressure data rather than assumed at the 24 h/day default: in the Zarqa pumped IWS system, the measured NDF was 14.2 h/day, and applying the default would have overstated daily leakage by a factor of approximately 1.7. LNC estimates should be based on local appliance data, since flush volumes and fixture use patterns in IWS contexts may differ substantially from European or North American defaults (Fanner, 2009).

Overall real loss uncertainty from MNF analysis in IWS is ±22–30% (Al-Washali et al., 2020). Standard BABE component estimates should be used for subcomponent planning purposes only; field evidence consistently shows that BABE substantially underestimates total leakage in IWS systems, with the majority of MNF-derived leakage attributable to hidden losses that standard BABE parameters do not represent (Al-Washali et al., 2019b).

Multi-method Triangulation

Because no single method is reliable in isolation, real loss estimates in IWS systems should be derived from the average of at least two independent methods — the adapted top-down Water Balance and MNF analysis where both are feasible, supplemented by the Water and Wastewater Balance where sewer data are available — with BABE used to inform the subcomponent structure of any reduction program. Divergence between methods is diagnostic of the dominant loss type and should be investigated rather than resolved by selecting the most convenient result. Method choice has material economic consequences: in the Zarqa case, estimated potential active leakage control savings ranged across a factor of three depending on the assessment method used, a range that would lead to fundamentally different investment decisions (Al-Washali et al., 2020).

Transition to Continuous Supply

Any transition from IWS to continuous supply will cause reported NRW volumes to rise, even where leakage management is effective, because infrastructure previously depressurized for most of the day begins leaking continuously. A pre-transition baseline, established using the multi-method approach described in this section, is therefore essential for interpreting post-transition loss estimates correctly. The temporary continuous-supply protocol employed in a five-day Zarqa field experiment (Al-Washali et al., 2019b) provides a replicable method for establishing this baseline at DMA scale. DMA infrastructure — boundary valves, flow meters, and pressure loggers — installed for IWS loss estimation serves directly as the pressure zone and monitoring framework required for post-transition leakage control, and is not rendered obsolete when supply becomes continuous.

4.3.3 DMA WITH PRESSURE CONTROL

Pressure management is one of the most effective interventions for reducing real losses, and its effects on the DMA flow signal require specific consideration when interpreting MNF data.

Effect on the MNF Signal

In a DMA without pressure control, pressure varies naturally and inversely with demand: it is highest at night when consumption is low, and lowest during morning and evening peaks. The MNF therefore occurs under the highest pressures the network experiences through the daily cycle, and the NDF-based extrapolation to daily leakage accounts for pressure variation across the full daily cycle in a predictable way (see Section 4.2.3).

In a DMA with active pressure control, this relationship is deliberately altered. Most pressure control schemes apply their greatest reduction during low-demand periods, including the MNF window, when demand is lowest and the risk of over-pressure is highest. As a result, the MNF is measured under reduced pressure conditions, and reflects leakage under the most favorable pressure conditions of the day. Extrapolating this value to the full 24-hour period requires pressure data from the entire daily cycle, not only from the MNF window; the NDF must be calculated by integrating the measured pressure curve over all pressurized hours rather than assuming that MNF-hour pressure is representative of daily conditions (see Section 4.2.3).

Quantifying the Leakage Reduction Effect of Pressure Management

The primary analytical question in a pressure-managed DMA is not whether pressure is being maintained— that is a service quality question —but whether the pressure reduction is producing the expected reduction in leakage, and by how much. This requires comparing the observed leakage against a model prediction based on the pressure difference achieved.

The appropriate tool is the FAVAD relationship (May, 1994; see Section 5.1), which relates leakage flow to pressure through a locally calibrated exponent N1. A step-test— a controlled, incremental change in PRV setpoint conducted during the MNF window while recording both flow and pressure simultaneously— yields a log-log regression from which N1 can be estimated for the specific DMA. With N1 established, the leakage saving attributable to pressure management can be quantified as the difference between modelled leakage at the pre-intervention pressure and observed leakage at the managed pressure. This is an evaluation of management benefit, not a normalization for inter-DMA comparison: standard pressure-referenced performance indicators serve the latter purpose adequately, provided the MNF analysis has been correctly applied and night consumption properly defined.

Implications for Night Consumption Separation

Pressure management increases the relative importance of correct night consumption separation. When pressure— and therefore leakage —is reduced, the night consumption component represents a proportionally larger share of the MNF, and errors in its estimate have a proportionally larger effect on the derived leakage value. This is compounded in DMAs that combine pressure management with large customers operating booster pumps: such customers may activate their pumps in response to reduced network pressure during the night period, creating flow events that distort the MNF signal precisely when the pressure control scheme is most active. Individual sub-metering of such customers (see Section 4.2) is therefore particularly important in pressure-managed DMAs.

The step-test procedure and FAVAD methodology are developed fully in Section 5.1.

Pressure control and meter chamber, Colombia

REFERENCES

Alegre H., Baptista J.M. and Covas D. (2004). Leakage management in Lisbon's water distribution system. *Water Utility Journal*, 6 (3), 12–20.

Al-Washali T.M., Sharma S.K., Al-Nozaily F., Haidera M. and Kennedy M. (2019). Monitoring the non-revenue water performance in intermittent supplies. *Water*, 11 (6), 1220.

Al-Washali T.M., Sharma S.K., Kennedy M.D., Al-Nozaily F. and Mansour H.(2019). Modelling the leakage rate and reduction using MNF analysis in an intermittent supply system. *Water*, 11(1).

Al-Washali T.M., Sharma S.K., Lupojad R., Al-Nozaily F., Mansour H. and Kennedy M. (2020). Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply. *Resources, Conservation and Recycling*, 2020. (Accessed 05 May 2025)

Amoatey P.K., Minke R. and Steinmetz H. (2014). Leakage estimation in water networks based on two categories of night-time users: a case study of a developing country network. *Water Supply*, 14 (2), 329–336.

AWWA (2009). *Loss Control Programs – Manual of Water Supply Practices M36*. American Water Works Association, Denver, USA.

Buchberger S.G. and Wu L. (1995). Model for random demands in water distribution systems. *ASCE Journal of Hydraulic Engineering*, 121 (3), 232–246.

Colombo A.F. and Karney B.W. (2002). Energy and costs of leaky pipes. *ASCE Journal of Water Resources Planning and Management*, 128 (6), 441–449.

CWMAG (2020). *Best Practice Guide to Hydraulic Modelling*. Clean Water Modelling Advisory Group.

CWMAG (2022). Model Build Guidance Workshop.

EU Reference Document (2015). *Good Practices on Leakage Management WFD CIS WG PoM*. European Union.

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

From intermittent to continuous water supply: A multi-dimensional evaluation of water system reforms from Hubli-Dharwad, Karnataka; Ray I., Billava N., Burt Z., Colford J.M. Jr., Ercümen A., Jayaramu K.P., Kumpel E., Nayak N., Nelson K. and Woefle-Erskine C. (2018). *Economic and Political Weekly*.

Good Practices on Leakage Management WFD CIS WG PoM (2015).

Hamilton S., Charalambous B. and Wyeth G. (2021). *Improving Water Supply Networks: Fit for Purpose Strategies and Technologies*. IWA Publishing.

IWA (2014). *Guidance Notes for DMA Management*. International Water Association.

IWA (2014). *International Statistics for Water Services*. International Water Association.

Jenks J., et al. (2023). Mobile DMA testing in Ontario, Canada. *Water Supply*, 23 (5), 1843–1857.

Kirstein J.K. and Høgh K. (2022). Minimum night flow and legitimate night consumption statistics using smart meter data. *IWA Water Loss 2022*, Prague, Czech Republic.

Lambert A. (2001). What do we know about pressure: leakage relationships in distribution systems? Proceedings of *IWA Conference on Systems Approach to Leakage Control and Water Distribution Systems Management*.

Lambert A. (2002). International report: water losses management and techniques. *Water Science and Technology: Water Supply*, 2 (4), 1–20.

Lambert A. and Taylor R. (2010). *Water Loss Guidelines*. Water New Zealand, New Zealand.

May J. (1994). Pressure dependent leakage. *World Water and Environmental Engineering Magazine*.

Mutikanga H., Sharma S. and Vairavamoorthy K. (2011). Assessment of apparent losses in urban water systems. *Water and Environment Journal*, 25 (3), 327–335.

Neergaard T.B. (2024). Digitized water leakage management - costs and benefits for the utility. *IWA Water Loss Conference*, San Sebastian. https://bronderslevforsyning.dk/media/12zdrxfc/leak365_full-scale-water-loss-mangement_ppt-and-full-paper-in-one-doc-1-0.pdf (Accessed 2025)

Pearson D. (2019). Standard definitions for water losses. *IWA*.

Puust R., Kapelan Z., Savic D.A. and Koppel T. (2010). A review of methods for leakage management in pipe networks. *Urban Water Journal*, 7 (1), 25–45.

Random Uncertainty in Water Balance | LEAKSSuite Library. *Assessing Random Uncertainty in Water Balance Calculations: Getting Started – A Practical Approach*. (Accessed May 2025)

Rubinstein R.Y. and Kroese D.P. (2016). *Simulation and the Monte Carlo Method*. John Wiley & Sons.

Sarisen D., Koukoravas V., Farmani R., Kapelan Z. and Memon F.A. (2022). Review of hydraulic modelling approaches for intermittent water supply systems. *AQUA - Water Infrastructure, Ecosystems and Society*, 71 (12), 1291–1310.

Seago C., Bhagwan J. and McKenzie R. (2004). Benchmarking leakage from water reticulation systems in South Africa. *Water SA*, 30 (5), 25–32.

Taylor J. (1997). *Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements*. University Science Books, New York, USA.

Thornton J. and Lambert A. (2005). Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. *IWA Leakage Conference*.

Thornton J., Sturm R. and Kunkel G. (2008). *Water Loss Control*. McGraw Hill Professional, New York, USA.

UK document (1980). Report 26.

UKWIR (2017). *Assessment of Key Parameters for Leakage Analysis*. UK Water Industry Research.

UKWIR (2020). *Understanding the Balance Between Customer Use, Supply Pipe Leakage & Plumbing Losses in Water Delivered to Household Properties.* UK Water Industry Research.

UKWIR (2024). *A Deep Dive into Leakage Using Smart Meter Data*. UK Water Industry Research.

United States Agency for International Development (USAID) (2010). *The Manager's Non-Revenue Water Handbook for Africa*.

Vermersch M., Carteado F., Rizzo A., Johnson E., Arregui F. and Lambert A. (2016). *Guidance Notes on Apparent Losses and Water Loss Reduction Planning*. LEAKSSuite Library, UK.

5 INTERPRETING AND USING DMA LEAKAGE DATA TO PLAN ACTIONS

T. Crowder[1], F. Garzón-Contreras[2]

[1] *Crowder Consulting, UK*
[2] *HydroFlux, Cali, Colombia*

ABSTRACT

This chapter presents a structured approach to interpreting DMA leakage data to drive operational decisions. It covers component loss modeling (background, reported, and unreported bursts), pressure analysis and its influence on leakage rates, and methods for estimating Infrastructure Condition Factors. The chapter further guides practitioners in setting leakage targets, analyzing Minimum Night Flow, and prioritizing field interventions. It equips water utilities with practical tools to move from data collection to evidence-based leakage reduction strategies.

Installing Brand New DMA Inlet Chamber with PRV

5.1 ASSESSING THE LEAKAGE REDUCTION OPPORTUNITY

Not all real losses within a DMA are recoverable through detection and repair. A portion — background leakage — is distributed across thousands of micro-defects in joints, fittings, and pipe walls. These losses are individually undetectable and persistent; their magnitude is governed by pressure conditions and the structural state of the pipe network, not by field intervention. The remainder — reported and unreported burst losses — consists of discrete failure events that can, in principle, be located and repaired. Only this second category constitutes a genuine leakage reduction opportunity, and its magnitude varies considerably between DMAs that may show similar total real losses.

This distinction has direct operational consequences. Figure 5-1 illustrates the point with two DMAs of comparable real loss volumes. When the component loss model is applied, their leakage profiles diverge sharply: in one DMA, unreported bursts represent the dominant component, indicating substantial potential for active leak detection and repair; in the other, losses are concentrated in the background component, and the practical reduction opportunity is far more limited requiring the consideration of pressure management or infrastructure replacement. Managing both DMAs with the same intensity and strategy — on the basis of their total losses alone — would misallocate resources and produce results well below what a targeted approach could deliver.

Figure 5-1 *Breakdown of Total Leakage in Example DMAs.*

The analytical path from total real losses to recoverable volume is illustrated in Figure 5-2. The MNF signal at the DMA boundary is a composite signal whose layers must be separated in sequence. The outermost layer is customer night use — assessed consumption and any exceptional night use — estimated using the methods established in Chapter 4. Once subtracted, what remains is the network leakage signal: the sum of background leakage and burst leakage. Separating these two requires establishing the background leakage floor — the volume of loss that cannot be recovered through conventional find-and-fix methods. This floor is not fixed: it responds to the operating pressure of the DMA and to the condition of its infrastructure. Once it is quantified and subtracted from total network leakage, what remains above it — reported and unreported bursts — is the recoverable volume. This figure is DMA-specific and will differ substantially across a portfolio, making it the natural basis for prioritization.

Figure 5-2 *MNF Signal Decomposition.*

The sections that follow develop each step of this decomposition. Before proceeding, it is assumed that each DMA in scope has been verified as operable — that is, its Water Balance and MNF Analysis results are consistent within the ±20% threshold established in Section 4.2.4. A non-operable DMA carries an unreliable leakage estimate and should not be subject to the analysis below until its data issues are resolved. Section 5.1.1 establishes the component loss model as the conceptual framework for the decomposition. Section 5.1.2 defines background leakage and develops the calculation method, including the Infrastructure Condition Factor that reflects DMA-specific pipe condition. Section 5.1.2.3 applies pressure corrections to ensure that background leakage estimates reflect actual operating conditions. Section 5.1.3 characterizes burst leakage — its calculation, its natural rate of rise, and the implications for active leakage control. Together, these four sections produce the single output that drives all subsequent decisions in the second part of this chapter: the recoverable leakage volume for each DMA in the portfolio.

5.1.1 COMPONENT LOSS MODEL

A component loss model is used to estimate real losses across the principal infrastructure components of a water distribution network. The scope of the model depends on the metering configuration of the system: at minimum it covers distribution mains and the utility-owned portion of service connections up to the customer meter; where the meter is located beyond the curb stop, it extends to include the customer-owned underground pipe from the curb stop to the meter (Lp); and in unmetered systems, it extends further to include losses on customer-owned pipes up to the point of first use. The implications of metering configuration for the background leakage calculation are addressed in Section 5.1.2.

This model is based on the Bursts and Background Estimates (BABE) methodology developed by Lambert (1994) and subsequently incorporated into the AWWA Component Analysis framework (Sturm et al., 2014). Both frameworks estimate annual real losses by linking night flow measurements with annual loss calculations.

For burst losses, the model characterizes each component by its flow rate, frequency, and duration; for background losses, by the length of mains, number of connections, and operating pressure. This distinction reflects a fundamental physical difference between the two loss types that has direct consequences for how each can be managed — and is the reason the component loss model, rather than a single aggregate leakage figure, is the appropriate starting point for assessing the leakage reduction opportunity in a DMA.

The model distinguishes three components:

- **Background Losses** are continuous, low-flow losses occurring at joints, fittings, service connection interfaces, and other points of minor structural imperfection across the pipe network. Each individual loss is below the threshold of standard acoustic detection methods (typically taken as 500 l/h; Lambert, 1994); collectively, they constitute a persistent baseline present to some degree in every pressurized network. Their magnitude is governed by operating pressure and by the structural condition of the pipe infrastructure. They cannot be reduced through find-and-fix activities alone, and define the floor of leakage for a given DMA under its current operating conditions. Background leakage constitutes on average approximately 49% of total real losses in well-monitored distribution networks (Water Breakthrough Challenge, 2023), making it the component that ultimately limits how far total leakage can be reduced in a given DMA.

- **Unreported Burst Losses** are underground failures — on distribution mains, utility-owned service connections, or customer-owned underground service pipes — that do not surface and are therefore not visible to customers or operational staff. In utilities with active leakage control programs, they are typically identified through proactive leak detection surveys or through sustained increases in DMA night flow; their duration is governed primarily by survey frequency and dispatch efficiency. In utilities without proactive leak detection programs, unreported bursts remain undetected until they surface or cause visible damage, and their duration can extend to months or years (Sturm et al., 2014). Their cumulative contribution to total real losses is substantial — approximately 31% of total real losses in systems with active leakage control programs (Water Breakthrough Challenge, 2023) and potentially considerably higher in reactive systems. Where unreported bursts occur on customer-owned underground service pipes, the utility can detect the loss through DMA nightline monitoring but cannot repair it directly; repair depends on customer awareness, willingness, and capacity to act, and run times are inherently longer than on utility-owned infrastructure (Sturm et al., 2014).

- **Reported Burst Losses** are failures that surface or otherwise become visible. Because they are visible, they are reported and dispatched promptly, keeping their duration short; despite often carrying high instantaneous flow rates, their contribution to total annual real losses is generally the smallest of the three components — approximately 5% in systems with active leakage control (Water Breakthrough Challenge, 2023). An exception is reported bursts on customer-owned service pipes, where repair depends on customer action and enforcement of repair obligations, and duration may therefore be considerably longer.

In field operations, the order of attention is typically reversed: reported bursts demand immediate response, unreported bursts are the primary target of active leakage control, and background losses represent the analytical baseline established in Section 5.1.2. In the analytical framework developed in this section, however, background leakage is established first — because it is only once the irreducible baseline is quantified that the recoverable volume above it can be meaningfully assessed.

5.1.2 BACKGROUND LEAKAGE

Having established background leakage as the irreducible floor of real losses in Section 5.1.1, this section develops the calculation method that allows the analyst to quantify that floor for a specific DMA. The calculated background leakage volume is the single most consequential input to the recoverable volume estimate: it determines how much of the total real losses measured in the DMA is genuinely available for reduction through active leakage control, and how much represents a structural minimum that can only be addressed through pressure management or infrastructure replacement.

5.1.2.1 Background Leakage Unit Rates

Background leakage is distributed across four infrastructure categories, each with distinct unit loss rates:

- Distribution mains — losses at joints, fittings, and pipe wall imperfections along the reticulation network.
- Utility-owned service connections — from the distribution main to the curb stop.
- Customer-owned underground service pipes— from the curb stop to the customer meter; present only where the meter is located beyond the curb stop.
- Internal plumbing losses — occurring within the property beyond the customer isolation valve; present only in unmetered systems and treated as a component of customer consumption in metered systems.

The unit loss rates for each category were originally derived from night-flow measurements in UK distribution systems and documented in the Managing Leakage series of reports (UK Water Industry, 1994; updated 2011). They are expressed at a reference pressure of 50 mH_2O and at average infrastructure condition (ICF = 1.0). Table 5-1 presents these rates across three infrastructure condition scenarios.

Table 5-1 Background Leak Unit Loss Flow Rates at 50m Pressure (UKWIR, 1994; updated 2011)

Background Loss Component	Unit Loss Flow Rate at 50m Pressure		
	Good	Average	Poor
Distribution Mains, (litres/km/hr)	20	40	60
Communication Pipes, (litres/conn/hr)	1.5	3	4.5
Underground Supply Pipes, (litres/conn/hr)	0.25	0.5	0.75

The IWA Water Loss Task Force provides an alternative set of unit rates expressed on a pressure-referenced basis, which eliminates the need for a separate pressure correction step and forms the basis of the calculation method in Section 5.1.2.3(Table 5-2).

Table 5-2 IWA Background Leakage Rates (Fanner & Thornton, 2005)

Infrastructure component	Rate at ICF=1.0	Units
Distribution mains	9.6	l/km/day/m H_2O
Service connections — main to curb stop	0.6	l/conn/day/m H_2O
Service connections — curb stop to meter (Lp)	16.9	l/km of connection/day/m H_2O

Service connections consistently constitute the largest contributor to total background leakage in most DMAs — often exceeding mains losses by a factor of three to five (Lambert, 1994; Fanner & Thornton, 2005). This reflects the large number of connection points and fittings relative to total pipe length, and underlines the importance of service connection replacement alongside mains rehabilitation in any infrastructure management program.

5.1.2.2 Metering Configuration and Calculation Scope

The scope of the background leakage calculation depends on the metering configuration of the system, as introduced in Section 5.1.1. Three scenarios apply:

Scenario A — Meter at Curb Stop (Lp = 0): Background leakage is calculated for distribution mains and utility-owned service connections only. The customer service pipe component (third row of Table 5-2) does not apply.

Scenario B — Meter Inside the Property (Lp > 0): The customer-owned underground pipe from the curb stop to the meter contributes to background leakage measured at the DMA boundary. The average length (Lp) per connection must be entered into the calculation. Where Lp data is unavailable, a default average of 15m per connection may be applied (Fanner & Thornton, 2005).

Scenario C — Unmetered System: Lp is taken as the average length of underground service pipe from the curb stop to the point of first use. Internal plumbing losses are excluded from the network calculation.

The three scenarios are illustrated in Figure 5-3. In all cases, losses beyond the customer isolation valve are excluded from the network background leakage calculation.

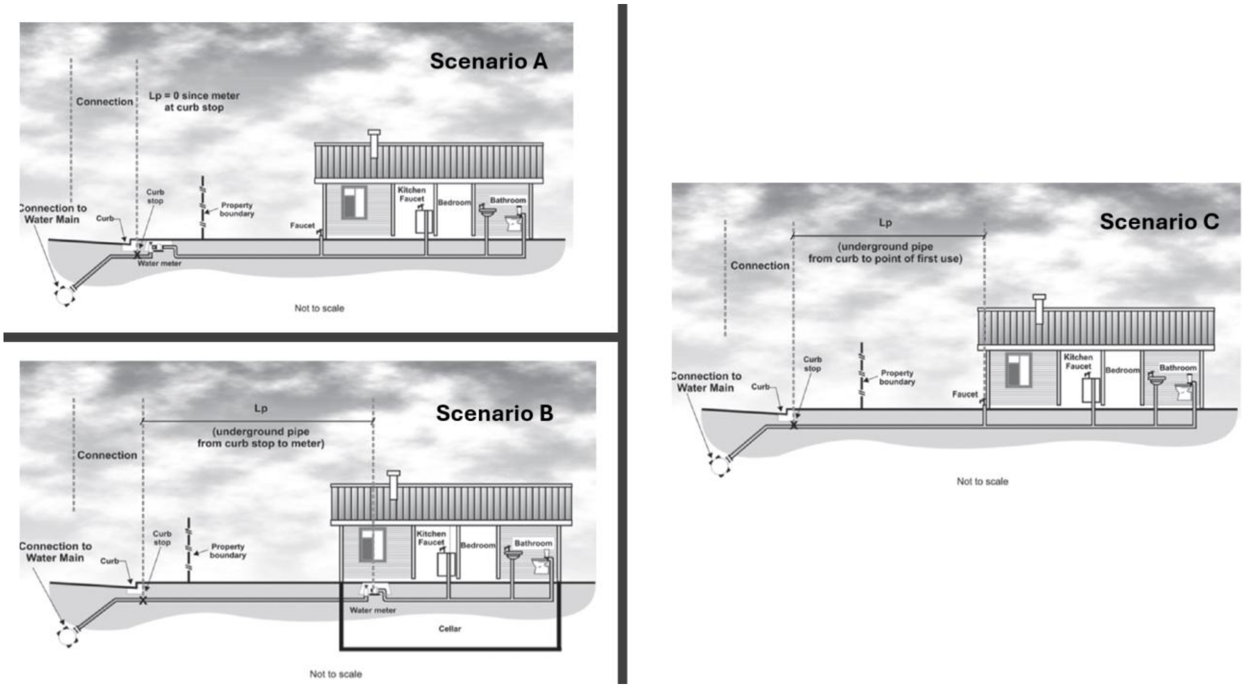


Figure 5-3 *Metering Configuration (AWWA, 2016).*

5.1.2.3 Background Leakage Calculation

Before presenting the calculation formulations, it is necessary to clarify the relationship between the background leakage unit rates in Table 5-2 and the Unavoidable Annual Real Losses (UARL) benchmark, which is developed fully in Section 5.2.2.

UARL represents the lowest technically achievable volume of real losses in a well-managed and well-maintained distribution system. It is not a single homogeneous quantity — it comprises three distinct unavoidable components present in every pressurized network regardless of management quality: unavoidable background leakage, minimum losses from reported failures under optimal repair standards, and minimum losses from unreported failures under optimal active leakage control. The UARL formula:

$$\text{UARL (l/day)} = (18 \times ML + 0.8 \times NC + 25 \times Lp) \times AZP$$

Where: ML = mains length (km); NC = number of service connections; Lp = total length of customer-owned underground service pipes (km); AZP = Average Zone Pressure (m H_2O)

uses three coefficients — 18 per km of mains, 0.8 per connection, and 25 per km of service pipe — each of which is the sum of all three unavoidable loss components for that infrastructure category. The background leakage rates in Table 5-2 (9.6, 0.6, and 16.9) are the background component only of those three coefficients. The background component represents approximately 53% of the mains coefficient, 75% of the connection coefficient, and 68% of the service pipe coefficient — the remainder being unavoidable burst contributions. (Lambert et al., 1999; Fanner & Thornton, 2005).

This distinction is fundamental: the background leakage calculation uses the rates in Table 5-2, not the UARL coefficients. The reported and unreported failure contributions to UARL are set aside in this section — they are addressed in Section 5.1.3 (Burst Leakage) and form part of the recoverable volume above the background floor. The full UARL — including all three unavoidable components — is used in Section 5.2.2 as the reference for the Infrastructure Leakage Index (ILI = Current Real Losses / UARL).

Defining BL_0 as the background leakage at ICF = 1.0 — calculated from the background-only rates in Table 5-2 applied to the DMA's infrastructure at its operating pressure — the background leakage for a DMA at its actual infrastructure condition is:

$$BL\_DMA = BL_0 \times ICF$$

This is the central relationship of Section 5.1.2. BL_0 represents the irreducible minimum background losses in the DMA assuming average infrastructure condition. ICF scales this minimum upward or downward to reflect the actual condition of the pipe network. A DMA in good condition ($ICF < 1.0$) has a background floor below BL_0; a DMA in poor condition ($ICF > 1.0$) has a background floor above BL_0. The original Managing Leakage framework defined three reference ICF values — Good (0.5), Average (1.0), Poor (1.5) — as default assumptions in the absence of site-specific data. Field determinations have demonstrated that actual ICF values can extend well beyond this range, as discussed in Section 5.1.2.4.

Managing Leakage / BABE Formulation

The Managing Leakage formulation calculates BL_0 from the unit rates in Table 5-1 at the 50m reference pressure, then applies the pressure correction and ICF in two explicit steps:

Step 1 — Calculate reference background leakage at ICF = 1.0:

$$BL_0 = [(L\_m \times F\_m) + (N\_c \times F\_c)] \times (AZNP/50)^\wedge N1 \times NDF$$

Step 2 — Apply infrastructure condition:

$$BL\_DMA = BL_0 \times ICF$$

Where: L_m = mains length (km); F_m = unit background loss rate for mains at 50m pressure (l/km/hr), from Table 5-1; N_c = number of service connections; F_c = unit background loss rate for service connections at 50m pressure (l/conn/hr), from Table 5-1; AZNP = Average Zone Night Pressure (m) — the pressure at the DMA at the time of MNF; N1 = pressure-leakage exponent — taken as 1.5 for background leakage regardless of pipe material (Lambert, 1994; Fanner & Thornton, 2005); NDF = Night Day Factor (Section 4.2.4) — converts the night-time background leakage rate to a daily volume; ICF = Infrastructure Condition Factor (Section 5.1.2.4)

For systems where the meter is located beyond the curb stop ($Lp > 0$), a third term is added to Step 1:

$$BL_0 = [(L\_m \times F\_m) + (N\_c \times F\_c) + (Lp\_km \times F\_sp)] \times (AZNP/50)^\wedge N1 \times NDF$$

Where Lp_km is the total length of customer-owned underground service pipes (km) and F_sp is the unit background loss rate for customer service pipes at 50m pressure (l/km/hr), derived from the IWA pressure-referenced rate: F_sp = (16.9 × 50) / 24 ≈ 35.2 l/km/hr.

IWA Pressure-referenced Formulation

The IWA formulation uses the background-only pressure-referenced rates from Table 5-2, which express background losses directly as a daily volume without a separate pressure correction step:

Step 1 — Calculate reference background leakage at ICF = 1.0:

$$BL_0 \text{ (l/day)} = [(9.6 \times ML) + (0.6 \times NC) + (16.9 \times Lp\_km)] \times AOP$$

Step 2 — Apply infrastructure condition:

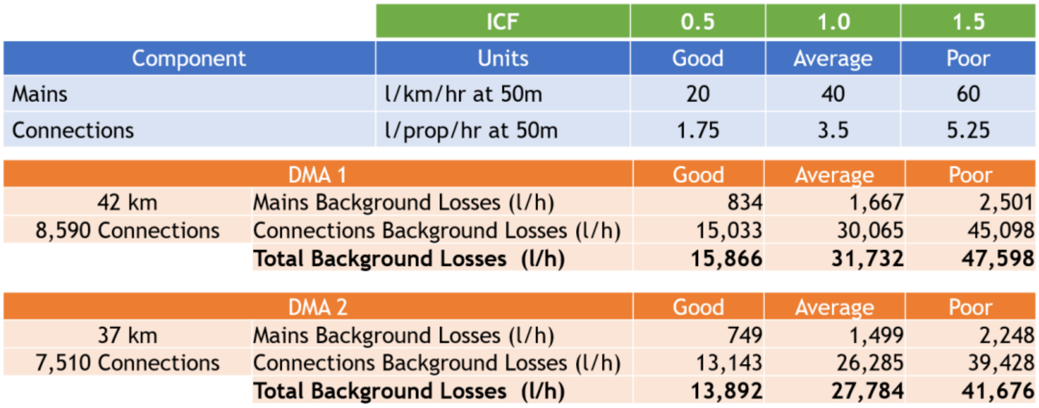
$$BL\_DMA = BL_0 \times ICF$$

Where: ML = mains length (km); NC = number of service connections; Lp_km = total length of customer-owned underground service pipes (km); zero where meters are at the curb stop. Where Lp is measured in metres per connection, convert: Lp_km = (Lp_m × NC) / 1000; AOP = Average Operating Pressure (m) — the mean pressure at the AZP over the full 24-hour period; ICF = Infrastructure Condition Factor (Section 5.1.2.4).

This formulation uses AOP rather than AZNP because the pressure-referenced rates produce a daily volume directly, with pressure variability over the 24-hour period implicitly captured through AOP rather than through a separate NDF step. The formulation assumes a linear pressure response (N1 = 1.0 within the unit rate definition). Where operating pressure is substantially outside the typical range, the Managing Leakage formulation with N1 = 1.5 is more precise and should be preferred, as the non-linear pressure response of background leakage becomes material at these pressure ranges.

Both formulations calculate BL_0 at ICF = 1.0 as their first step and apply ICF in a second step, making $BL\_DMA = BL_0 \times ICF$ explicit and consistent across both approaches. Table 5-3 illustrates the background leakage calculation for two example DMAs using the Managing Leakage formulation across three ICF values.

Table 5-3 Example Background Loss Calculation



	ICF	0.5	1.0	1.5
Component	Units	Good	Average	Poor
Mains	l/km/hr at 50m	20	40	60
Connections	l/prop/hr at 50m	1.75	3.5	5.25

DMA 1		Good	Average	Poor
42 km	Mains Background Losses (l/h)	834	1,667	2,501
8,590 Connections	Connections Background Losses (l/h)	15,033	30,065	45,098
	Total Background Losses (l/h)	**15,866**	**31,732**	**47,598**

DMA 2		Good	Average	Poor
37 km	Mains Background Losses (l/h)	749	1,499	2,248
7,510 Connections	Connections Background Losses (l/h)	13,143	26,285	39,428
	Total Background Losses (l/h)	**13,892**	**27,784**	**41,676**

The results confirm that ICF has a greater effect on calculated background leakage than any other single variable. Fanner & Thornton (2005) demonstrated through sensitivity analysis that a factor-of-two uncertainty in ICF produces a factor-of-two uncertainty in the estimated recoverable volume — making accurate ICF determination the most consequential single step in the component analysis.

5.1.2.4 Determining the ICF for a DMA

The ICF cannot be measured directly — it must be inferred from field measurements, operational data, or proxy indicators. Three methods are described here in ascending order of reliability (Fanner & Thornton, 2005). The analyst should use the most data-rich method available for each DMA.

Method 1 — Screening Approximation from ILI

In the absence of field measurements or operational history, a practical first approximation is:

$$\text{ICF} \approx \text{ILI}$$

where ILI = Current Annual Real Losses / UARL. This approximation has been observed across multiple systems and is recommended as an initial screening tool (Fanner & Thornton, 2005). It holds when the DMA has been recently surveyed, current leakage is close to its minimum, and the dominant remaining leakage is background in nature.

The approximation becomes unreliable in three circumstances: where the DMA carries significant unreported burst leakage not yet detected; where apparent losses are poorly characterized, making the Water Balance real losses figure unreliable; and at high ILI values, typically above 3, where the relationship between ILI and ICF diverges (Fanner & Thornton, 2005). In these cases, Methods 2 or 3 should be used.

Method 2 — N1 Pressure Step Test

A pressure step test conducted during the MNF window allows the leakage signal to be decomposed into fixed-area (burst) and variable-area (background) components using the

FAVAD relationship. The ICF is derived by comparing the calculated background component against BL_0 at ICF = 1.0:

$$ICF = \text{Background leakage from step test} / BL_0\ (ICF = 1.0)$$

This method was demonstrated for a zone in Boston, USA (West Roxbury / Roselindale), producing ICF = 1.6 from a measured background leakage of 8.02 l/s against a calculated BL_0 of 4.92 l/s (Fanner & Thornton, 2005). The method is applicable only to rigid pipe systems where the burst N1 value is approximately 0.5. In networks with predominantly plastic pipework, variable-area bursts cannot be distinguished from background leakage using the step test, and the resulting ICF will be overestimated. For plastic-dominant networks, Method 3 is preferred.

Method 3 — Field Measurement from Minimum Achievable Leakage

The most reliable determination of ICF requires driving the DMA to its lowest achievable leakage level through a comprehensive active leakage control campaign, then measuring the residual leakage under stable boundary conditions and known pressure:

$$ICF = \text{Residual leakage after ALC campaign} / BL_0\ (ICF = 1.0\text{, pressure-adjusted})$$

This is the defining measurement of ICF (Fanner & Thornton, 2005) and the only method that directly measures the background floor rather than inferring it from proxies. Field determinations conducted in the development of this guidance produced ICF values ranging from 4 to 27, confirming that background leakage in severely degraded DMAs can be 4 to 27 (Thornton, 2007) times BL_0. These values are not anomalies — they reflect real infrastructure deterioration in systems where pipe condition has declined far beyond the Managing Leakage reference range.

In DMAs where Method 3 produces ICF values above approximately 2.0, background leakage dominates total real losses and the recoverable volume is substantially smaller than the UARL benchmark suggests. In these DMAs, pressure management or infrastructure replacement will deliver greater and more sustainable leakage reduction than active leakage control campaigns. This is one of the most operationally significant conclusions that component analysis can produce — and it cannot be reached without a reliable ICF determination.

Method 3 is resource-intensive and is recommended specifically for: DMAs where Methods 1–2 indicate ICF above 2.0; DMAs that repeatedly fail to reach their leakage target despite intensive active leakage control; and DMAs being assessed for infrastructure investment decisions where the accuracy of the recoverable volume estimate is financially material.

Where ICF cannot be determined by any method, the default of ICF = 1.0 should be applied, representing average infrastructure condition. This default carries the highest uncertainty and will overestimate the recoverable volume in degraded networks. Any analysis using the ICF = 1.0 default should be clearly flagged as subject to infrastructure condition uncertainty.

Sensitivity of the Component Analysis to ICF

Because BL_DMA = BL_0 × ICF is linear in ICF, the estimated recoverable volume is directly sensitive to the assumed value. Table 5-4 illustrates this sensitivity for the two example DMAs, varying ICF from 1.0 to 5.0. The results demonstrate that an ICF error of factor two — assuming ICF = 1.0 when the true value is 2.0 — halves the estimated recoverable volume and produces an active leakage control program that will consistently underperform against its targets.

Table 5-4 Example Background Loss Calculation

ICF	DMA 1 | ML = 12 km · NC = 1500 · AOP = 65 m · RL = 420 m³/day · ILI = 4.6				DMA 2 | ML = 15 km · NC = 2000 · AOP = 42 m · RL = 510 m³/day · ILI = 6.5			
	BL_0 (m³/day)	BL_DMA (m³/day)	Recoverable Volume (m³/day)	Recoverable (%)	BL_0 (m³/day)	BL_DMA (m³/day)	Recoverable Volume (m³/day)	Recoverable (%)
0.5 (good)	66.0	33.0	387.0	92%	56.4	28.2	481.8	94%
1.0 (avg)	**66.0**	**66.0**	**354.0**	**84%**	**56.4**	**56.4**	**453.6**	**89%**
1.5 (poor)	66.0	99.0	321.0	76%	56.4	84.7	425.3	83%
2.0	66.0	132.0	288.0	69%	56.4	112.9	397.1	78%
2.5	66.0	165.0	255.0	61%	56.4	141.1	368.9	72%
3.0	66.0	198.0	222.0	53%	56.4	169.3	340.7	67%
4.0	66.0	264.0	156.0	37%	56.4	225.8	284.2	56%
5.0	66.0	329.9	90.1	21%	56.4	282.2	227.8	45%

■ *ICF 0.5–1.5 — Managing Leakage reference range (Good to Poor condition)*

■ *ICF 2.0 — Threshold: background leakage begins to dominate; infrastructure intervention warranted*

■ *ICF 3.0–5.0 — Severely degraded infrastructure; field-confirmed range 4–27 (this guidance)*

Table 5-4 demonstrates that the estimated recoverable volume is highly sensitive to the assumed ICF. At ICF = 1.0 (average condition), DMA 1 appears to offer 354 m³/day of recoverable leakage (84% of total real losses) and DMA 2 offers 454 m³/day (89%). If the true ICF of DMA 1 is 2.0 — a value that field determinations regularly produce — the recoverable volume falls to 288 m³/day, meaning the ICF = 1.0 assumption has overestimated the reduction opportunity by 66 m³/day. An active leakage control program designed around that figure will systematically underperform, and the shortfall will be misattributed to detection inefficiency rather than to an incorrect ICF assumption. At ICF = 3.0, background leakage accounts for 47% of DMA 1's total real losses; at ICF = 5.0, only 21% of real losses remain recoverable through find-and-fix activities. Field determinations conducted in the development of this guidance produced ICF values up to 27, at which point the background floor effectively consumes all measured real losses and detection campaigns cease to deliver sustained reductions.

