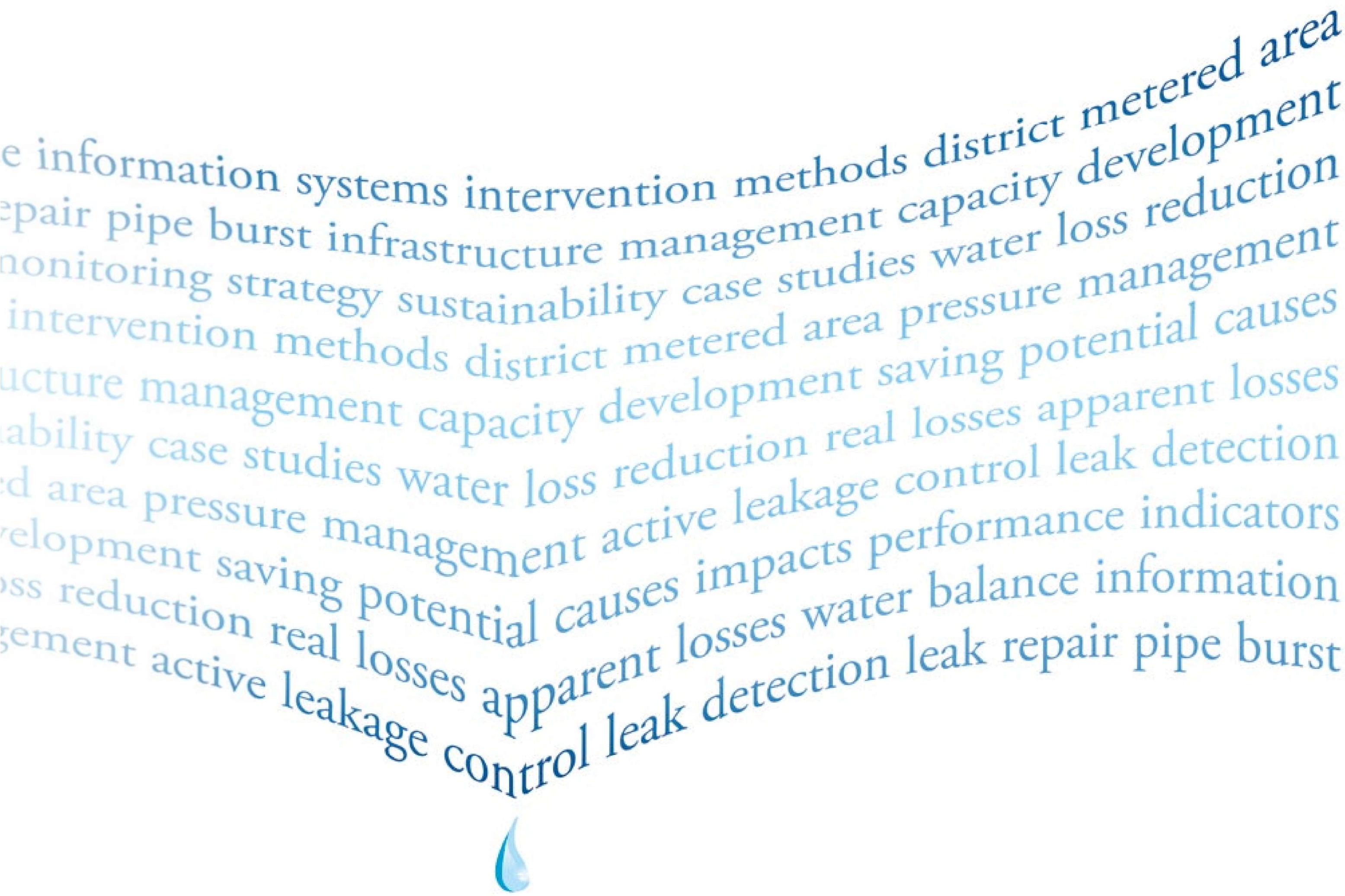

Guidelines for water loss reduction

A focus on pressure management

giz

On behalf of
Federal Ministry
for Economic Cooperation
and Development

VAG

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"Pressure management is most relevant for water supply systems that suffer from high leakage rates, as leakage can be reduced considerably by reducing water pressure in specific districts at times of low consumption. However, although pressure management projects have proved to pay off in the short run by the revenue water they generate, they are certainly not a substitute for long-term network rehabilitation programs."

Prof. Dr.-Ing. Raimund Herz, Emeritus of Urban Engineering,
Dresden University of Technology

"Active pressure management is useful in principle, but still not applied sufficiently. Depending on situation analysis, measures of rehabilitation and pressure management should complement each other in order to reach an ideal concept for water loss reduction."

Dr. Stefan Gramel, Technical Advisor,
Competence Center Water Supply, Wastewater, Solid Waste KfW Bankengruppe

Guidelines for water loss reduction

A focus on pressure management

Photo: © Shutterstock ®

Important notice

These guidelines describe an incremental approach to pressure management (PM). The approach taken to implementing PM depends on the national context. We have to understand that the level of economic development, environmental consciousness, political priorities, good governance and cultural habits influence the dynamics and time frame of modernising water management in a country. The implementation of PM must be seen as a part of this change process, and will advance differently from country to country.

The guidelines should be implemented in a spirit of cooperation between the public and the private sector. This will not happen overnight; thus a gradual phasing-in is needed based on the given political, social and legal circumstances as well as achievable and realistic milestones.

A water association, an individual local water utility or the public sector can act as the driving force behind the introduction of PM in accordance with these guidelines. The agents that promote this activity should do so in a transparent manner and within a defined and binding time frame.

About these guidelines & acknowledgements

One of the major objectives of these guidelines is to reduce water loss by improving the management of existing water supply networks, with a special focus on the method of pressure management. The guidelines have been prepared within a development partnership (formerly known as *public private partnerships*, PPP) between the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and VAG Armaturen GmbH. The Institute for Ecopreneurship (IEC) at the University of Applied Sciences Northwestern Switzerland (FHNW) supported project management. The Institute for Water and River Basin Management (IWG) of the Karlsruhe Institute of Technology (KIT) coordinated the elaboration of the document.

Support and advice were further provided by a variety of external experts from the public and private sector working in the field of water loss reduction. The UN-Water Decade Programme on Capacity Development (UNW-DPC) which is actively organising training workshops worldwide on water loss reduction has granted its support for the dissemination and implementation of the guidelines. The technical manual has been reviewed and commented upon by experts from the International Water Association (IWA), the Technical University of Dresden, Germany and the Kreditanstalt für Wiederaufbau (KfW). Additionally, the structure and contents of the water loss reduction guidelines have been presented at stakeholder dialogues in Beirut, Lebanon attended by 44 participants from Lebanon, Jordan, Syria and the Palestinian Territories and in Lima, Peru with more than 200 participants from Peru and Bolivia. Furthermore, the project and the guidelines have been presented to representatives of German consulting companies as well as at the IWA Conference *Water Loss 2010* in São Paulo, Brazil. Feedback from participants has been collected and incorporated into the documents.