The table also shows that high-pressure DMAs are more sensitive to ICF uncertainty than low-pressure ones. DMA 1 at 65m average pressure has a BL_0 representing 16% of its total real losses; DMA 2 at 42m has BL_0 at 11%. The higher the operating pressure, the greater the impact of an ICF error on the recoverable volume estimate, making high-pressure DMAs the priority candidates for field ICF determination. The practical conclusion for the analyst is that where the ICF — or its screening proxy, the ILI — is below 2.0, active leakage control is the appropriate primary intervention and the recoverable volume estimate is reliable. Where ICF exceeds 2.0, background leakage is material and the strategy must address infrastructure condition rather than burst detection alone. This conclusion cannot be reached from total real losses alone — it requires the component analysis that Section 5.1.2 provides.

As Fanner & Thornton (2005) conclude, the sensitivity of component analysis to ICF means that field measurements to determine the actual system ICF should ideally precede any component analysis.

5.1.3 BURST LEAKAGE

Burst leakage is the volume of water lost through discrete failure events on distribution mains, service connections, fittings, and valves. Background leakage is distributed continuously across micro-defects and cannot be reduced through find-and-fix activities. Burst leakage, by contrast, consists of individual failure events that can be located and repaired. It is therefore the primary component of the recoverable volume established in Section 5.1.1 and Section 5.1.2.

5.1.3.1 Reported and Unreported Bursts

Section 5.1.1 defined reported and unreported bursts as the two components of the recoverable volume. The distinction is operationally significant for the estimation method developed in Section 5.1.3.2 because the two burst types have fundamentally different duration profiles.

Reported bursts are visible. They are identified quickly and repaired promptly. Their total run time is typically measured in hours to days. Despite often carrying high flow rates, their short duration keeps their annual leakage volume small.

Unreported bursts are not visible. Detection depends on nightline monitoring or active leak detection surveys, and locating the failure requires specialist field investigation. Their run time is measured from weeks to months, and in reactive systems it can extend to years. Low individual flow rates on service connections and fittings compound this effect: a small leak flowing at 0.4 m^3/h for 200 days contributes 1,920 m^3 — a volume that a main burst at 3.0 m^3/h would accumulate in only 27 days. The combination of high frequency, long run time, and the dominance of service connections makes unreported burst leakage the primary component of the recoverable volume in most actively managed DMAs.

These contrasting run time profiles are the basis for the component loss model developed in Section 5.1.3.2. Figure 5-4 illustrates both profiles in the DMA nightline.

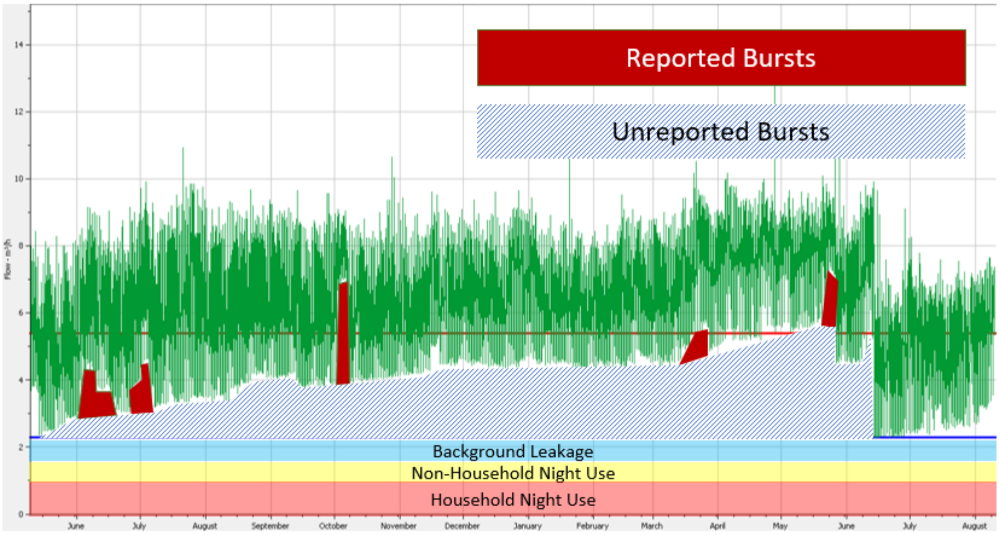


Figure 5-4 *DMA Burst Leakage.*

5.1.3.2 Burst Leakage Estimation

The total burst leakage in a DMA can be estimated using a component loss model. The total water loss from a burst event is a function of flow rate and duration. Burst duration is the sum of three intervals, defined in Figure 5-5 and Table 5-5.

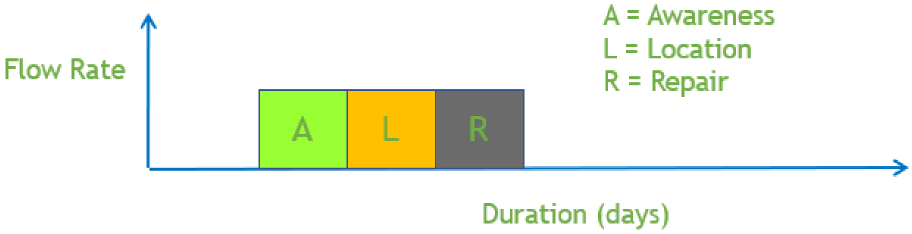


Figure 5-5 *Burst Leakage Time Components.*

Table 5-5 Burst Leakage Time Components.

Component	Definition
(A) Awareness Time	Length of time to become aware that a burst has broken out on the network.
(L) Location Time	Length of time to find a burst and pinpoint it to a section of pipe.
(R) Repair Time	Length of time to carry out a repair, once a burst has been pinpointed.

Burst duration is:

$$Burst\ Duration = A + L + R$$

Each component of burst duration is derived from operational records. Where DMA-specific records are not available, use average values derived from operational history within the same utility or district.

For reported bursts, awareness time (A) is the interval between the estimated burst occurrence and the first customer or staff report. For unreported bursts, A is the interval between the last clean nightline reading and the date of detection by active leakage control. Location time (L) is the interval between dispatch of the detection team and confirmation of the burst position. Repair time (R) depends on the repair method. Some repairs require a service interruption; others are completed on a live main without cutting supply. For repairs requiring service interruption, R ends at valve shutoff. Flow through the burst stops at shutoff. Using repair completion as the end point overstates burst volume. For live service repairs, R ends at repair completion because flow continues until the repair is made.

In practice, individual burst records are often incomplete, and awareness and location times are not always logged. In these cases, use average burst duration values by burst type derived from operational history. Table 5-6 presents default duration ranges from UK water industry practice (UKWIR, 2006) for reference.

Table 5-6 Default Burst Duration Ranges by Category (UKWIR, 2006).

Category	A + L + R (days)
Reported burst — mains	0.5 -2
Reported burst — service connection	1 - 10
Unreported burst — mains (active ALC)	10 - 60
Unreported burst — service connection (active ALC)	60 – 300
Unreported burst — any category (reactive only)	200 - 730

The burst volume per leak is calculated as:

$$Burst\ Volume = Burst\ Flow\ Rate\ \times Burst\ Duration$$

The average daily leakage contribution of a burst over an annual analysis period is:

$$Average\ Daily\ Leakage\ per\ Burst = \frac{Burst\ Volume}{365}$$

When average burst parameters are applied across all bursts recorded in a DMA over a year, the total annual burst leakage is:

$$Burst\ Leakage = Burst\ Frequency\ \times Average\ Daily\ Leakage\ per\ Burst$$

Burst flow rates vary widely depending on failure type, infrastructure category, pipe diameter, material, and location. The flow rate of individual bursts can be estimated from the reduction in nightline MNF observed before and after repair. Where nightline data quality is sufficient, this method is preferred because it reflects actual conditions in the DMA. Where nightline data are not reliable or the repair is too small to produce a detectable nightline reduction, use average values by infrastructure category. Three levels of average values are available in ascending order of generality: DMA-specific values derived from local repair history, company- or area-level values calibrated against nightline data, and industry default values such as those in Table 5-7.

Table 5-7 Representative Burst Flow Rates by Infrastructure Category (UKWIR, 2006).

Burst Type	Flow Rate (m³/h)
Mains Leak	3.00
Mains Fittings	0.15
Communication pipe (utility-owned service connection)	0.40
Supply pipe (customer-owned service connection)	0.40
Communication and supply pipe fitting	0.10

Communication pipes and supply pipes — the two service connection categories — represent the most frequent failure type in most DMAs, consistent with the dominance of service connections established in Section 5.1.2. Their individual flow rates are lower than mains failures, but their high frequency makes their cumulative contribution to total burst leakage substantial.

Figure 5-6 illustrates the burst volume components for a typical unreported service pipe leak. Figure 5-7 shows the resulting annual burst leakage for a DMA with ten unreported bursts per year at the representative service pipe flow rate.

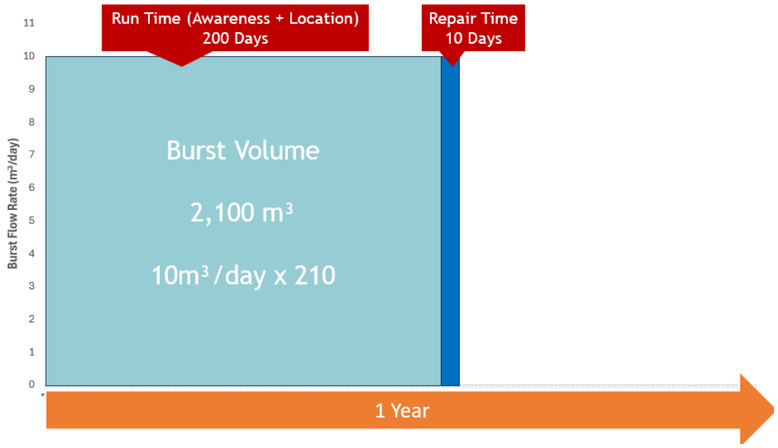


Figure 5-6 *Annual Burst Volume.*

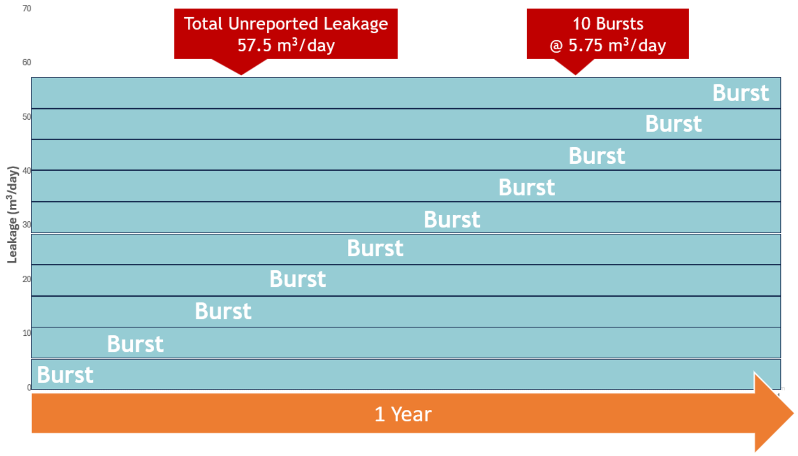


Figure 5-7 *DMA Burst Leakage.*

5.2 DEFINING LEAKAGE POLICY AND REDUCTION TARGETS

5.2.1 LEAKAGE MANAGEMENT

Water utilities manage leakage to achieve two objectives. The first objective is to maintain leakage at or below a target level across the network. The second objective is to reduce leakage to lower target levels where required. Maintaining performance takes priority; a utility pursues reduction targets once leakage is under control. Target levels depend on the circumstances of each water utility.

Leakage management relies on four pillars: Pressure Management, Active Leakage Control, Repair Management, and Infrastructure Management. Figure 5-8 illustrates these pillars and their relationships. Each pillar is described in this section.

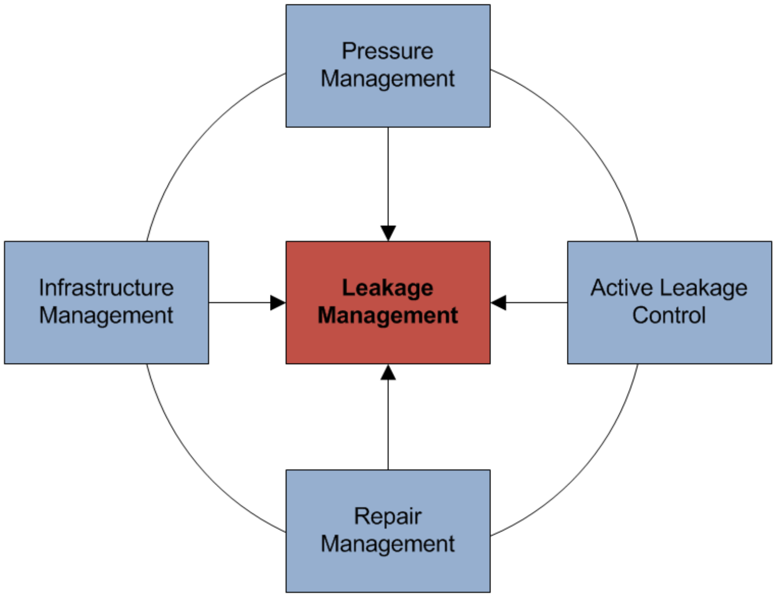


Figure 5-8 *Four Pillars of Leakage Management.*

The four pillars are applied in order of increasing cost and time to deliver results. A water utility should first improve repair response — reducing the time to become aware of, locate, and repair bursts — because this action requires no capital investment and produces immediate reductions in burst leakage. Where unreported burst leakage remains high, active leakage control detects and repairs leaks that repair management alone does not find. Where background leakage or burst frequency is high despite effective ALC and repair management, pressure management reduces network pressure to lower both components. Where pipe condition has degraded to the point that pressure management cannot achieve the leakage target, infrastructure replacement or refurbishment is required.

Each successive pillar requires greater capital investment and delivers results over a longer period. In practice, all four pillars operate at the same time. The sequence defines the order in which to prioritize investment when resources are limited.

5.2.1.1 Repair Management

Repair management is the timely repair of leaks identified through ALC or reported by customers and staff. Its purpose is to limit burst duration and prevent the accumulation of unrepaired leaks.

Longer repair times increase the volume lost from each burst and cause leakage to rise. Extended backlogs of unrepaired leaks make it progressively harder to maintain target leakage levels and increase the risk of supply disruption and customer complaints.

Repair time can be reduced through efficient dispatch, effective coordination between detection and repair teams, and rapid mobilization once a burst has been located. Repair management depends on ALC to locate bursts to within approximately one meter before excavation begins.

Repair management performance is constrained by several factors. Burst activity increases during adverse weather, and repair resources may be insufficient to meet demand during these periods. Individual repairs may also be delayed by traffic management requirements, customer consent, regulatory approvals, and the need to schedule supply interruptions.

5.2.1.2 Active Leakage Control

Active Leakage Control (ALC) is the systematic detection and repair of underground leaks before they surface. ALC is required to counteract the Natural Rate of Rise in leakage — the rate at which new leaks emerge on the network (Section 5.2.2.5). Without ALC, new leaks accumulate and leakage rises continuously.

ALC performance improves by locating leaks that have not previously been detected, both within DMAs and on assets outside DMA boundaries, and by reducing the time required to become aware of and locate each burst.

ALC effectiveness depends on the skill and experience of detection personnel and on the suitability of the equipment used. Detection tools range from listening sticks and ground microphones to correlators, noise loggers, and hydrophones. Each tool has specific applications and limitations. No single technology is suitable for all detection scenarios.

Leak detection is more difficult in rural areas, on trunk mains, and in busy urban environments. Pressure management reduces burst flow rates, which can make leaks harder to detect acoustically. ALC and repair management are interdependent: poor repair practices reduce the leakage savings that ALC achieves. ALC alone cannot reduce background leakage levels or burst frequency.

Figure 5-9 illustrates the leakage decomposition for an DMA. Total leakage is 117.5 m^3/day, composed of background leakage (50 m^3/day), reported burst leakage (10 m^3/day), and unreported burst leakage (57.5 m^3/day) from 10 bursts at an average of 5.75 m^3/day each. The leakage target is 100 m^3/day. The recoverable volume — the gap between total leakage and background leakage — is 67.5 m^3/day.

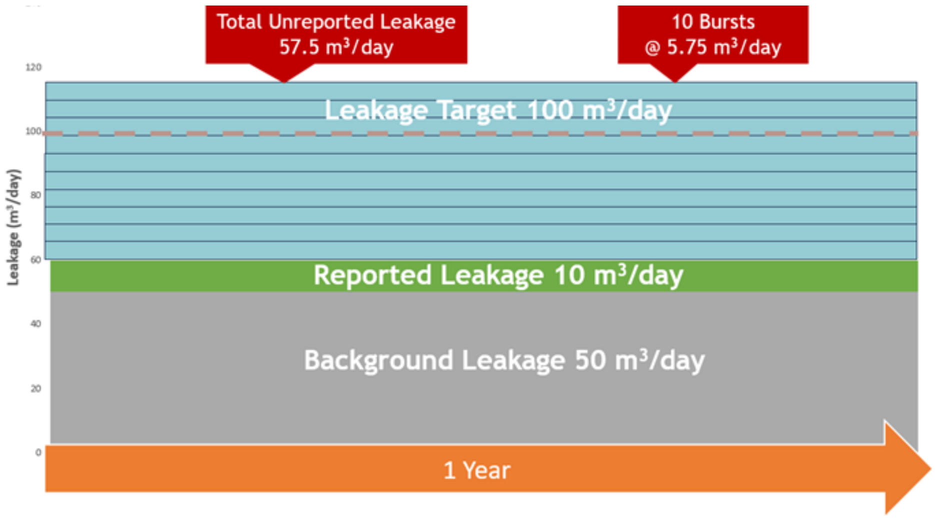


Figure 5-9 *DMA Total Leakage.*

Figure 5-10 shows the same DMA after faster detection and repair reduce average burst duration, lowering average leakage per burst from 5.75 m³/day to 4 m³/day. With burst frequency and flow rates unchanged, total unreported leakage falls to 40 m³/day and total DMA leakage reaches exactly 100 m³/day — the leakage target is met solely through improvement in repair response time.

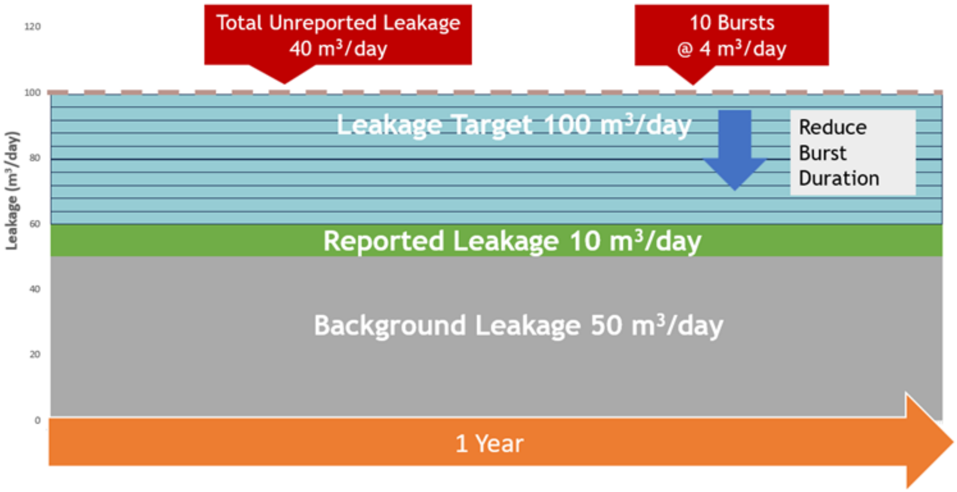


Figure 5-10 *Reducing Burst Duration.*

5.2.1.3 Pressure Management

Pressure Management controls network pressure through pressure management schemes to reduce background leakage and limit burst frequency. Lower pressure reduces the force exerted on pipe walls, which decreases both the rate of background leakage and the rate at which new bursts develop.

Pressure management performance improves by installing new schemes and optimizing existing ones. When correctly designed and operated, pressure management reduces both background leakage and burst leakage. The minimum pressure in any part of the network must remain above the required service level for all customers at all times. This constraint limits how far pressure can be reduced.

Pressure management can reduce the flow rates of undetected bursts and thereby lower leakage; however, it does not eliminate the underlying failures and must not be used as a substitute for burst detection and repair, as this would mask real losses and produce leakage figures that do not reflect the actual network condition.

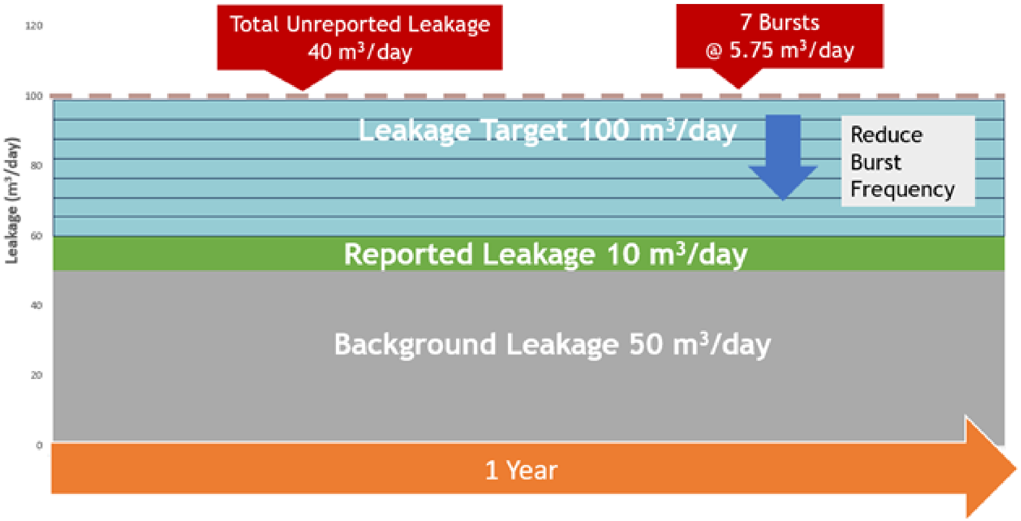


Figure 5-11 *Reducing Burst Frequency.*

Figure 5-11, shows the same DMA as in Figure 5-9, where burst frequency was reduced through the implementation of pressure management. For this illustration, it is assumed that the leakage per burst remains unchanged; however, in practice, it may also be reduced.

5.2.1.4 Infrastructure Management

Infrastructure Management is the planned replacement or refurbishment of pipes and service connections that are no longer performing adequately. Priority assets for intervention are those with the highest burst frequencies, the highest background leakage rates, water quality problems, or poor pressure performance. Refurbishment techniques include pipe relining and pipe bursting, among others, and are applied where full replacement is not required or not justified.

Infrastructure management reduces both background leakage and burst frequency by improving the structural condition of the pipe network. It is the appropriate primary intervention when the ICF for a DMA exceeds approximately 2.0 (Section 5.1.2.4), indicating that background leakage dominates total real losses and that ALC alone cannot achieve the leakage target sustainably. Service connections are a priority target because they carry the largest share of both background and burst leakage in most DMAs (Section 5.1.2, Section 5.1.3).

Infrastructure management performance improves by expanding the scale of replacement and refurbishment programs and by targeting the assets that contribute most to leakage. Identifying the worst-performing assets requires statistical analysis of burst history, leakage data, and pipe age and material, because pipe condition cannot be assessed directly until the pipe is excavated. Infrastructure management is the most capital-intensive of the four leakage management pillars. This limits the rate at which replacement and refurbishment programs can be implemented and makes accurate asset prioritization essential.

5.2.2 DETERMINING DMA LEAKAGE MINIMUM POLICY

Section 5.1 established the recoverable volume for each DMA as the difference between measured real losses and pressure-adjusted background leakage. This recoverable volume identifies how much leakage can be reduced but does not define the level at which a utility should stabilize each DMA. That level is the DMA Leakage Minimum Policy.

The DMA Leakage Minimum Policy is the lowest level of leakage that can be realistically sustained in a DMA under the utility's current operational practice. It is not a fixed physical value. It depends on the leakage control methods applied, the intensity of active leakage control, the effectiveness of pressure management, and the condition of the pipe network (Creasey et al., 2004). Factors outside utility control — such as soil type — are fixed. All other factors can be improved through changes in policy or investment.

Three benchmarks are used together to determine the minimum policy for a DMA:

- Unavoidable Annual Real Losses (UARL) — a theoretical lower bound calculated from the physical characteristics of the network. It represents the minimum leakage achievable under optimal conditions across all components.
- Minimum Achieved Leakage (MAL) — the lowest leakage level historically recorded in the DMA under the utility's current operational practice. It confirms what has already been attained.
- Minimum Achievable Leakage (MAbL) — derived from the background leakage calculation of Section 5.1.2 at the DMA's known or estimated infrastructure condition. It defines what is physically attainable given the current state of the network.

These three benchmarks bracket the realistic range of minimum leakage for the DMA. They provide the basis for setting the exit level, leakage target, and entry level that govern active leakage control operations (Section 5.2.3).

Once the minimum policy level is established, the Natural Rate of Rise (Section 5.2.4) determines how quickly leakage grows between ALC interventions. NRR converts the minimum policy level into an ALC resource requirement — the frequency and intensity of detection campaigns needed to sustain leakage at or near the target.

5.2.2.1 Unavoidable Annual Real Losses

UARL is introduced in Section 5.1.2.3 in the context of its relationship to the background leakage calculation. In Section 5.2.2, UARL serves as the theoretical lower benchmark for the DMA Leakage Minimum Policy.

Each UARL coefficient combines all three unavoidable loss components — background leakage, minimum unreported burst losses, and minimum reported burst losses — for each infrastructure category. Table 5-8 presents the full breakdown from Lambert et al. (1999).

Table 5-8 UARL Coefficient Breakdown (Lambert et al., 1999)

Infrastructure Component	Background Losses	Reported Bursts	Unreported Bursts	UARL Total	Units
Mains	9.6	5.8	2.6	18	Liters/km mains/ Day/meter of pressure
Service Connections, meters at edge of street	0.60	0.04	0.16	0.80	Liters/Connection/ day/meter of pressure
Underground pipes between edge of street and customer meters	16.0	1.9	7.1	25	Liters/km u.g. pipe/ Day/meter of pressure

The background leakage column matches exactly the IWA rates in Table 5-2 of Section 5.1.2.3. The remaining portion of each coefficient is the unavoidable burst contribution — losses that persist even under optimal management because some burst run time is irreducible regardless of ALC intensity or repair speed. This is why UARL is always greater than background leakage alone, and why real losses can approach but not reach the background leakage floor through find-and-fix activities alone.

The standard UARL equation (Lambert et al., 1999) was derived for systems with more than 5,000 service connections and average pressures between 45 and 60 m H_2O. Most individual DMAs fall outside these conditions — they are smaller systems, often operating at pressures outside this range. In these cases, the standard equation can over-predict or under-predict unavoidable real losses by more than 10%.

Research into small systems in Austria demonstrated this effect: well-managed utilities with fewer than 3,000 service connections consistently achieved real losses below the standard UARL, producing ILI values less than 1.0 (Lambert et al., 2014). This is not a water balance error. It reflects that the standard equation overestimates the unavoidable minimum for small systems at those pressures.

The System Correction Factor (SCF) corrects this by applying a non-dimensional multiplier to the standard UARL formula. It accounts for three factors. First, pipe material rigidity: following the FAVAD relationship, leak flow rates vary with pressure to the power 0.5 for rigid pipes and to the power 1.5 for flexible pipes and background leakage. Second, burst frequency in small systems: bursts are rare events and average frequencies overestimate their expected occurrence; the SCF uses median values derived from Poisson probability distributions instead. Third, the pressure-burst frequency relationship: lower pressures reduce the rate at which new bursts develop, and this effect is more pronounced in small systems.

For DMA-level analysis, the UARL with SCF is the recommended calculation. The standard equation without SCF is appropriate only as a first approximation where SCF inputs are not available. The same principles apply to the background leakage calculation in Section 5.1.2, where infrastructure condition and pressure interact in ways that are also sensitive to system size. The SCF methodology is described in Lambert (2020).

Table 5-9 presents UARL calculations for two DMAs with differing characteristics. As shown, DMA 1 has a higher UARL than DMA 2, due to the combined influence of the four contributing components.

Table 5-9 UARL Calculation DMA Example.

Component	DMA 1	DMA 2
Mains Length (km)	10	29
Number of Connections	2,000	860
Length of Service Pipe (km)	29	12
Average Operating Pressure (m)	25	35
Unavoidable Annual Real Losses (l/day)	**62,625**	**52,850**

The difference between current real losses and UARL is the UARL-based leakage gap — the maximum volume that could theoretically be eliminated if the network were operated under optimal conditions. Table 5-10 shows this gap for the two example DMAs.

Table 5-10 Recoverable Leakage using UARL DMA Example

Component	DMA 1	DMA 2
Real Losses (m^3/day)	207	151
Unavoidable Annual Real Losses (m^3/day)	63	53
Recoverable Leakage (m^3/day)	**144**	**98**

DMA 1 has a larger leakage gap than DMA 2. This reflects its higher real losses, not a difference in network size — DMA 2 has longer mains and a comparable number of connections, but lower pressure produces a lower UARL.

UARL is a theoretical minimum. A utility operating under standard ALC practice will not reach UARL because background leakage depends on infrastructure condition, which is rarely at the ICF = 0.5 level assumed in the UARL derivation, and because some unreported burst leakage persists above the unavoidable level. Where real losses are at or below UARL, the DMA is performing at or near best practice and further reduction requires a change in leakage policy rather than additional ALC effort.

5.2.2.2 Minimum Achieved Leakage

The Minimum Achieved Leakage (MAL) is the lowest valid leakage level recorded in a DMA. It is determined by analyzing daily or weekly MNF or leakage data over a defined historical period — typically the previous five years — to identify the lowest values achieved after intensive ALC activity. Figure 5-12 illustrates the concept.

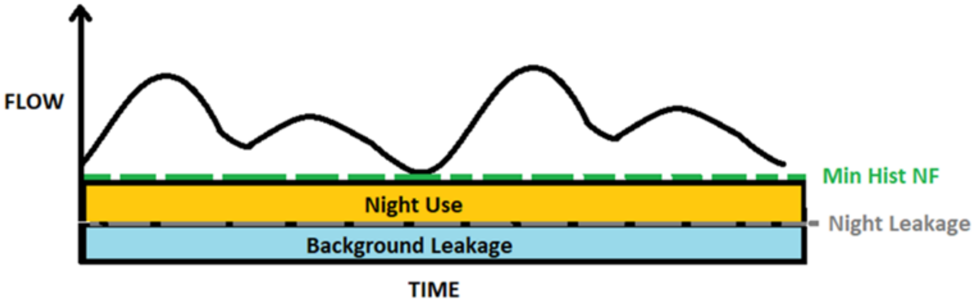


Figure 5-12 *Minimum Achieved Leakage.*

When determining MAL from MNF data, subtract estimated night use from the MNF to isolate the leakage component. Apply the DMA-specific Night Day Factor to convert the result to a daily real losses volume.

Statistical techniques are required to remove outliers. Use low percentiles rather than absolute minimums, and apply thresholds based on standard deviations from the mean. Before accepting any candidate MAL value, verify that no anomalies were present at the time it was recorded — including network breaches, flow meter faults, and changes to the DMA boundary. A low MNF caused by a meter fault is not a valid MAL. Table 5-11 presents MAL values for the two example DMAs.

Table 5-11 MAL DMA Example

Component	DMA 1	DMA 2
Minimum Achieved Leakage (m^3/hr.)	8	5
Night Day Factor	22.5	23.5
Minimum Achieved Real Losses (m^3/day)	182	106

MAL is an empirical benchmark — it confirms what the DMA has already achieved under the utility's current operational practice, as opposed to UARL which is a theoretical lower bound. This makes MAL a reliable basis for setting the exit level in ALC operations (Section 5.2.3): if the DMA reached this level before, it can reach it again.

However, MAL has two limitations. First, the MAL may have been achieved during a period of unusually intensive ALC effort that cannot be sustained routinely. Second, the MAL may still include residual unreported burst leakage that was not detected at the time. In both cases, the MAL overstates the policy minimum — it is higher than the true background leakage floor. Where the MAL is suspected to be above the true policy minimum, the Minimum Achievable Leakage (Section 5.2.2.3) provides a more reliable estimate.

The difference between current real losses and MAL indicates the leakage reduction achievable by returning the DMA to its previously recorded best performance. Table 5-12 shows this gap for the two example DMAs. This is not the recoverable volume defined in Section 5.1.1 — it is a narrower estimate that reflects only what has been demonstrated historically, not what is physically possible.

Table 5-12 Recoverable Leakage using MAL DMA Example

Component	DMA 1	DMA 2
Real Losses (m^3/day)	207	151
Minimum Achieved Real Losses (m^3/day)	182	106
Recoverable Leakage (m^3/day)	**25**	**45**

DMA 2 has a larger MAL-based gap than DMA 1, which reverses the ranking produced by the UARL-based gap in Section 5.2.2.1. The two benchmarks give different answers because they measure different things: UARL measures distance from the theoretical optimum, while MAL measures distance from demonstrated historical performance. Both are needed to bracket the realistic minimum policy range.

5.2.2.3 Minimum Achievable Leakage

UARL and MAL bracket the minimum policy range from opposite directions. UARL establishes the theoretical lower bound — the minimum achievable under optimal conditions across all components. MAL establishes the empirical upper bound — the lowest level the DMA has actually reached under the utility's current operational practice. The gap between them reflects uncertainty about the true policy minimum for the DMA.

The Minimum Achievable Leakage (MAbL) resolves this uncertainty by estimating the background leakage floor at the DMA's actual infrastructure condition. It is calculated using the background leakage method of Section 5.1.2.3, applied at the DMA's known or estimated ICF rather than at ICF = 1.0. The ICF for the DMA is determined using the methods described in Section 5.1.2.4.

This calculation is repeated at three ICF levels — Good (ICF = 0.5), Average (ICF = 1.0), and Poor (ICF = 1.5) to produce a range of background leakage estimates that reflect uncertainty in infrastructure condition. Table 5-13 shows the background leakage calculation at ICF = 1.0 for the two example DMAs. Table 5-14 extends this to all three condition levels.

Table 5-13 Background Leakage Calculation DMA Example

Component	DMA 1	DMA 2
Mains Length (km)	10	29
Number of Connections	2,000	860
Average Zone Night Pressure	36.5	45.5
N1 Leakage Exponent	1.5	1.5
Background Leakage (m^3/hr)	**4.62**	**3.62**
Night Day Factor	22.5	23.5
Background Losses (m^3/day)	**104**	**85**

Table 5-14 Background Losses for Good, Average and Poor Conditions

Component	ICF	DMA 1	DMA 2
Good Condition Background Losses (m^3/day)	0.5	52	43
Ave Condition Background Losses (m^3/day)	1.0	104	85
Poor Condition Background Losses (m^3/day)	1.5	156	128

Figure 5-13 places these background leakage estimates alongside the MAL and UARL for each DMA. The MAL bar shows where the DMA has already been. The background leakage range shows where the physical floor lies under different infrastructure conditions. The UARL is closely aligned with the Good condition background leakage estimate, which is consistent with the UARL derivation — its coefficients include background leakage at ICF ≈ 0.5 as one of three unavoidable components (Section 5.1.2.3).

Two observations follow from Figure 5-13. For DMA 1, current real losses exceed all three background leakage benchmarks and MAL, indicating substantial scope for leakage reduction through ALC. For DMA 2, current real losses fall between the Average and Poor condition estimates, suggesting that infrastructure condition is a significant contributor to measured leakage and that ALC alone may not be sufficient to reach the leakage target.

MAbL is not identical to the background leakage floor. It is higher, because in practice the policy minimum includes leakage from sub-threshold failures — small leaks that are present but undetectable with current methods (Creasey et al., 2004). The background leakage calculation provides the lower bound of MAbL. MAL provides the upper bound. The DMA owner determines the realistic policy minimum within this range based on knowledge of local infrastructure condition and ALC capability.

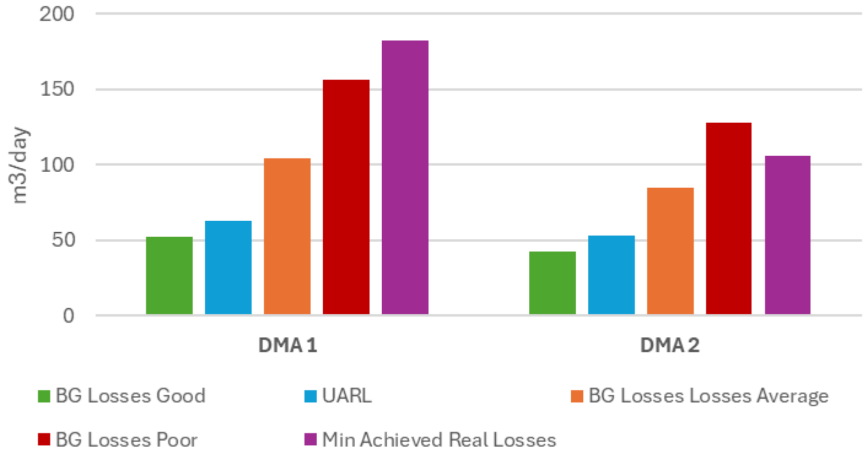


Figure 5-13 *Minimum Achievable versus Minimum Achieved Leakage.*

5.2.2.4 Setting the DMA Minimum Policy

The next step is to assess the equivalent ICF for the Minimum Achieved Leakage, assuming that it is all attributable to Background Leakage. This is calculated by dividing the MAL by the Background Leakage under average conditions, as shown in the formula below:

$$\text{Equivalent ICF} = \text{MAL} / \text{Background Leakage (Ave Condition)}$$

Table 5-15presents an example of the calculation of the equivalent ICF using this approach for the same two DMAs. As shown, DMA 1 has an equivalent ICF of 1.75, while DMA 2 is 1.25.