The management team behind this initiative wishes to express its sincere thanks to the experts from VAG, GIZ, IWG-KIT and IEC-FHNW and all who participated by sharing their time, information and insights.

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Foreword

Dear readers,

In these early years of the 21st century, 900 million people – around one seventh of the world's population – lack access to sufficient drinking water. Water scarcity and poor water quality are among the primary causes of poverty, disease and environmental degradation. With the global population growing rapidly, urbanisation on the increase and the effects of climate change already apparent, it is becoming more and more difficult to provide and maintain adequate water supplies.

In developing and emerging countries, between 40 and 80 per cent of water fed into drinking water supply networks is lost due to leakages. This loss of the world's most precious resource has considerable financial consequences. Funds are being spent on increasing water production to compensate for water losses when they could be invested in the maintenance or extension of existing infrastructure.

Germany is one of the world's largest donors in the field of water and sanitation and the largest donor in Africa. Each year the German Government spends around 350 million euros on water-related interventions, with an estimated 80 million people benefiting from ongoing activities in the water sector. Reducing water loss is an important aspect of our development projects.

Many countries already have a water management strategy in place and water loss reduction is generally considered an important issue. Germany enjoys an excellent reputation around the globe for sophisticated, high-quality water technology. Technically it is possible to reduce water loss in the supply system to approximately 5 per cent. However, water loss reduction is not only about technical solutions: effective strategies need to be embedded in a well-regulated and inclusive water governance system. Implementation is usually a challenge, as new ways of sharing responsibility have to be established and changes in traditional consumer behaviour are required. Reform processes related to water governance are often complex and time-consuming – but they are absolutely necessary.

This is why I welcome the publication of the *guidelines for water loss reduction* and their strong focus on technical and managerial issues. They are the result of successful cooperation between the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and VAG Armaturen GmbH within the framework of the programme for development partnerships *www.develoPPP.de*. This partnership promotes broad-based capacity development for decision-makers and stakeholders at national and regional levels. The guidelines raise awareness of the causes of water loss and identify ways of reducing it. Presented in the form of an open source document, they are an effective means of knowledge transfer and help to support the sustainable use of water worldwide.

This development partnership is an excellent example of the progress that can be achieved when development cooperation and the private sector work together. As Federal Minister for Economic Cooperation and Development, I am convinced that this publication will motivate decision-makers, executive managers, engineers and technicians from water supply companies in developing and emerging countries to increase their efforts to reduce water loss and thus contribute to efficient and sustainable water management.

Yours

Dirk Niebel
Federal Minister for Economic Cooperation and Development

Editors notice

These guidelines are the result of a development partnership with the private sector between the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH und VAG Armaturen GmbH (VAG), which was established in 2009. The partnership's aim was to improve the capacity of water utilities to manage water supply systems sustainably and to reduce water losses, with a special focus on pressure management (PM). PPP are gaining importance and acceptance in German development cooperation following numerous positive experiences. PPP presuppose a long-term commitment on the part of the private business rather than focusing on its own short-term interests and rapid returns. Development measures and private sector know-how can complement one another and aim to achieve efficient and sustainable results.

VAG *(www.vag-group.com)* is a highly experienced manufacturer of valves for water and wastewater applications which has gained the reputation of being a pioneer in providing modern, global solutions. GIZ *(www.giz.de*) is a federally owned cooperation enterprise for sustainable development with worldwide operations. The project further incorporated the knowledge of two universities: the Karlsruhe Institute of Technology (KIT) *(www.kit.edu)* and the Institute for Ecopreneurship (IEC) *(www.fhnw.ch/lifesciences/iec/institut-fuer-ecopreneurship)* of the University of Applied Sciences Northwestern Switzerland (FHNW) *(www.fhnw.ch/hls)*. KIT is one of Germany's leading technical universities and a national large-scale research centre, and participated in the project through the Institute for Water and River Basin Management (IWG). The Water Supply Networks Section of the IWG *(http://iwk.iwg.kit.edu)* works mainly in the field of hydraulic modelling, the analysis of water distribution networks and water loss reduction. The focal areas of the IEC are teaching and applied research in the fields of sustainable resource management, biotechnology and eco-toxicology.

Pooling the national expertise of the two global players GIZ and VAG and supplementing it with academic expertise have proven to be a very successful endeavour. We are convinced that using and implementing these guidelines and the included recommendations on how to overcome existing problems will directly and indirectly lead to more sustainable network management, including a reduction in water loss and guarantee constant, safe and fair water supply for an increased number of households. In Jordan, for example, water losses have effectively been reduced by up to 40% in the project area and the water input required to fulfil the needs of the customer has decreased considerably. Additionally, the guidelines will contribute towards a more preventative network operation and maintenance, which is less cost-intensive than only reacting on current damages over the long term. In effect, pipe bursts will be reduced and the lifespan of the network increased. Furthermore, short, medium and long-term investment planning for the sustainable management of water supply networks will be improved. Eventually, better water distribution network management and maintenance will reduce the pollution of drinking water (quality issues) and will thus decrease water-borne infections through cleaner and safe water supply.