Table 5-15 Equivalent ICF DMA Example

Component	DMA 1	DMA 2
Minimum Achieved Leakage (m^3/hr)	8.00	5.00
Background Leakage ICF = 1 (m^3/hr)	4.62	3.62
Equivalent DMA ICF	**1.75**	**1.25**

Following the concept of the Infrastructure Condition Factor (ICF) used in leakage modelling (Farley & Liemberger, 2004), the condition of each DMA can be approximated based on the proportion of plastic pipes. This approach assumes that plastic pipes are inherently in 'Good' condition. The modeling is based on the assumptions that a DMA with 100% plastic pipes is assigned an ICF of 0.5 (Good). A DMA with 0% plastic pipes is assigned an ICF of 1.5 (Poor). To estimate the ICF for any given DMA, the following formula is used as approximation (but it is not generally considered applicable in low- and middle-income countries context):

$$\text{Modelled ICF} = (1.5 - 0.5) \times (\% \text{ Plastic})$$

The modelled ICF range of 0.5 to 1.5 was developed for networks in which infrastructure condition falls within a range typical of well-maintained systems. In developing-country contexts, or in networks with severely deteriorated infrastructure, the equivalent ICF derived from the Minimum Achieved Leakage may exceed 1.5. In these cases, the plastic-pipe model is not applicable, and the ICF should be assessed directly from the Minimum Achieved Leakage using the equivalent ICF formula, supported by field investigation to characterize actual pipe condition.

Figure 5-14 illustrates the modelled ICF values for each DMA based on DMA 1 having 25% plastic pipes and DMA 2 having 70% plastic pipes. As shown, DMA 1 is modelled to be in comparatively poorer condition (1.25), while DMA 2 is modelled closer to 'Good' condition (0.80).

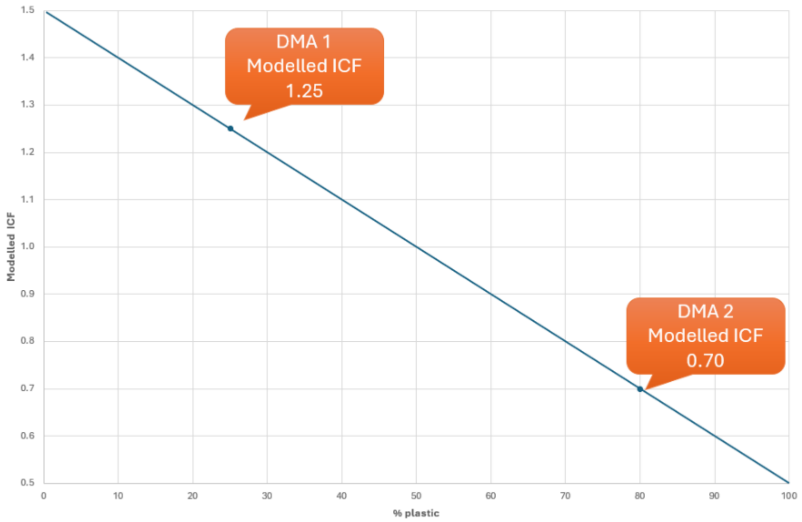


Figure 5-14 *Modelled ICF DMA Example.*

Once the ICF has been modelled for each DMA, the Background Leakage can be reassessed and compared against the Minimum Achieved Leakage. The results are summarized in the Table 5-16.

Table 5-16 Modeled Background Leakage DMA Example

Component	DMA 1	DMA 2
Minimum Achieved Leakage (m^3/hr)	8.00	5.00
Background Leakage Modelled ICF (m^3/hr)	5.77	2.53
Recoverable Leakage (m^3/hr)	**2.32**	**1.98**

As shown in Table 5-16, there is a notable difference between the Minimum Achieved Leakage and the modelled Background Leakage. If the model is considered reliable and the modelled Background Leakage is considered achievable, then the gap represents potentially recoverable leakage that has not yet been identified. It is the responsibility of the DMA owner to define appropriate upper and lower limits for the ICF to determine what is realistically achievable when assessing the MAL for a DMA.

5.2.2.5 Natural Rate of Rise

Applying a component loss model is useful for understanding DMA leakage and breaking it down into its components. However, there are key challenges related to obtaining accurate input values for the model. For example, determining the flow rate of bursts, the duration of leaks from occurrence to detection, and capturing repair times or recording the number and type of leaks can be difficult. Improving the quality of these data inputs is essential for improving your understanding of leakage within a DMA.

One way to analyze this is through the DMA Natural Rate of Rise (NRR) of leakage, which gives insight into leakage patterns and helps to plan targeted interventions. NRR is defined as the rate at which leaks emerge on a system that must be detected and repaired. If these leaks were not identified and repaired, the overall leakage would continue to increase over time.

Figure 5-15 illustrates the NRR for a DMA, showing how unreported leakage continues to increase over time when there are no active interventions to detect and repair these “invisible” leaks. In the figure, reported leakage is assumed to remain constant, as leaks that break out visibly are quickly reported and repaired. The rate at which unreported leakage rises represents the NRR, which must be managed through active leakage control to maintain overall leakage at a steady state. This is demonstrated in Figure 5-16 which shows the same DMA where leakage is managed through active leakage interventions to counteract NRR.

There are two main techniques for estimating the NRR of a DMA: the Burst Frequency Approach and the Nightline Approach. The simplest application of the burst frequency approach is to multiply the number of bursts per year in a DMA by an average burst flow rate:

$$Burst\ Frequency\ NRR = Burst\ Frequency \times Ave\ Burst\ Flow\ Rate$$

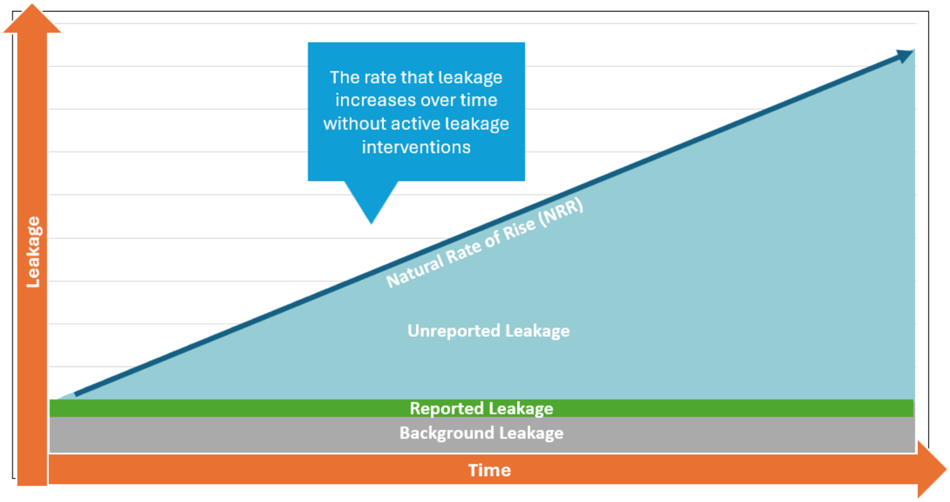


Figure 5-15 *DMA Natural Rate of Rise.*

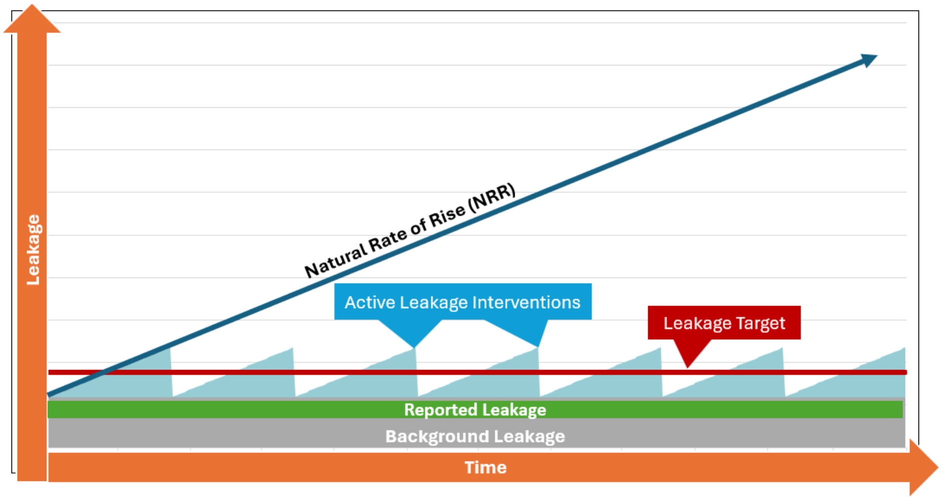


Figure 5-16 *DMA Active Leakage Intervention.*

In the previous section, the DMA example had 10 bursts per year with an average flow rate of 10 m³/day. Using the simple burst frequency approach the DMA would have an NRR of 100 m³/day per year. This means that, in the absence of active leakage interventions, leakage in the DMA would increase by 100 m³/day over a year. NRR can also be normalized to facilitate comparison between DMAs by converting it to liters per day and dividing by the number of connections. For example, if our example DMA has 1,000 connections, its normalized NRR would be 100 liters/day per connection per year. NRR can also be expressed in other units, such as m³/hour per year, liters/second per year, or normalized by the length of mains.

The burst frequency approach can be improved when you apply more representative flow rates to individual bursts. This can be done by assigning nominal flow rates according to burst type, or by using flow rates derived at the DMA level, or for individual bursts where sufficient data exist. In these cases, the NRR is calculated by multiplying the number of bursts of each type by their corresponding flow rate and then summing the results.

The gradient of NRR represents the daily rate at which leakage is expected to increase, enabling more accurate prediction of leakage growth and planning of interventions. In our example, an NRR of 100 m^3/day per year, when divided by 365 days and converted to liters, corresponds to approximately 274 liters per day, representing the average daily increase in leakage for the DMA. However, the best practice to find the true gradient of NRR is to use the nightline approach, which is illustrated in Figure 5-17. In this figure, each repair date of an unreported burst divides the DMA MNF history into distinct periods. The MNF data between two consecutive unreported burst repairs are referred to as Regression Periods. For each regression period, a linear trend is fitted to the nightline graph. Using the linear relationship y = mx + c, the gradient m of the trend line is calculated and represents the NRR for that period.

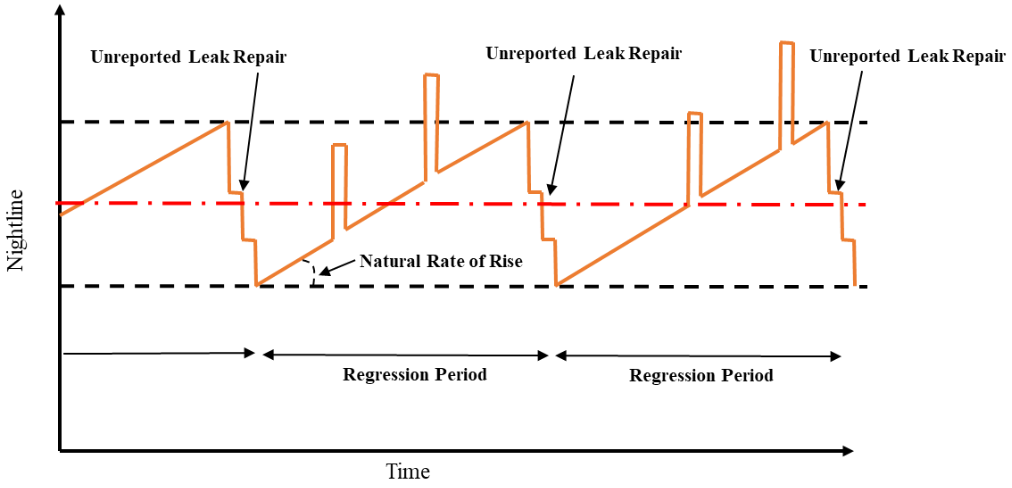


Figure 5-17 *DMA Nightline NRR.*

To determine NRR using the minimum night flow method, it is necessary to undertake data cleaning and apply a set of validation rules. These include removing MNF outliers that may distort the calculated NRR and ensuring that each regression period meets a minimum duration requirement, for example, at least 20 days. Shorter periods can lead to unreliable NRR estimates due to increased night-use variability.

Table 5-17 Example DMA Annual NRR Calculation

1-Year Analysis		Night Day Factor		22.5	No. of Connections		1500
Regression Period	**Period Start Date**	**Period End Date**	**Total Days**	**Period Weighting**	**NRR Daily (m^3/hr/day)**	**NRR Yearly (m^3/day/yr)**	**Normalized NRR (l/day/conn/yr)**
1	01/01/2025	22/01/2025	21	7%	0.008	66.5	44.3
2	07/02/2025	03/03/2025	24	8%	0.007	60.8	40.5
3	18/03/2025	25/05/2025	68	23%	0.003	20.5	13.7
4	09/06/2025	15/11/2025	159	53%	0.005	42.7	28.5
5	03/12/2025	31/12/2025	28	9%	0.014	115.8	77.2
		Total/Average	**300**	**100%**	**0.006**	**47.6**	**31.7**

5.2.2.6 Application of NRR for Leakage Management

There are many applications of NRR in the leakage management of DMAs; however, this section provides only a brief overview. First, NRR is a key performance indicator that can be used to compare DMAs and support informed decision-making. Understanding the NRR of a DMA allows leakage behavior to be better predicted and enables planning for each DMA. For example, DMAs with higher NRRs will typically require more frequent active leak interventions throughout the year, while DMAs with lower NRRs will require fewer interventions.

Table 5-18 demonstrates how the NRR of a DMA can be used to estimate the total number of leak detection interventions required annually and, based on the time needed to carry out leakage detection, the associated annual resource requirements.

Table 5-18 Using NRR to Derive Resource Requirements

Component	Value		
Annual Real Losses Target (m^3/day)	100		
Exit Level (m^3/day)	50		
Entry Level (m^3/day)	150		
Intervention Threshold (m^3/day)	100		
Detection Effort Per Intervention (Days)	10		
NRR (m^3/day/year)	50	100	200
Number of Interventions	0.5	1	2
Number of FTE Days Per Year	5	10	20

Referring to Table 5-18, the intervention threshold for the DMA must first be calculated as the difference between the entry level and the exit level. The number of interventions is then determined by dividing the NRR by the intervention threshold, ensuring both values are expressed in the same units (for example, m^3/day, m^3/hour, or liters per second). Finally, multiplying the number of interventions by the detection effort per intervention provides an estimate of the full-time equivalent (FTE) days per year required to maintain leakage at steady state. The table presents three scenarios—high, medium, and low NRR—illustrating the corresponding impact on annual resource requirements.

NRR can also be used to back-calculate DMA-specific burst flow rates and run times, allowing the component loss model to be refined. This refined model can then be used to simulate different scenarios and assess their impact on leakage. In addition, the derived burst flow rates can be used to estimate NRR using the burst frequency approach for DMAs where the nightline method cannot be applied. Figure 5-18 presents an example of a component loss model for a zone containing multiple DMAs, illustrating the range of analyses that can be undertaken using NRR and burst leakage analysis techniques.

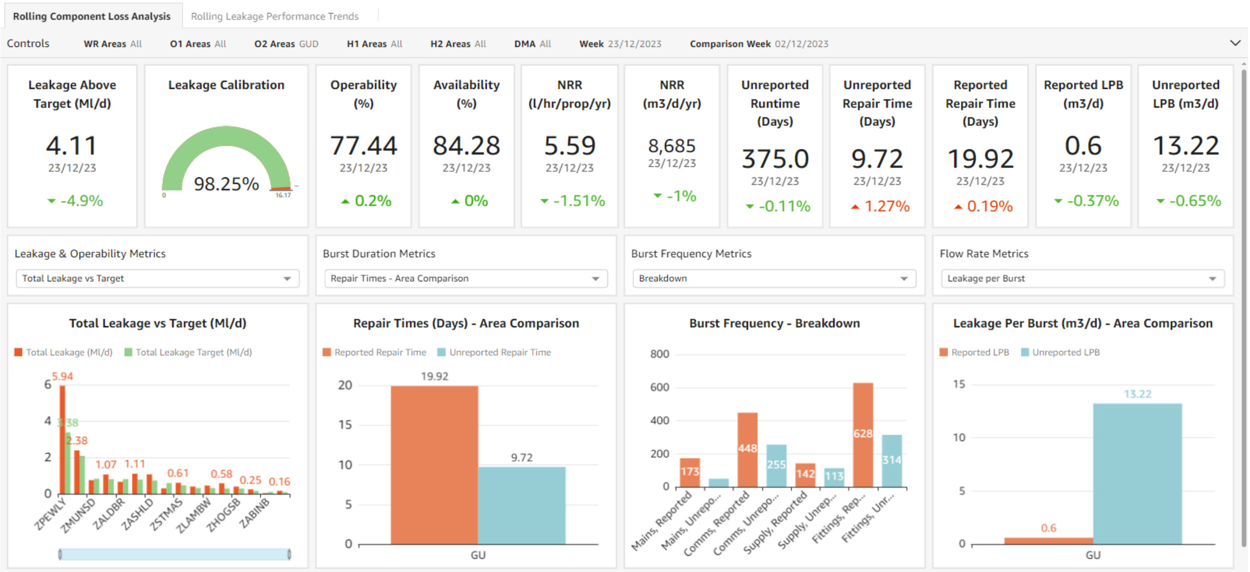


Figure 5-18 *Component Loss Model Utilizing NRR Example (source: Crowder Consulting, 2025).*

5.2.3 SETTING LEAKAGE TARGETS

A Water Loss Specialist Group initiative has considered the whole subject of targets for water loss and recommends that:

- Targets should be set taking account of all PESTLE factors (Political, Economic, Social, Technical, Legislative and Environmental)
- Target should be set at a water supply or demand zone level
- Zonal targets should then be aggregated up to a utility wide target, and down to the DMAs within that zone

This section highlights the importance of setting leakage targets at the DMA level. It explores the components of DMA Real Losses and the key factors influencing target setting. Additionally, it provides practical approaches for establishing leakage targets and applying them effectively.

5.2.3.1 Infrastructure Leakage Index

A simple method for setting leakage targets at the DMA level is to base them on Infrastructure Leakage Index (ILI) values. This approach assumes that an overall Real Losses target has already been established at the company or zonal level. It also requires that Unavoidable Annual Real Losses (UARL) have been calculated for the entire company or zone, as well as for each individual DMA within it. With these inputs, the overall Real Losses target can be translated into a corresponding ILI target by applying the following formula:

Target ILI = Real Losses Target / Unavoidable Annual Real Losses

Table 5-19 shows how the Real Loss Target has been converted into a Target ILI for an example zone.

Table 5-19 Example Zone Target ILI

Component	Zone
Real Losses Target (m^3/day)	1,778
Unavoidable Annual Real Losses (m^3/day)	639
Target ILI	**2.8**

The Target ILI for the zone can then be applied to each DMA contained within it and used to calculate specific Real Losses targets by applying the following formula:

DMA Annual Real Loss Target = Target ILI x DMA UARL

Table 5-20 illustrates how the target ILI for the zone has been applied to individual DMAs. This ILI-based approach allows the required reduction in Real Losses to be determined for each DMA, supporting the achievement of overall leakage reduction objectives.

Table 5-20 Example DMA Targets based on ILI-Based Approach

DMA	UARL (m^3/day)	Real Losses Target (m^3/day)	Annual Real Losses (m^3/day)	ILI	Target Leakage Reduction (m^3/day)
DMA 1	63	169	207	3.3	38
DMA 2	53	142	151	2.9	9
DMA 3	53	143	150	2.8	7
DMA 4	38	102	195	5.2	93
DMA 5	61	163	175	2.9	12
DMA 6	106	285	345	3.3	60
DMA 7	83	224	225	2.7	1
DMA 8	68	183	330	4.8	147
DMA 9	45	122	117	2.6	-5
DMA 10	91	244	222	2.4	-22
Total	**660**	**1778**	**2117**	**3.2**	**339**

However, one limitation of this method is that it applies a uniform target across all DMAs, without accounting for the current level of Real Losses in each area. As a result, some DMAs may appear to be over-performing if their existing ILI is already below the target which could potentially discourage proactive leakage management in those areas.

5.2.3.2 Excess Leakage

Excess Leakage refers to the volume of water loss in a DMA that can be attributed to detectable and repairable bursts. To calculate Excess Leakage, you must first determine both the Real Losses and the Background Losses within the DMA. Excess Leakage is then calculated as the difference between Real Losses and Background Losses, as shown in the formula below:

Excess Leakage = Real Losses- Background Losses

It is important to calculate Excess Leakage values for each DMA and use them as the basis for target setting and prioritization. Excess Leakage provides a more accurate indication of the volume of leakage that can be addressed through detection and repair. The key factors influencing Excess Leakage are the levels of Real Losses and Background Losses as the closer these values are, the fewer detectable and repairable bursts exist within the DMA. Leakage targets based on Excess Leakage are more realistic, achievable, and appropriate to the specific conditions of each DMA.

Figure 5-19 illustrates why Excess Leakage should also guide DMA prioritization. A DMA may have a high overall leakage volume, but if most of it is background loss, the opportunity for effective intervention is limited.

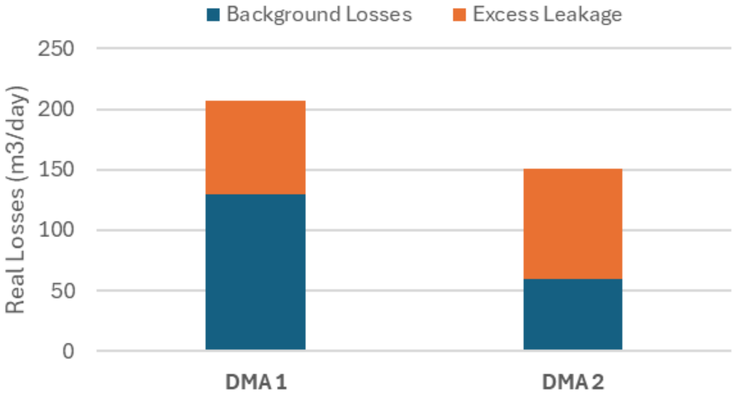


Figure 5-19 *DMA Excess Leakage Example.*

5.2.3.3 Economic Level of Leakage

Economic Level of Leakage (ELL) is a key concept for water utilities, used to determine the most cost-effective level at which to control leakage. ELL is widely recognized and documented in the water loss community; ELL has several interpretations and practical applications. This guide focuses specifically on applying ELL at DMA level and outlines a practical approach to doing so by disaggregating an Economic Leakage Target to DMAs.

This approach treats ELL as a value already established at Zone level. In this context, ELL acts as a leakage target that must be disaggregated to individual DMAs. This ensures that local DMA targets are consistent with the overall ELL strategy, promoting alignment across the entire system.

Table 5-21 provides a simple example of how a zone-level leakage target can be broken down. In this example, the leakage target is divided into two core components: Background Losses and the Excess Leakage. Together, these components make up the total ELL.

Table 5-21 Example Target for a Zone

Component	Zone
Background Losses (m^3/day)	1,278
Excess Leakage Target (m^3/day)	500
Total Leakage Target (m^3/day)	**1,778**

The method for disaggregation relies on establishing the level of Background Losses within each DMA, as this typically represents a large component of any leakage target. The core principle is that the sum of the DMA Background Losses should match the Background Losses portion included in the overall ELL. Table 5-22 illustrates this approach using the same Zone example, now broken down into ten DMAs.

Table 5-22 Background Losses ELL Example

DMA	Background Losses (m^3/day)	
DMA 1	130	Zone
DMA 2	60	
DMA 3	106	
DMA 4	76	
DMA 5	121	
DMA 6	212	
DMA 7	166	
DMA 8	136	
DMA 9	91	
DMA 10	182	
Total	**1278**	**1278**

Once Background Losses have been accounted for, the Zone Excess Leakage Target needs to be disaggregated across the DMAs contained within it. To distribute this fairly across DMAs, the Annual Real Losses in each DMA must be assessed and the Background Losses subtracted so the actual Excess Leakage for each DMA can be determined. This Excess Leakage should then be proportionally adjusted using a consistent method to ensure alignment with the Zone Excess Leakage Target. The outcome is a set of DMA-specific leakage targets which, when combined, match the total ELL comprising both background and excess leakage elements.

Table 5-23demonstrates this approach using the same ten-DMA Zone example. In this case, the Excess Leakage Target has been set at 60% of the total actual Excess Leakage across the DMAs. This ratio has been applied consistently to proportionally allocate the Excess Leakage Target among the ten DMAs. As can be seen, the result is that the Annual Real Loss Target for the individual DMAs aligns with the ELL for the Zone.

Table 5-23 Setting Annual Real Loss Targets for DMAs Example

DMA	Back-ground Losses (m³/day)	Annual Real Losses (m³/day)	Excess Leakage (m³/day)	Excess Leakage Target (m³/day)	Real Losses Target (m³/day)
DMA 1	130	207	77	46	176
DMA 2	60	151	92	55	114
DMA 3	106	150	44	26	132
DMA 4	76	195	119	71	147
DMA 5	121	175	54	32	153
DMA 6	212	345	133	79	291
DMA 7	166	225	59	35	201
DMA 8	136	330	194	116	252
DMA 9	91	117	26	16	106
DMA 10	182	222	40	24	206
Total	**1278**	**2117**	**838**	**500**	**1778**
Zone Excess Leakage Target			**500**	**60%**	

5.2.3.4 Entry & Exit Levels

Once annual real loss targets have been set for individual DMAs in line with the ELL, a mechanism must be established to ensure these targets are achieved through Active Leakage Control (ALC). This method relies on setting Entry and Exit Levels for individual DMAs.

The Entry Level represents the threshold that triggers leakage detection activities, while the Exit Level is the point to which leakage should be reduced as a result of these activities. By maintaining leakage within the range defined by the Entry and Exit Levels, the DMA leakage target can be consistently achieved, as illustrated in Figure 5-20.

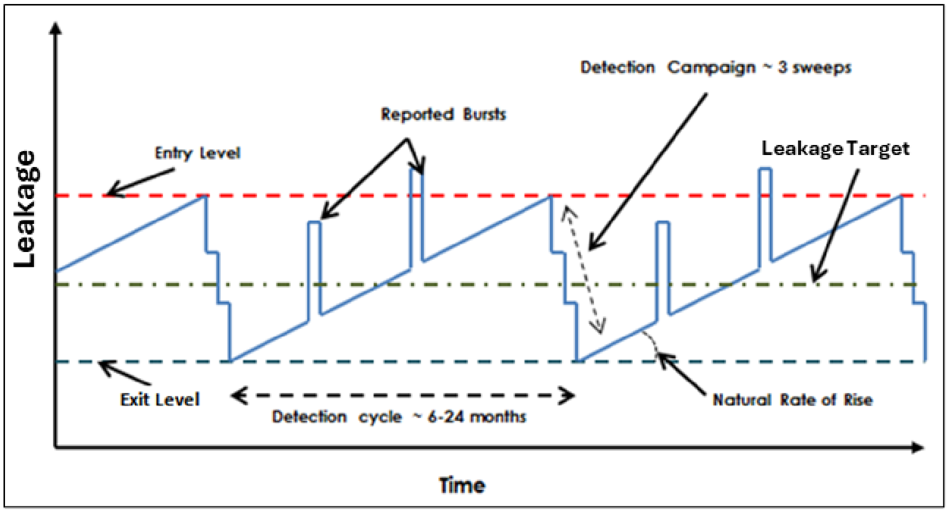


Figure 5-20 *DMA Entry & Exit Level Illustration.*

In the Figure 5-20, the solid line represents the 'stylized' leakage (or MNF) recorded on the DMA, showing a gradual increase over time as unreported leaks accumulate. Occasionally, reported leaks will occur and be repaired. When leakage (or MNF) reaches the Entry Level, leakage detection is initiated, and the nightline is reduced to the Exit Level, which may require several sweeps. The DMA leakage target, shown by the dashed line, is positioned midway between the Entry and Exit Levels. Figure 5-21 illustrates a real-world example of a DMA's leakage being maintained within the Entry and Exit Level 'train tracks' to achieve the leakage target.

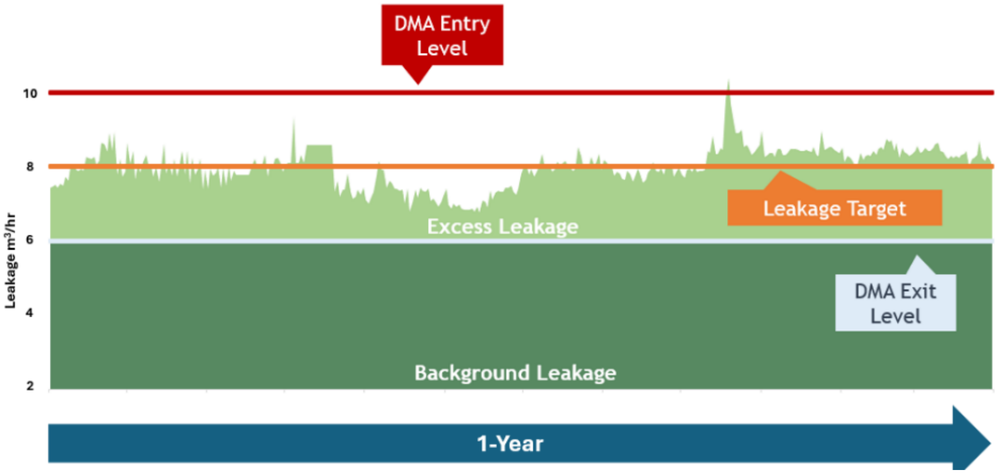


Figure 5-21 *Tracking DMA Leakage Illustration.*

Table 5-24 provides an example for two DMAs, showing the derived Exit Level, Leakage Target, and Entry Level.

Table 5-24 DMA Entry & Exit Levels Example

Component	DMA 1	DMA 2
Background Losses (m^3/day)	130	60
Annual Real Losses Target (m^3/day)	176	114
Night Day Factor	22.5	23.5
Exit Level (m^3/hr)	5.77	2.53
Leakage Target (m^3/hr)	7.80	4.86
Entry Level (m^3/hr)	9.84	7.19

Referring to Table 5-24, to derive the Exit Level, Leakage Target, and Entry Level for a DMA the following applies:

- The Exit Level for a DMA should correspond to either the Minimum Achieved Leakage or the Minimum Achievable Leakage, which represents the assessed Background Leakage for that DMA. It is equivalent to the Background Losses for a DMA divided by the Night Day Factor.
- The Leakage Target is equivalent to the Annual Real Loss Target for the DMA divided by the Night-Day Factor.

- The Entry Level is calculated by adding the difference between the Exit Level and the Leakage Target to the Leakage Target, ensuring that the Leakage Target sits midway between the Entry and Exit Levels.

5.2.3.5 Economic Volume Index

The Economic Volume Index (EVI) method is based on carrying out active leakage control interventions in a DMA at an economic level, balancing the cost of water loss against the cost of leakage detection. An intervention is triggered when the cost of a leakage detection campaign equals the value of the water lost since the previous detection sweep. The campaign reduces leakage to the exit level.

The EVI method uses the following parameters for the DMA:

- The Exit Level
- The Marginal Value of water in that DMA
- The Leak Detection Cost to return the leakage to exit level
- The Natural Rate of Rise (to predict interventions)

Figure 5-22 illustrates the EVI method. Following a leak detection sweep that returns leakage to the exit level, leakage is then allowed to increase until the value of the water lost, calculated as the volume lost (m^3) multiplied by the marginal cost of water (£/m^3), equals the cost of the leakage detection campaign. This point is referred to as the *Entry Volume* in the illustration and triggers an intervention.

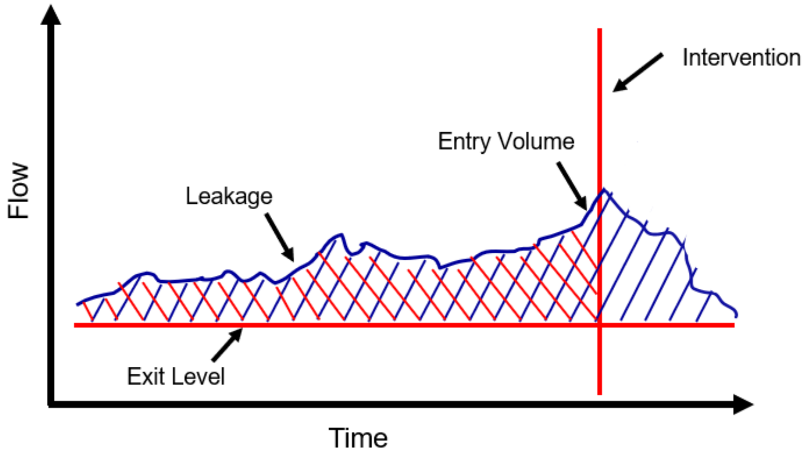


Figure 5-22 *DMA Economic Entry Volume Illustration.*

In some cases, where leakage rises slowly over a long period, the leakage detection campaign may be undertaken before the leakage reaches the entry level referred to in the previous section. In other cases, where leakage increases rapidly, the detection campaign may be carried out when leakage exceeds the entry level. Following an intervention, leakage is reduced back to the exit level, and the accumulated water loss volume is reset, with tracking recommencing until the entry volume is reached once again.

5.2.4 MONITORING LEAKAGE LEVELS

This section emphasizes the importance of monitoring leakage levels at the DMA level. It explores key concepts such as DMA availability and operability, explaining their impact on leakage monitoring. Additionally, it presents practical approaches for tracking DMA MNFs and leakage, while addressing potential challenges in the process.

5.2.4.1 DMA Availability

DMA availability validates the inlet and outlet meters that contribute to the DMA net flow calculation. When a DMA is classified as available, it provides confidence that the net flow data used to derive the MNF and TDF is reliable. For a DMA to be classified as available on any given day, all inlet and outlet meters must have valid flow data, and the net flow must be positive, resulting in a valid MNF and TDF. Figure 5-23 illustrates an example of a DMA with two inlet meters and one outlet meter.

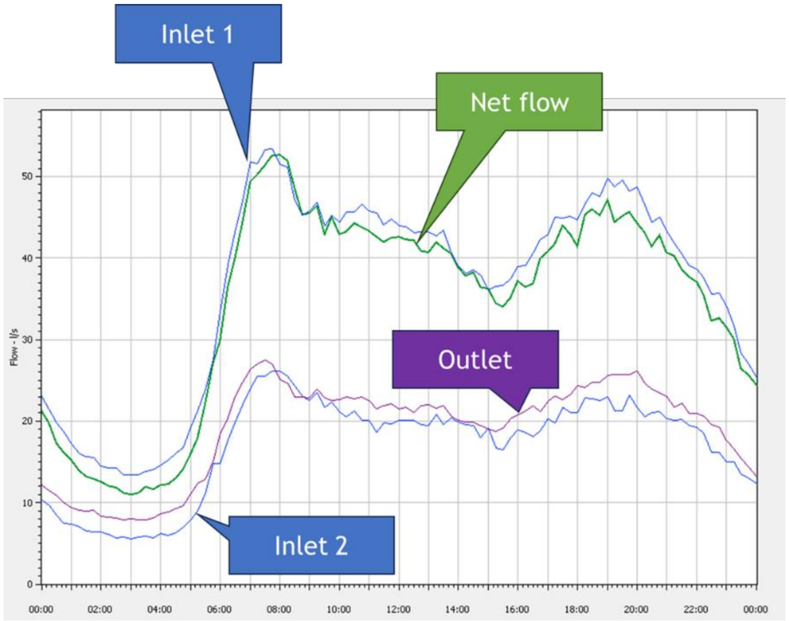
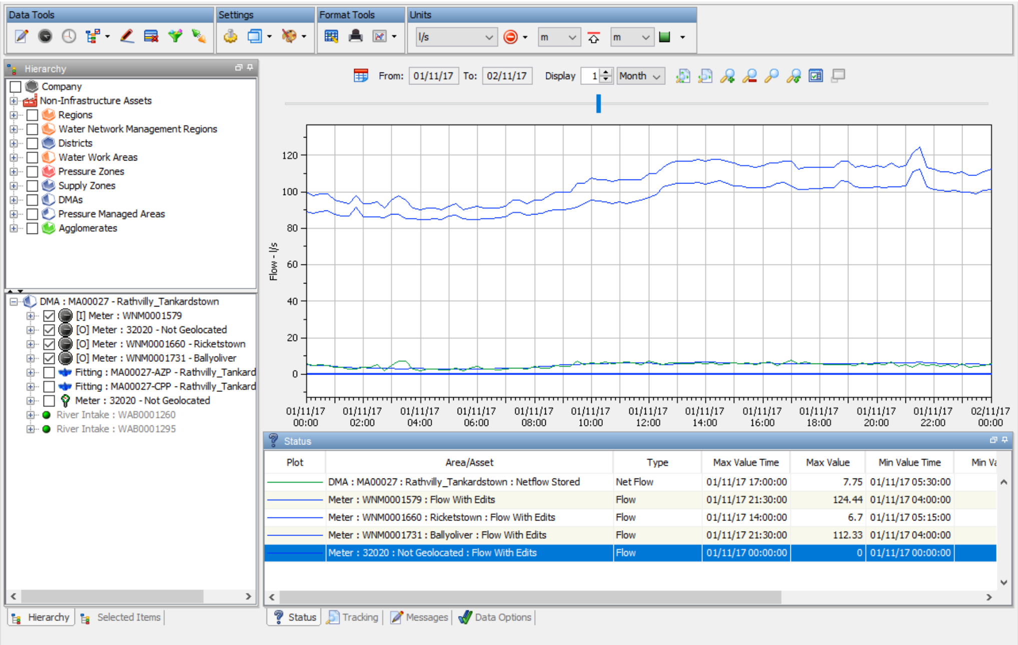


Figure 5-23 *DMA Availability Illustration.*

In the case of Figure 5-23, all meters have valid flow data for the entire day, and the net flow is positive, meaning that both the MNF and TDF are valid, and the DMA is classified as available.

For more advanced analysis, DMA availability can be extended to include valid daily AZP pressure data, which is essential for deriving both the AZNP and the Night-Day Factor (NDF) on a daily basis. When a DMA is fully available, it enables leakage levels to be monitored and targeted based on actual flow and pressure measurements.

Common causes of a DMA being unavailable include missing inlet and outlet meter data or flows that remain at zero (flatlining). Figure 5-24 shows a DMA that has one inlet meter and three outlets, but one of the outlet meters is flatlining causing the DMA to be unavailable.