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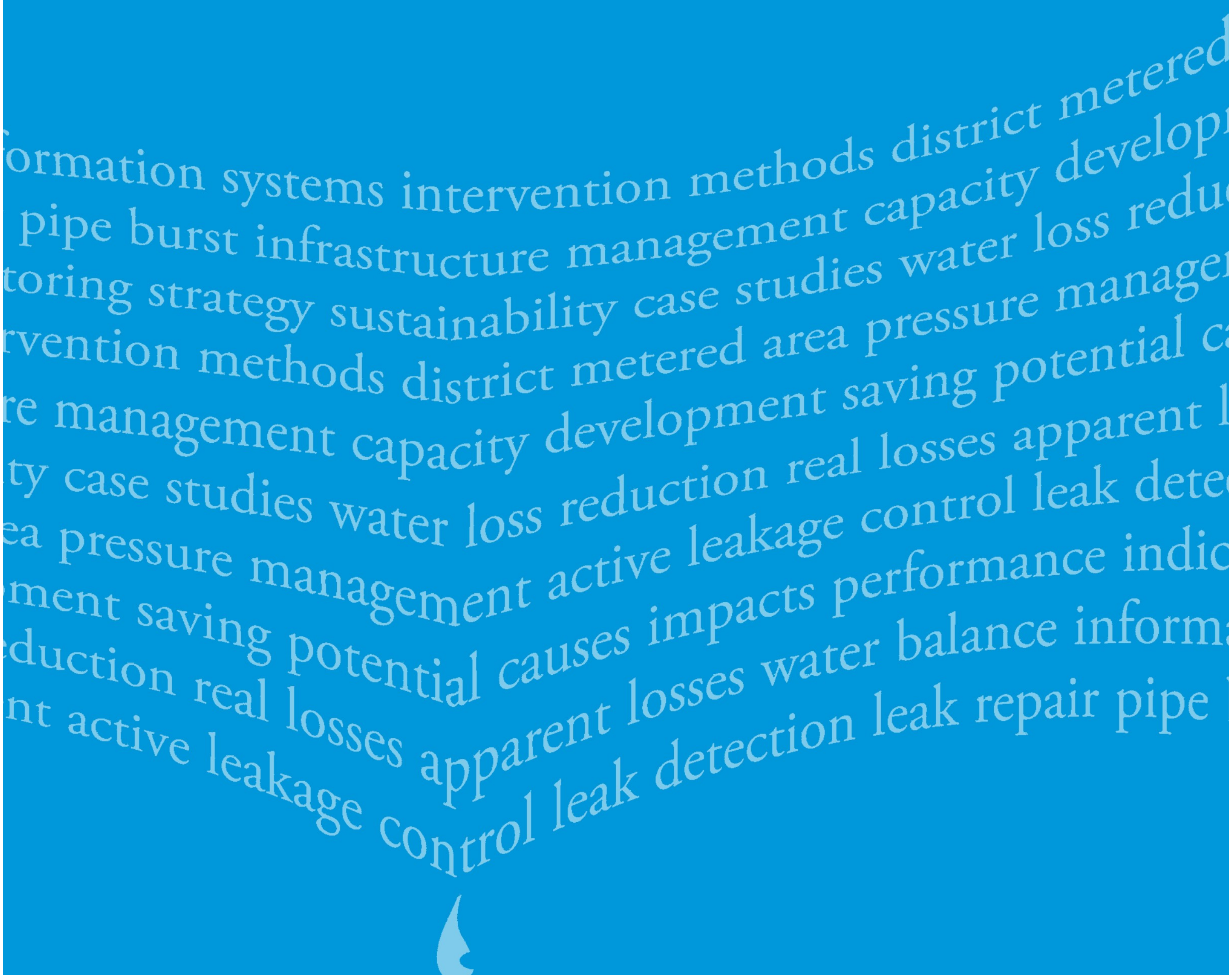
Guidelines for water loss reduction



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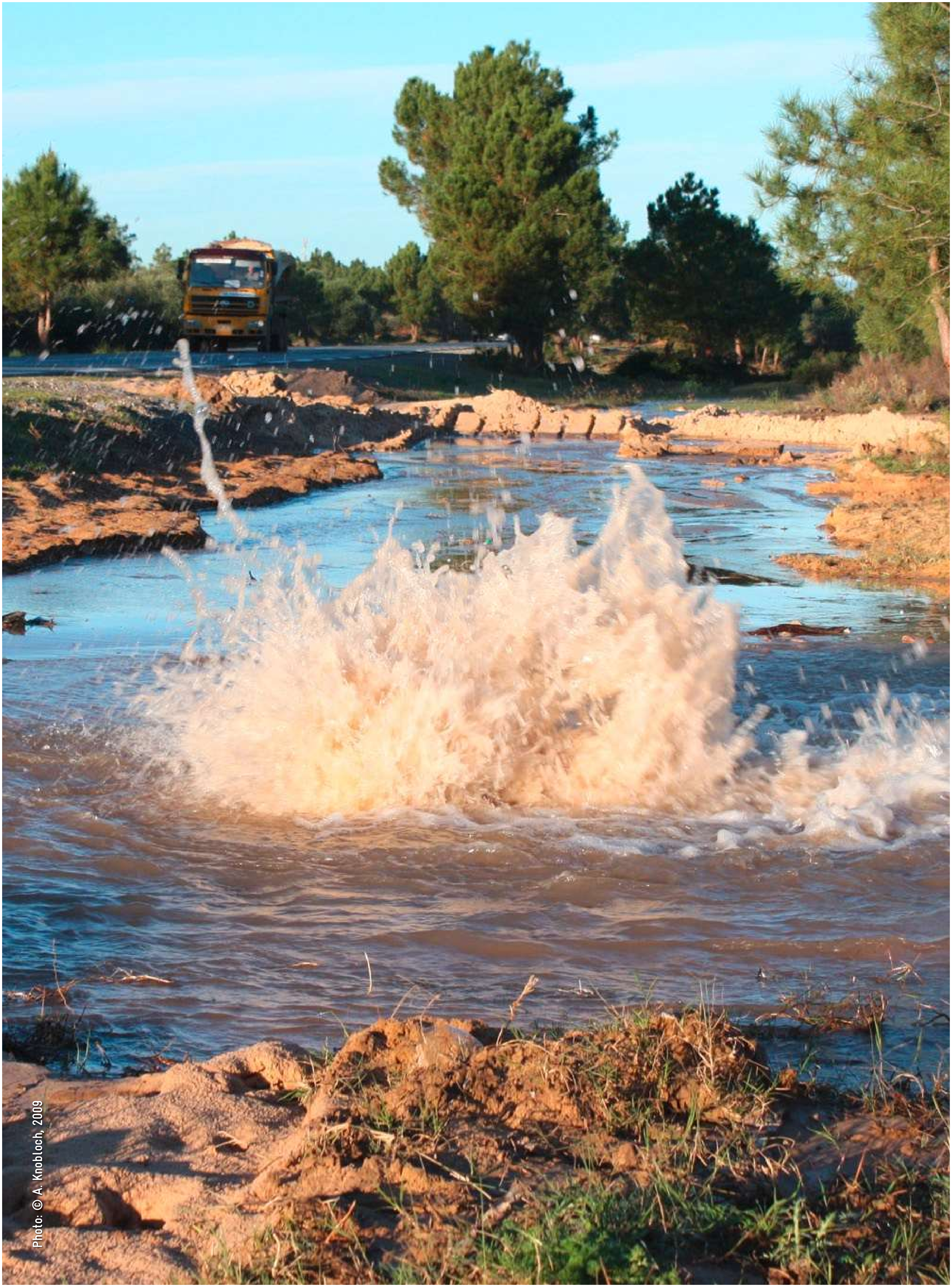

Overview


Photo: © F. Boyer, 2010

Introduction to the guidelines

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1.1 Objective and background

These guidelines aim to impart knowledge about water loss reduction to decision-makers and stakeholders at the national level and to the management team, planning and design department and operating staff at local water utilities in developing and transition countries. The guidelines are accompanied by capacity development materials as well as the implementation of pilot projects in order to transfer know-how and implement state-of-the art pressure management (PM) technology in practice.

(a) Guidelines for water loss reduction

The overall structure of the guidelines for water loss reduction consists of:

- → a summary brochure for decision-makers
- → this technical manual
- → supplementary materials.

The materials are meant to provide authorities from the water sector, water utilities and professional associations with all information required to understand the origin, nature and impact of water losses, to develop and implement a customised counter-strategy and to choose the most efficient methods and instruments for water loss reduction.

Various types of water losses exist and there are many different causes and factors influencing the amount and type of water lost in a water distribution network. Without proper knowledge of the nature of water losses, it is thus impossible to find the correct and most efficient solutions to reduce them. Therefore, the first objective of these guidelines for water loss reduction is to provide a good understanding of water losses so that answers can be found to the following basic questions: where is the system losing water, how is the water lost, why is it lost and how much of it is lost? Reducing water losses usually is an expensive and time-consuming undertaking. Therefore, the second objective of the guidelines is to show why it is important and why it is usually very profitable for a water utility to take action against water losses. Finally, the guidelines shall present state-of-the-art methods and technologies for assessing and reducing water losses, with a special focus on pressure management as a powerful instrument for decreasing real water losses.

The guidelines have three target groups: the first group consists of decision-makers from national water ministries, authorities, water utilities and from professional associations within the water sector. The *Summary* brochure will make them aware of the importance of water loss reduction and provide brief information about pressure management's potential for reducing real water losses. The technical manual is geared towards the second group: mainly technical directors, engineers and technicians working for water utilities. The supplementary materials are intended for technicians and for water utilities' operating personnel.

All documents will be available as hard copies and can also be downloaded free of charge from the project website: *www.waterlossreduction.com*

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(b) Capacity development materials

The guidelines for water loss reduction provide expertise on the economic, technical, social and environmental aspects of water loss management in general and pressure management in particular.

A set of training modules supplementing the guidelines has been developed as an instrument for capacity development, and is designed to teach personnel from the public and private sector about water loss reduction. The training modules take into consideration the specific framework conditions in developing and transition countries, and will enable participants to understand the benefits and potential of water loss reduction as a contribution towards sustainable development.

The training modules are available for download from the project website and are aimed to be used as lecture notes for workshops and seminars.

However, the need for capacity development regarding water loss reduction varies largely for different countries and utilities. Country-specific capacity development strategies are required to empower national stakeholders to achieve successful water loss reduction. These training sessions should thus form part of a comprehensive capacity development strategy *(c.f. Chapter 2.1.4)*.

(c) Implementation of pilot projects

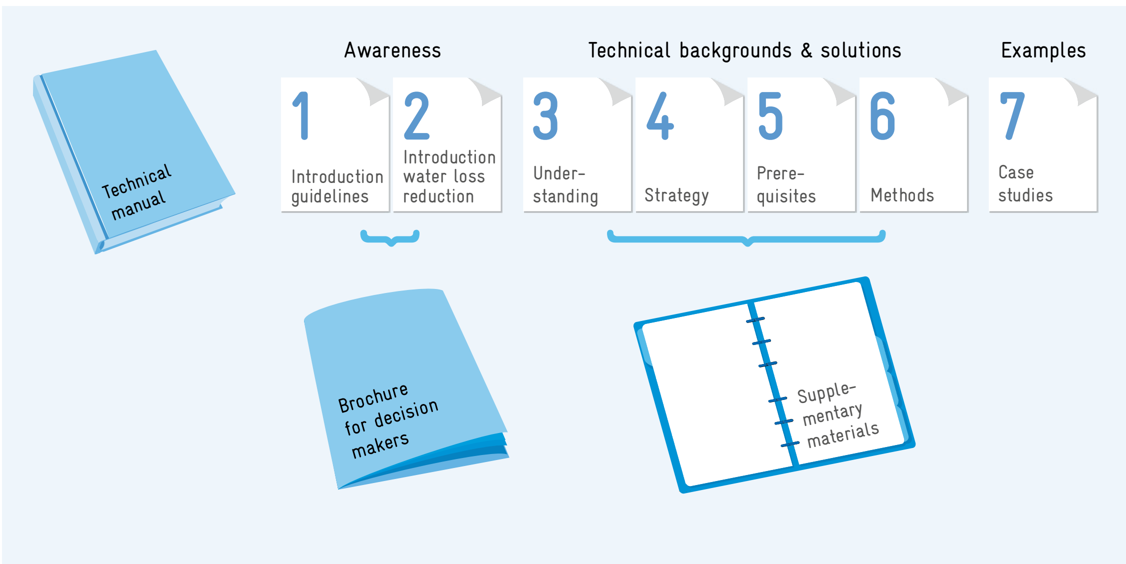
Another measure accompanying the water loss reduction guidelines is the implementation of pilot projects in cooperation with interested water utilities. The objective of the pilot projects is to demonstrate the applicability and efficiency of pressure management as a short to medium-term measure to combat real water losses. During the last five years, VAG has successfully installed several pressure management systems in Ain El Basha (Jordan), Santo Amaro and Belo Horizonte (Brazil) as well as in Lima (Peru), amongst others. VAG thus not only possesses the technology but also a very experienced team. More details about these projects can be found in the selected case studies in *Chapter 7*.

At the time of writing this manual, preparations were under way to implement potential pilot projects in Saida (Lebanon) and Ouagadougou (Burkina Faso).

1.2 Structure of this technical manual

The guidelines are composed of *three sets of documents*, as shown in *Figure 1.1*: the technical manual with two introductory chapters, four technical chapters and one chapter which presents case studies. The introductory chapters, which shall raise awareness of the importance of water loss reduction, are also summarised in a separate brochure for decision-makers. The four technical chapters are accompanied by a set of supplementary materials which offer detailed insights into selected topics.

Figure 1.1 Components and structure of the water loss reduction guidelines



The technical manual ends with a *list of references* which includes all literature that has been used to elaborate this manual. References are indicated in the text by the use of bracketed numbers, e.g. [0]

The contents of the technical manual follow the five main steps described in *Figure 1.2*. This sequence is followed throughout chapters 2 to 6 of the manual. However, each chapter is self-contained and can be read independently from the others depending on the reader's needs. All chapters have the same structure and start with the aims and objectives of the chapter. Every chapter ends with a short summary in order to evaluate the lessons learned and look forward to the next steps.