Units: l/s, m, m

From: 01/11/17 To: 02/11/17 Display 1 Month

Plot	Area/Asset	Type	Max Value Time	Max Value	Min Value Time	Min Va
─	DMA : MA00027 : Rathvilly_Tankardstown : Netflow Stored	Net Flow	01/11/17 17:00:00	7.75	01/11/17 05:30:00	
─	Meter : WNM0001579 : Flow With Edits	Flow	01/11/17 21:30:00	124.44	01/11/17 04:00:00	
─	Meter : WNM0001660 : Ricketstown : Flow With Edits	Flow	01/11/17 14:00:00	6.7	01/11/17 05:15:00	
─	Meter : WNM0001731 : Ballyoliver : Flow With Edits	Flow	01/11/17 21:30:00	112.33	01/11/17 04:00:00	
─	Meter : 32020 : Not Geolocated : Flow With Edits	Flow	01/11/17 00:00:00	0	01/11/17 00:00:00	

Figure 5-24 *Example of Unavailable DMA (source: Crowder Consulting).*

In some cases, data may be manually invalidated, resulting in unavailability. A DMA may also be unavailable if, despite all meters providing data, the resulting net flow contains frequent negative values, which indicates a data or hydraulic issue. Unavailable DMAs should still be targeted regularly, with leakage estimated using historic data.

5.2.4.2 Monitoring DMA Minimum Night Flows

It is important to monitor DMA MNFs daily to quickly identify potential new leaks. A sudden rise in MNF often indicates that a leak developed the previous day. It is possible to monitor several types of MNF at the same time, for example, Fixed, Rolling, and Actual, to provide the best possible indication of a new leak breakout.

Typically, loggers on DMA inlet and outlet meters are configured to report data just after 06:00, allowing MNFs to be automatically calculated for all DMAs and enabling analysts to generate reports and look at trends that highlight sudden increases.

Figure 5-25 illustrates a 30-day MNF trend for a DMA, showing two distinct increases in MNF over one month, both of which are indicative of potential leak breakouts. Not all MNF increases indicate a leak. Some increases result from customer usage, short-term network events, or seasonal temperature changes.

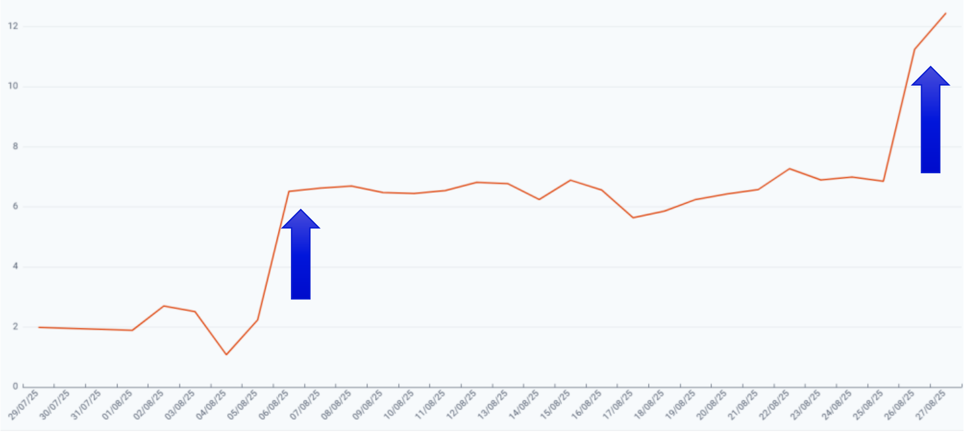


Figure 5-25 *Example DMA MNF Trend.*

The process of monitoring MNFs reduces the need for manual inspection of flow graphs for every DMA. However, any increase in MNF should still be reviewed against the flow data to confirm it is valid. One key limitation in monitoring MNFs is the delay in detection: confirmation of a burst is typically available only the following morning, once the MNF data has been processed.

Figure 5-26 shows the net flow graph for the same DMA that had an increase in MNF. Two distinct rises in flow can be observed, confirming the potential leak breakout within the DMA.

Figure 5-26 *Example DMA Net Flow Graph.*

5.2.4.3 Monitoring DMA Leakage

The night-flow water balance is used to calculate leakage in DMAs where a valid MNF and reliable night use allowances are available. The best practice is to derive and monitor DMA leakage using the night-flow balance method on a daily and weekly basis. More details on calculating DMA night-flow balance and other leakage estimation methods can be found in Section 4.2.

The NDF is applied to convert night leakage to daily leakage, as described in Section 4.2.4.

Figure 5-27 illustrates how leakage varies on a weekly basis over a year. Increases may occur during cold periods, when bursts are more likely to develop, or during warm periods if night-use allowances are not adjusted to reflect seasonal consumption. The chart also highlights the importance of considering all components of the night-flow water balance for a DMA, rather than focusing only on the MNF. Some of the increases in DMA MNF are actually the result of higher night use, which needs to be correctly accounted for, especially for large users.

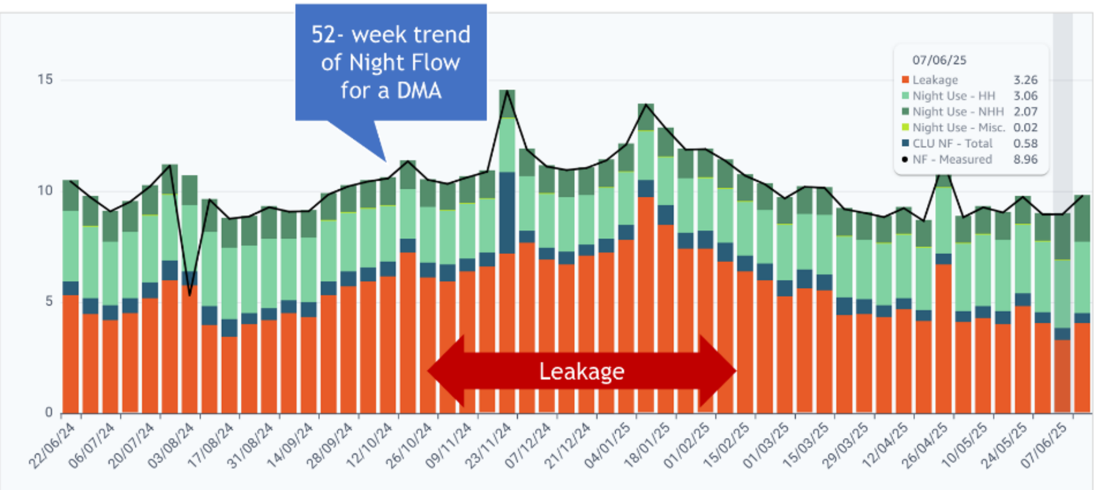


Figure 5-27 *Example DMA Night Flow Water Balance Trend (source: Crowder Consulting).*

Figure 5-28 presents the daily leakage trend for the same DMA after applying the NDF adjustment. The results clearly show a rise in leakage during the cold period, while the warm period suggests a possible overestimation of leakage.

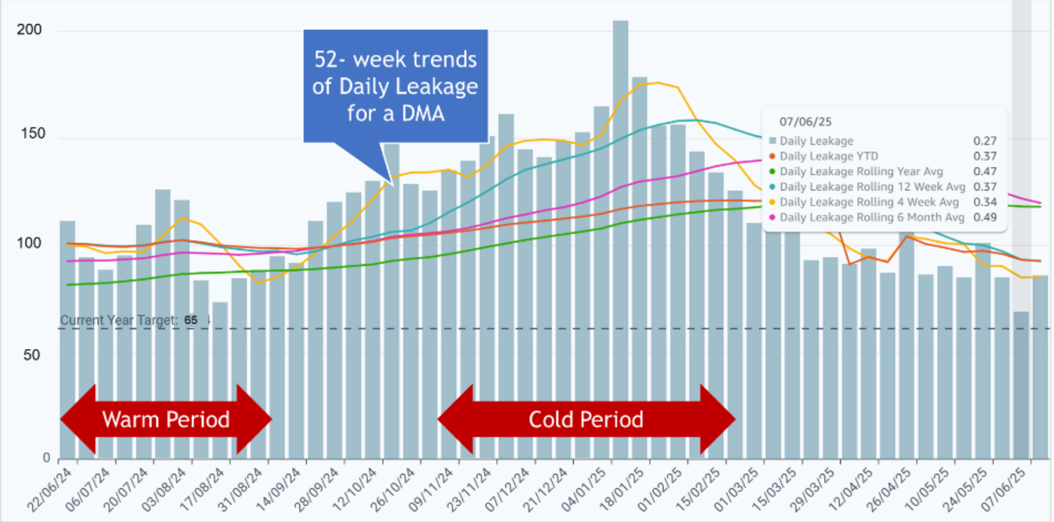


Figure 5-28 *Example DMA Daily Leakage Trend (source: Crowder Consulting).*

In addition to monitoring individual DMAs, daily leakage should be aggregated to higher-level areas such as zones and the overall water utility. Monitoring at these broader levels provides greater visibility and transparency, helping to confirm that overall DMA leakage is trending in the right direction and that leakage targets are on track to be achieved.

Figure 5-29 presents the daily leakage trend over a two-year period for the aggregated DMAs within a zone. The results show a significant leakage breakout across the DMAs, which was subsequently addressed to bring the zone back on target.

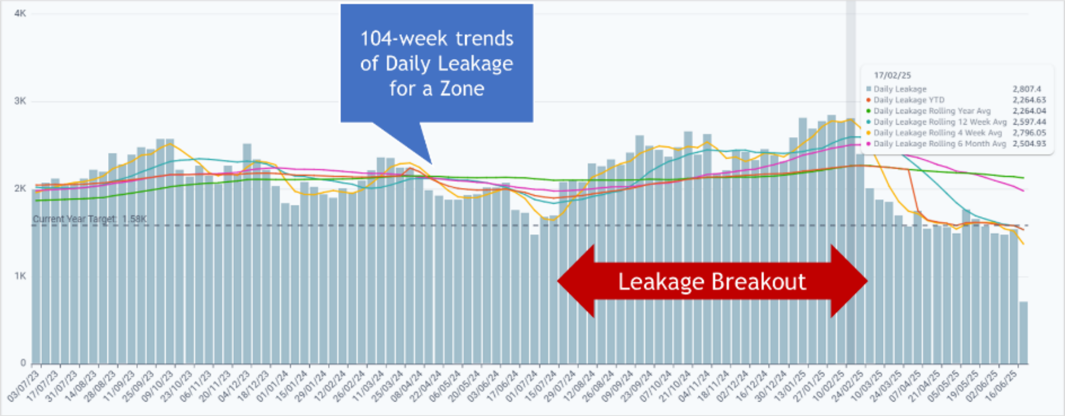


Figure 5-29 *Example Zone Daily Leakage Trend Aggregated from DMAs (source: Crowder Consulting).*

5.2.4.4 DMA Operability

DMA operability is assessed using Residual check. A DMA is classified as operable when its Normalized Residual is within ±20% of TDF. Non-operable DMAs should not be targeted for leakage detection until the data issue is resolved.

Figure 5-30 shows a comparison of the results from the two water balance methods, night flow and daily flow. This comparison is considered good practice because it helps identify data issues within a DMA. When conducted with reliable data, this comparison can also give insight into the levels of Real and Apparent losses in a DMA.

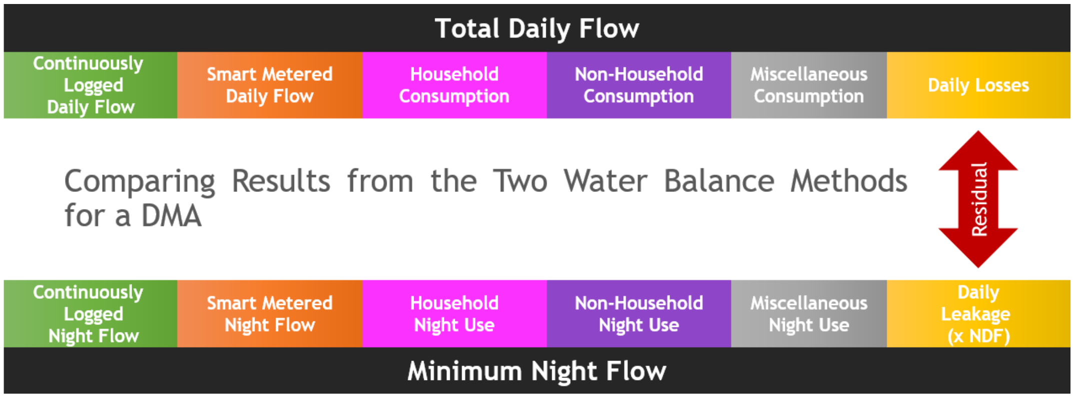


Figure 5-30 *DMA Operability Assessment (source: Crowder Consulting).*

Typically, for a DMA to be classified as operable, the Residual should be within ±20% of the Total Daily Flow. The Residual is defined as the difference between Daily Losses derived from the TDF and Daily Leakage derived from the MNF multiplied by the Night-Day Factor. A Residual closer to zero indicates better agreement between the two methods. Simpler operability checks include identifying cases where Daily Losses or Daily Leakage are calculated as negative values, which would indicate that the DMA is non-operable.

5.2.4.5 *Typical DMA Issues*

When a DMA is operable, it provides confidence that teams are targeting actual leakage during DMA detection activities. A non-operable DMA indicates an underlying issue, which may be caused by incorrect baseline data or by a physical issue in the network affecting flow or pressure. To investigate a non-operable DMA, it is important to examine all components of the leakage calculation to identify what may be incorrect and determine the necessary actions to resolve these issues.

Targeting a non-operable DMA for leakage detection is ineffective because the calculated leakage is likely to be inaccurate. Therefore, the best practice is to resolve DMA operability issues first, ensuring data reliability before undertaking leakage detection activities.

Figure 5-31 provides some typical issues that would cause a DMA to become non-operable. Any one of these issues can make the leakage calculation inaccurate.

Figure 5-31 *Typical DMA Operability Issues.*

Some examples of DMAs with operability and data issues are provided in the Appendix F – Practical examples of DMA data issues.

5.2.5 CRITERIA FOR DMA PRIORITIZATION

5.2.5.1 *Using Minimum Night Flow*

Reactive DMA leakage management involves daily monitoring of MNFs to detect any significant increases. By responding quickly to a rise in MNF, leaks can be located and repaired before they escalate. This reduces burst run times and minimizes the leakage impact.

As best practice, the daily MNFs for each DMA should be compared with their MNFs for the previous day (deducting any continuously logged night flow). A significant difference between the two may indicate a potential breakout. In addition, the daily MNFs for DMAs should also be compared with the previous week, as a breakout could have occurred and still be ongoing, which is something that a day-to-day comparison alone might not detect.

This difference, whether compared with the previous day or the previous week, is known as the Night Flow Change, and its daily monitoring is a fundamental practice in DMA leakage management. DMAs should be ranked by their Night Flow Change, allowing those with the most significant breakouts, and therefore requiring investigation, to be quickly identified.

Using MNFs for leakage management is a useful starting point to prioritize DMAs, but it has its limitations. The best practice is to base DMA leakage estimates on a night-flow water balance, which should then be used to prioritize DMAs for active leakage control (see Section 5.2.4.3).

Table 5-25 presents an example of 10 DMAs, where the MNF for the current day is compared against both the previous day and the previous week. For each DMA, the larger of the two differences (highlighted in red) is taken as the Night Flow Change. These values are then ranked in descending order to highlight the DMAs with the greatest Night Flow Changes.

Table 5-25 DMA Night Flow Change Monitoring Example

DMA	Night Flow Change (m³/hr)	MNF Today (m³/hr)	MNF Prev Day (m³/hr)	MNF Prev Week (m³/hr)	Prev Day Diff (m³/hr)	Prev Week Diff (m³/hr)
DMA 5	6.0	16.3	14.2	10.2	2.0	6.0
DMA 4	2.1	7.0	5.0	6.3	2.1	0.7
DMA 3	2.0	3.4	3.0	1.4	0.4	2.0
DMA 8	1.6	12.2	10.6	11.2	1.6	1.0
DMA 7	0.9	11.4	11.5	10.5	-0.1	0.9
DMA 10	0.8	4.9	4.1	4.3	0.8	0.5
DMA 1	0.5	11.5	11.5	11.0	0.0	0.5
DMA 6	0.5	4.1	3.8	3.6	0.3	0.5
DMA 9	0.4	4.4	4.1	4.0	0.4	0.4
DMA 2	-0.3	5.6	6.0	5.8	-0.5	-0.3

DMA MNFs can also be reviewed weekly against an MNF target to identify gradual increases over time that need to be recovered. Ranking DMAs by their variance from target helps prioritize leakage detection activities, which are particularly valuable during periods with fewer burst events, when the focus shifts to driving down DMA leakage.

Figure 5-32 shows an example of a DMA, illustrating how leakage is managed through MNF monitoring.

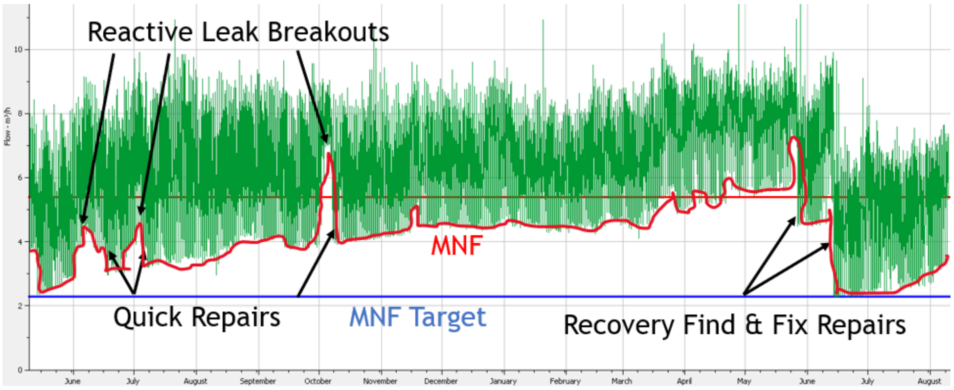


Figure 5-32 *DMA MNF Leakage Management Example.*

5.2.5.2 Using DMA Leakage

The prioritization process begins with the DMA MNF, from which continuously logged consumption and night-use allowances are deducted. A robust night-use model should be applied, considering seasonal variation and the different patterns of night-time consumption across user types. To target leakage effectively, DMAs must be both available and operable, making it essential that leakage calculations are accurate. This, in turn, drives improvements in data quality and reliability.

Each DMA should have a leakage target that aligns with company and zonal targets. By managing DMAs to achieve their individual leakage targets, higher-level performance commitments can also be met. Each DMA should have an exit level, either the lowest level of leakage previously achieved or the minimum achievable level. In addition, each DMA can have an entry level that triggers when to start a leakage detection campaign.

The exit level represents background leakage in the DMA, and any leakage above this level is considered excess leakage, which can be targeted through active detection and find-and-fix activities.

Figure 5-33 shows a chart illustrating how leakage is calculated from the MNF. In this example, the red bar represents leakage, which is the largest component of the night flow.

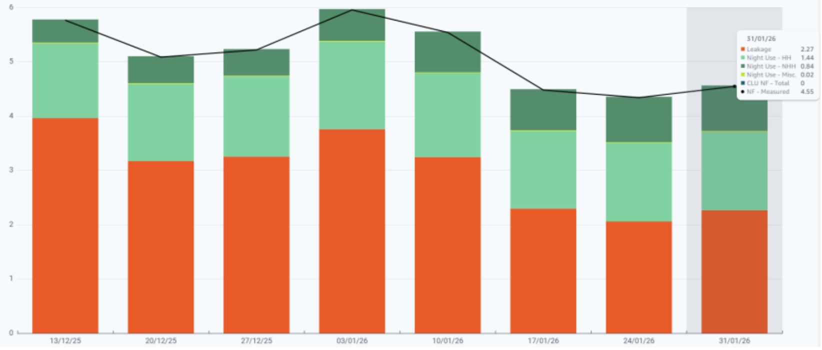


Figure 5-33 *DMA Night Flow Leakage Example (source: Crowder Consulting).*

Figure 5-34 shows a chart for the same DMA, illustrating how calculated leakage can be tracked against the leakage target, as well as the entry and exit levels.

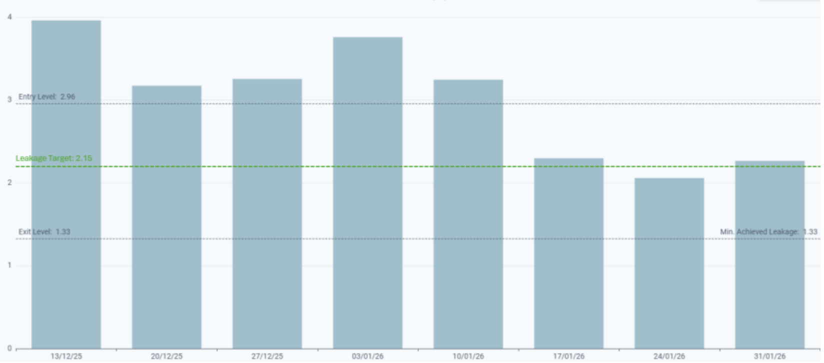


Figure 5-34 *DMA Leakage Target, Entry & Exit Level Example (source: Crowder Consulting).*

Figure 5-35 shows a chart for the same DMA, illustrating how leakage can be separated into background and excess components. In this example, the red bar represents excess leakage, which is the largest component of total leakage in the DMA.

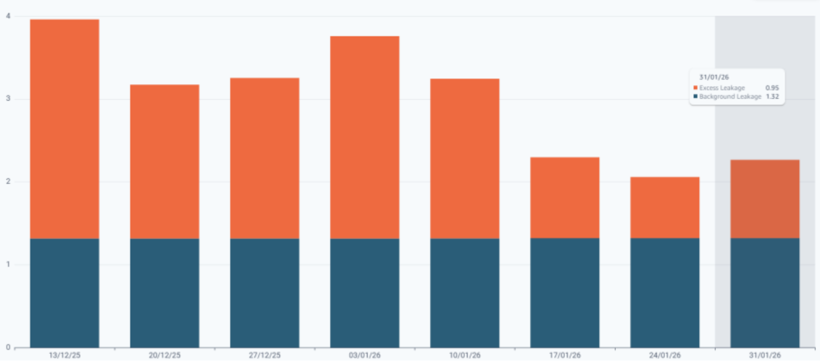
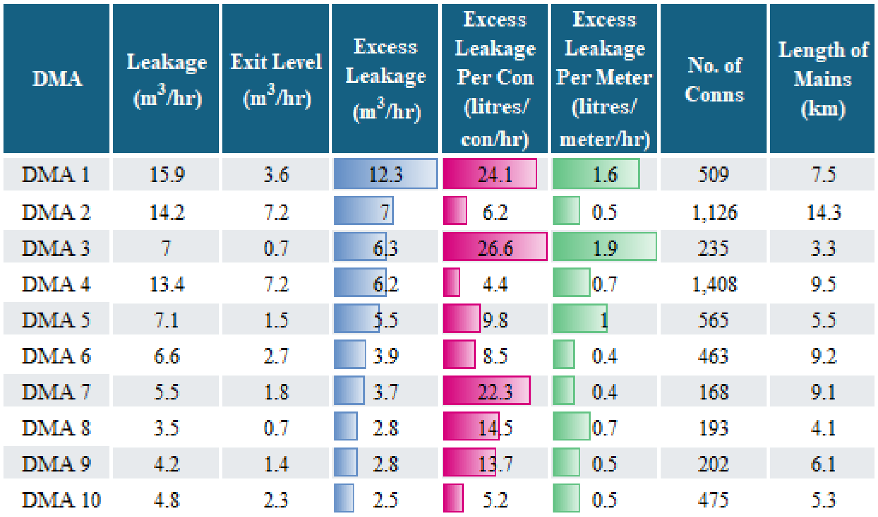


Figure 5-35 *DMA Excess Leakage Example (source: Crowder Consulting).*

DMA prioritization should be based on excess leakage, assessed either by its absolute volume or by normalizing the excess to drive efficiency and ensure effective allocation of resources. Table 5-26provides an example of ten DMAs prioritized by excess leakage. If ranked by volume alone, DMA 1 would appear at the top of the list. However, DMA 3, although showing a lower overall volume, appears proportionally leakier, ranking first when assessed by excess leakage per connection and per length of main. These considerations highlight the importance of how excess leakage is measured and prioritized, and they provide a useful basis for discussion.

Table 5-26 DMAs Prioritized by Excess Leakage



DMA	Leakage (m^3/hr)	Exit Level (m^3/hr)	Excess Leakage (m^3/hr)	Excess Leakage Per Con (litres/ con/hr)	Excess Leakage Per Meter (litres/ meter/hr)	No. of Conns	Length of Mains (km)
DMA 1	15.9	3.6	12.3	24.1	1.6	509	7.5
DMA 2	14.2	7.2	7	6.2	0.5	1,126	14.3
DMA 3	7	0.7	6.3	26.6	1.9	235	3.3
DMA 4	13.4	7.2	6.2	4.4	0.7	1,408	9.5
DMA 5	7.1	1.5	5.5	9.8	1	565	5.5
DMA 6	6.6	2.7	3.9	8.5	0.4	463	9.2
DMA 7	5.5	1.8	3.7	22.3	0.4	168	9.1
DMA 8	3.5	0.7	2.8	14.5	0.7	193	4.1
DMA 9	4.2	1.4	2.8	13.7	0.5	202	6.1
DMA 10	4.8	2.3	2.5	5.2	0.5	475	5.3

Not all DMAs behave in the same way, and prioritization is only the first step in effective targeting. Some DMAs may appear on the list frequently due to recurring bursts that must be managed back down to the exit level. Others may remain near the top for longer periods, with leaks that are difficult to locate and requiring greater effort to reduce. A key outcome of effective leakage management is lowering the DMA exit level to a value below what was previously achieved. This pushes the boundaries of leakage management and demonstrates the real value of operating with DMAs.

5.2.6 KPIS FOR LEAKAGE CONTROL ACTIVITIES

5.2.6.1 Non-Revenue Water

Non-Revenue Water (NRW) is often expressed as a percentage of the Total Daily Flow (TDF). However, this metric can be misleading because several factors can lower the NRW percentage without reducing actual water losses. For example, in DMAs with high consumption per connection, such as highly urbanized regions with high-rise buildings, each connection uses significantly more water than connections in DMAs with low-rise buildings. Expressing NRW as a percentage can therefore indicate lower water losses where none exist.

Table 5-27presents ten example DMAs ranked by their NRW percentage. These same DMAs will be used to assess other leakage performance indicators and their effect on rankings.

Table 5-27 DMAs Ranked by NRW%

DMA	Rank	TDF (m^3/day)	Consumption (m^3/day)	NRW (m^3/day)	NRW %
DMA 1	1	264	88	176	67%
DMA 2	2	552	193	359	65%
DMA 3	3	240	88	152	63%
DMA 4	4	216	88	128	59%
DMA 5	5	360	150	210	58%
DMA 6	6	336	146	190	57%
DMA 7	7	336	158	178	53%
DMA 8	8	720	350	370	51%
DMA 9	9	312	155	157	50%
DMA 10	10	1080	638	442	41%

5.2.6.2 Infrastructure Leakage Index

A water balance is conducted for each DMA to determine the average level of Real Losses. To calculate the DMA-specific Infrastructure Leakage Index (ILI), the Real Losses are divided by the Unavoidable Annual Real Losses (UARL) within the DMA. ILI is a simple and effective performance indicator that can be applied to DMAs once Real Losses are quantified. It provides a more accurate representation of leakage performance than percentage-based metrics and allows for direct comparisons between different DMAs or areas. A full description of ILI is provided in Section 5.2.3.1. When applying UARL to smaller DMAs, a system correction factor should be used.

Table 5-28 presents the same ten DMAs, with Real Losses derived and ranked according to their ILI. As shown, DMA 1 has the worst performance and DMA 7 has the best. DMA 10, which recorded the lowest NRW percentage, has the third-worst ILI.

Table 5-28 Example DMAs Ranked by ILI

DMA	Rank	Real Losses (m^3/day)	UARL (m^3/day)	ILI
DMA 1	1	164	18	9.0
DMA 2	2	352	53	6.5
DMA 3	7	130	29	4.5
DMA 4	5	122	21	5.8
DMA 5	4	174	31	5.9
DMA 6	6	98	20	5.0
DMA 7	10	110	43	2.6
DMA 8	8	323	74	4.4
DMA 9	9	152	35	4.4
DMA 10	3	365	61	6.4

5.2.6.3 Normalized DMA Leakage Level

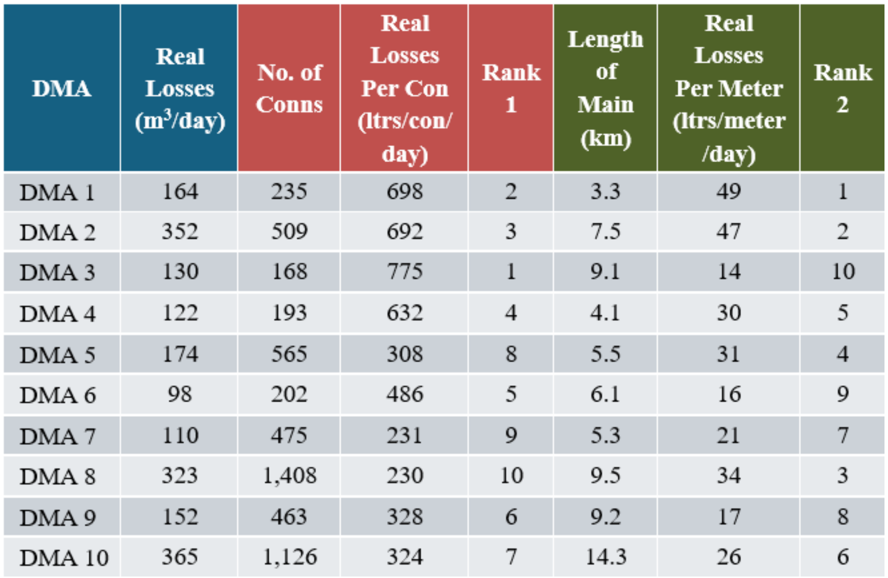
The recommended way to express Real Losses in a DMA is to use a normalized value. This allows direct comparison across DMAs without the influence of variations in consumption. These normalized values include:

- Real Losses per connection (liters/connection/day or hour)
- Real Losses per length of main (liters/meter of main/day or hour)

Normalized DMA leakage levels provide a simple and effective performance indicator that can be applied once Real Losses are quantified.

Table 5-29 presents the same ten DMAs ranked according to Real Losses per connection and Real Losses per length of main. When ranking by Real Losses per connection, DMA 3 is the worst performing DMA, while DMA 8 ranks the best. When ranking by Real Losses per length of mains, DMA 1 is the worst performing DMA, while DMA 3 ranks the best.

Table 5-29 DMAs Ranked by Real Losses Per Connection & Per Meter



DMA	Real Losses (m^3/day)	No. of Conns	Real Losses Per Con (ltrs/con/day)	Rank 1	Length of Main (km)	Real Losses Per Meter (ltrs/meter/day)	Rank 2
DMA 1	164	235	698	2	3.3	49	1
DMA 2	352	509	692	3	7.5	47	2
DMA 3	130	168	775	1	9.1	14	10
DMA 4	122	193	632	4	4.1	30	5
DMA 5	174	565	308	8	5.5	31	4
DMA 6	98	202	486	5	6.1	16	9
DMA 7	110	475	231	9	5.3	21	7
DMA 8	323	1,408	230	10	9.5	34	3
DMA 9	152	463	328	6	9.2	17	8
DMA 10	365	1,126	324	7	14.3	26	6

As the examples demonstrate, results can vary depending on the characteristics of each DMA. For example, in urbanized DMAs where connections are denser, normalizing Real Losses per connection is more appropriate. In rural DMAs with fewer connections and longer mains, the per-kilometer method provides a more accurate representation. Therefore, the best practice is to apply both methods to enable the most reliable comparisons.

5.2.6.4 Combined Real Losses Indicator

The choice between normalizing Real Losses per connection or per length of main can vary by context. The Combined Real Loss Index (CRLI) addresses this by providing a density-independent leakage performance indicator. It combines two commonly used metrics — liters per connection per day and liters per meter of main per day — into a single index using their geometric mean. This allows DMAs with differing characteristics to be compared on a consistent basis. The recommended way to express Real Losses in a DMA using the CRLI is Real Losses per size of distribution network. CRLI is calculated using the following formula:

$$CRLI = (\text{Real Losses per connection x Real Losses per length of main})^{1/2}$$

Table 5-30 presents the same ten DMAs ranked according to CRLI. As shown, DMA 1 is the poorest performer, while DMA 7 ranks the best. Unlike traditional indicators, CRLI enables fairer comparisons between urban and rural systems by reducing sensitivity to network density. It is therefore the most reliable measure of leakage performance at the DMA level. CRLI is simple to calculate, technically robust, and applicable at multiple scales — from individual DMAs and zones to regional and national levels.

Table 5-30 Example DMAs Ranked by CRLI

DMA	Rank	Real Losses (m^3/day)	Real Losses Per Conn (litres/conn/day)	Real Losses Per Meter (litres/meter/day)	CRLI (litres/day/size of network)
DMA 1	1	164	698	49	185
DMA 2	2	352	692	47	180
DMA 3	4	130	775	14	105
DMA 4	3	122	632	30	137
DMA 5	5	174	308	31	98
DMA 6	8	98	486	16	88
DMA 7	10	110	231	21	69
DMA 8	7	323	230	34	89
DMA 9	9	152	328	17	74
DMA 10	6	365	324	26	91

REFERENCES

Lambert A. O., Brown T. G., Takizawa M. and Weimer D. (2000). A Review of Performance Indicators for Real Losses from Water Supply Systems.

Lambert A. O., Trow S. and Myers S. (1998). *Managing Leakage: Economic and Technical Issues*. Financial Times, London, UK. ISBN 84083 011 5.

Morrison J., Tooms S., Rogers D. and others (2024). *Guidance Notes for DMA Management*. IWA Water Loss Specialist Group.

Parker J. (2011). *Managing Leakage 2011, Report Ref: 10/WM/08/42, Leakage Estimation & Analysis (Report 4)*. UK Water Industry Research (UKWIR), London, UK.

Pearson D. and Donnelly A. (2019). *Standard Definitions for Water Losses*. IWA Publishing, London, UK.

WRC (1994). *UK Water Industry: Managing Leakage, Interpreting Measured Night Flows (Report E)*. Water Research Centre, Swindon, UK.

Wyatt A. (2024). Overview of the Combined Real Loss Index (CRLI).

Leakssuite Library (n.d.). *Leaks Suite Library*. https://www.leakssuitelibrary.com (accessed 18 February 2026).

6 DMA DATA MANAGEMENT SYSTEMS

A. Bojko[1], T. Crowder[2], G. Féry[3], C. Henriquez[4], F. van der Hulst[5], T. Kressin[6]

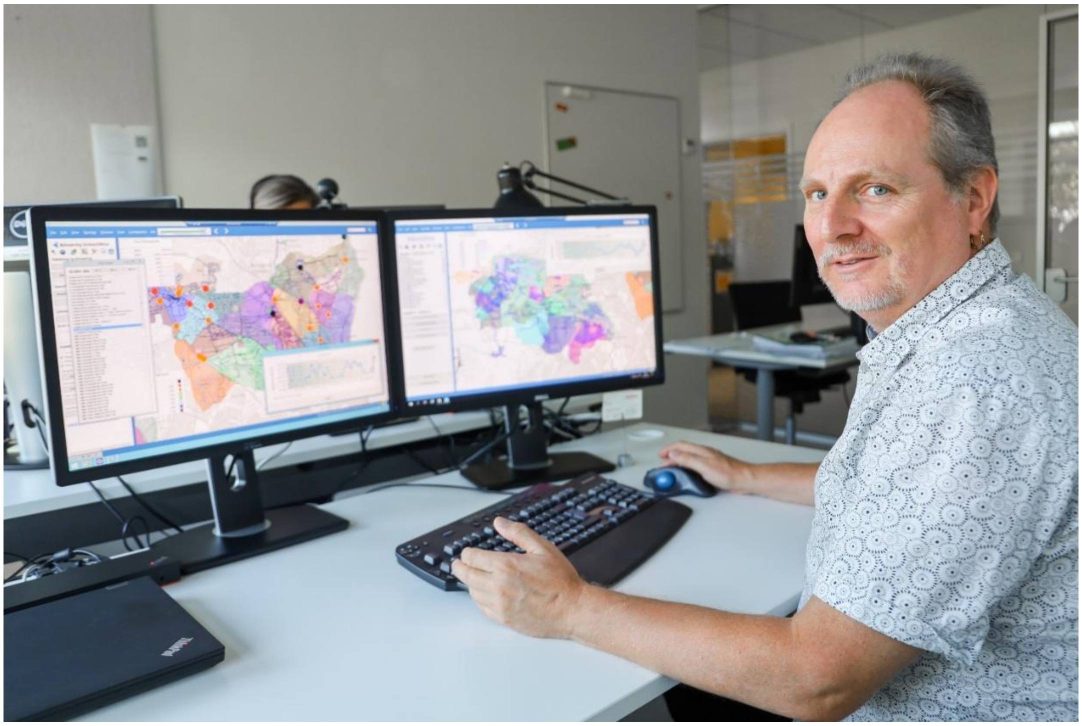
[1] Independent, French Guyana; [2]Crowder Consulting, UK; [3]Independent, Switzerland; [4]Aguas Antofagasta, Chile; [5]HULO, Netherlands; [6] Gutermann, Germany

ABSTRACT

Effective data management is the foundation of modern water Utility operations. Without a robust Data Management System, Utilities risk inefficiencies, higher leakage, and missed opportunities for cost savings. This chapter shares important principles which you can build on to help you to select, implement, and optimize data management systems that deliver measurable improvements in performance, sustainability, and customer service.

This chapter offers practical guidance on DMS for DMAs and their role in reducing Non-Revenue Water and improving operational efficiency. It explains how Utilities can turn raw data into actionable insights through integrated platforms and advanced analytics.

Additionally, Appendix G describes the real life example of the Utility in Denmark that has implemented the fully digitized, data-driven approach to diurnal water balance calculation and the continuous monitoring of water loss fluctuations and night flows within District Metered Areas (DMAs) and full coverage of smart meters.



NIRAS analyzing and comparing DMA Data in Denmark

6.1 DMS ARCHITECTURE AND FUNCTIONAL COMPONENTS

The minimum level of data required to perform a basic assessment of DMA performance may consist only of monthly inlet bulk flow meter readings taken manually, and monthly billed consumption volumes from registered customers. While such limited datasets allow for a coarse water balance and very high-level NRW estimation, they provide insufficient resolution for meaningful operational analysis.

In practice, Utilities increasingly collect a broader range of data streams, typically transmitted from the physical network to the telemetry or SCADA system on a daily—or even almost continuous—basis. These include, but are not limited to:

- DMA inlet and outlet flow
- Pressures at DMA boundaries (inlets/outlets)
- Internal DMA pressure (including average and critical points)
- Valve status, settings, and operational changes
- Customer consumption data (monthly, daily, or smart-meter intervals)
- Leak detection and repair
- Network construction or maintenance activities
- Customer complaints related to service level, supply, or pressure
- Water quality measurements.

As most water Utilities operate multiple DMAs, the overall volume of data grows rapidly, becoming difficult—if not impossible—to manage and analyze manually. This is where DMA DMS becomes essential.

Adding to the complexity, a DMA DMS often needs to interface with multiple corporate systems, such as the Customer Information System (CIS), Work Order/CMMS system, GIS, Asset Management System, and financial or billing systems. Effective data integration across these platforms enables consistent analysis, supports operational decision-making, and creates a single, authoritative view of network performance.

[redacted]

[redacted]

DMA

Properties

Total	1215
House	1153
Non-H[illegible]	62

Consumptions

Total (m³/d)	394.85
Household (m³/d)	343.14
Non-Household (m³/d)	51.71

Characteristics

Area Classification	Semi-Rural
Highest Connection Height (m)	130.85
Average Connection Height (m)	76.83
Lowest Connection Height (m)	65.90
Mains Length (km)	18.71
Background Losses (m³/d)	33.18
AZNP (m)	45.46

Figure 6-1 *Example of a dashboard of DMA Data Management System (source: Crowder Consulting).*

There are several components involved in managing DMA-related data:

- Data Storage
- Data Processing
- Data Analysis
- Decision Making
- Actions
- Feedback and Improvement

These components—and their relevance for NRW reduction and leakage management—are explored in detail in the following sections of this chapter, a typical architecture of a DMA Data Management System includes the following core layers (Figure 6-2):

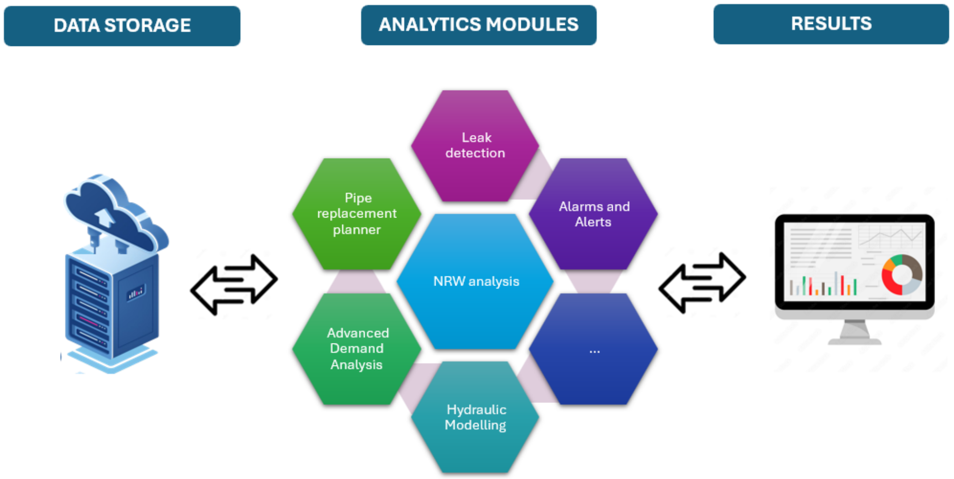


Figure 6-2 *Typical components of DMA Data Management Systems.*

With modern technologies and continuous innovation, many of the processes described above can be highly automated and executed at high speed. However, each Utility must carefully decide what level of technology and automation is appropriate for its current context. In practical terms, this means assessing whether the organization has the "infrastructure" (systems, data, staff skills, procedures) to operate a highly advanced, fully automated Data Management System, or whether a simpler, more manual approach (for example, well-structured Excel spreadsheets) is more appropriate given the Utility's current data quality and organizational capacity.

There are many turnkey analytical platforms on the market that claim to support all stages of DMA data management, but they usually involve significant costs, integration requirements, and complexity. Each Utility should therefore define its own functional needs and, most importantly, its level of readiness in terms of budget, data quality, IT environment, and human resources. Main criteria in DMS selection gives practical guidance on this process.

6.1.1 DATA STORAGE

With the large volumes of data generated by each DMA on a regular basis, data storage solutions must consider the physical storage infrastructure (offline devices, servers, backup systems, and online or cloud platforms), the selected database types, and the associated management practices (type of database, archiving, metadata).

HELPFUL TIPS

SCADA systems are mostly designed for real-time control and visualization, and often do not include data storage solutions (data historian), therefore additional costs may apply, including software licenses, data historian subscriptions, storage infrastructure, and specialist staff.

The technical design of data storage systems falls outside the scope of this book and should be undertaken by qualified Data Engineers. However, it is important for water supply practitioners to understand the basic concepts that influence how data are stored, structured, and retrieved, which are presented below.

Table 6-1 Common DMA data types Water Utility stores.

Type	Examples	Update frequency
Time-series data	Flow, pressure, level, chlorine readings	Every few minutes/hours/days
Spatial data (GIS)	Pipes, valves, meters, DMAs	updated when network changes
Event/Log data	Alarms, leaks, maintenance work	as events occur
Reference/Metadata	Customer zones, meter IDs, units	rarely changes

Structured and Unstructured Data

Structured data – organized in rows and columns like Excel or SQL tables (e.g. hourly flow readings by meter ID). Unstructured data – documents, photos, PDFs, reports (e.g. leak inspection photos or field reports). The DMS system should be able to store structured data in a database and can link unstructured files through references.

Data Granularity

The best approach is to store raw data and derive aggregated versions (e.g., hourly, daily) for faster dashboards.

Data Warehouse

A data warehouse is a structured, query-optimized repository designed to consolidate operational data from multiple sources for analysis and reporting. Unlike operational databases, it is optimized for read-heavy analytical queries rather than real-time transactional updates.

Data Lake

A data lake is a large-scale repository that stores raw data in its native format — structured, semi-structured, and unstructured. Unlike a data warehouse, no structure is imposed at ingestion; schema is applied at the point of retrieval (schema-on-read).

Metadata
Metadata means "data about the data", e.g. where the sensor is located (DMA, coordinates, pipe ID), units of measurements, communication type (GPRS, manual).

Single Source of Truth
The Utility must decide whether to use one central database as the single source of truth for all operational data or to maintain a separate database dedicated to NRW and / or leakage.

Big Data
A typical Water Utility operates at a scale of gigabytes rather than terabytes — below the threshold usually associated with Big Data infrastructure.

Data Pipeline
The process of moving raw data file through data processing and bringing it to the final form. Data pipelines have logging, monitoring, leaks – just like real water pipelines.

Data Archiving
Not all data needs to stay forever in the live system. You can plan to have Active Storage for the last 12–24 months of data (for dashboards, reports) and Archived Storage for older data compressed or exported (for audits or studies).

Backup and Redundancy
Data safety includes automatic backups (daily or hourly), Cloud or off-site storage for redundancy and version control (so data can be recovered after errors).

Integration

For integration between corporate platforms (SCADA, GIS, CMMS, hydraulic models), the recommended approach is to use APIs (Application Programming Interfaces) with standardized naming conventions, units, and timestamps.

Cyber Security
Cyber security in water Utilities focuses on ensuring that only authorized personnel can access specific systems at the appropriate time, and that operations remain safe and functional even when incidents occur. This is particularly important for highly automated networks with remote monitoring and telecontrol of equipment. The main risks arise from dealing with sensitive information (e.g. customers' personal data) and with operational equipment critical for public health.

Core principles include restricting external access to Utility systems through firewalls and controlled logins, preventing file corruption through effective antivirus measures, and maintaining reliable backup and redundancy procedures so that operations can be restored quickly if something goes wrong.

Recent analyses found that the most common vulnerabilities in the water sector remain outdated software, unpatched systems, and weak authentication practices.

6.1.2 DATA PROCESSING

At a minimum, raw data must be processed to standardize values and remove obviously erroneous records — for example, those caused by equipment failures, de-calibrated sensors, missing signals, or persistent zero readings. This stage also involves integrating data from different corporate systems and ensuring consistency across sources, particularly when information is imported from SCADA, GIS, CIS, or asset management platforms. At this point, data are converted into the formats needed for analysis, including consistent units, time formats, and sampling frequencies, so that they can be viewed and interpreted meaningfully.

An important consideration is where this processing takes place: within the data storage platform or within the data analysis environment. Typical data cleaning and standardization activities include:

- Adjusting timestamps (consistent time zone)
- Removing duplicate entries (if same timestamp repeated)
- Generating continuous time-series from fragmented inputs
- Filling gaps and flagging missing data records
- Assigning quality flags for each record (OK, estimated, missing, sensor error)
- DMA-specific validation: meter drift detection, partially open boundary valve identification, inlet/outlet flow consistency checking, pulse resolution rounding errors in data loggers.
- Aggregation and resampling: temporal synchronization for the MNF analysis window, volume integration vs instantaneous flow rate readings, pressure averaging methods, handling of missing intervals.
- Unit harmonization: flow rate vs volume accumulation conventions, pressure unit standards, time zone and daylight-saving time handling, alignment of billing cycle data with operational 15-minute records.
- Derived parameter calculation: net DMA inflow from multiple inlet/outlet meters, rolling MNF statistics, AZNP and AZP derivation from pressure logger networks, smart meter aggregate demand profiles.

The data processing steps described here directly affect estimation uncertainty; see Chapter 3 for a framework for assessing and documenting data quality.

6.1.3 DATA ANALYSIS

Data Analysis component is where all collected information is turned into useful insights. It connects technical field monitoring systems with the end user and supports their decisions and actions.

Data analysis involves applying automatic algorithms that can match data sets between each other and make a meaningful conclusion, easy to interpret. The five core analytical functions of a DMA DMS are:

- Continuous performance monitoring: automated daily water balance, rolling MNF statistics, ILI tracking, pressure performance indicators across the DMA network.
- Anomaly detection and leakage event identification: time-series analysis of MNF step changes, pressure transient detection, statistical deviation from seasonal baselines.
- Root cause analysis and diagnostic support: correlating flow anomalies with pressure events, CMMS work orders, weather data, and meter maintenance records.
- Leakage component analysis: automated water balance decomposition, BABE component tracking over time, background leakage estimation from pressure-flow relationships.
- Trend analysis and performance benchmarking: multi-DMA comparison, year-on-year ILI progression, intervention effectiveness measurement.

As the analytical engine, or “brain” of a Data Management System, it applies a range of analytical models, from simple statistical methods to more advanced algorithms, including machine learning and other AI-based techniques, capable of handling large and varied data inputs.

This book presents the main data analysis methods relevant to leakage and NRW, described in Chapters 4. In a broader sense, DMA Data Management System may include multiple analytical modules, or functionalities, extended to analyze such parameters as advanced analysis of customer consumption and billing data, assets conditions, water quality, hydraulics of the network among others.

To support practitioners in navigating these methods, several important terms and concepts used in modern data analytics are explained below.

AI

Artificial Intelligence (AI) refers to computational systems capable of performing tasks that typically require human intelligence — such as pattern recognition, classification, prediction, and decision support — by learning from data.

ML

Machine Learning (ML) is a branch of AI in which algorithms are trained on data to identify patterns and improve predictive performance, without requiring manually coded decision rules.

Digital Twin

Following Torfs et al. (2022), a Digital Twin of a water network is a virtual model that continuously evolves alongside the physical system and updates automatically in real time to replicate actual hydraulic conditions. It can send control and operational commands back to the physical network. In a DMA context, a Digital Twin differs from a static hydraulic model in that it is continuously updated with real-time field data, enabling dynamic simulation of current network conditions.

Deep Learning
Subset of Machine Learning algorithms that teaches computers to perform tasks by learning from examples using "neural networks," which are inspired by the human brain.

LLM
Large Language Models - AI systems designed to understand and generate human-like text and are trained on massive datasets (like books, websites, and articles) to learn patterns, grammar, and context in language. Within water sector applications, LLMs can power natural-language query interfaces for DMS dashboards.

Predictive Data Models
One important component of data analytics is prediction, which is usually realized using Predictive Data Models: it looks at how things behaved in the past → finds patterns → and uses those patterns to forecast what will happen next. Predictive Models help water Utilities move from reactive operations (“fix it when it breaks”) to proactive management (“anticipate and prevent problems”). Predictive data models can vary widely in complexity (Newhart K., 2023), and the analytical engine of a DMS should be optimized to use the appropriate mix of model types. This helps minimize the demand on storage, processing power, and operational memory, while ensuring that analyses run efficiently and at the required speed.

6.1.4 DECISION MAKING

The Decision Support component of the DMS converts analytical insights into structured options and recommendations, which authorized personnel use to make operational decisions. Based on data analysis results, it includes routine operational decision-making (e.g. prioritizing leak repairs or adjusting valve operations), as well as longer-term planning (e.g. investment programming or asset renewal strategies).

It is important to define who the decision maker is (e.g., a network operator or senior management), the level of decisions authorized for each user, and the type of output required, such as dashboards, KPIs, and reports. Final decisions may be executed automatically or manually and can incorporate different levels of hierarchical approval. Typically, decision authorization categories are:

(1) automated pre-authorized routine responses (e.g., alert classification thresholds)
(2) operator-initiated responses requiring explicit human authorization (e.g., field crew dispatch)
(3) management-authorized strategic responses (e.g., pressure zone reconfiguration, rehabilitation investment).

Common NRW-related outputs to support operational and planning decisions are:

- Geographical representation of DMA parameters (NRW, NF, consumption, customers)
- DMA dashboards and reports
- Alarms and alerts (leaks, bursts, anomalies, equipment failure)
- KPIs (NRW, ILI, carbon balance, energy efficiency, service level)
- Multiparameter Risk Matrices (assets failure, preventive maintenance, pipe replacements)
- What-if tools (pressure optimization, pump operation, pipe isolation).

Another tool to support decision-makers is an automated chatbot, which can respond to natural-language queries and retrieve relevant data and reports from the DMS. Operators should verify chatbot responses against primary data sources before taking action.

6.1.5 ACTIONS

DMS can include various components to initiate, assign responsibility, follow up status and conclude actions followed from the decisions. Some examples of such actions in water network could be:

- Further investigation of alarm/alert
- Triggering emergency response
- Issuing remote control commands (valve open/close operations, pump start/stop, pressure control valve setting changes)
- Issuing work order for leak repair team
- Repair dispatches (leaks, instruments, teams)
- Issuing customer communications (water cuts, changes in pressure/quality)
- Scheduling preventive maintenance and replacement (pipes, valves, bulk and customer meters)

Section 6.3 “Event Management Systems” covers some specifics related to systems that deal with actions and events in the water network.

6.1.6 FEEDBACK AND IMPROVEMENT

The Feedback and Improvement component closes the loop of the DMA data management cycle. Once data-driven decisions and actions have been implemented — such as leak repairs, pressure adjustments, the creation or modification of DMAs, or new customer connections — it is essential to assess their actual impact on network performance. This component ensures that actions based on analytical insights are verified, lessons are captured, and processes are continuously improved.

Feedback begins when the results of operational actions are sent back to the data system. For example, after repairing a leak, the DMA flow and pressure data should be re-analyzed to confirm that the MNF decreased and service was restored. Such confirmation helps validate the effectiveness of the intervention and builds confidence in the data-driven decision process. Similarly, if expected improvements are not observed, engineers can identify whether the cause lies in incomplete repairs, inaccurate data, or system modeling assumptions.

Each feedback cycle refines the accuracy of the system and strengthens collaboration between field teams, data analysts, and decision-makers. Over time, the platform evolves from simple monitoring into a learning system that helps Utilities plan smarter, operate more efficiently, and reduce losses sustainably.

6.2 MAIN CRITERIA IN DMS SELECTION

The term “DMA Data Management System” covers a wide range of products and capabilities. Utilities can easily be misled by marketing language without fully understanding what each term means in practice. For Water Utility it is important to choose the software that will really solve its day-to-day problems and to ensure that these tools serve the price paid—instead of the other way around.

Experience also shows that Utilities often fall into the trap of over specifying functional requirements for Data Management Systems. This not only drives up costs unnecessarily but also complicates the implementation process and leaves many advanced features unused (Féry G., 2022). This challenge is closely tied to the need for establishing key prerequisites before implementing DMS — including a clear digitalization roadmap, the right technologies in place, well-defined organizational processes, and the allocation of dedicated human resources. DMS selection should be driven by actual operational needs and data maturity — not by the sophistication of marketing materials.

The following is the list of DMS considerations that will hopefully guide Water Utilities to narrow down the choice, define the technical and economic requirements, shape the financing options and navigate the pool of offers.

6.2.1 NEEDS ASSESSMENT

Before any system evaluation, a Utility must define:

- Operational scope (number of DMAs, leakage management maturity, required analytical functions, decisions to be supported), see Appendix A for DMA Maturity Matrix
- Data readiness (collection frequency, quality, completeness, existing corporate systems)
- Organizational capacity (IT skills, staff training feasibility, change management context),
- Financial envelope (capital and operational budget over a 10-year horizon).

The Business-IT Maturity Model from Harris et al. (2013) provides a directly applicable five-level framework (Initial/Chaotic through Optimizing) for positioning a Utility's current state before DMS procurement. A Utility at Level 1 has fundamentally different selection criteria than one at Level 3 — selecting a sophisticated DMS for a Level 1 Utility is likely to fail because the organizational prerequisites for operating it do not exist.

6.2.2 DATA INTEGRATION ARCHITECTURE

Integration complexity is consistently one of the top causes of IT project overruns in Water Utilities (Harris et al., 2013). A full integration assessment requires:

- Source system heterogeneity analysis (different asset IDs across SCADA, GIS, billing, CMMS; reconciliation effort required)
- Temporal synchronization analysis (15-minute SCADA data vs monthly billing vs sporadic GIS updates)
- API availability and vendor lock-in assessment (proprietary protocols, closed legacy systems, middleware costs)
- Real-time vs batch integration requirements (which analytical functions require live feeds vs daily transfers).

The architecture decision — point-to-point connections, enterprise application integration hub, or web service/service-oriented (SOA) model — must be made at the strategic level before any individual system is selected, because it constrains which systems are compatible and determines real total cost of ownership.

6.2.3 DATA GOVERNANCE FRAMEWORK

A governance framework defines:

- Data ownership and accountability (who owns each data stream, who resolves quality problems, who authorizes archiving)
- Data quality standards and enforcement (minimum acceptable standards, violation escalation procedures)
- Access control and user authorization (regulatory traceability, audit trail for reported figures)
- Data lifecycle management (retention periods, archiving authorization, regulatory requirements)
- Metadata governance (reference data management, change propagation, analytical reproducibility)
- Interoperability standards (FIWARE NGSI-LD, WaterML, OGC standards for vendor lock-in prevention).

Governance readiness assessment should precede DMS selection — governance maturity determines which DMS capabilities are realistically achievable. The Thomas (2004) definition adopted by Harris et al. is directly applicable: governance is 'a system of decision rights' and accountabilities for information-related processes, executed according to agreed-upon models, which describe who can take what actions with what information, and when, under what circumstances, using what methods.

6.2.4 MODULES

Modern IT firms can deliver tailored data software solutions in a matter of weeks and can include almost any required functionality. It is therefore essential to decide carefully which functions should be integrated into the DMS, as this will determine the platform's cost, implementation time, complexity, and the human resources needed for deployment and operation.

Table 6-2 Main types of functionalities (modules) of water networks DMS.

Category	Module
Data Integration	Automated import of sensor signals
	Automated import of data from smart meters
	Automated import of data from permanent leak detection devices
Data Management and Processing	Centralized data storage
	Data processing
Non-Revenue Water	DMA-based NRW performance tracking
	Utility-wide NRW performance tracking
	Automatic leak and anomalies detection
	Tracking effectiveness of leak repairs
Asset Management	Management of customer meter inventory
	Smart meters management
	Network hydraulics
	GIS
	Work orders management
	Equipment and Material Inventory Management
	CAPEX planning
Operations	Telecontrols (SCADA-functionality)
	Alarms and event management
	Tracking leaks detection and repair
	Pumping optimization
	Energy consumption optimization
Client Management	Customer Billing Management
	Customer Relationship Management
	Advanced analytics of customer consumption and billing
User Interface	Virtual assistant (chat bot)
	Interactive GIS-based interface
	Mobile applications
	Customizable KPIs and reporting

6.2.5 TRADITIONAL DMAS VS OPEN NETWORKS

If the network is already divided or can be sectorized into traditional physical DMAs (with clear inlet meters and limited interconnections), there are many tools that work very well on a DMA-by-DMA basis. These tools calculate NRW, MNF, leakage indicators and pressures for each DMA, and then aggregate the results to provide an overview of the entire system.

If the network is very difficult to divide into fully isolated sectors – for example, in dense and highly looped urban grids or in long branched tree-like rural networks – strict physical DMAs may not be practical. In these situations, specialized tools can work with Open Networks. Many of these tools use AI-based methods to analyze large and complex datasets (flows, pressures, meter readings, detected leaks) and to identify correlations between various characteristics of network and associated leakage levels and locations.

6.2.6 ON-PREMISES OR CLOUD-BASED

Cloud-solutions utilize specialized AI data centers, which allow processing of very large data sets and billions of operations in short time. Replicating similar computational capacity on the local server will require very large infrastructure investments. Given the large volume of data routinely handled by water Utilities, the cost of additional server hardware, space, maintenance, and human resources required for on-premises solutions often outweighs the cost of a Cloud-based solution.

The main constraint to using those powerful Cloud-based facilities is local regulation, which often prohibits storing sensitive information (such as customers' names and addresses) outside the country. This challenge is well known across many industries and can be overcome by using data centers physically located within the country or adopting hybrid architectures where sensitive data remains on premises also known as Sovereign Cloud.

HELPFUL TIPS

It is also important to note that the cybersecurity protections of most commercial Cloud platforms are generally stronger than those of many

6.2.7 LICENSING

The heritage service type is perpetual license installed on-premises and includes one-time payment based on the number of licenses. Most of the providers steer clear of this licensing option nowadays.

HELPFUL TIPS

Perpetual licenses typically include annual maintenance fees; failure to pay these fees may render the license invalid.

More common service type nowadays is SaaS (Software as a Service), where yearly license subscription includes continuous maintenance, updates, technical assistance and trainings. The cost is typically based on the size of network and number of licenses and often has additional setup fee.

The most advanced type is DaaS (Data as a Service) where the Utility shares system information and reporting needs, while the provider installs and maintains all loggers, connections, analytics, and reporting. Under a DaaS model, the Utility pays a recurring subscription fee in exchange for a fully managed data service — including sensor installation, transmission, analytics, and reporting — delivered by a specialized provider.

6.2.8 LICENSE-FREE TOOLS

One of the useful NRW tools and an industry standard is Excel-based WB-EasyCalcs (www.liemberger.cc). It is free, straightforward and estimates physical and commercial water losses based on Water Balance method recommended by IWA. Newer version WBC-EasyCalc (https://github.com/Liemberger-Partners/easycalc), extends the tool to include carbon balance calculations alongside the standard water balance, supporting Utilities reporting on energy and emissions.

GISWATER (www.giswater.org) is another free open-source software platform designed to help water Utilities manage, analyze, and plan their water supply systems more efficiently. It acts as a bridge between GIS (free QGIS) and hydraulic modeling software (free EPANET) with the central integrated database for all assets and parameters. It supports DMA management, NRW estimates, leak detection zones and hydraulic audits, other modules can be coded and are continuously added by the open-source community.

The main drawback of GISWATER is its steep learning curve. The interface is not very intuitive, and setting up and deploying the system typically requires a team of highly skilled IT and programming specialists. It is best suited for Utilities and consultants with strong in-house GIS and IT capacity, who prioritize full control and flexibility over polished interfaces and extensive vendor support.

6.2.9 ADDITIONAL COSTS

Usually, DMS license cost will depend on the size of the system: length of pipes, number of customers, number of DMAs, number of users, number of data signals, functionality modules included, etc. Some providers include setup costs in the licensing payment over the first period and others state it as a separate fee. Maintenance and technical support may or may not be included in the base license.

Another important hidden cost that should be anticipated is internal staff time. During the setup and configuration phase, which often lasts from three to twelve months, internal personnel will be heavily involved in workshops, data extraction and cleaning, validation of results, and testing of dashboards and workflows. Operations, NRW, GIS and IT staff will therefore have less time for their usual daily tasks, and other projects may slow down.

Beyond the initial project, there are long-term internal resources to consider. A DMS usually requires ongoing attention from people who understand both data and the water system and new positions might need to be created (e.g. Data Analyst) or existing roles expanded (which might meet staff resistance).

On top of that, the DMS will often sit at the center of a wider ecosystem of tools which in turn will require additional licenses: online storage rental, data historians, GIS software, cybersecurity tools, and other specialized applications.

Hardware and infrastructure also contribute to the overall bill. Even with a Cloud-based solution, Utilities still need office workstations, laptops, large screens for control rooms, and tablets or smartphones for field teams. For on-premises or hybrid solutions, there may also be local servers, network equipment, cooling, power and physical space requirements, all of which must be installed, maintained and periodically renewed.

When comparing the costs of DMS, it is recommended to assess costs over a minimum 10-year horizon. It is also important to discuss with the vendor beforehand the following topics and clarify the roles, responsibilities and expenses involved:

- Full access to the data and algorithms
- Upgrades of platform to the newer version (every 3-5 years)
- Data growth (increased storage and license fees)
- New sensors added (license expansion)
- New user added (team expansion)
- Temporal access rights for third parties (consultants, sub-contractors)
- Additional training
- What happens if vendor pricing model changes
- What happens if vendor goes out of market and stops the support.

6.2.10 PROVIDER

Providers of NRW Data Management Systems generally fall into the following categories:

Large Multinational Corporations

These are well-established global companies that offer water system analytics as part of a broader suite of water management products. These companies often specialize in hardware solutions, integrating advanced data analytics with sensors, meters, and automation tools. While their scale and resources allow for robust, long-term support and stability, their primary business model may also focus on selling proprietary hardware and software ecosystems, which could limit flexibility in integration with third-party systems.

Large Software Providers

These companies specialize in hydraulic modelling and digital water management software, often expanding into NRW analytics as part of their broader solutions. Their core strength lies in hydraulic simulation, asset management, and predictive analytics, leveraging decades of expertise in engineering-grade modeling tools.

While these providers offer highly sophisticated, scalable platforms, they may require specialized expertise in implementation and customization. Additionally, their business model is often subscription-based, and they may prioritize integration with their own ecosystem of modeling and GIS tools, which could pose challenges for Utilities seeking vendor-agnostic solutions.

International Consultancies

These are consulting firms specializing in NRW reduction, water network optimization, and Utility reform, including the commercial software brands of private Water Operators. Many have developed in-house data platforms and analytical tools as part of previous or ongoing projects and now offer them commercially as stand-alone products.

A key advantage is that their platforms usually provide a very practical, problem-focused approach based on the real needs of Water Utilities. Typical drawbacks include a strong dependence on the consultancy for configuration, updates, and advanced analyses, and the software may be less standardized and less documented than products from software vendors.

Specialized IT startups

Smaller, agile companies focus primarily on software-driven analytics. These firms excel in data science, artificial intelligence, and customized software solutions. Their ability to quickly adapt and innovate gives them an edge in developing tailored, cutting-edge analytics tools. However, startups often operate with limited financial backing, meaning they may either be acquired by larger companies or face funding challenges. This introduces a level of uncertainty regarding their long-term availability and support.

SCADA Providers

These providers originate from the operational technology (OT) side, supplying SCADA systems, PLCs, RTUs, and telemetry solutions. Many have expanded their offers with basic to intermediate analytics, dashboards, and event management tools tightly integrated with their SCADA platforms. For Utilities that already use their control systems, this can provide a natural, low-friction path to real-time monitoring, alarms, and simple NRW indicators at plant or DMA inlet level.

However, SCADA-centric solutions are often less flexible for advanced NRW, customer, or commercial analytics and may have limited capabilities for open integration with external data sets.

6.2.11 LANGUAGE AND GEOGRAPHICS

Digital platforms today can technically be accessed from almost anywhere in the world, and many user interfaces can be translated into multiple languages. In practice, however, language and geography still matter a lot when choosing and operating a DMS for a water Utility. Cultural misunderstandings are still common in communication, especially when dealing with technical support and training accompaniment.

Some countries restrict the storage of personal or operational data outside national borders or require that primary databases be hosted on servers physically located in the country. This fact can greatly limit the choice of fully Cloud-based platforms.

Many digital water tools have been developed and tested in Utilities with high data availability and quality: dense metering, stable SCADA, good asset registers and continuous supply. In regions where data is sparse, intermittent, or of uncertain quality these tools may be overdesigned and expensive for what is realistically possible. Moreover, they will most probably produce unreliable results if fed with low-frequency or incomplete data.

Rural areas or Utilities in low-income regions may have limited bandwidth or unstable internet. In such cases, solutions that include offline-capable mobile apps, local buffering of data, and light web interfaces become more important design criteria.

When planning a DMA DMS project, it is important to align early with the funding agency and procurement team on any geographical or local-content constraints.

6.2.12 IMPLEMENTATION

Water Utility practitioners are typically more familiar with linear project management — planning, design, construction, and closeout — than with the iterative approaches used in software development. Digital tool development is inherently iterative—user needs evolve, problems surface during setup and use, and requirements change with time. To succeed in digital transformation, we must embrace Agile Concepts like sprints, user stories, MVPs (Minimum Viable Products), and continuous feedback loops. Successful DMS implementation requires iterative development, close collaboration between IT, NRW, and field teams, and a willingness to refine the system based on operational feedback.

Many modern DMS providers offer to implement a pilot platform on a small part of the network (for example, a few DMAs) either free of charge or at a discounted price. The real challenge is to turn these pilots into standard practice, supported by documented procedures, staff training, and a dedicated budget.

6.3 EVENT MANAGEMENT SYSTEMS

An EMS is a module within a Data Management System that focuses on detecting, classifying, prioritizing, and tracking water network events such as leaks, bursts, pressure anomalies, sensor failures, and unusual consumption patterns. It uses data from monitoring devices to flag potential incidents and support subsequent diagnosis, decision-making, and response. Although EMS platforms can raise alarms in near real time, detection speed depends on data transmission frequency, latency, and the reliability of the sensor network.

Daily Leakage

Night Flow Breakdown

Operability (%)

Percent Difference +189.17%

Target 0.07

0.21

289.17%

Excess Leakage (Ml/d)

Difference -0.03 ↓

0.18 ↓

28/03/26 0.2

Operability (%)

Difference 0

100 →

28/03/26 100

Region	DMA	Week Commencing	Operable Status	Night Leakage (l/s)	Leakage Target (l/s)	Leakage Exit Level (l/s)	Excess Leakage (l/s)	Excess Leakage per Size Factor (l/s)	Excess Leakage per Property (l/hr)	Excess Leakage per KM (l/hr)	Excess Leakage (%)	Leal Le
[redacted]	[redacted]	04/04/26	Operable	2.53	0.87	0.37	2.16	2.2	6.4	415.56	85.38	

Figure 6-3 *Example of dashboard of Event Management System (source: Crowder Consulting).*

Modern EMS has evolved through three distinct generations whose capabilities, data requirements, and false positive rates differ significantly:

- **Generation 1 (Rule-based)**: deterministic threshold alerting on absolute values (e.g., MNF > threshold). Simple, interpretable, but high false positive rate due to seasonal and demand variations.
- **Generation 2 (Statistical Pattern Recognition)**: ARIMA models, seasonal decomposition, time-series anomaly detection. A step change in MNF detected by these methods is a direct automated leakage flow estimate — this is continuous automated MNF Analysis. This generation dramatically reduces false positives by establishing dynamic baselines.
- **Generation 3 (ML-enhanced)**: supervised classification of event types, unsupervised clustering of events, LSTM networks for multi-variable detection. Adds event type classification (burst vs background leak vs meter fault vs boundary valve movement) beyond detection.

Within an EMS, the full lifecycle of an event can be managed—from the moment it is opened until it is resolved. Statistical methods and, increasingly, machine learning are used to learn the network's normal behavior and build predictive models. Incoming measurements are continuously compared against historical patterns and expected values to highlight deviations, enabling earlier detection of leaks, bursts, equipment malfunctions, or abnormal consumption.

A key strength of EMS lies in its ability to combine signals from multiple sources—flows, pressures, levels, customer meters, complaints, and sensor status—to improve the accuracy of detection. This integration helps distinguish genuine incidents from noise and reduces the number of false alarms, so that Utilities can focus on real issues and respond faster. Alarms still need validation, which typically involves assessing the duration, magnitude, and shape of the anomaly.

The anomaly detection engine of a modern EMS automates the MNF step-change analysis described in Section 4.2.3, applying it continuously across all monitored DMAs and generating alerts when new leakage signatures are detected.

6.3.1 TYPES OF EMS

An EMS can be deployed with varying levels of complexity and automation, depending on the needs and digital maturity of the Utility. Consider starting with a simple task management system where a full logbook is maintained from events of the network. If you are part of a large Utility (200+ km of pipe), think about full integration, to overcome manual errors and reduce labor intensity.

Basic Level – Manual Systems

At the most fundamental level, a simple Task Management System may be sufficient. In this setup, data collection and reporting are largely manual. Utilities can still classify events into categories such as leaks, bursts, or maintenance activities, while also recording valuable contextual information about the network. For example, records may include whether a leak was caused by asset ageing, pressure surges, or third-party activity. Even at this basic stage, the captured data can support future asset management strategies by building a historical record of network events.

Advanced Level – Integrated Digital Systems

At more advanced stages, EMS are fully integrated into the Utility's digital ecosystem. Events are automatically enriched with all relevant data, including location, asset information, and event classification. Sophisticated platforms can automatically determine the type of event using predefined rules or AI-based algorithms.

In such setups, Utilities often rely on several specialized systems, for example, SCADA, GIS, CIS, and maintenance platforms—that are interconnected. Despite the complexity, a "single source of truth" is maintained so that all teams work from consistent and reliable event information.

Commercial Turnkey Solutions

Beyond custom-built integrations, there are complete commercial EMS packages available. These provide ready-made solutions that combine advanced integration, automation, and reporting functions. While more costly, they offer Utilities a faster path to digital maturity with standardized best practices already embedded.

6.3.2 WORKFLOW

At its core, an EMS is a central hub where events from different monitoring and operational systems are collected and managed throughout their lifecycle. Events may originate from leak detection platforms, network monitoring tools, or critical infrastructure such as pumps.

For example, in case of a leak detection scenario, the typical workflow of EMS would be:

Event Detection and Classification

- From minimal night flow detection systems an anomaly in DMA-03 shows increased night flow.
- System classifies this as a potential leak with medium priority based on flow rate and pressure readings.
- Events are automatically generated and assigned to the network operations team.

Initial Assessment and Planning

- Historical trends confirm this is a new anomaly, not a recurring pattern, for example from minimal night flow.
- Work order management system is checked if maintenance activities are ongoing in the area.
- Customer service system is verified if residents have reported service issues.
- Operations engineer (or an automated algorithm) classifies and validates the event, deciding whether it is a false positive or requires further investigation by a field crew.
- Team schedules field investigation within 24 hours based on leak classification.

Field Investigation

- Field team uses system-generated possible perimeter of the leak.
- Acoustic leak detection equipment is deployed along the suggested pipe segments.
- Field team documents leak size, location, and surrounding conditions.

Response Coordination

- Work order is automatically generated in the event management system.
- Repair priority is set based on leak severity and potential service impact.
- Required resources (staff, equipment, materials) are allocated.
- Affected customers are notified if service interruption is necessary.

Resolution and Documentation

- Post-repair flow monitoring confirms return to normal network behavior.
- System transitions event status from "active" to "resolved".

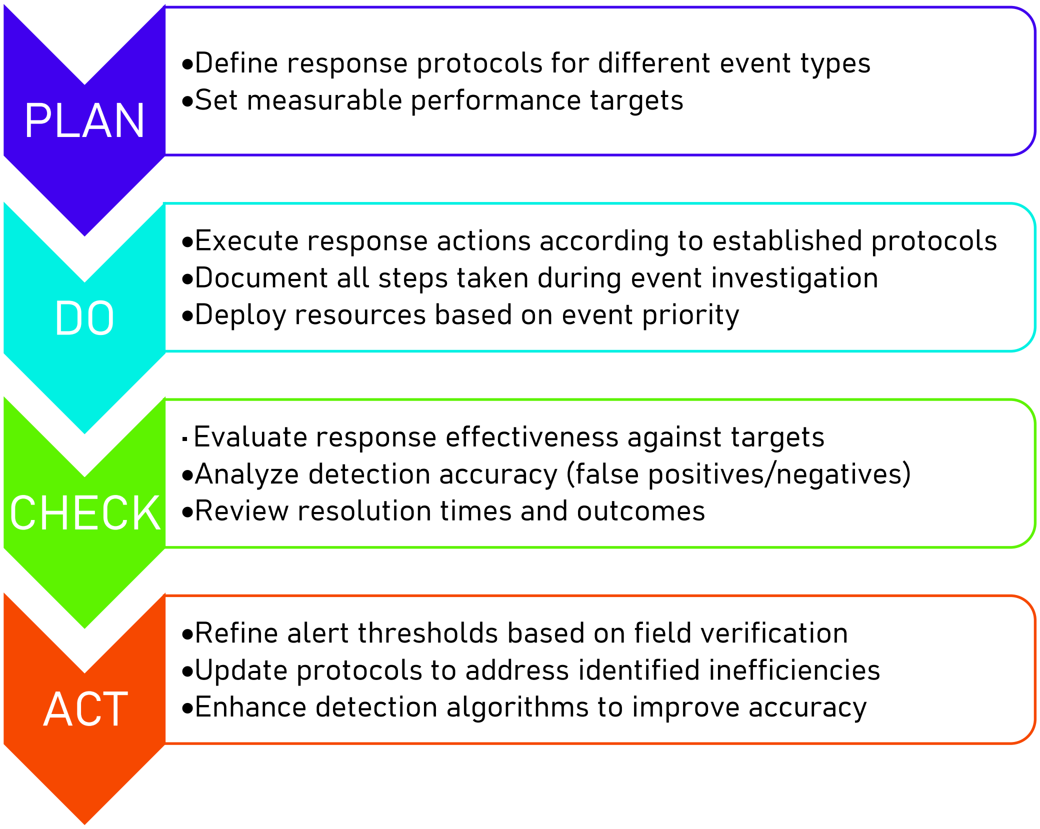
Analysis and Learning (PDCA)

- Response time metrics are compared against performance targets.
- Insights about pipe material and age are recorded for asset management.
- Alert thresholds are refined based on successful detection.