Figure 1.2 Principal steps of the technical manual

Awareness & benefits Chapter 1 & 2	Economic impacts Technical impacts Social & environmental impacts
Understanding water losses Chapter 3	Types of water losses Reasons & influencing factors Impacts of water losses
Developing a strategy Chapter 4	Methods Analysis of the present state Performance evaluation Action plan
Basic data prerequisites Chapter 5	'Hard data' management 'Soft data' management Hydraulic modelling
Methods for water loss reduction Chapter 6	District metered areas (DMAs) Pressure management Active leak control (ALC) Leak repair Infrastructure management


Photo: © A. Knobloch, 2009

2 Introduction to water loss reduction

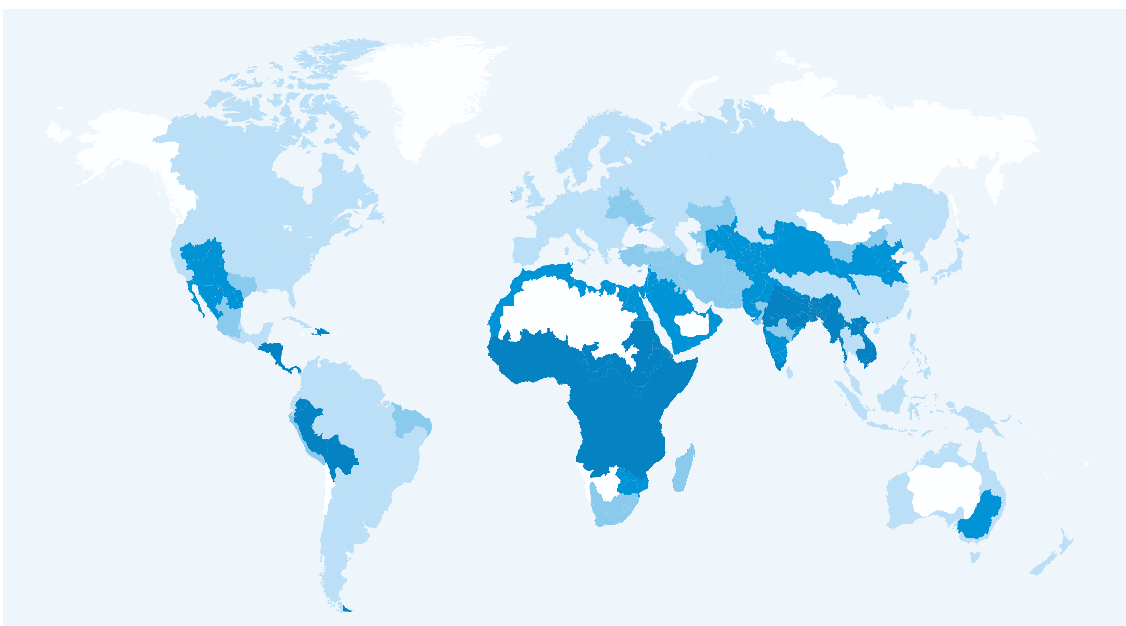
2.1 The need for water loss reduction

2.1.1 Water losses – a global problem

Water is a vital resource no matter where in the world we live. Fresh water is not only indispensable for human alimentation but also an important primary product for industrial and agricultural production. Therefore, the availability of fresh water is directly linked to the welfare and prosperity of our society.

However, fresh water is a limited, sometimes even scarce, resource and rapid global changes, such as population growth, economic development, migration and urbanisation, are placing new strains on water resources and on the infrastructure that supplies drinking water to citizens, businesses, industries and institutions. [91] Political, financial and/or technical barriers can also prevent equal water distribution, even in regions where the physical presence of water is sufficient. This effect, which is known as economic water scarcity, affects a large number of countries, especially in sub-Saharan Africa, the Middle East and South Asia, but also in South and Central America, as *Figure 2.1* illustrates.

Figure 2.1 Global distribution of physical and economic water scarcity [86]