This process not only improves the accuracy of event handling in real time but also builds a structured historical record that can be leveraged for asset management, predictive maintenance, and long-term planning.

6.3.3 PLAN-DO-CHECK-ACT (PDCA)

An event has its lifecycle from when it is detected to when it is closed. In most cases the traditional Plan-Do-Check-Act (PDCA) scheme is suitable for the follow-up of events, and most modern EMS should have this included:



PLAN

- Define response protocols for different event types
- Set measurable performance targets

DO

- Execute response actions according to established protocols
- Document all steps taken during event investigation
- Deploy resources based on event priority

CHECK

- Evaluate response effectiveness against targets
- Analyze detection accuracy (false positives/negatives)
- Review resolution times and outcomes

ACT

- Refine alert thresholds based on field verification
- Update protocols to address identified inefficiencies
- Enhance detection algorithms to improve accuracy

Figure 6-4 *PDCA process for EMS events.*

6.3.4 COMMON CHALLENGES

Incorrect setup of an EMS is often the result of recurring mistakes. The most frequent ones include:

Lack of a Single Source of Truth

EMS platforms typically collect events from various subsystems. For example, a pressure monitoring system may generate an event containing pressure data. However, the true source of this data is usually the SCADA system or the historian. Operations engineers should always reference the original source of truth to make accurate judgments.

Multiple EMS Systems in Parallel

Many commercial leak detection or anomaly detection tools include their own built-in event management features. Running several EMS platforms in parallel increases integration complexity and leads to fragmented information flows. Historical event records are often not centralized, making it harder to use them for other purposes such as asset management or long-term planning.

Poor or Inconsistent Data Logging

Some systems capture insufficient event details, limiting the usefulness of logged data. In other cases, engineers apply inconsistent or subjective criteria (e.g., when assigning impact levels), which undermines data quality and comparability. Consistency and completeness in logging are essential for reliable analysis and decision-making.

6.3.5 EXAMPLES OF EMS ALERTS

DMA Flow Alerts

Alerts generated based upon flow data indicate whether flows are High/Low/Flat/Dead/Faulty. For example, a high flow may indicate that a burst has broken out on the network.

Flow Alerts are generated based upon:

- Comparison of actual flow data for individual meters with upper and lower flow profiles (envelope).
- Comparison of actual DMA net flow data with upper and lower flow profile (envelope).
- Identify significant increases in MNFs for DMAs.
- Identify significant changes in Total Daily Flow for DMAs or individual meters.
- Identify smaller changes over time that represent a shift in behavior

Validation example: If a high flow alert is triggered but lasts only a short period, it may not meet the threshold to be classified as a potential event. In contrast, a sustained high flow alert that does not resolve could indicate a more serious issue, such as a burst developing within a DMA.

DMA Pressure Alerts

Alerts generated based upon pressure data indicate whether pressures are High/Low/Flat/Dead/Faulty. For example, low pressure may indicate that customers are without a water supply due to failure on the network.

Pressure Alerts are generated based upon:

- Comparison of actual pressure data for individual sensors with upper and lower pressure profiles (envelope).
- Identify significant surges or drops in pressure between readings.
- Identify significant changes in Maximum, Minimum and Average Pressures for individual pressure sensors.
- Identify smaller changes over time that represent a shift in behavior.

Validation example: When pressure drops below the lower threshold for short periods but occurs frequently throughout the day, it may indicate a potential event. While each individual alert is brief, the recurring pattern suggests a broader issue within the network. Grouping these alerts can help identify underlying problems, such as a pressure control issue which may require further investigation.

Reservoir Level Alerts

Alerts generated based upon level data indicate whether levels are High/Low/Flat/Dead/Faulty. For example, a consistently high level may indicate that the ball valve on the service reservoir is failing causing it to overflow.

Level Alerts generated based upon:

- Comparison of actual level data for individual sensors with upper and lower-level profiles (envelope).
- Identify if level sensor at or above top water level for significant period.
- Identify if level sensor at or above bottom water level for significant period.
- Identify if level sensor has significant drop in level over a period.

Validation example: A flat level measurement in a water tower or tank over parts of the day is not, on its own, enough to indicate a potential event. However, if the flat level exceeds the tank's top water level, it may signal an overflow potentially caused by a faulty float valve or a timing issue with the pumps feeding the tank. It is important to consider both the magnitude of the level and any irregular patterns, as these can provide critical context for identifying abnormal behavior in the system.

Smart Consumption Meter Events

Smart Consumption Meters are Automatic Meter Reading (AMR) or Advanced Metering Infrastructure (AMI) meters; they can use static or mechanical measuring principle with integrated or add on electronics used for consumption metering. They can generate data and alerts far beyond normal meter index data.

The data and alerts can be generated by the smart meter itself (i.e. edge analytics) or within the head end system using granular interval data (at least hourly). It is important to note that a meter that is read manually, or only annually, or used solely for billing index reporting is not functioning as a smart meter and represents an investment with questionable return.

Appendix G describes the real case of a Dannish utility that has successfully implemented a digital Leak Management strategy powered by Smart Meter Technology.

Some example data:

Leakage downstream of meter (customer side leakage):

Most smart meters have a functionality to identify a potential leak after the meter. Those alerts are generated based on the analysis of minimum flows over a period to identify continuous flows. For example, a residential meter should stop at least once per day (or during a defined period) if not a leakage alert is sent.

Leakage upstream of meter:

Recently smart meters appeared on the market which use ultrasonic flow measurement sensors to perform acoustic noise level analytics similar to noise loggers for acoustic leak detection. When installed at sufficient density alongside meters of the same type in neighboring locations, this approach makes it possible to identify zones of potential upstream leakage.

Validation example: A sudden increase in consumption for smart-metered customers may indicate water wastage particularly if the minimum flow rate remains above zero for an extended period. Assessing how much the flow has increased and over what duration can help validate whether the alert represents a potential event requiring further investigation.

REFERENCES

A.Bojko, G. Féry (2026), *NRW Digital Platforms: Practical Advice for Water Utilities.* www.nrwtech.org/nrw-digital-platforms.

Agence nationale de la sécurité des systèmes d'information (ANSSI). (2024). *Secteur de l'eau, état de la menace informatique.*

AI in the Water Industry. (2023). CwMAG Workshop, November 2023. Tridend Group Solutions.

Cahn, A. and Mertzanis, M. (2024). *DaaS Playbook: It's All About Services.* SWAN, UK.

Digital Transformation for Growing Water Utilities. (2025). Boston Consulting Group (BCG) and Japan International Cooperation Agency (JICA).

EasyCalc. Liemberger & Partners. Available at: www.liemberger.cc and https://github.com/Liemberger-Partners/easycalc

Eckerson, W. (2020). *The Rise of Unified Data and Analytics Platforms.* Eckerson Group / Datalere.

EPA Interagency Water Workforce Workgroup. (2020). *America's Water Sector Workforce: Report to Congress.* U.S. Environmental Protection Agency, Washington DC, USA. Available at: https://www.epa.gov/sites/default/files/2020-04/documents/epa_water_workforce_report_to_congress_2020.pdf (accessed November 2025).

Féry, G. (2022). *The Digital Journey of Water and Sanitation Utilities in Latin America and the Caribbean: What Is at Stake and How to Begin.* Inter-American Development Bank (IDB), Washington DC, USA.

Foundation for Water Research. (2023). *Bridging the skills gap in the water sector.* Available at: https://www.fwr.org/water-sector-skills-gap (accessed 16 June 2025).

GISWATER Project. *GISWATER.* Available at: www.giswater.org

Global Water Research Coalition. (2023). *The Digital Water Utility of the Future.*

Grigg, N. S. (2025). Digital Transformation in Water Utilities: Status, Challenges, and Prospects. *Smart Cities,* 8(3), 99.

GSMA. (2022). *Water Utility Digitalisation in Low- and Middle-Income Countries: Experiences from the Kenyan Water Sector.* GSMA, UK.

Hamilton, S., Charalambous, B. and Wyeth, G. (2021). *Improving Water Supply Networks: Fit for Purpose Strategies and Technologies.* IWA Publishing, London, UK.

International Water Association (IWA). (2022). *Digital Water Book 2022 – Digital Water White Papers Series.* IWA Digital Water Programme.

Harris, D and Azagra, E. (2013) *High-Performing Information Systems Aligned With Utility Business Strategy*, WRF.

Mahajan, P. and Dhanasekar, A. (2025). Bridging the Gap: Bringing Agile Innovation to the Water Sector. *Water Online,* 8 May 2025.

Martinez Alzamora, F., Conejos, P., Castro-Gama, M. and Vertommen, I. (2021). *Digital Twins – A New Paradigm for Water Supply and Distribution Networks.*

Muncaster, P. (2023). Over Half of Attacks on Electricity and Water Firms Are Destructive. *Infosecurity Magazine,* April 2023.

Pérez Penalosa, F., Lombana, C. and Saltiel, G. (2024). *Utility of the Future 4.0.* International Bank for Reconstruction and Development / The World Bank.

Plumlee, M., Newhart, K. and Thompson, K. (2023). *Webinar: Artificial Intelligence (AI) in the Water Industry.* Orange County Water District. Available at: www.youtube.com/watch?v=M3AQTs5iN5g

PUB, Singapore's National Water Agency. (2020). *Digitalising Water – Sharing Singapore's Experience.* IWA Publishing.

Sarni, W., Sheehan, J. and Cox, T. (2023). *The Digital Journey of Water and Sanitation Utilities in the Caribbean.* Inter-American Development Bank (IDB), Washington DC, USA.

Thomas, Gwen. (2004). *DGI Data Governance Framework*. The Data Governance Institute.

Torfs, E. et al. (2022). The transition of WRRF models to digital twin applications. *Water Science and Technology,* May 2022.

WRF (2013), *High-Performing Information Systems Aligned With Utility Business Strategy, Water Research Foundation*.

World Bank. (2025). *Digital Transformation Overview.*

Water Utility Control Center (image generated by AI, Nano Banana, 2026)

APPENDIX A DMA MATURITY MATRIX

T. Kressin, F. Garzón, M. Willmott, A. Bojko

To help practitioners assess the maturity level of their network, this appendix provides a **DMA Maturity Matrix.** The matrix is based on the experience and judgment of several leading leakage practitioners. Ideally every DMA within a utility could be assessed using this matrix.

The matrix serves three main purposes:

- **Assessment of Current Maturity**
  It allows leakage practitioners to evaluate the maturity level of their DMAs. By understanding their maturity, they can determine which concepts and recommendations in this book are most applicable.
- **Roadmap for Improvement**
  It outlines a pathway for utilities seeking to develop more advanced DMAs. The matrix shows how to progress from a “Basic” to a “Leading” level across different areas.
- **Template for Customization**
  It provides a framework that utilities can adapt into a simpler or more advanced maturity matrix. Utilities may develop their own scoring systems. For instance, they might award:

  - 1 point for each area where a DMA is assessed as “Basic,”
  - And 4 points for areas assessed as “Leading,”

To give a worked example, a DMA which was Basic in 12 areas, Intermediate in 3 areas, Advanced in one area and leading in one area, could score 25 points (assuming 1 point for Basic, 2 points for Intermediate etc).

Criteria		Basic	Intermediate	Advanced	Leading
Physical Assets	DMA Integrity	DMA proven to be valved in at time of commission	Boundary proven to be tight with PZT test (or equivalent) within last 5 years	Boundary proven to be tight with PZT test (or equivalent) within last 2 years	Ongoing proactive monitoring to ensure tightness of boundary
	Customer connections	Estimation based on sampling, peer DMA or other means (satellite images, households / sqm, census figures etc.) Estimation should be with precision of at least 20%	Connections are known with precision of at least +/-10% Updated within a year of a change	Connections are known with precision of at least +/-5% Updated within a month of a change	Connections are known with precision of at least +/-2% Updated within a week of a change
	Pipe length	Estimated based on maps	Based on actual records Updated within a year of a change	Based on actual records Updated within a month of a change	Based on actual records Updated within a week of change
	GIS	As built drawings Key assets available (such as pipe work & valves), but other assets such as hydrants may be missing Customer connections coverage is optional	Fully operational GIS Updated on a regular basis and contained all key assets All assets are digitized in GIS with attributes and unique references (DMA polygons, boundary valves, inlet outlet meters, pressure monitoring points)	Fully operational GIS Updated within a week of any changes All assets are digitized in GIS with attributes and unique references (DMA polygons, boundary valves, inlet outlet meters, pressure monitoring points) All customers and revenue meters geo-coded, with unique reference that matches with billing system records All items have elevation data All assets have complete information & attributes	Fully operational GIS Updated within 24 hours of any changes All assets are digitized in GIS with attributes and unique referencing (DMA polygons, boundary valves, inlet outlet meters, pressure monitoring points, customer connections) All customers and revenue meters geo-coded, with unique reference that matches with billing system records All items have elevation data Additional information digitized (such as leaks, repairs, customer contacts)
	Hydraulic model	No hydraulic model Only operational knowledge of network hydraulics	A simple, static hydraulic model Updated occasionally	Calibrated hydraulic model based on GIS updates Maintained and updated regularly	Fully integrated, dynamic hydraulic model linked with real-time DMA data (SCADA) and GIS
Demand Estimates	Population served	Based on the Government Census Data	Based on high level company data	Based on zonal or regional data	Based on DMA specific data
	Consumption	Consumption measurement accuracy within +/- 20% Manual eyeball and self-reading Paper based records No night use consumption model	Consumption measurement accuracy within +/- 15% >75% operational meter penetration Yearly Keyed meter reading with consistency checks (paper based not accepted anymore) Customer night consumption based on regional sampling with consistent and adapted peer groups reference values not older than (5) years Top 5% C&I consumers have AMI daily reading of hourly data	Consumption measurement accuracy better than +/- 10% >90% operational meter penetration >50% AMR reading with monthly consumption values, nightline & customer leakage data < 50% Keyed meter reading with consistency check at least Quarterly Top 10% C&I consumers have AMI daily reading 15min data	Consumption measurement accuracy better than +/- 5% >95% operational meter penetration 80% AMI penetration 90% daily reading with hourly values <20% AMR reading with daily consumption and nightline data Keyed meter reading not accepted anymore Large (>48m3/day) or irregular consumers that have a material effect on night lines have AMI daily reading 5min data

Sensing and Control	DMA inflow monitoring	Multiple inlets and outlets without logging Temporary DMA metering and logging Manual reads	Multiple inlets and outlets accepted only with permanent metering and datalogging if combined measurement accuracy <10% Meter data logging at least weekly	Multiple inlets and outlets accepted only with permanent metering and datalogging if combined measurement accuracy <5% Meter Data Logger or PLC sends in data daily	Multiple inlets and outlets accepted only with permanent metering and datalogging if combined measurement accuracy <2% Meter Data Logger or PLC sends in data hourly
	DMA Meter Maintenance	Reactive meter checks Meters are replaced on terminal failure	Meters replaced on fixed time frame	Modelled approach to meter replacement based on companies metering stock and testing	In addition to companies own replacement modelling, proactive flow tests every three years
	Pressure control	Temporary pressure readings Adjustment for AZP if pressure not monitored at AZ	Permanent monitoring of pressure Adjustment for AZP if pressure not monitored at AZ.	Permanent logging of AZP and CP Time or flow modulated Pressure Management	Permanent logging of AZP and CP Pressure modulated to CP Transient Pressure Monitoring & Analytics
DMA Performance	Assessment Frequency	Infrequent (at least every 12 months)	Regular (at least every month)	Frequent (at least weekly)	Daily
	Data management and reporting	Manual process Standalone data sources and systems PC spreadsheets accepted	Multiple databases Systems with semi-automatic data validation PC Spreadsheets accepted for utilities with <20 DMAs	Unified database with automatic data validation Peer group DMAs & seasonal adjustments	Advanced Leakage Management System Using AI to detect abnormal patterns, demand trending
	KPI reporting	Manual process Updated at least every year Shared with stakeholders	Defined process for targets, sharing and actions	Integrated KPIs & dashboards	Full Audit Trail Integrated KPI Dashboard
	Data Availability	At least enough data to provide annual assessment	75% of months of the full data (9 months)	At least 44 weeks (85%) of full data	At least 330 days (90%) of full data
	Data Handling Staff	No dedicated data staff	Some staff have data responsibilities alongside other duties	Dedicated team (2-3 people) trained in relevant tools	Specialized data analytics team with advanced skills (data engineers and analysts)
Loss Management	Active leak detection	Infrequent surveys	Regular surveys at least every 24 months unless justified	Targeted approach of surveys based on flow and pressure data	Permanent Leakage Detection System (such as acoustic loggers) working alongside Advanced Leakage Management System
	Repair Times	Within 7 days	Within 3 days	Within 24 hours	Within 8 hours

TABLE A-1 DMA Maturity Matrix.

APPENDIX B DATA LOGGERS

C. Henriquez, T. Kressin, J. Sepulveda, G. Waley

DMA DATA LOGGERS

LPWAN COMMUNICATION MODES

Today lift and shift logging with local read out is still used but the availability of cost-effective remote communications has drastically increased during the last years especially with the enhancement of cellular based technology with excellent deep underground, battery lifetime and communication cost performances. As DMA meters are often installed underground and the amount of data is not too high, NB-IoT is often considered the best option to choose (see Figure B-*1 Typical installation of a NB IoT & LTE CAT M1 pressure logger using a modified hydrant cap to access the pipe.* as an example of an Installation).

Most data loggers offer today multiband and multimode connectivity so that the ease of use is unprecedented to what the industry was used just some years ago.

For Europe, North America and Australia coverage even in rural areas and read success rates have reached levels which could only described with “plug & play”. Latin America and Asia are catching up quickly and LTE / 5G based loggers provide a reasonable alternative to previously mentioned LPWAN technologies.

DATA LOGGER TRANSMISSION INTERVALS

Transmission intervals for data logging should be set to at least once every 24 hours, preferably scheduled for the early morning hours, just before normal service staff working hours. This ensures that any operational anomalies detected overnight can be addressed promptly at the start of the working day.

High-quality data loggers allow thresholds to be configured directly in the device. When these thresholds are exceeded, the logger can trigger a dedicated alarm message to prompt immediate action. However, such alarms only reflect a single snapshot in time and can easily become excessive if the thresholds are set too narrowly, leading to “alarm fatigue” where important alerts risk being overlooked.

Recent advancements in Low Power Wide Area Network (LPWAN) communications and electronic design now enable more frequent transmissions without compromising multi-year battery life. Some modern models can transmit data hourly while still achieving a 5-year battery lifespan. Hourly transmissions provide near real-time visibility, enabling operators to track evolving events in the field and respond more effectively.

With more frequent transmissions, the risk of alarm overloading is greatly reduced, as complex, multi-parameter alarm logic can be implemented in the head-end software rather than relying solely on single-value thresholds in the field device. While there are scenarios—such as rapid transient detection—where higher frequency data could offer added value, for most DMA applications hourly transmission intervals strike the right balance between operational insight and battery efficiency.

THE IMPORTANCE OF TIME / INTERVAL SYNCHRONIZATION

Interval data must be accurately time-synchronized; otherwise, they cannot be reliably used for operational analysis or decision-making. The real-time clocks in data loggers naturally drift over time due to factors such as aging of components, temperature fluctuations, design specifications, and manufacturing tolerances.

Modern LPWAN-based devices can frequently synchronize their internal clocks with internet time servers, often on a daily basis, achieving precision better than one second. This level of accuracy reduces the additional error in flow measurements to less than approximately 0.1%, making it operationally insignificant.

In contrast, older models of data loggers often drift more than five minutes from the actual time. Such discrepancies make precise calculations—especially those involving multiple inlets, outlets, or synchronized pressure and flow datasets—unreliable or even impossible.

FIT FOR PURPOSE IN INSTALLATION CONDITIONS

Besides the connectivity and battery life aspects some further selection criteria are important to consider:

Water Tightness
While many models provide a IP68 rating on paper it is important to consider the duration of exposure. When submerged under water or in installed in conditions with permanent condensation, water will migrate through plastic materials such the housing, potting or coating and can generate failures of electronics after some months or years in service. Most IP68 ratings are only valid for a limited amount of time and as there is no defined definition on depth and duration in IP68, each vendor can use different specifications.

In any case data loggers should be mounted outside the frequently area and connections should be sufficiently protected. In some cases, also animals could be attracted by specific additives of plastics and bite into cables resulting in erratic or broken connections.

External vs. Internal Antennas
While internal antennas provide an easier way of installation it is due to the nature GSM based communication at high frequencies with multiple bands (in the range of 700-1900MHz), those internal multiband antennas are a compromise which comes at the cost of performance. In the reality of underground installation, specific antennas adjusted to the target bands provide significantly better signal and connectivity.

A 10dB improved antenna signal offers by a factor 10 better signal strength: +6dB = x 4, 10dB = x 10 and +20dB is a factor x 100. A well-tuned efficient antenna can be compared to a tuning fork where it resonates only efficiently on a single band frequency (and its harmonics).

Beside the pure connectivity "yes or no" status, it also important to consider that if the signal is weaker, the data logger will transmit at higher power with lower data rates and/or more repetitions – thus is resulting in a reduced battery life and potential loss or delay of data.

Configuration Interface

The data logger needs to be easy to configure by the field team. In the past, often a dedicated complex PC software was used with special hardware interfaces to communicate via wired serial or infrared interfaces. Those setups require special additional hardware interfaces and training.

Today Near Field Communication (NFC) or Bluetooth are more readily available. These technologies enable the logger to be configured and activated in more challenging conditions. Although Bluetooth is more energy hungry and can require a special wake up procedure (e.g. via swiping a magnet), it offers the possibility to communicate through the closed chamber lid, therefore enabling call tests to check signal strength in real world environments. NFC is an alternative option, where the target data logger device is directly selected by bringing the mobile phone close to it and no special pairing or wake up step is needed. However, some utilities do not allow the use of NCF or Bluetooth due to cyber security concerns.

FIGURE B-1 *Typical installation of a NB IoT & LTE CAT M1 pressure logger using a modified hydrant cap to access the pipe.*

LOGGER INTERFACE AND APPLICATION SUITABILITY

Table B-2 summarizes meter to logger interfaces and their application suitability and following sections explain them in more detail.

TABLE B-2 Flow meter to logger interfaces summary.

Method	Description	Pros	Cons	Suitability for DMA
Volume Pulses per Interval (PIV)	Logger counts pulses per interval.	Simple and widely used Reverse flow detection possible	Poor resolution at low flow if large turndown ratio is required	Most suitable for DMA applications
Pulse Interval Time (PIT)	Logger measures time between pulses	Efficient for low or no-flow periods Captures short high-flow bursts accurately	Complex processing Poor synchronization in multi-inlet/outlet DMAs	Rarely used in DMA
4–20 mA Analog Interface	Flow rate represented as current (4 mA = min, 20 mA = max).	Industry standard Continuous flow representation	Power hungry Not suitable for battery-powered devices	mains-powered production meters
Modbus (RTU/ASCII)	Serial protocol over RS-485/RS-232.	Open and widely supported	No security Master-slave only High power use	Not used in battery-powered DMA metering (reserved to production meters)
HART	Digital over 4–20 mA, used in process industries.	Digital over analogue wiring Widely adopted in industry	Slow & Power intensive	
M-Bus (EN 13757)	Wired protocol designed for metering.	Low power Long cable runs Real index transmission	Limited to specific regions Not ideal for high flow/short intervals	Suitable for battery-powered DMA, but logger options limited

PULSE INTERVAL VOLUME BASED (PIV) INTERFACE

Pulses per Interval Volume Based (PIV) is the most widely used interface method for connecting a flow meter to a data logger. In its simplest form, it relies on a mechanical reed switch located inside the meter, which is briefly closed each time a magnet in the register passes by—typically after a defined volume of water has passed (e.g., every 100 litres). The data logger monitors the state of this contact and counts the number of closures, or “pulses,” within the configured logging interval.

Although the term “pulse output” is commonly used in the industry, it is technically imprecise, as the signal is actually a change in the contact state rather than an electrical pulse. Modern electronic interfaces—either for mechanical meters or for the electronic registers of static meters—replicate this functionality using a semiconductor switch instead of a mechanical reed. This provides higher reliability and longer operational life.

Many meter models today also offer enhanced functionality, such as the ability to measure reverse flow by providing a second output or an additional status line.

When using pulse outputs, it is critical to carefully select both the pulse weight (volume represented by each pulse) and the logging interval. Incorrect configuration can lead to two main problems:

- Missed pulses – This occurs when the maximum counting frequency of the logger is exceeded (less common).
- Insufficient resolution at low flows – This is a frequent issue, especially for night flow monitoring, where low pulse rates make the data unusable.

As a general rule, at the lowest expected flow rate, the logger should record at least 10 pulses per logging interval to ensure meaningful data resolution.

Example:
With a 15-minute logging interval and a pulse weight of 100 L/pulse, the minimum flow rate should not drop below **4 m³/h**:
100 L × 10 pulses per 15 min = 4 m³/h (≈ 1.1 L/s).

If the flow rate falls below **3 pulses per logging interval**, the data loses accuracy and becomes unreliable for analysis.

Most static meters allow the pulse weight to be reconfigured via software, while modern mechanical meters equipped with incremental inductive encoders often support interchangeable pulse modules with different pulse weight resolutions, enabling optimization for specific operational needs.

PULSE INTERVAL TIME BASED (PIT) INTERFACE

Historically, the use of PIT (Pulse Interval Time) mode was driven by the limitations of memory capacity and data transmission bandwidth. In this mode, the logger records the time interval between two successive pulses and calculates the corresponding flow rate. Unlike conventional fixed-interval logging, there are no predefined recording periods; instead, the timing of each pulse determines the data capture points.

The main advantage of PIT is its efficiency in scenarios where flow is very low or intermittent. For example, in residential metering applications, if the meter remains stopped for long periods (such as at night), only minimal data needs to be stored and transmitted. Conversely, if short-term, very high flow rates occur, PIT captures these peaks accurately, as each pulse is individually timed.

In DMA monitoring, flows are usually continuous, and the primary focus is on maintaining synchronized datasets across multiple meters and loggers, however PIT can be very useful in small DMAs with low flows to provide a more accurate calculation of MNF. In some loggers it is possible to log both PIV and PIT in separate channels and transmit this data to the servers for further analysis.

4-20 MA INTERFACE – SOURCING VS. SINKING

The 4–20 mA analogue signal is a long-established standard in industrial instrumentation for transmitting measurement data. In flow metering, it is used to represent the flow rate as a proportional current signal. For example, 4 mA might correspond to the minimum flow (e.g., 0 m³/h) and 20 mA to the maximum flow (e.g., 100 m³/h). The data logger reads this current, converts it into a flow rate, and can then calculate cumulative consumption.

Two electrical configurations are common:
- Sourcing mode: The meter supplies the current loop to the logger.
- Sinking mode: The logger supplies the current loop to the meter.

In both cases, the continuous nature of the current loop presents a significant power demand. For battery-powered meters or data loggers, this results in severely reduced battery life, making the method impractical for long-term field deployments. Consequently, the 4–20 mA interface is generally limited to production meters or other applications where mains power is available.

Some data loggers address this limitation by sampling the current loop only at set intervals rather than continuously. However, this approach eliminates the main advantage of the 4–20 mA method—permanent, real-time monitoring—and in such cases, a PIV (Pulse Interval Volume) interface would usually be the more efficient and effective option.

WIRED SERIAL PROTOCOL BASED INTERFACES

A variety of wired communication protocols are available for connecting flow meters to SCADA systems, PLCs, and data loggers. Their suitability depends heavily on power availability, data resolution requirements, and system integration capabilities.

Modbus (RTU/ASCII over RS-485 or RS-232)

Modbus is a widely used, open protocol, common in SCADA, PLC, and industrial metering applications.
- **Pros:** Broad industry support, open standard, simple and robust design, reliable over RS-485 for multi-drop networks.
- **Cons:** No built-in security, limited to master–slave architecture, requires protocol knowledge for proper integration, relatively high-power consumption.

HART (Highway Addressable Remote Transducer)

HART allows both analogue and digital communication over a standard 4–20 mA current loop, typically used in process industries and mostly available for production-grade meters.
- **Pros:** Can overlay digital data on existing analogue wiring, widely adopted in process control environments.
- **Cons:** Slow communication rates, relatively high-power consumption, impractical for battery-powered long-term deployments.

M-Bus (Meter-Bus, EN 13757 standard)

Designed specifically for metering, M-Bus supports large multi-device networks and long cable runs.

- **Pros:** Purpose-built for metering, supports up to 250 devices, low power consumption compared to other industrial protocols, capable of transmitting the actual meter index, suitable for cable lengths up to 1 km.
- **Cons:** Less common outside European markets, less suited for applications requiring high flow rate logging or very short intervals, higher power demand than simple pulse-based interfaces.

For battery-powered DMA flow monitoring requiring multi-year operation, neither Modbus nor HART are commonly used due to their relatively high energy demand. In these cases, wired M-Bus maybe better suited. However, their adoption can be limited by the availability of compatible data loggers and local market support.

In production metering or at reservoir locations where mains power is available, these higher-power protocols can be implemented effectively. In such cases, the main challenge often shifts from hardware constraints to head-end system integration, particularly when managing diverse datasets and multiple communication protocols.

CONNECTING TWO DATA LOGGERS TO THE SAME OUTPUT

If the data logger is connected to the meter through a volt-free “open collector” contact—also commonly called a pulse output—it is possible to share the same output signal with two separate data loggers by using a pulse splitter box.

A pulse output works like a simple electrical switch inside the meter that closes and opens in proportion to the volume of water passing through it. Each time the switch changes state, it sends a “pulse” signal representing a fixed volume of water (for example, 1 pulse = 1 litre). A volt-free or “open collector” design means that the signal is electrically isolated from the meter’s own power system, making it safe and compatible with different logging devices.

By installing a pulse splitter, the signal from the meter can be sent to two different logging systems at the same time. The exact technical specifications—such as voltage, current limits, and pulse duration—must be confirmed for both the meter and the data loggers to ensure compatibility and avoid signal errors.

This setup is particularly useful when the water consumption data needs to be used for two different purposes. For example:

- Logger channel one could be connected to the SCADA system, recording data at a standard interval such as every 15 minutes for operational monitoring.

- Logger channel two could be configured for fast logging at 1-minute intervals, sending the data to specialized NRW analysis software to allow more accurate MNF assessment.

By combining both, utilities can maintain a consistent operational record in SCADA while also capturing the high-resolution data needed for advanced leakage analysis and network diagnostics.

APPENDIX C ASSESSMENT OF UNCERTAINTY BUDGETS

G. Waley

In addition to Chapter 3, this Appendix provides a more detailed assessment of uncertainty budgets associated with primary measured data (electromagnetic, ultrasonic and mechanical flow meters, and pressure measurements), as well as with derived parameters such as water balance calculations and MNF estimation methods.

PRIMARY MEASUREMENT UNCERTAINTY

FLOW MEASUREMENT UNCERTAINTY

Flow measurement uncertainty varies significantly with meter technology, installation conditions, and operating point within the meter's range.

Electromagnetic Flow Meters

Electromagnetic meters typically exhibit accuracy specifications of ±0.2% to ±0.5% of reading, with additional zero-stability specifications. The standard uncertainty comprises multiple components:

Meter Accuracy: Manufacturer accuracy class converted to standard uncertainty. For a specified accuracy of ±a% at 95% confidence (coverage factor k = 2):

$$u_{accuracy} = (a/100) \times Q / 2$$

where Q represents the measured flow rate.

Zero Stability: Drift in zero reading affects absolute uncertainty, particularly significant at low flows. Zero stability specifications typically range from ±0.5 to ±2 mm/s velocity equivalent. Converting to volumetric uncertainty:

$$u_{zero} = v_{zero} \times A / \sqrt{3}$$

where v_{zero} is the zero-stability specification and A is the pipe cross-sectional area. Division by √3 assumes rectangular probability distribution.

Installation Effects: Non-ideal installation (insufficient straight pipe lengths, eccentric mounting, flow disturbances) introduces additional uncertainty. Conservative estimates suggest 1-3% additional uncertainty for partially compliant installations:

$$u_{installation} = 0.01 \text{ to } 0.03 \times Q / \sqrt{3}$$

Temperature Effects: Operating temperature deviation from calibration conditions affects measurement accuracy. Typical temperature coefficients range from 0.1% to 0.2% per 10°C:

$$u_{temperature} = \alpha_T \times \Delta T \times Q / \sqrt{3}$$

where α_T is the temperature coefficient and ΔT is temperature deviation.

Ultrasonic Flow Meters

Transit-time ultrasonic meters demonstrate similar accuracy specifications but with distinct uncertainty characteristics:

Path Configuration: Multi-path configurations (2, 4, or 8 acoustic paths) reduce uncertainty compared to single-path installations. Single-path uncertainty typically ranges from ±1% to ±2%, while four-path configurations achieve ±0.5%.

Signal Quality: Degraded signal-to-noise ratio from pipe conditions increases uncertainty. Signal strength monitoring enables adaptive uncertainty quantification:

$$u_{signal} = f(SNR) \times Q$$

where f(SNR) represents an empirically determined function relating signal quality to measurement uncertainty.

Reynolds Number Effects: At low Reynolds numbers (<10,000), velocity profile assumptions become less accurate, increasing uncertainty. Flow-dependent uncertainty functions should reflect this behavior:

$$u_{Q(Re)} = u_{base} \times [1 + \beta \times \exp(-Re/Re_0)]$$

where β and Re_0 are empirically determined profile sensitivity parameters.

Mechanical Meters

Turbine meters exhibit non-linear uncertainty characteristics strongly dependent on flow rate relative to capacity:

Rated Accuracy Zone: Within the optimal flow range (typically 30-100% of Q_{max}), manufacturer accuracy specifications apply directly.

Low Flow Degradation: Below 30% of rated capacity, uncertainty increases substantially. Empirical characterization requires:

$$u_{Q\ (q)} = u_{nominal} / [1 - \exp(-q/q_{threshold})]$$

where $q = Q/Q_{max}$ is the normalized flow rate and $q_{threshold}$ represents the onset of degraded performance.

Wear Effects: Mechanical wear progressively degrades accuracy. Time-since-installation should factor into uncertainty assessment:

$$u_{wear\ (t)} = k_{wear} \times \sqrt{t} \times Q$$

where k_{wear} represents an empirically determined wear coefficient.

PRESSURE MEASUREMENT UNCERTAINTY

Pressure transducer uncertainty typically ranges from ±0.1% to ±0.25% of full scale, requiring careful consideration of installed range versus measurement range.

Full-Scale Referenced Uncertainty

Manufacturer accuracy specifications referenced to full scale result in absolute uncertainty independent of measured value:

$$u_{P,base} = (a_{FS}/100) \times P_{FS} / 2$$

where a_{FS} is the accuracy class as percentage of full scale and $P_{FS<}$ is the maximum rated pressure.

This creates proportionally higher relative uncertainty at lower pressures. For pressure measurements at 10% of full scale, relative uncertainty increases tenfold compared to full-scale measurements.

Temperature Compensation Uncertainty

Temperature-compensated transducers introduce additional uncertainty from compensation algorithm imperfection:

$$u_{temp,comp} = u_{compensation} \times |\Delta T| / \sqrt{3}$$

where $u_{compensation}$ represents residual temperature coefficient after compensation (typically 0.01-0.05% FS per °C).

Long-Term Stability

Pressure sensor drift over time contributes to uncertainty between calibration events:

$$u_{drift\ (t)} = d_{annual} \times \sqrt{(t/12)} / \sqrt{3}$$

where d_{annual} is the annual drift specification (typically 0.1-0.25% FS/year) and t is time in months since calibration.

Combined Pressure Uncertainty

$$u_P=\sqrt{(u_{P,base}{}^2 + u_{temp,comp}{}^2 + u_{drift}{}^2 + u_{calibration}{}^2)}$$

TEMPORAL RESOLUTION AND INTEGRATION UNCERTAINTY

Time-series integration for cumulative volumes introduces additional uncertainty components:

Sampling Interval Effects: Discrete sampling at interval Δt approximates continuous integration. For signals with characteristic frequency f_{char}, the integration uncertainty is approximately:

$$u_{sampling} \approx 0.1 \times Q_{variation} \times \sqrt{(\Delta t \times f_{char})}$$

where $Q_{variation}$ represents the standard deviation of flow variation.

Data Gap Interpolation: Missing data periods require interpolation, introducing uncertainty proportional to gap duration and flow variability:

$$u_{gap} = \sigma_Q \times \sqrt{(t_{gap}/t_{ref})}$$

where σ_Q is the standard deviation of flow during similar periods and t_{ref} is a reference averaging period.

DERIVED PARAMETER UNCERTAINTY

WATER BALANCE COMPONENT UNCERTAINTY

A volumetric water balance is an arithmetic subtraction of water demand components from the water supplied into the DMA, using daily volumes, and calculating water loss as a balancing item. It is commonly referred to as a “top-down” water loss calculation as described in Section 4.2.2.

For water losses (real or apparent) to be derived as the balancing item in the water balance all of the components of water use need to be identified for them to be measured or estimated. Also, the timeframe for conducting the balance is important. The following 3 overarching factors drive the uncertainty in the top-down water balance water loss calculation:

Measurement Uncertainty

The measurement uncertainty will be from a combination of the following factors which have already been set out in this document within the Uncertainty Budget Structure section above. The overall aggregated uncertainty can be quantified from these factors stated below.

- **Instrument Measurement Uncertainty** including the data acquisition steps of the workflow.
- **Instrument Calibration Uncertainty** e.g. extent and age of calibration.
- **Instrument Installation Uncertainty** including dimensions and condition of surfaces and sensors.
- **Temporal Uncertainty** from sampling intervals, interpolation and alignment.
- **Model Uncertainty** in applied computations.
- **Operational Uncertainty** related to system state variability and boundary condition definition.

Estimation Uncertainty

The estimation uncertainty will be determined by the input data and methodology used to make the estimation. The estimation could rely on extrapolation, a sampling approach (limited in scope or highly statistically significant), engineering judgement, benchmarking, previous experience or guess work. By definition the uncertainty of the estimated range cannot be known. Therefore, an engineering judgement is likely to be required to qualify the estimation uncertainty into a value. The lower the penetration of customer metering the higher the reliance on estimates.

Timeframe Uncertainty

Water balance period – at a minimum 9 days of DMA flows, including 2 weekends, is an absolute minimum duration to target. However ideally the timeframe for the DMA analysis will align with available meter reads to reduce interpolation errors. This may extend the period to several months. When this isn't possible then temporal uncertainty from interpolation will need to be accounted for.

This period allows volume averages to be built up establishing a stable set of conditions and observation in the difference between weekdays and weekends. This assists in letting random errors play out, outlier errors to be identified as such, periods of instability to be identified and quarantined, and global allowances to be more confidently applied to the average situation over a number of days.

Overall Water Balance Uncertainty

The "top-down" water balance water loss calculation is an arithmetic subtraction from the water supplied into the DMA. The overall uncertainty calculation is aggregated using a Root-Sum-Square (RSS).

This method can provide the best certainty for evaluating absolute leakage volumes over time periods of weeks or months. By extension this source of leakage volumes is often preferred for reporting leakage volumes and inputting to the evaluation of leakage performance indicators (PI). Where this may not be the case is when customer meter penetration is very low. The efficacy of the reported leakage volumes comes down to the management and mitigation of the uncertainty factors.

MINIMUM NIGHT FLOW UNCERTAINTY

The MNF water loss calculation is an analysis of the water supplied into a DMA during the period of lowest customer water use as described in Section 4.2.3. This period, typically 2-4am in many residential areas, is chosen for analysis as any water loss present in the DMA will be at its highest proportion of the DMA flow - an attribute which assists in the identification of excess flow as water loss. It is commonly referred to as a "bottom-up" water loss calculation.

In one respect the MNF benefits from a simpler calculation as the analysis window can have less demand components due to minimal active water users being present within the analysis period. However, the MNF analysis is highly sensitive to several factors:

- Accurate data acquisition of the true minimum DMA net flow.
- Modelling of night use to represent the segments of the customer base.
- Identification and quantification of all users including Exceptional Night Use (ENU).
- Measuring and accounting for the impact of diurnal pressure profiles .

The inclusion of pressure profiles, and effects on leakage flow, is a notable source of additional uncertainty within the MNF algorithm compared to the top-down approach. Pressure contributes in two ways to each specific DMA;

- How much the average pressure within the zone changes from day-night (i.e. high demand – low demand) due to head losses.
- The pressure-leakage relationship which is the response of the individual leak flow paths to the pressure in the zone as described by the fixed and variable area discharge (FAVAD) relationship.

For volumetric water loss to be derived from a MNF analysis the DMA net-flow needs to be measured, all components of night water use need to be measured or estimated, the Average Zone Pressure (AZP) recorded, and the pressure-leakage relationship accounted for. There are now five over-arching factors driving the uncertainty in the MNF water loss calculation:

Measurement Uncertainty

The measurement uncertainty will be from a combination of the factors which have already been set out in this document within the Uncertainty Budget Structure section.

Estimation Uncertainty

The lower the penetration of customer metering in the DMA the higher the reliance on estimates. The mature way to produce night use (NU) estimates is from models which take customer segment and annual billed volume (ABV) and relate these to NU. Then NU allowances become available for all customers even if they are not metered or logged.

The uncertainty of the night-time use model outputs, at the DMA level, rests on the following factors:

- statistical significance of the measured input data
- strata applied to produce customer segments
- extent of unmetered customers and unlogged ENUs present in the DMA
- local water uses behaviors of the unmetered/unlogged customers when compared to the average water use behaviors of their respective customer segments.

Day-Night Factor Uncertainty

The diurnal pressure profile needs to be understood and applied to the evaluated nighttime leakage, as a factor, in order to derive a 24-hour leakage volume from the nighttime leakage flow rate calculated during the MNF period. This is called the night-day factor (NDF).

This part in the MNF algorithm is crucial because it accounts for when the pressure, and hence leakage flow rate, varies from day to night. In many gravity fed zones the network pressure at night is at a maximum resulting in a maximum leakage flow rate. This however doesn't hold in the case where there is active pressure management or booster pumping. In the process of translating night-time leakage into 24-hour leakage the following uncertainty factors arise:

- Successful measurement (or estimation) of the average zone pressure (AZP) and the average zone night pressure (AZNP)
- Selection of the day-time timeframe and the night-time timeframe

Pressure-Leakage Relationship Uncertainty

- The pressure-leakage relationship is how the flow rate of a leak path varies in relation to changes in pressure. This is an important factor because leak orifice areas are not always fixed as pressure varies. The obvious example being a longitudinal split in a plastic pipe where the orifice will increase in size when pressure increases. Furthermore, the behavior of multiple background leak paths across multiple pipe material types responds differently to pressure than a hole in a ductile iron pipe.
- The pressure-leakage relationship is described by the fixed and variable area discharge (FAVAD) power law shown below
- $L_1 = L_0(\frac{P_1}{P_0})^{n_1}$ where

  L_1 - leakage flow at pressure 1 (future leakage rate)

  L_0 - leakage flow at pressure 0 (current leakage rate)

  P_1 - pressure 1 (pressure changes may come about from e.g. re-zoning, pressure management, mains rehabilitation)

  P_0 - pressure 0

  n_1 - Power law exponent (varies between 0.5 and 2.5)

Uncertainty arises dependent on how well the variables are measured or estimated.

Timeframe or Temporal Uncertainty

The MNF analysis needs to be supported by metered data which has been collected at minute or hourly sampling rates. If using industry, or company, norms as allowances then the selected DMA net-flow sampling rate will need to match that intended for use with the night-use allowances e.g. 1min, 5min, 15min. Note: UK allowances are based on 15min sampling rate.

MNF analysis period – Night to night analysis for immediate reactive leakage targeting. Times of the year which coincide with cultural habit changes e.g. Christmas, New Year or Ramadan should be avoided.

Overall MNF Analysis Uncertainty

The MNF analysis water loss calculation is approach which is quick to reveal changes in leakage rates and is an algorithm which translates the water loss from the period of minimum water use to a 24-hour leakage volume for the DMA. The overall uncertainty calculation is an aggregation using a root-sum-square (RSS). The combining of uncertainties for MNF analysis has to ingest both pressure and volume variables. The FAVAD element of the leakage-pressure relationship has a variable exponent n1 in the power law.

Note: MNF analysis requires higher sampling rates than the top-down approach.

Whilst the MNF analysis can have a higher absolute uncertainty for calculating 24 hour leakage, it can provide a much lower uncertainty when monitoring relative leakage changes night to night. This is because a lot of the uncertainty factors can manifest in the same way each night, creating repeatable systematic bias, which provides a clear signal from the relative leakage changes.

APPENDIX D USING HYDRAULIC MODELS TO ESTIMATE DMA WATER LOSSES

A. Bojko, I. Dundovic, M. Nicol, F. van de Hulst

Hydraulic modelling is a powerful tool for the design, analysis, and management of water distribution networks, particularly in the context of DMAs. A calibrated model enables utilities to estimate real losses, understand operational behavior, and evaluate strategies for reducing Non-Revenue Water (NRW). Once calibrated, the model can help estimate real and apparent losses within the DMA.

WATER LOSS DETECTION USING HYDRAULIC MODELS

The following mechanisms are common for water loss detection using hydraulic models of DMA:

Flow and Pressure Discrepancy Analysis
By comparing simulated flow and pressure values with observed data from field sensors (e.g., flow meters and pressure gauges), hydraulic models can identify anomalies such as unexpected pressure drops or unexplained flow increases. These discrepancies often point to leaks or unauthorized water usage within the network. For example, nocturnal flow analysis, where consumption is expected to be minimal, helps isolate areas with higher-than-expected flows attributed to leaks.

Leakage Modelling and Pressure-Leakage Relationships
Hydraulic models incorporate pressure-leakage relationships to simulate how changes in pressure impact leakage rates. Empirical equations, such as the Orifice Equation, are used to model leaks as a function of pipe pressure and leak characteristics. Higher pressures typically exacerbate leakage, and hydraulic models can simulate scenarios to determine thresholds for pressure management aimed at reducing losses (Lambert, 2001).

Precise Estimation of AZP
Pressure data within a DMA is often limited to permanent sensors installed at the inlet and at a critical point, or to short-term measurement campaigns. The most accurate estimation of the Average Zone Pressure (AZP) can be obtained from a calibrated hydraulic model of the DMA, where pressures are simulated across all nodes and time steps. This significantly improves the accuracy of water loss estimation, which is highly sensitive to the precision of AZP, as discussed in Chapter 4.

Validating DMA Flow Components
The hydraulic model can be effectively used to validate the different DMA demand components, including physical losses (leakage flow and patterns), apparent losses, and night consumption. Demand allocation in the model typically includes the spatial distribution of billed consumption with associated diurnal profiles, leakage rates and patterns, and apparent losses estimated using the formulas presented in Section 4.2.3. Once all components are incorporated, the simulated total DMA inflow is compared with the measured flow at the DMA entry. Any

discrepancy in magnitude or profile highlights potential inaccuracies in the estimated components and supports their refinement.

DMA Analysis

Hydraulic models simulate the expected consumption and pressure patterns within DMAs based on demand data, network topology, and recorded measurements. Any discrepancies between modelled and measured values within a DMA can localize potential leak zones for further investigation.

Inverse Modelling for Leak Detection

Inverse modelling techniques use hydraulic models to estimate the location and magnitude of leaks by optimizing model parameters to match observed data. This approach often employs advanced computational algorithms, such as genetic algorithms or artificial neural networks, to refine leak estimates.

Scenario Testing for Loss Reduction Strategies

Hydraulic models allow scenario testing of interventions, such as pressure management, pipe replacement, or valve adjustments, to evaluate their effectiveness in reducing water losses. By simulating these scenarios, utilities can prioritize actions based on cost-benefit analyses and operational feasibility.

CALIBRATION PROCESS

Calibration serves as the critical link between mathematical simulation and physical reality. This process involves:

- Systematic comparison of model predictions against field measurements
- Identification of discrepancies between simulated and observed values
- Targeted adjustment of model parameters to achieve acceptable agreement
- Validation of calibrated parameters across various operating conditions

This iterative methodology requires both technical expertise and structured approach to ensure the resulting model accurately represents network behavior under both steady-state and dynamic conditions.

An important remark on calibration is that the current network structure is not changed. So, to start a calibration process it is important to have all pipes, valves and pumps correctly identified and documented in the hydraulic model. Also pressure monitoring and consumptions parameters is invaluable to document correctly.

HELPFUL TIPS

Pressure monitoring locations should be selected to provide comprehensive coverage of pressure zones, elevation variations, and known hydraulic constraints.

REQUIRED DATA FOR CALIBRATION

Pressure measurements constitute the primary calibration dataset. Quality pressure data acquisition requires strategic deployment of pressure sensors. Pressure sensors can be placed best on points with high observability, i.e. where pressure transducers can best represent the unmeasured points in regard of the hydraulic equations.

Flow measurements complement pressure data by quantifying water movement through the system:

TABLE D-1 Typical measurement types in DMAs.

Measurement Type	Typical Range	Recommended Accuracy
Inlet Transfer Flows	10-1000 l/s	±2%
Consumption Patterns	0.1-100 l/s	±5%
Fire Flow Testing	20-40 l/s	±5%

Flow measurements should be collected at boundary points, major trunk mains, DMA interfaces, and representative consumption points.

CALIBRATION PARAMETERS AND SENSITIVITIES

The calibration process typically focuses on adjusting several key parameters with varying degrees of influence on model behavior. The Table below summarizes these parameters and their typical sensitivity impacts:

TABLE D-2 DMA calibration parameters and their sensitivity.

Parameter Category	Sensitivity Impact
Pipe Roughness Coefficients (C-factor or k)	High
Minor Loss Coefficients	Medium-Low
Demand Allocation Factors	High
Control Element Settings	High (localized)
Network Connectivity	Very High (localized)

Calibration efforts should prioritize parameters with high sensitivity values. Adjusting parameters with low sensitivity may mask actual network conditions without improving model accuracy.

AUTOMATED CALIBRATION PROCESS

Contemporary hydraulic modelling platforms incorporate sophisticated automated calibration functionality to synchronize model outputs with field measurements. These systems algorithmically adjust critical parameters including pipe roughness coefficients, demand allocation factors, and control element settings to minimize discrepancies between simulated and observed hydraulic behaviors. The calibration process employs advanced optimization techniques including genetic algorithms, differential evolution, particle swarm optimization, and Bayesian statistical methods.

The automated calibration process typically follows these steps:

- Import field measurement data (pressure readings, flow rates, etc.)
- Define calibration parameters and their acceptable ranges
- Group elements with similar characteristics (by age, material, zone)
- Set optimization criteria and error metrics
- Execute iterative simulation sequences
- Automatically adjust parameters to minimize differences
- Validate results across multiple operating conditions

Leading-edge platforms now integrate machine learning capabilities and surrogate modelling approaches to accelerate computational processes and facilitate adaptive calibration protocols with near-real-time responsiveness. Calibration outputs generally comprise prioritized parameter configurations, comprehensive error metrics, and diagnostic information for model reliability assessment.

An example is the Darwin Calibrator in Bentley's WaterGEMS uses genetic algorithms to find optimal combinations of roughness values, demand multipliers, and other parameters (Bentley Systems, 2025). The process imports field measurements, sets parameter boundaries, and runs multiple simulations to evolve better parameter combinations. It supports both steady-state and extended-period calibration, providing comprehensive validation capabilities. Effective use requires careful preparation of observational data, defensible parameter ranges, and logical grouping strategies (e.g., by pipe material or installation era). Though operating in batch mode rather than real-time, Darwin is valuable for initial configuration and periodic recalibration after field measurement campaigns.

APPLICATION OF HYDRAULIC MODELS

A properly calibrated hydraulic model supports numerous water utility functions without requiring disruptive field interventions. While detailed exploration of these applications falls outside our current scope, calibrated models enable:

- Network optimization and energy efficiency initiatives
- Pressure management planning and implementation
- Resilience assessment and contingency planning
- Water quality simulations and residence time analysis
- Capital improvement planning and infrastructure sizing
- Operational troubleshooting and anomaly detection
- Design and implementation of expansions of the network
- Regulation compliance simulation, such as minimal pressure requirements, or fire hydrant capacity.

The calibration effort should be tailored to support the intended applications, with more stringent calibration typically required for water quality modelling than for general hydraulic analysis.

APPENDIX E DMA PRESSURE ANALYSIS

T. Crowder

This Appendix examines the influence that pressure has on leakage, and at the end, we will demonstrate how applying pressure adjustments can correct the level of background losses in two example DMAs. It outlines the key principles and data requirements for effective pressure monitoring at Average Zone Points (AZPs). We introduce the concepts of Discreet Pressure Areas (DPAs), explaining their importance in DMA leakage calculations.

DISCREET PRESSURE AREAS

For DMA pressure analysis to be applied accurately, DPA residing at DMA level or below needs to be set up and configured appropriately with an AZP. There are three different scenarios to cater for in the setup of DPAs which are explained in the table below.

TABLE E-1 DMA Discreet Pressure Area Setup Scenarios.

DPA Scenario	DPA Description
Entire DMA	DMAs with no internal pressure managed areas, or those fully pressure managed at the inlet. In this case, the entire DMA functions as a single DPA.
Pressure Managed Area (PMA)	PMAs have pressure controlling assets at inlets which alter downstream pressure, such as pressure control valves, pumps or boosters, or service reservoirs. Each PMA forms its own DPA and therefore requires one AZP.
Residual Pressure Area (RPA)	The RPA represents portion of DMA that is not pressure managed but still sits alongside PMAs. Each RPA acts as a separate DPA and requires its own AZP.

FIGURE E-2 *DMA Discreet Pressure Area Illustration.*

Figure below shows an illustration of a DMA with 1,000 properties consisting of two PMAs and one Residual Pressure Area. In total, this DMA has three DPAs and therefore requires three AZPs to apply pressure analysis accurately.

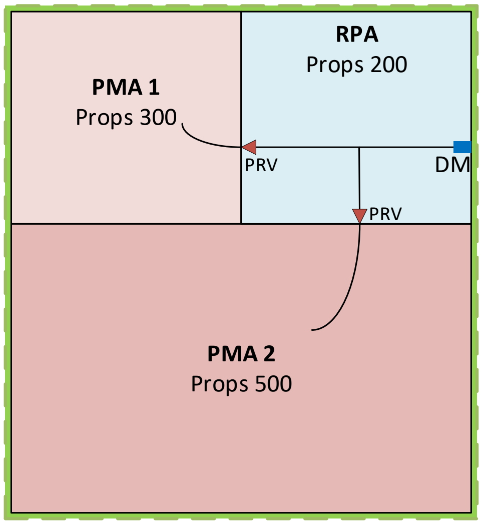


FIGURE E-2 *DMA Discreet Pressure Area Illustration.*

Continuous pressure monitoring across each DPA is essential to ensure that pressure remains within the required standards and to obtain key parameters used in adjusting DMA leakage calculations. In practice, pressure is typically measured at DPA inlets, high-point locations, and representative average zone points. An example of permanent pressure monitoring within a DPA is shown in the figure below:

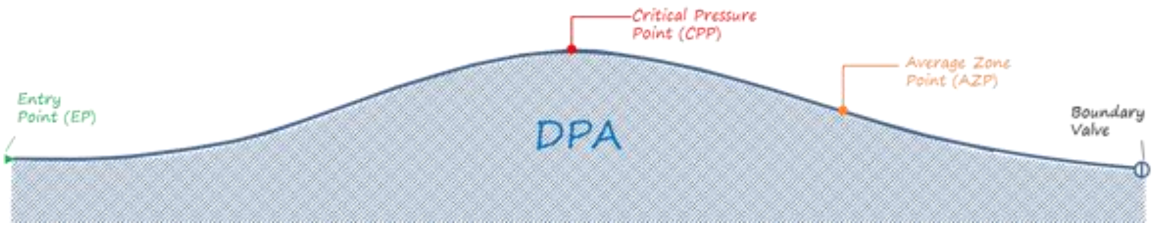


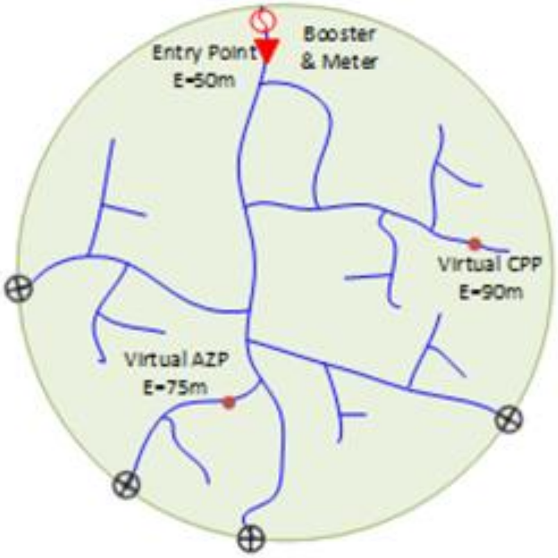
FIGURE E-3 *DPA Pressure Monitoring Points Illustration.*

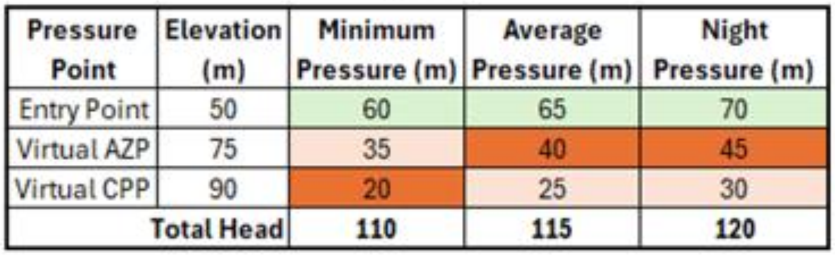
USE OF SURROGATE PRESSURES

It is always preferable to directly monitor the AZP and Critical Pressure Point (CPP) within a DPA. However, where this is not possible, virtual AZPs and CPPs can be generated. The virtual AZP should be located at the average property height within the DPA and used to determine the average pressure, AZNP, and NDF. The virtual CPP should be located at the highest service connection elevation within the DPA and used to monitor the minimum level of service and assess the potential for pressure reduction.

Surrogate pressures are monitored by pressure sites within a DPA, such as Entry Points, that are associated with a virtual AZP and CPP. These sites provide pressure data from which pressures at a virtual AZP or CPP can be derived, based on differences in elevation and applying head loss coefficients, where available. Surrogate pressure sites must be located within the same DPA and should be prioritized based on their proximity to virtual AZPs and CPPs. Where available, monitored water levels on storage tanks may also be used as surrogate measurements and associated with downstream virtual pressure points.

Figure in continuation illustrates a DPA comprising an entire DMA in which the actual AZP and CPP are not directly monitored. In this example, the entry point downstream of the booster station is pressure-monitored and used as the surrogate for both the generated virtual AZP and CPP. The elevations of each point and the corresponding minimum, average, and night pressures derived from the differences in elevation. This approach assumes zero head loss, such that the total head remains constant across all pressure measurement locations. In practice, head losses may occur and, where known, can be applied to adjust the differential pressure between the measured pressure point and the virtual locations. In the accompanying table, cells highlighted in green represent measured pressures, while cells highlighted in orange represent estimated pressures. Cells highlighted in dark orange indicate the key measurements required for leakage calculations and pressure management purposes





Pressure Point	Elevation (m)	Minimum Pressure (m)	Average Pressure (m)	Night Pressure (m)
Entry Point	50	60	65	70
Virtual AZP	75	35	40	45
Virtual CPP	90	20	25	30
	Total Head	110	115	120

FIGURE E-4 *Surrogate Pressures Illustration.*

KEY PRESSURE CALCULATIONS FOR LEAKAGE ANALYSIS

Leakage within a DMA varies throughout the day in response to changes in pressure. This relationship is illustrated in the figure below, which shows how pressure, monitored at the AZP, directly influences the leakage profile. The figure also highlights key pressure parameters used in DMA leakage calculations, including average pressure and AZNP.

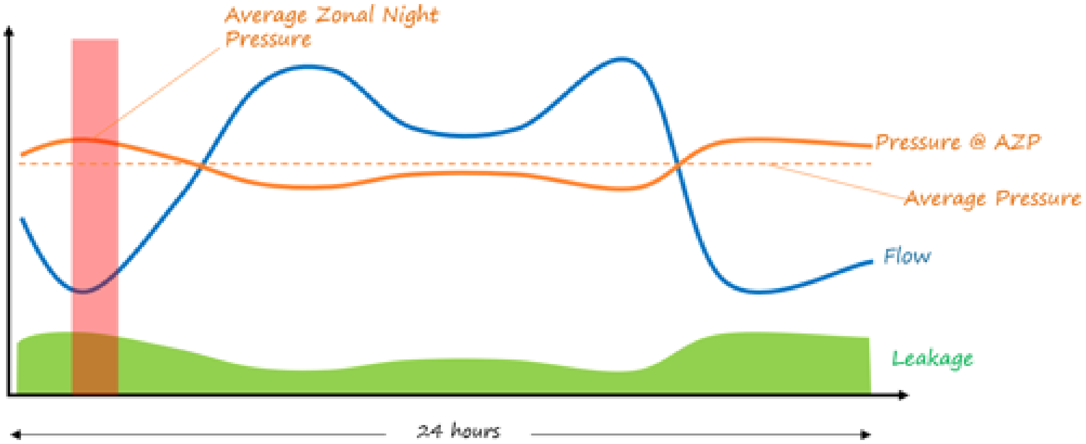


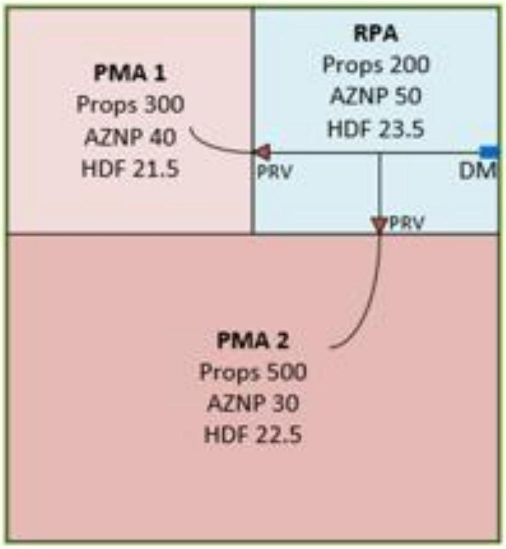
FIGURE E-5 *AZP Pressure & Leakage Illustration.*

With reference to this graphics, average pressure is defined as the arithmetic-mean of all pressure measurements recorded at the AZP over a 24-hour period, from midnight to midnight. Whilst AZNP is the corresponding pressure at the AZP at the time when the DMA Minimum Night Flow (MNF) occurs. For example, if the MNF is calculated as the average DMA net flow between

03:00 and 04:00, the AZNP would be the average pressure recorded at the AZP during the same time. Another key pressure calculation is the Night Day Factor (NDF), which is used to scale hourly night-time leakage to a daily leakage value that is representative of the full 24-hour period by adjusting the leakage using the ratio of AZNP to Average Pressure

When a DPA represents the entire DMA, these calculations are straightforward, as no aggregation is required. However, where a DMA contains multiple PMAs and RPAs, the key pressure calculations must first be determined at the AZP for each DPA and then aggregated to the DMA level using a weighted average.

Calculations below show the same example DMA with 1,000 properties, comprising two PMAs and one Residual Pressure Area. As shown, the Average Pressure, AZNP, and NDF have been calculated for each DPA within the DMA. These values have then been aggregated to the DMA level using a weighted average based on the number of properties in each DPA.



Area	Props	Weight	Average Pressure	AZNP	NDF
RPA	200	20%	49	50	23.5
PMA 1	300	30%	36	40	21.5
PMA 2	500	50%	28	30	22.5
DMA Total	**1000**	**100%**	**35**	**37**	**22.4**

FIGURE E-6 *Key Pressure Calculations Illustration.*

PRESSURE LEAK FLOW RATES RELATIONSHIP (N1)

The N1 factor describes the relationship between pressure and leakage within a DMA. A higher N1 value indicates that existing leakage is more sensitive to changes in pressure. The N1 factor is expressed as a pressure exponent, as illustrated in the graph in continuation.

In this chart, the reduction in leakage resulting from a pressure reduction is shown in percentage terms. Three curves are presented, representing N1 exponent values of 0.5, 1.0, and 1.5. For example, where the N1 value for a DMA is 1.5, a 50% reduction in pressure results in an approximate 65% reduction in leakage. In contrast, when the N1 value is 0.5, the same 50% pressure reduction achieves only around a 30% reduction in leakage. This example highlights the significant influence of the N1 factor on DMA leakage and underscores the importance of understanding the relationship between pressure and leak flow rates.

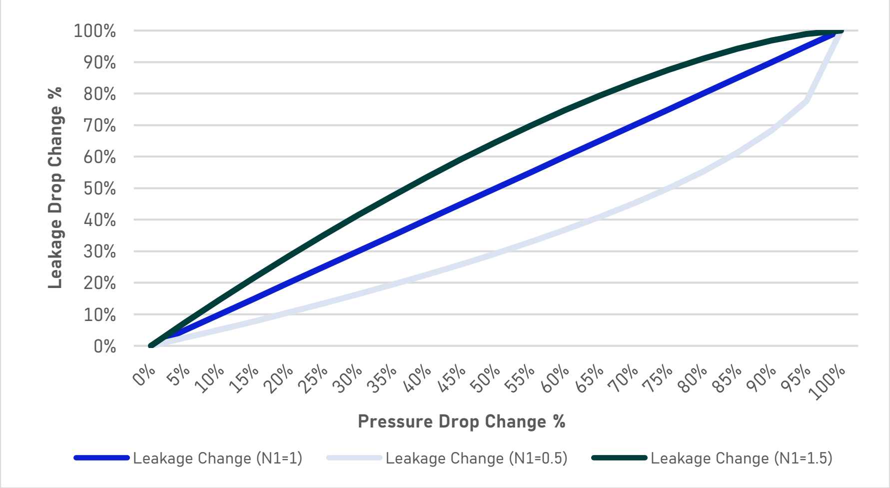


FIGURE E-7 *Pressure Versus Leakage Illustration.*

The N1 factor is DMA specific and depends on factors such as pipe material and the proportion of background versus burst leakage within the DMA. Ideally, each DMA should have its own accurately determined N1 factor, obtained through an N1 step test. During an N1 step test, pressure within the DMA is reduced in a series of controlled steps. The resulting pressure reductions, together with the corresponding changes in the DMA Net Flow, are then used to calculate the N1 factor.

The following table shows that N1 factors typically range between 0.5 and 1.5, depending on both pipe material and the type of leakage being assessed. For example, in DMAs with predominantly plastic pipes, an N1 factor of 1.5 can generally be assumed. Whilst in DMAs with mostly metallic pipes, the N1 is harder to gauge, as it can range between 0.5 and 1.5 depending upon the split between background leakage and burst leakage. Where a DMA contains a mix of pipe materials, a linear leakage and pressure relationship (N1 = 1) may be assumed until an N1 step test is undertaken to determine a more representative value.

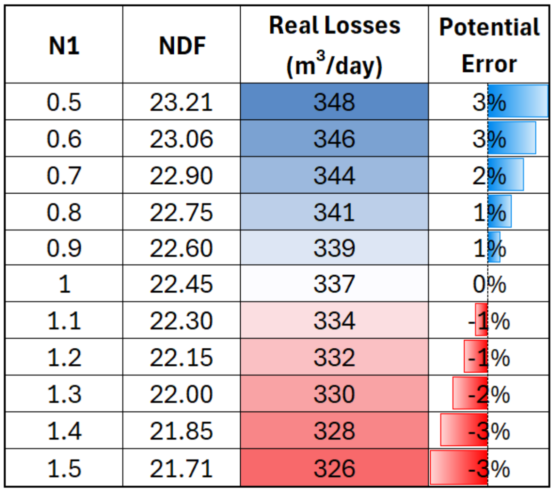
TABLE E-1 N1 Factors for Metallic and Plastic Pipes.

Component	Metallic	Plastic
Background Leakage	1.5	1.5
Bursts Leakage	0.5	1.5
Overall Leakage Mixed Pipes	**1.0**	

Notably, for background leakage, pipe material is not a determining factor, and an N1 value of 1.5 may be assumed regardless of pipe type. In metallic and mixed DMAs, this can be interpreted that the closer the actual N1 value is to 1.5, the greater the proportion of leakage attributable to background leakage; conversely, lower N1 values indicate a higher proportion of burst related leakage. Carrying out an N1 step test to determine the actual N1 factor for a DMA improves the accuracy of the overall leakage calculation.

When the N1 factor is equal to 1, it has no impact on the NDF. However, when the N1 factor is less than 1, it increases the NDF and the calculated DMA daily leakage (real losses). Conversely, when the N1 factor is greater than 1, it reduces the NDF and the DMA real losses. This effect is illustrated in the following table, which shows the impact of different N1 factors on the NDF and real losses. In the table, the night-time leakage is assumed to be 15 m³/hr and the baseline NDF is 22.45. Real Losses is calculated by multiplying the night-time leakage by the NDF.

TABLE E-1 Impact of N1 Factors on NDF & Real Losses.



N1	NDF	Real Losses (m^3/day)	Potential Error
0.5	23.21	348	3%
0.6	23.06	346	3%
0.7	22.90	344	2%
0.8	22.75	341	1%
0.9	22.60	339	1%
1	22.45	337	0%
1.1	22.30	334	-1%
1.2	22.15	332	-1%
1.3	22.00	330	-2%
1.4	21.85	328	-3%
1.5	21.71	326	-3%

As shown in Error! Reference source not found., this example indicates that the error in the l eakage calculation could be approximately ±3% due to the N1 factor. While this may not appear to be a significant concern in isolation, the potential error can be much greater in practice. When discrepancies across multiple DMAs are aggregated, they can result in a substantial overall discrepancy.

PRESSURE ADJUSTED BACKGROUND LOSSES

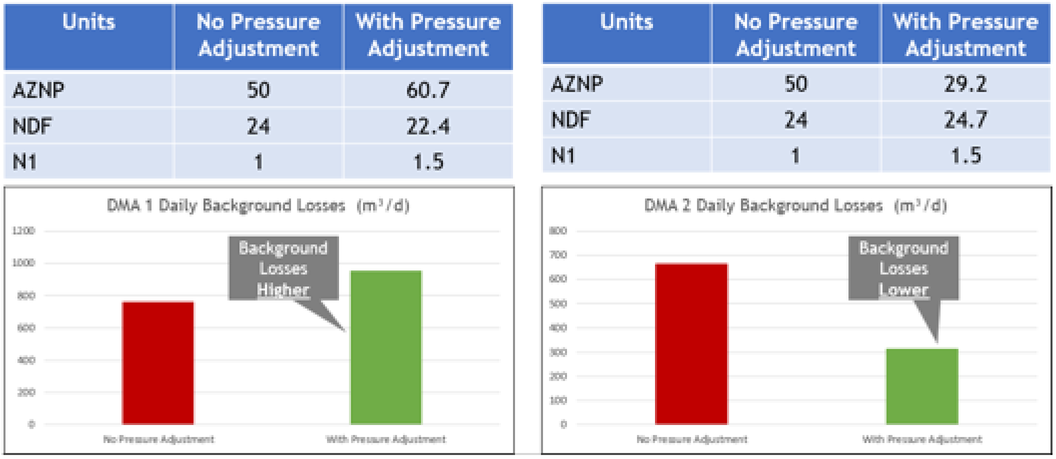
The Pressure Correction Factor (PCF) is used to adjust background losses to account for operating pressures. The flow rates applied assume an AZNP of 50m and an N1 value of 1; therefore, an adjustment is required to incorporate the DMA specific AZNP and N1 Factor.

The PCF is calculated as follows: $PCF = \left(\frac{AZNP}{50}\right)^{N1}$

Where the PCF is lower than 1 it will adjust the background losses down, conversely when the PCF is greater than 1 it will adjust the background losses upwards. In addition, we also need to apply to the DMA specific NDF to convert the night-time background losses to a daily volume. The full formulae for calculating Background Losses, which can be applied to a DMA is:

$$BG\ Losses = ICF \times\ [(L_m \times F_m) + (N_c \times F_c)\,] \times \left(\frac{AZNP}{50}\right)^{n1} \times \text{NDF}$$

Table in continuation shows the background losses calculation for two DMAs, assuming an Infrastructure Condition Factor of 1 (average condition). Prior to applying any pressure adjustment, the background losses for the two DMAs were at a similar level. However, DMA 1 has a significantly higher AZNP than DMA 2 and, as a result, its background losses have been adjusted upwards. Conversely, the background losses for DMA 2 have been adjusted downwards.

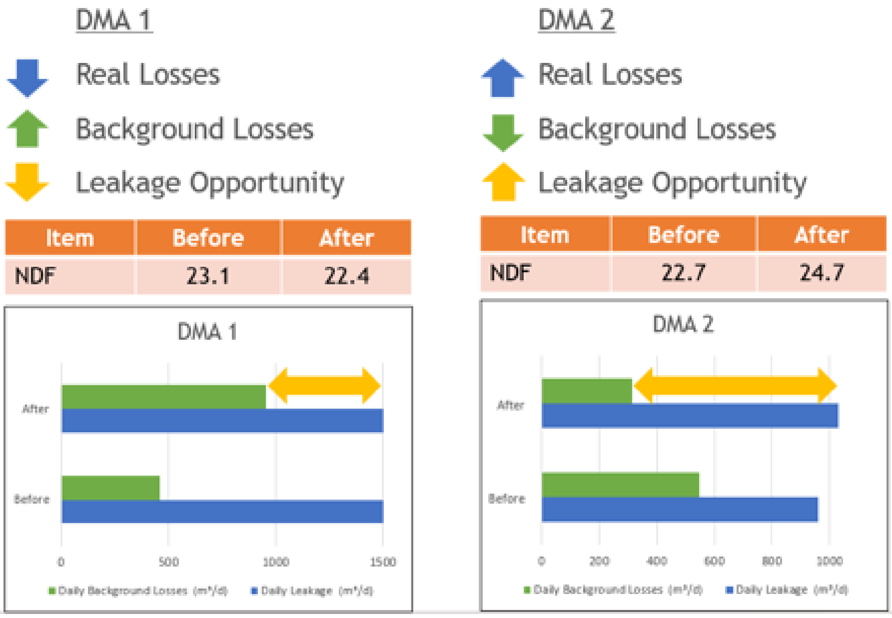


Units	No Pressure Adjustment	With Pressure Adjustment
AZNP	50	60.7
NDF	24	22.4
N1	1	1.5

Units	No Pressure Adjustment	With Pressure Adjustment
AZNP	50	29.2
NDF	24	24.7
N1	1	1.5

FIGURE E-8 *Example Background Loss Calculation with Pressure Adjustment.*

Example below shows the revised leakage opportunity (sometimes referred to as excess leakage) for the two example DMAs once all key pressure calculations have been applied and background losses and real losses have been recalculated with greater accuracy. As shown, DMA 1 exhibits significantly less excess leakage due to its higher background losses and slightly lower real losses. In contrast, DMA 2 shows greater excess leakage because of lower background losses and higher real losses. This demonstrates the importance of incorporating pressure adjusted background losses when prioritizing DMAs for leakage detection.



Item	Before	After
NDF	23.1	22.4

Item	Before	After
NDF	22.7	24.7

FIGURE E-9 *Example DMA Leakage Opportunity After Pressure Adjustment.*

.