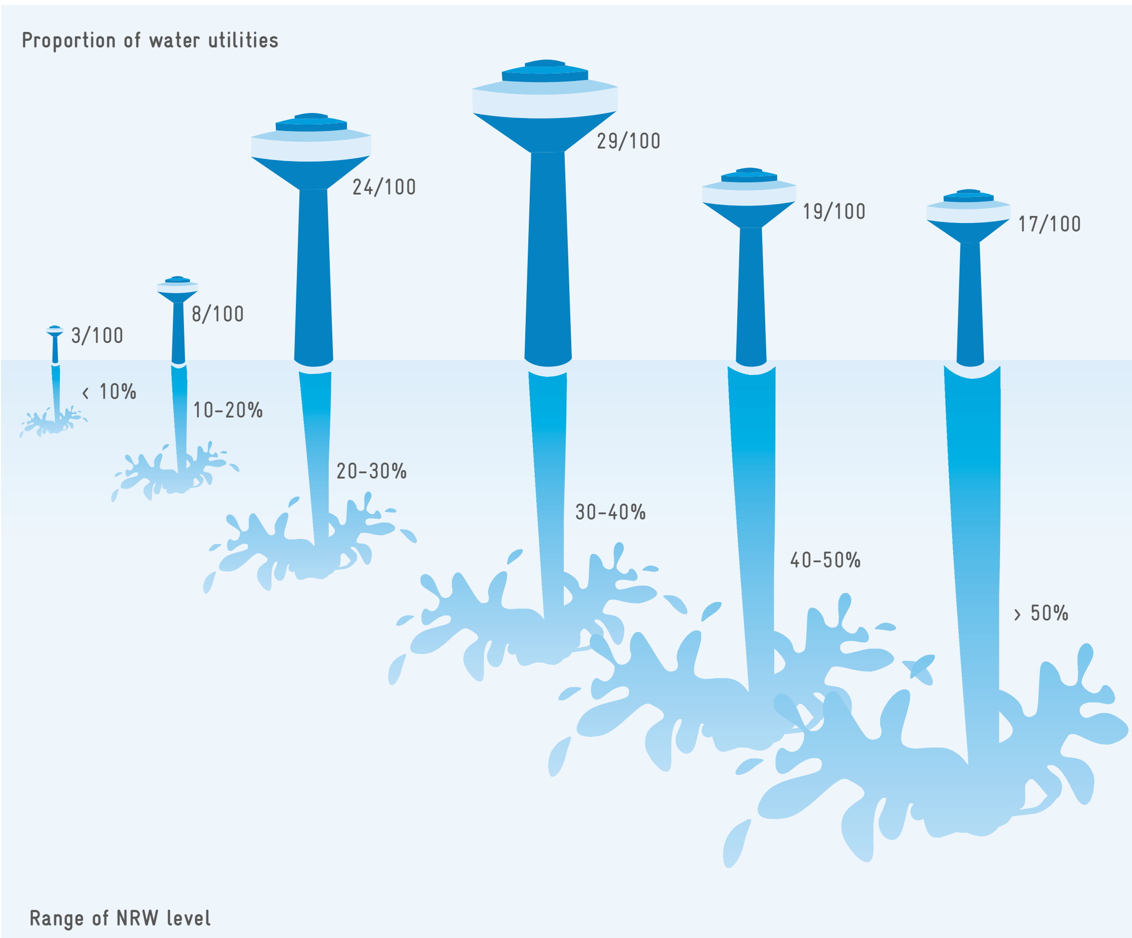


The huge amount of water lost through leaks in some urban water distribution networks (physical or *real* water losses) and the volumes of water distributed without being invoiced (*apparent* water losses) can compound the water supply situation, especially in developing and transition countries. Real and apparent water losses together with unbilled authorised consumption (e.g. for flushing mains or fire fighting) make up the amount of non-revenue water (NRW) in a water supply system.

Based on a study covering 40 water utilities in South-East Asia and the IBNET database on water utility performance covering over 900 utilities in developing countries, the World Bank estimates that *the actual figure for overall NRW levels in the developing world is probably in the range of 40 - 50% of the water produced.* [1] [39]

Figure 2.2 shows the proportion of water utilities and their respective level of NRW based on the IBNET database.

Figure 2.2 Levels of NRW in water utilities in the developing world, based on IBNET database [39]

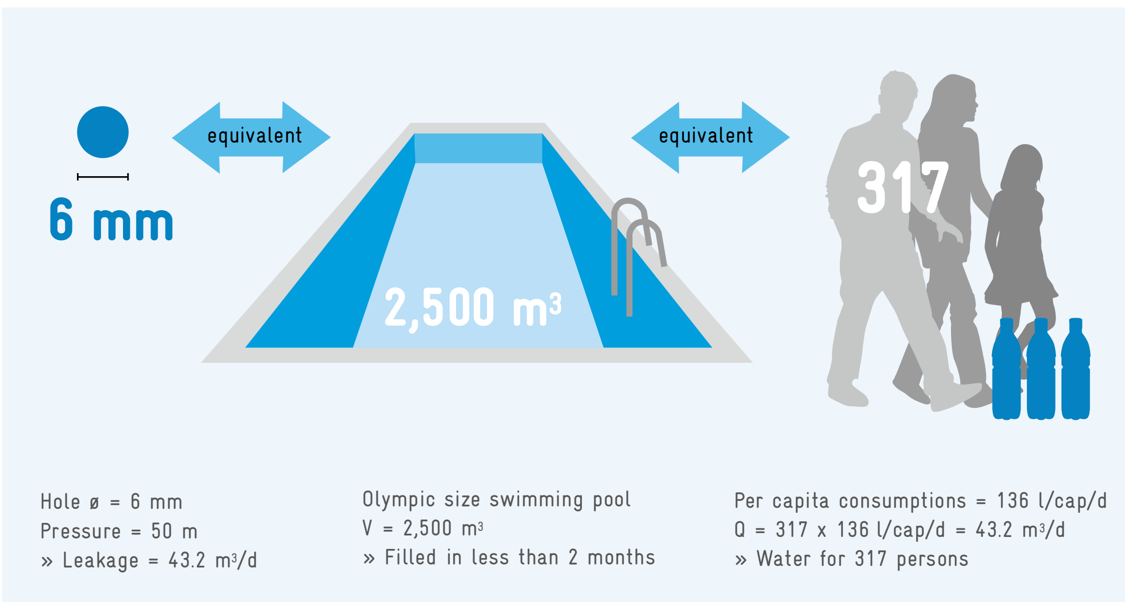


Recovering some of the lost water through water loss reduction measures often represents an economic alternative to exploiting new resources through cost-intensive measures, such as new dams, deep wells or seawater desalination.

Even using a more conservative figure that puts the average level of water losses at 35% of the system input, the World Bank estimates the annual volume of NRW in developing countries to be in the range of 26.7 billion m³, representing approximately USD 5.9 billion lost by water utilities every year. [39] Halving this amount of water lost would generate considerable earnings and enough water to supply an additional 90 million people in developing countries.

These figures are staggering, but may be hard to grasp due to their sheer size. Therefore, it is helpful to have a closer look at the problem on a smaller scale: leakage discharge tests show that water loss from a single circular hole with 6 mm diameter *(as illustrated in Figure 2.3)* in a distribution pipe at 60 m pressure amounts to 1.8 m³ per hour or 1,300 m³ per month. This discharge would be enough to fill an Olympic-size swimming pool (50 x 25 x 2 = 2,500 m³) in less than two months. The same water discharge would theoretically be enough to serve 317 inhabitants in the city of Moshi, Tanzania. [37]

Figure 2.3 Leak flow rate from a single 6 mm hole and the equivalent volume of water



It should be kept in mind that these enormous amounts lost arise from one small hole. Considering how many of these holes a large water distribution network may contain, it is clear that taking action against water losses is crucial. It is not only essential for ethical reasons to supply more people with safe drinking water and to reduce the spread of water-borne diseases. Reducing water losses will also mitigate environmental problems and alleviate the stress on scarce water resources. Furthermore, this action will save energy for water treatment and pumping. Last, but not least, water loss reduction will increase the revenues generated by private or municipal water utilities and improve the prosperity of commercial and domestic customers.

2.1.2 Water loss reduction for sustainable development

The term *sustainable development* means nothing less than successful business that facilitates greater prosperity and more equitable opportunities and uses natural resources in a way that preserves them for generations to come. Sustainability requires that economic, technical, social and ecological aspects are considered and various fields and levels of society are linked.

The *Istanbul Water Consensus (5th World Water Forum, Istanbul, 2009)* also emphasises the importance of an *equitable, optimal and sustainable management of water resources* in order to cope with increasing water demands due to *population growth, economic development, migration and urbanisation* and the negative effects of climate change. [91]

When it comes to operating water supply systems, water losses are a clear obstacle to sustainability, as the following list of potential impacts shows:

- → **Economic impacts:** costs for exploiting, treating and transporting water which is lost on its way to the customer without generating any revenue for the water utility. Pipe bursts and leaks necessitate expensive repair works and may also cause considerable damage to nearby infrastructure.
- → **Technical impacts:** leakage leads to reduced coverage of the existing water demand, possibly so much so that the system can no longer operate continuously. Intermittent supply will cause further technical problems by air intruding into the pipes and will tempt customers to install private storage tanks.
- → **Social impacts:** water losses result in customers being adversely affected by supply failures, such as low pressure, service interruptions and unequal supply, but also by health risks which may arise from the infiltration of sewage and other pollutants into pipe systems under low pressure or intermittent supply.
- → **Ecological impacts:** compensating water losses by further increasing water extraction places additional stress on water resources and requires additional energy and thus causes carbon dioxide emissions that could have been avoided.

These few examples impressively demonstrate that water loss impairs all aspects of operating a water supply system sustainably. Water utilities worldwide should thus strive to analyse, quantify, combat and reduce physical and apparent water losses from their water supply systems. A successful and sustainable reduction in water losses requires a political and financial framework that encourages water loss reduction activities by means of binding regulations, incentives, benchmarking and setting leakage targets.

2.1.3 Political and financial framework for efficient and sustainable water loss management

The framework surrounding water loss management and water loss reduction (WLR) is complex and involves many components. Efficient and sustainable water loss management necessitates not only that technical solutions are found and implemented, but also that political, financial and managerial aspects are considered. The following factors, which are crucial for the success of water loss management, must be taken into account when starting to develop a successful process:

- → Which framework conditions can be considered as an opportunity or an obstacle to WLR? (Water law and policies; water utilities structure including private sector engagement).
- → Is WLR an objective for water utilities, and do they actively promote it?
- → What are the possible incentives for the water utility to implement WLR?
- → Which financial instruments favour or inhibit WLR measures? (Subsidies, water tariff structure, private investments, cost recovery)
- → Which institutions and stakeholders promote WLR? Which institutional or structural settings are opportunities or obstacles to WLR?
- → Are there external factors, such as cultural specificities or environmental issues, which have to be considered?

Political aspects

Many countries already have a water strategy in place and quite often consider water loss reduction to be important. However, its implementation is usually complex as it requires new forms of sharing responsibilities and a change in traditional consumer behaviour.

Reform processes related to water governance are often complex and slow. The German Federal Ministry for Economic Cooperation and Development's water sector strategy stresses this, too: *"Even if good governance, participation, institutions and capacities are in* *place, implementing comprehensive reform processes may take many years. Success factors include a viable and robust basis for cooperation with decision-makers and staff in key sectoral institutions, appropriate involvement of representative of interest groups, especially poor and disadvantaged groups, and sufficient willingness on the part of partners to undertake reform."* [24] Water loss reduction is sometimes neglected, even if it presents more economical solutions than exploiting alternative water resources, such as e.g. desalination.

Financial aspects

Fixed items may account for around 80% of water supply costs, while variable costs often represent around 20%. This implies effects on the motivation of different actors as cost savings can often be considered as marginal. However, WLR's ability to improve the business' performance and decrease operating costs immediately should be understood.

Managerial and other aspects

Long-term water loss reduction will only be successful if a water utility's top management is fully committed. Appropriate benefits and incentives are additional factors that can motivate the entire staff. Organisational improvements like network sectorisation with metered inflows into pressure management areas (PMAs) and district metered areas (DMAs) help to identify, define and manage real losses. Effective customer metering helps to quantify non-revenue water and reduce wastage. Improving public awareness may contribute towards reducing water losses, e.g. by reporting leaks and curbing water wastage.

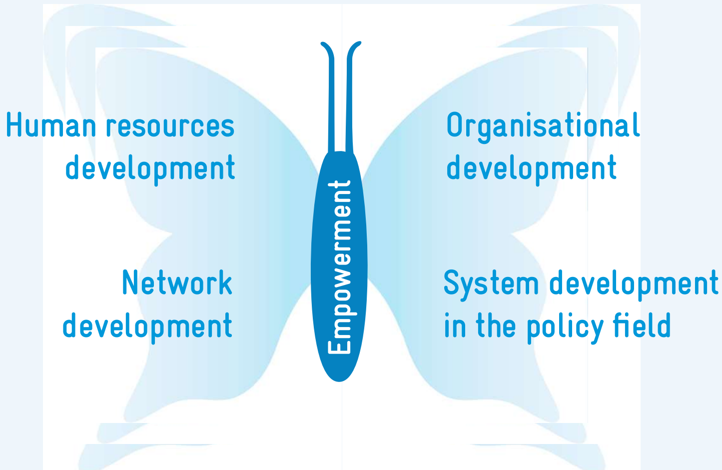
2.1.4 Capacity development in the field of water loss reduction

Capacity development is the process of strengthening the abilities of individuals, organisations, companies, and societies to make effective and efficient use of resources in order to realise their own goals on a sustainable basis. Various interconnected aspects of capacity development can be distinguished, as *Figure 2.4 on the following page* illustrates.

In the context of these guidelines, capacity development first of all comprises the transfer of knowledge, experience, skills and values to empower national stakeholders to reap the benefits of successful water loss reduction. It further involves improving management systems and extending networking. Change management and mediation in conflicting situations are essential parts of organisational development.

When national and local decision-makers choose to integrate water loss reduction methods and instruments into their water management systems, the legal and institutional framework must be adapted. Moreover, government and business stakeholders need deep insight into the implications of their decision. A comprehensive capacity development strategy

Figure 2.4 Interconnection between various elements of capacity development [94]