APPENDIX F PRACTICAL EXAMPLES OF DMA DATA ISSUES

A. Bojko, K. Chwastek, T. Crowder

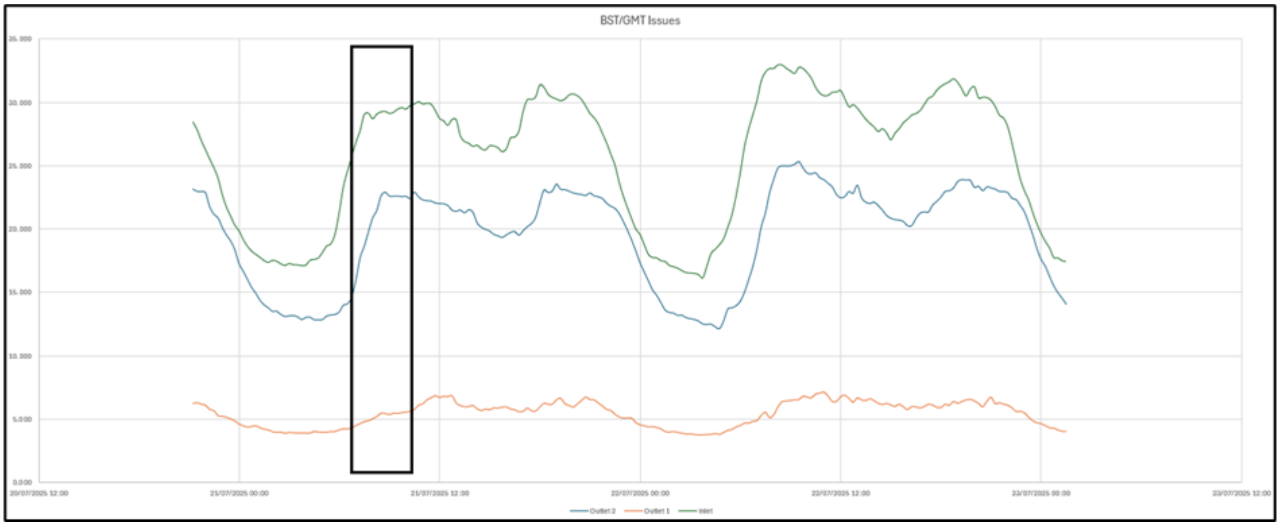
This appendix presents practical examples of the most common issues encountered in DMA data analysis. It highlights typical data inconsistencies, measurement errors and operational anomalies observed in real utility datasets and illustrates how these problems can affect the interpretation of DMA performance indicators.

TIME OFFSET ERROR

The synchronization of signal timing plays a pivotal role in the reliability of DMA MNF and leakage calculations.

In the example below, discrepancies between British Summer Time (BST) and Greenwich Mean Time (GMT) protocols caused inlet flow signal in a DMA to register approximately one hour earlier than their corresponding outlet flow measurements. This temporal misalignment skews net flow calculations (Net Flow = Inlet Flow – Outlet Flow) toward negative values.

The example illustrates how minor timing inconsistencies can significantly distort the net flow calculation. It underscores the necessity of precise signal arrival timing and consistent synchronization across all measurement points to ensure accurate MNF and leakage calculations.



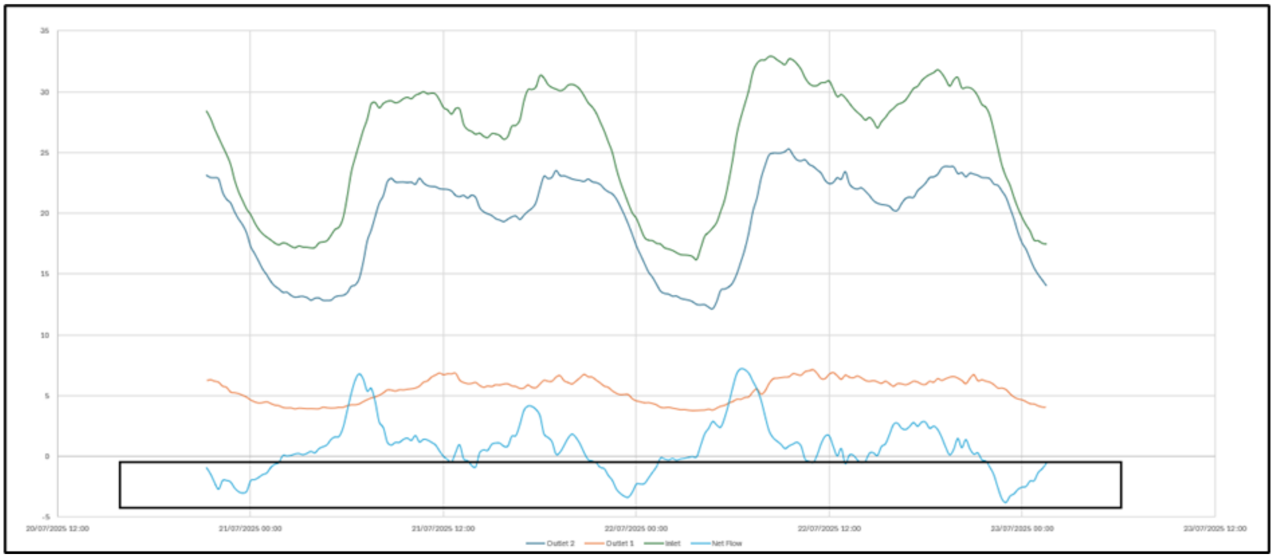


FIGURE F-10 *Example of flow signal with time offset error.*

UNITS ERROR

Another data quality problem in DMAs stems from scaling factor issues caused by incorrect unit assignments in the logger configuration.

As illustrated in the figure below, Flow 2 accurately reflects an average flow rate of 5.4 l/s. In contrast, Flow 1, despite measuring the same physical flow, reports an inflated average of 19.5 l/s due to misconfigured units. These scaling errors can significantly distort flow balance calculations, leading to inaccurate leakage assessments.

This issue can be resolved through systematic verification and correction of unit assignments in the data logger setup.

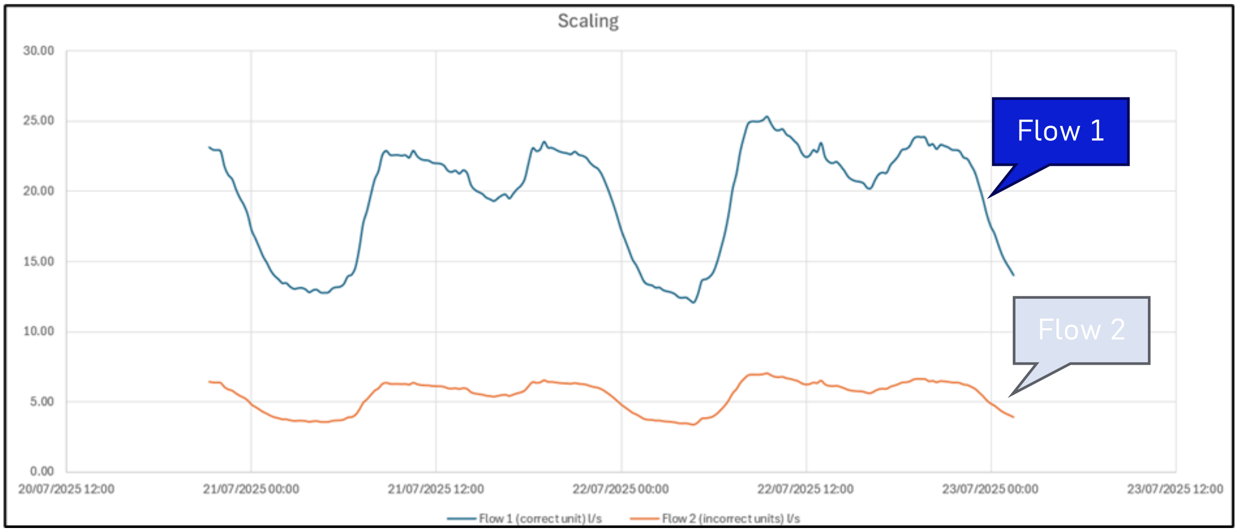
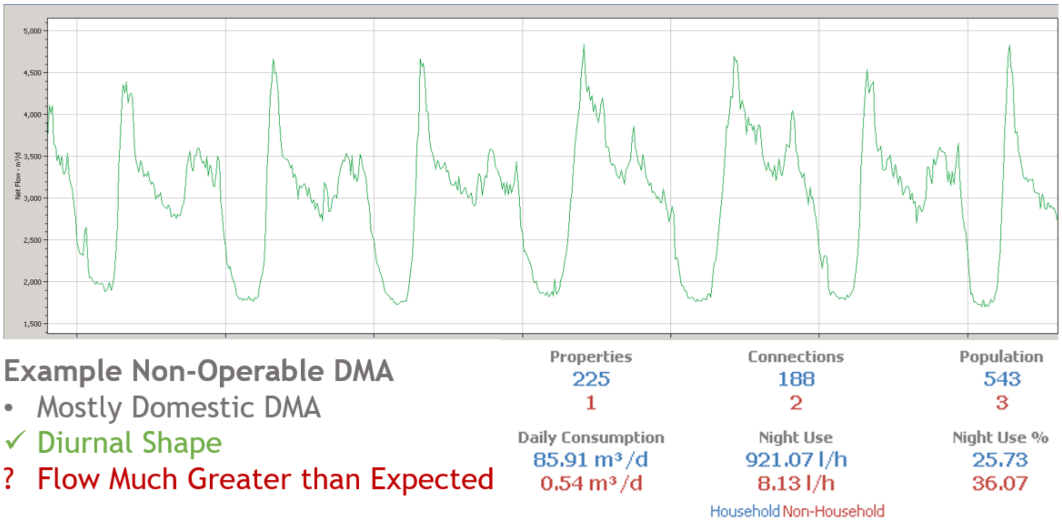


FIGURE F-11 *Example of flow signal with a unit's error*

The example below shows a DMA with a logger scaling factor error that was identified because the flow is much greater than the consumption data.



Example Non-Operable DMA

- Mostly Domestic DMA

✓ Diurnal Shape

? Flow Much Greater than Expected

Properties	Connections	Population
225	188	543
1	2	3
Daily Consumption	**Night Use**	**Night Use %**
85.91 m³/d	921.07 l/h	25.73
0.54 m³/d	8.13 l/h	36.07

Household Non-Household

FIGURE F-12 *Example of non-operable DMA with scaling factor error*

METERING & LOGGER ERROR

Logger calibration and meter verification are critical for maintaining data quality and accurate flow measurement.

In the example below, a logger that should record an average flow of around 6.5 m³/d instead reports approximately 1,180 m³/d. This discrepancy underscores the need for continuous trend monitoring over extended periods to detect and correct measurement errors.

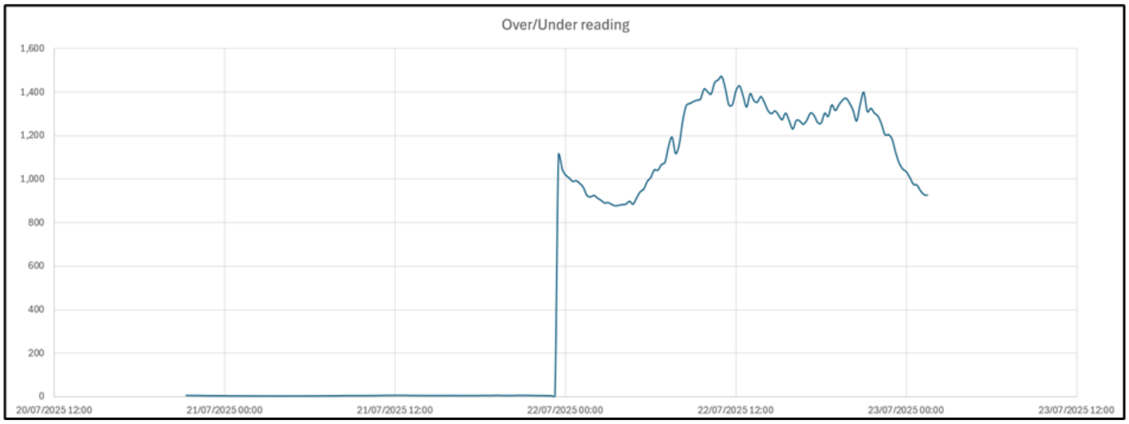
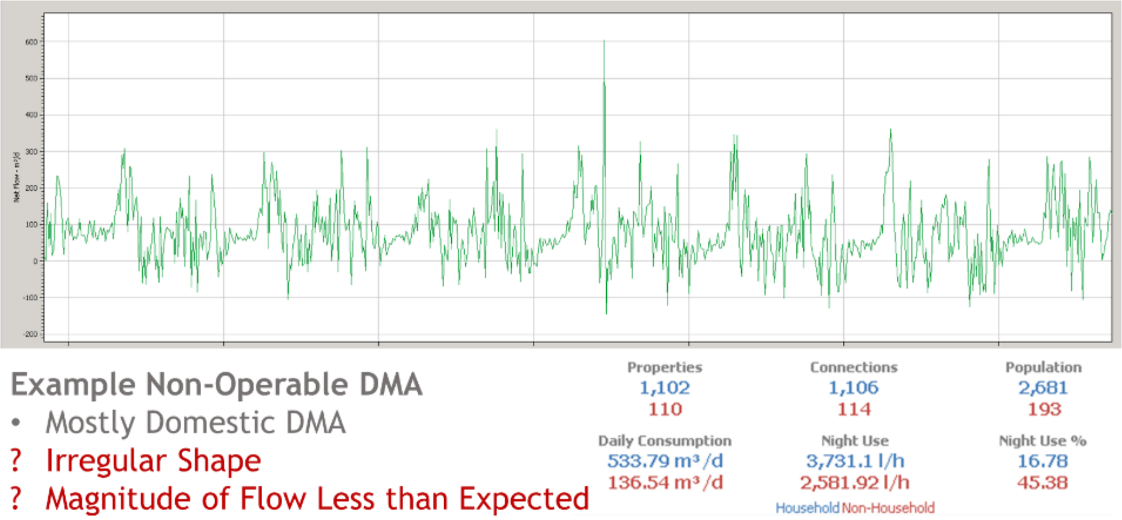


FIGURE F-13 *Example of flow signal with a logger calibration problem*

The example below shows a DMA with a metering issue causing the net flow to be inaccurate. Without being validated, the leakage in this DMA would be significantly underestimated.



Example Non-Operable DMA

- Mostly Domestic DMA

? Irregular Shape

? Magnitude of Flow Less than Expected

Properties	Connections	Population
1,102	1,106	2,681
110	114	193
Daily Consumption	**Night Use**	**Night Use %**
533.79 m³/d	3,731.1 l/h	16.78
136.54 m³/d	2,581.92 l/h	45.38
	Household Non-Household	

FIGURE F-14 *Example of non-operable DMA with metering problem*

METER CONFIGURATION ERROR

Accurate network configurations within telemetry systems are a critical factor in reliable leakage assessment.

The example below illustrates a storage reservoir with inlet and outlet meters located between two DMAs. The diurnal flow pattern shown on the graph indicates flow into the reservoir, rather than the expected outflow direction.

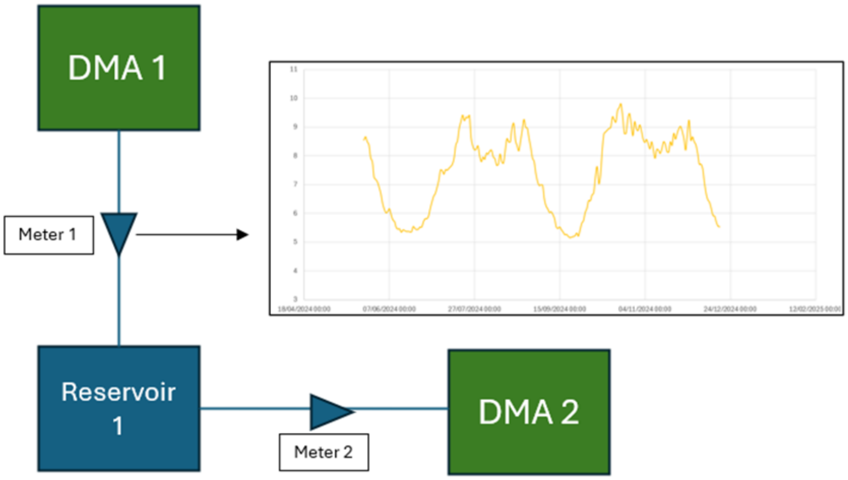


FIGURE F-15 *Example of meter configuration of storage reservoir & DMAs*

In this configuration, the inlet meter to the reservoir (Meter 1) should be assigned as the outlet from DMA 1, while the outlet meter from the reservoir (Meter 2) should be assigned as the inlet to DMA 2. It is essential that these assignments are correct, as the reservoir has its own operational regime meaning it fills and empties periodically. Over time, the inflow and outflow should balance, assuming there is no overflow or leakage.

A persistent negative balance may indicate misassigned meters or incorrect signal direction. Similarly, if the meters are incorrectly allocated to their respective DMAs, the reservoir's filling and emptying cycle can distort the Net Flow, leading to inaccurate leakage calculations. Therefore, careful verification of meter/signal configurations is vital to ensure that system connectivity is correctly represented and that leakage assessments remain accurate.

PRESSURE CONFIGURATION ERROR

Beyond asset configuration, maintaining accurate records of pressure logger locations is equally critical. This involves ensuring that any changes to logger positions are correctly reflected in the DMA configuration.

The example below shows pressure data indicating that a logger has been relocated twice to different points within the network. It is essential to track such changes; otherwise, the pressure signals will misrepresent the DMA to which they are assigned. This can lead to incorrect calculations of Average Zone Pressure, Average Zone Night Pressure, and Night-Day Factors which are key components in leakage analysis. Inaccurate data at this stage can result in inappropriate operational decisions. Moreover, since pressure data also informs hydraulic modelling, inconsistencies can negatively affect model accuracy and the resulting insights.

Field maintenance activities or infrastructure modifications may necessitate repositioning loggers, but unless these updates are properly recorded, relocated sensors will produce misleading data that undermines the integrity of the entire monitoring system.

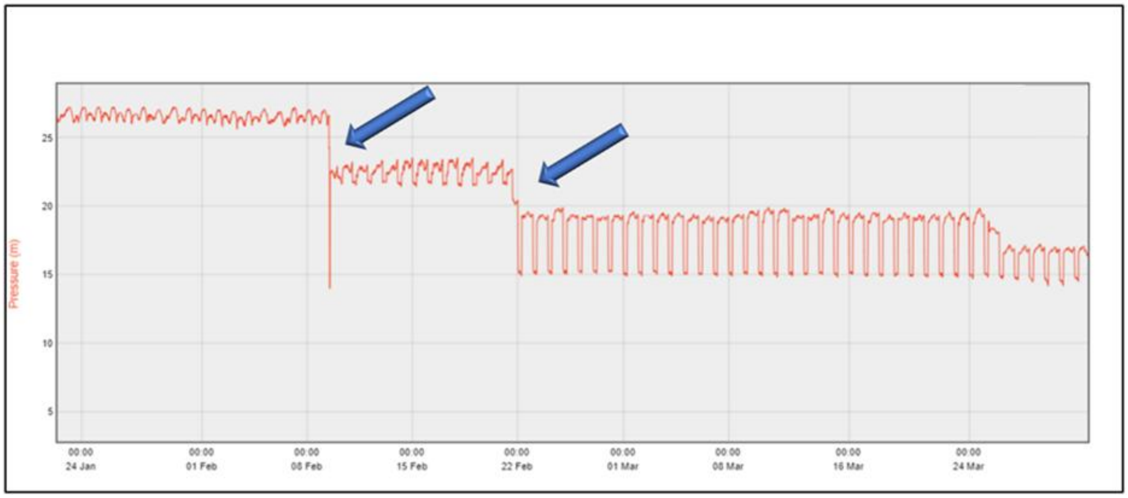


FIGURE F-16 *Example of pressure configuration error*

PUMPED PROFILE DMA

A DMA should exhibit a consistent diurnal flow pattern to provide a reliable basis for MNF and leakage calculations. When the flow profile does not accurately represent actual consumption within the DMA, the scope and reliability of any subsequent analysis are significantly reduced. The example below illustrates a DMA with a net flow pattern influenced by pumping activity. In this case, the pumps at the inlet meter supply a storage reservoir, which in turn serves most of the consumers within the DMA.

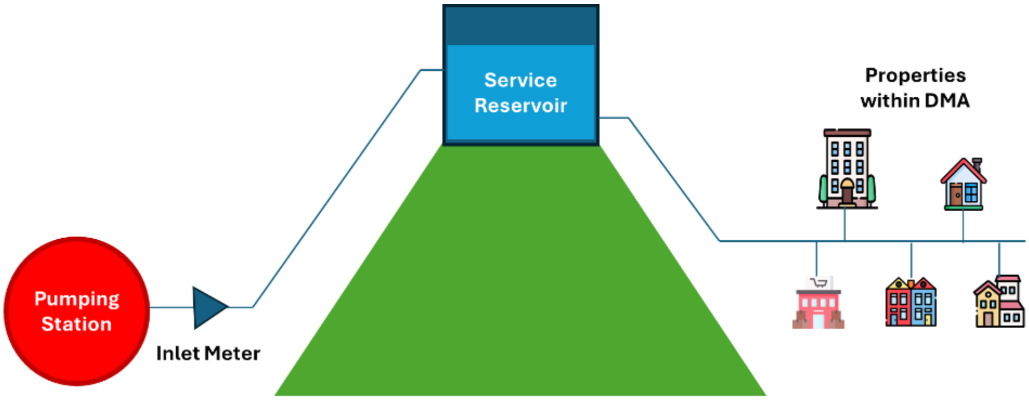


FIGURE F-17 *Pumped DMA Illustration*

In the above example, ideally, both the inlet and outlet of the reservoir should be metered and logged to generate an accurate representation of the net flow for the DMA. Because of this setup, the flow profile corresponds to the pump turning on and off when supplying the reservoir as shown in the example below. This means that the recorded MNF does not correspond to true minimum consumption and therefore should not be used as the basis for leakage calculations. Instead, the daily water balance method, using total daily flow, should be applied to determine leakage more accurately.

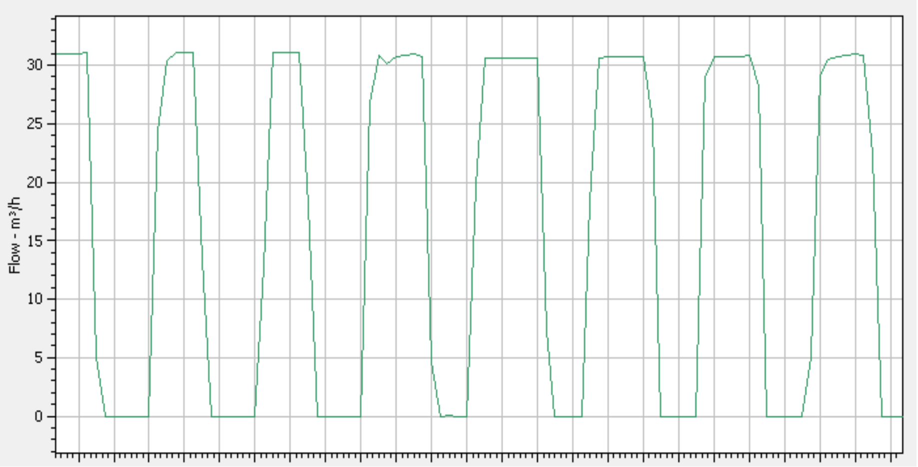


FIGURE F-18 *Example pumped profile DMA*

LARGE USER WITHIN DMA

A large user, typically a non-domestic customer, can significantly distort the net flow of a DMA. If such users consume water during the night and this usage is not accurately accounted for, it may be misinterpreted as leakage.

To mitigate this, large consumers with an average daily demand above a certain threshold should ideally be continuously logged. A practical benchmark is 40 m³ per day; however, any user with consumption large enough or irregular enough to distort the flow profile should also be monitored.

The example below demonstrates how a large user can distort the net flow of a DMA, resulting in unreliable leakage calculations. Once the user is continuously logged and their consumption is properly accounted for, the net flow data becomes a much more dependable basis for DMA leakage analysis.

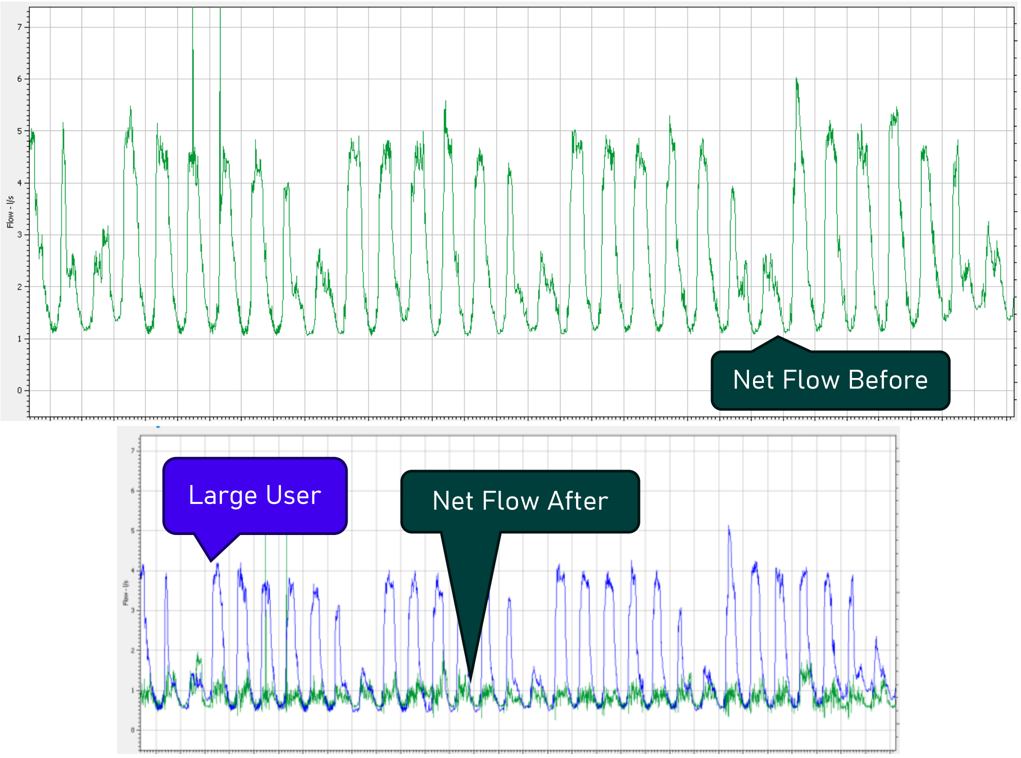


FIGURE F-19 *Example of large user impacting DMA net flow before & after logged.*

CUSTOMER ERROR IN DMA

Customer data inaccuracies present another key challenge to the reliability of leakage calculations and the hydraulic modelling of DMAs. Accurate customer data is essential, as it directly influences consumption estimates within each DMA.

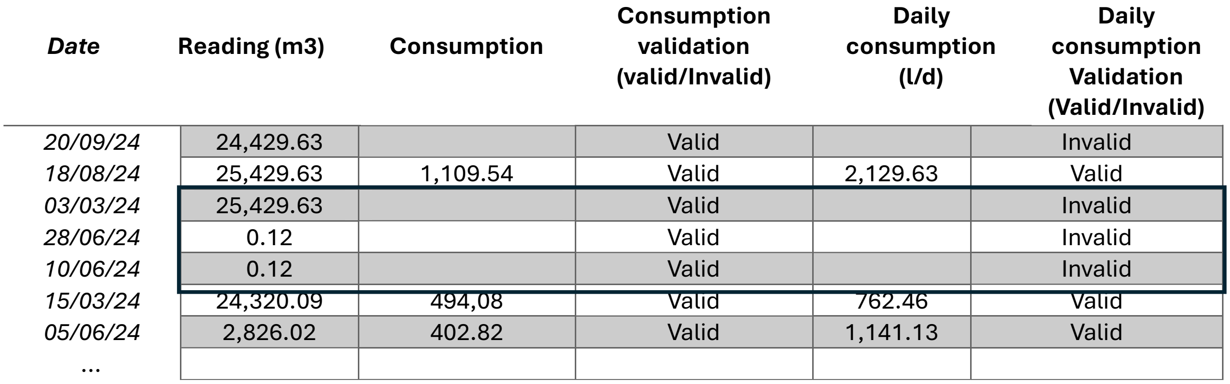
Several factors can contribute to incorrect customer data, including:

- Inaccurate customer locations or DMA assignments
- Non-domestic customers incorrectly classified as domestic properties
- Missing customer data due to incomplete billing information
- Misclassification of customer types

The example below highlights a case where a large user was incorrectly assigned to the wrong DMA. This misallocation caused consumption and night-use figures to appear excessively high in one DMA and too low in another, leading to misleading conclusions and potentially directing leakage detection activities to the wrong area.

FIGURE F-20 *Example of customer DMA assignment error*

In another example, customer meter readings were recorded incorrectly. As a result, the consumption data had to be invalidated to prevent distortion of demand analysis and ensure data integrity.



Date	Reading (m3)	Consumption	Consumption validation (valid/Invalid)	Daily consumption (l/d)	Daily consumption Validation (Valid/Invalid)
20/09/24	24,429.63		Valid		Invalid
18/08/24	25,429.63	1,109.54	Valid	2,129.63	Valid
03/03/24	25,429.63		Valid		Invalid
28/06/24	0.12		Valid		Invalid
10/06/24	0.12		Valid		Invalid
15/03/24	24,320.09	494,08	Valid	762.46	Valid
05/06/24	2,826.02	402.82	Valid	1,141.13	Valid
…					

FIGURE F-21 *Example of customer reading error.*

APPENDIX G EXAMPLE OF REAL CASE DATA-DRIVEN DMA LEAKAGE ESTIMATION SYSTEM

T. Neergaard

This appendix describes a comprehensive example of a fully digitized, data-driven approach to diurnal water balance calculation and the continuous monitoring of water loss fluctuations and night flows within District Metered Areas (DMAs).

A prime example of this methodology in action is Brønderslev Water Company in Denmark (Figure G-1). Since 2021, the utility has successfully implemented a digital Leak Management strategy powered by Smart Meter Technology. This system provides a robust framework for real-time oversight, as documented by Neergaard (2024), demonstrating how high-resolution data can transform traditional water loss reduction into a proactive, automated process.

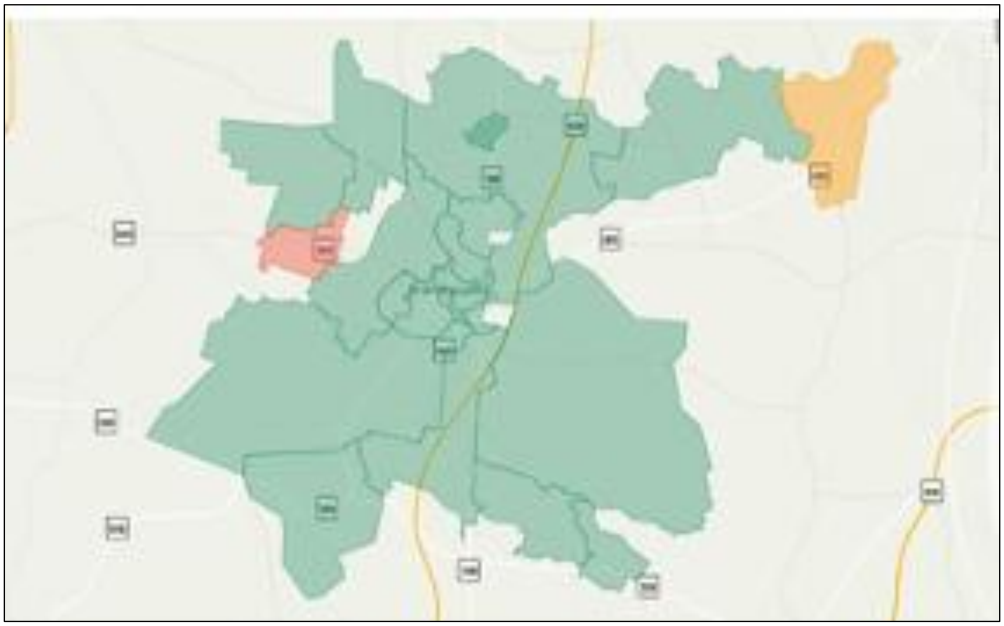


FIGURE G-1 *Operational area of Bronderslev Water Company*

This data-driven approach is based on the following essential characteristics:

- Smart Meters were installed in the entire distribution system at every household/consumer.
- A digitized diurnal data collection system from smart meters uses advanced data transmissions systems (ex. Mioty) or a system based on fixed antennas and extenders, which secure daily or hourly meter reading.
- Ensuring regular readings from 98% of all smart meter-installations (even with more unstable performance the system would still work).
- Long battery life of consumer meters under normal use (15+ years).
- An accuracy of consumer meter reading at +/- 2 pct.
- Automatic trending/extrapolation of data (if some are temporarily missing).

- The entire water distribution network was subdivided into unique and well-defined DMAs.
- Each DMA was equipped with an inlet Bulk Meter connected online with the SCADA.
- The SCADA is able to calculate reliable daily inflows to the distribution system from the waterworks taking into account filling of the water reservoirs.
- The pipe GIS database and the DMAs are fully digitized allowing changes automatically to be incorporated into the GIS system.

Additionally, an overall data surveillance and management system was applied with an easy-to-understand GIS-based user interface (Figure G-2).

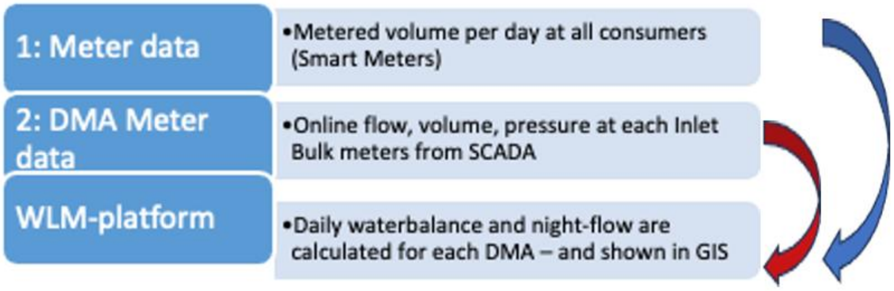


FIGURE G-2 *Data surveillance and management system*

Figure G-3 shows the water loss before implementation of Water Leakage Management System (2017-18) and after (2019-2025). Here, losses are defined as the differences between measured water input from waterworks to the distribution system and the billed consumption at the smart meters in every DMA.

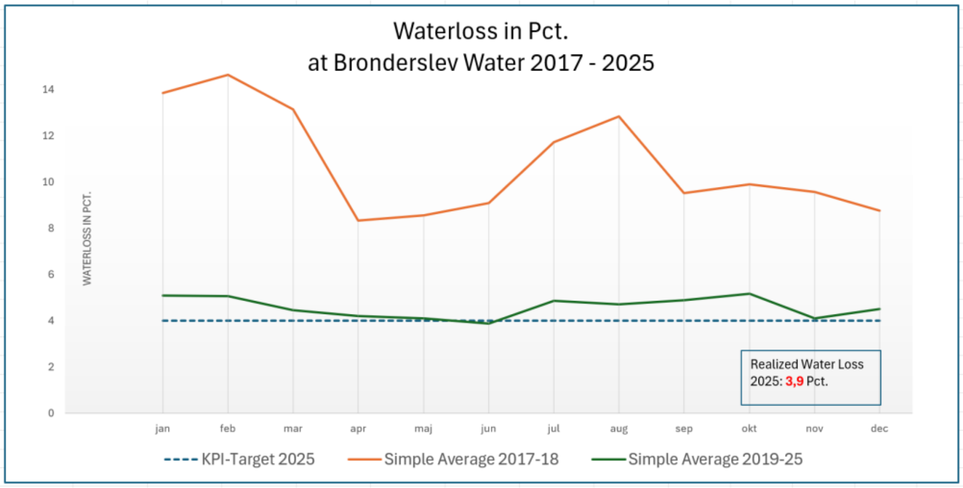


FIGURE G-3 *Water Loss Trend*

DMAs vary in size, composition, and consumption patterns—some are purely residential, others include storage tanks, industries, or institutions, and many are mixed. Once the system was implemented and commissioned, it was essential for the operational team to understand each DMA's profile to respond effectively to consumption anomalies.

A consistent and active use of water data significantly reduces losses from newly emerging leaks, as operators can react promptly to changes within DMAs on a daily basis. However, the benefits extend well beyond addressing new leaks. Daily monitoring and follow-up also enable utilities, over time, to identify and repair long-standing, hidden background leaks—often the most frustrating to detect. Experience shows that reducing these hidden losses can result in substantial cost savings.

While some inaccuracies will inevitably exist— such as uncertainties related to meter performance— these are generally of little practical concern. In daily operations, the precise calculation of water losses (e.g., percentage to decimal points) is less important than the ability to identify diurnal trends and detect deviations as they occur. By gaining better daily control of the distribution system, utilities can profoundly improve their water loss performance. This enhanced control also allows the utility to provide better customer service, for example by communicating timely information about leaks occurring on the customer's side of the meter.

It is true that acquiring the necessary infrastructure—such as smart meters, fixed networks, IoT systems (e.g., Mioty), and associated monitoring platforms—requires significant investment. Additional costs include staff training, implementation of new procedures, and the time and resources needed to ensure data quality across meters and DMAs. At first glance, the business case for such investments may appear unviable, with a negative bottom line. However, when the full range of benefits from a data-driven approach is incorporated into the business case—including those that emerge during system operation— the financial outlook often shifts from negative to positive. Moreover, further unforeseen advantages frequently arise as utilities learn to harness the power of their data. As the saying goes, "the gold is in the data". Without actively mining that gold, many valuable opportunities and cost-saving measures will remain undiscovered.

Smart meters and the active use of data in management systems should now be viewed as essential components of an advanced water utility. These technologies provide transparency and organizational control across the distribution network—particularly where DMAs are already established. Achieving these benefits requires serious commitment from senior management.

Active data use enables staff to respond quickly and effectively to anomalies, such as leaks, as soon as they arise. Beyond cost savings, data-driven management opens the door to new customer services and inspires innovative thinking among staff, helping to accelerate the utility's transition to a digital future.

In short, fully exploiting the potential of smart meters and data-driven solutions may well be the most important next step in the journey toward the truly digital water utility.

DISCLAIMER

This is a publication created on behalf of the IWA Waterloss Specialist Group. The information provided and the opinions given in this publication are not necessarily those of the IWA and the IWA Waterloss Specialist Group and should not be acted upon without independent consideration and professional advice. The IWA, the IWA Waterloss Specialist Group, the editors and contributors, will not accept responsibility for any loss or damage suffered by any person acting or refraining from acting upon any material contained in this publication.

Copyright of any material shared in the document, including figures and tables, belongs to the original creators of the material.

Artificial intelligence (AI) tools were used as a supporting aid in the preparation of this book. AI was applied to assist with tasks such as language correction, text editing and summarization, translation, and the generation or modification of selected graphical elements. All technical content, interpretations, opinions, and conclusions were defined, reviewed, and validated by the authors. The use of AI did not replace professional judgment, domain expertise, or critical review, and no AI-generated content was included without human verification and contextual assessment.

Cover photo courtesy of WMI (Vinci Construction Grands Projets), 2020, Colombia