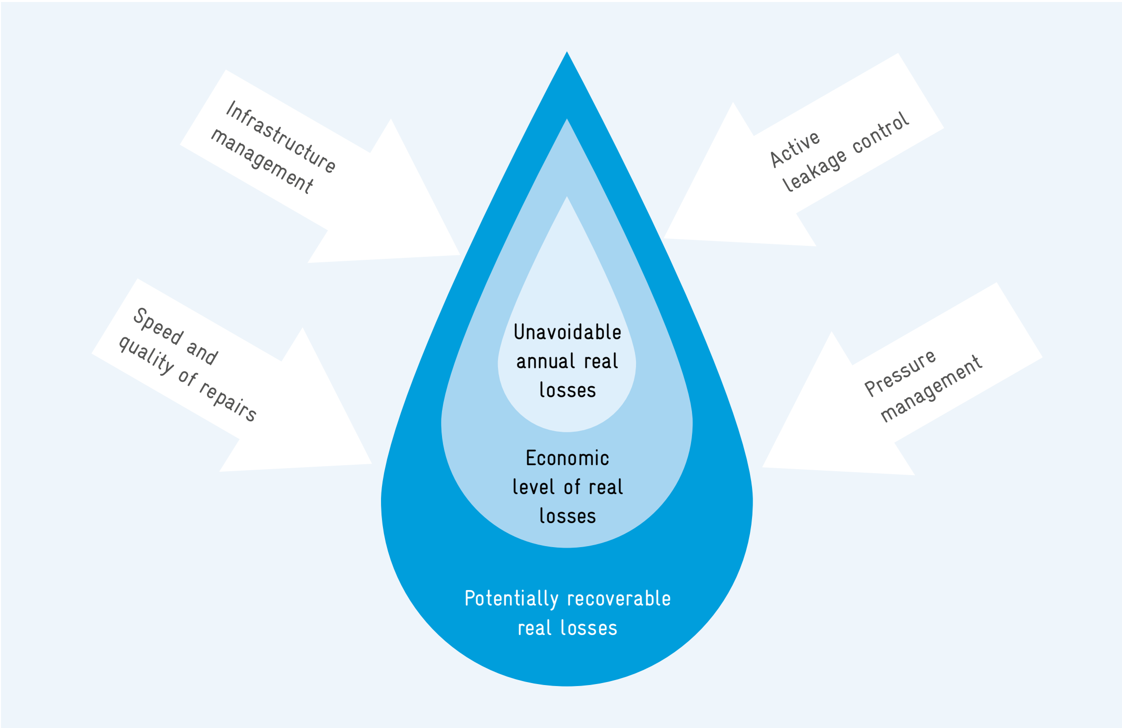
should be designed and agreed on with stakeholders. Training could be performed by or in cooperation with bilateral and multilateral organisations. Depending on the target group (decision-makers, executive staff, and/or operators), the objectives of the capacity development strategy could include gaining information on legal, technical, social, environmental, and financial issues related to water loss reduction in general and pressure management in particular. Since conditions vary from country to country, an individual and carefully designed capacity development strategy, including a comprehensive training concept, must be agreed upon.

2.1.5 The four central intervention methods to combat real water losses

Over the past two decades, many methods have been developed which are now recognised as state-of-the-art technologies for reducing water losses. Nevertheless, many water utilities around the world have yet to implement sustainable water loss management strategies despite the obvious benefits. These guidelines summarise current state-of-the-art of water loss reduction technologies and shall serve as incentive and guidance for those water utilities which want to make use of the enormous hidden potential of water loss reduction.

As this technical manual will show later in greater detail, many different factors influence the occurrence and extent of real losses in a water distribution network. Before deciding which intervention methods are appropriate, a water utility thus has to understand

Figure 2.5 The four central intervention methods to combat real water losses [69]



which factors attribute to the real losses in their particular system. A single method or a combination of different methods will constitute the most efficient and economic instrument for water loss reduction depending on the local situation.

In 2003, the IWA Water Loss Task Force defined the four principal intervention methods to combat real water losses as illustrated in *Figure 2.5*: pressure management, active leak detection, speed and quality of repairs and infrastructure management. [69]

Chapter 6 of this manual explains all four methodologies in detail. A special emphasis is placed on pressure management as a very efficient short to medium-term intervention method, which will also be briefly presented in the next section.

2.2 Pressure management

2.2.1 Principles

Pressure management can be defined as the *practice of managing system pressures to the optimum levels of service while ensuring sufficient and efficient supply to legitimate uses.* [78] The positive effects of pressure management are to decrease real water losses by reducing unnecessary or excess pressures as well as eliminating strong pressure fluctuations or transients. These factors frequently cause new pipe breaks and bursts within water distribution networks. The direct relationship between the leak flow rate and pressure means that pressure management is the only intervention method to have a positive impact on all three components of real water losses: background leakage, reported and unreported leakage *(c.f. Chapter 3.4)*.

The leak flow rate is directly connected to the water pressure in the defective pipe, and can be calculated using *Equation 3.1 on page 52* for a particular leak. Returning to the example of the 6 mm hole in *Chapter 2.1.1*, the impact of pressure reduction on the leak flow rate can easily be calculated, as illustrated in *Table 2.1*.

Table 2.1 Leak flow rate from a 6 mm hole for different pressures and pipe materials

Ø Hole	Pipe material	Leakage exponent	Leak flow rates at pressure of		
			50 m	40 m	30 m
6 mm	Rigid (e.g. steel, cast iron, ...)	0.5	1,800 m^3/h	1,610 m^3/h	1,394 m^3/h
6 mm	Flexible (e.g. PE, PVC, ...)	1.5	1,800 m^3/h	1,288 m^3/h	837 m^3/h

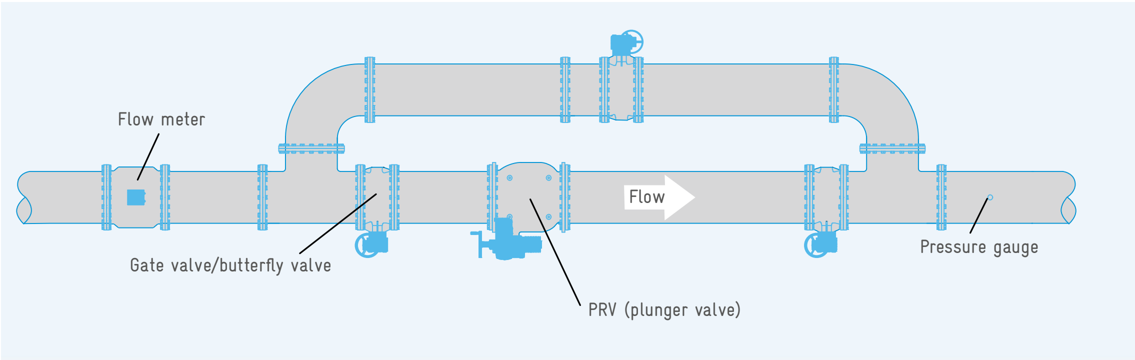
The same equation can also be used to estimate the effects of pressure management on an entire network made out of mixed pipe materials where the average overall leakage exponent is close to 1.0. The pressure-leakage relationship means that, as a rule of thumb, the ratio of pressure reduction approximately equals the ratio of leak flow reduction in large networks.

The pressure-leakage relationship explains why it still might be economic to manage or reduce pressure in a distribution network where pressure is already low: reducing average from 30 m to 27 m (10%) could decrease the leak flow by 5% to 15%, which could be significant in regions with scarce water resources or high leakage. [36]

2.2.2 Technology and mode of operation

While several different types of operating pressure management systems exist, the basic steps and installations are always similar: first, a suitable pressure management area (PMA) has to be selected and separated from neighbouring zones by closing boundary valves. A pressure reduction valve (PRV), a pressure sensor and a flow meter then have to be installed at the inlet point into the PMA. In advanced pressure management systems, a programmable logic controller (PLC) records, processes and archives the measured sensor data that is needed to control the PRV.

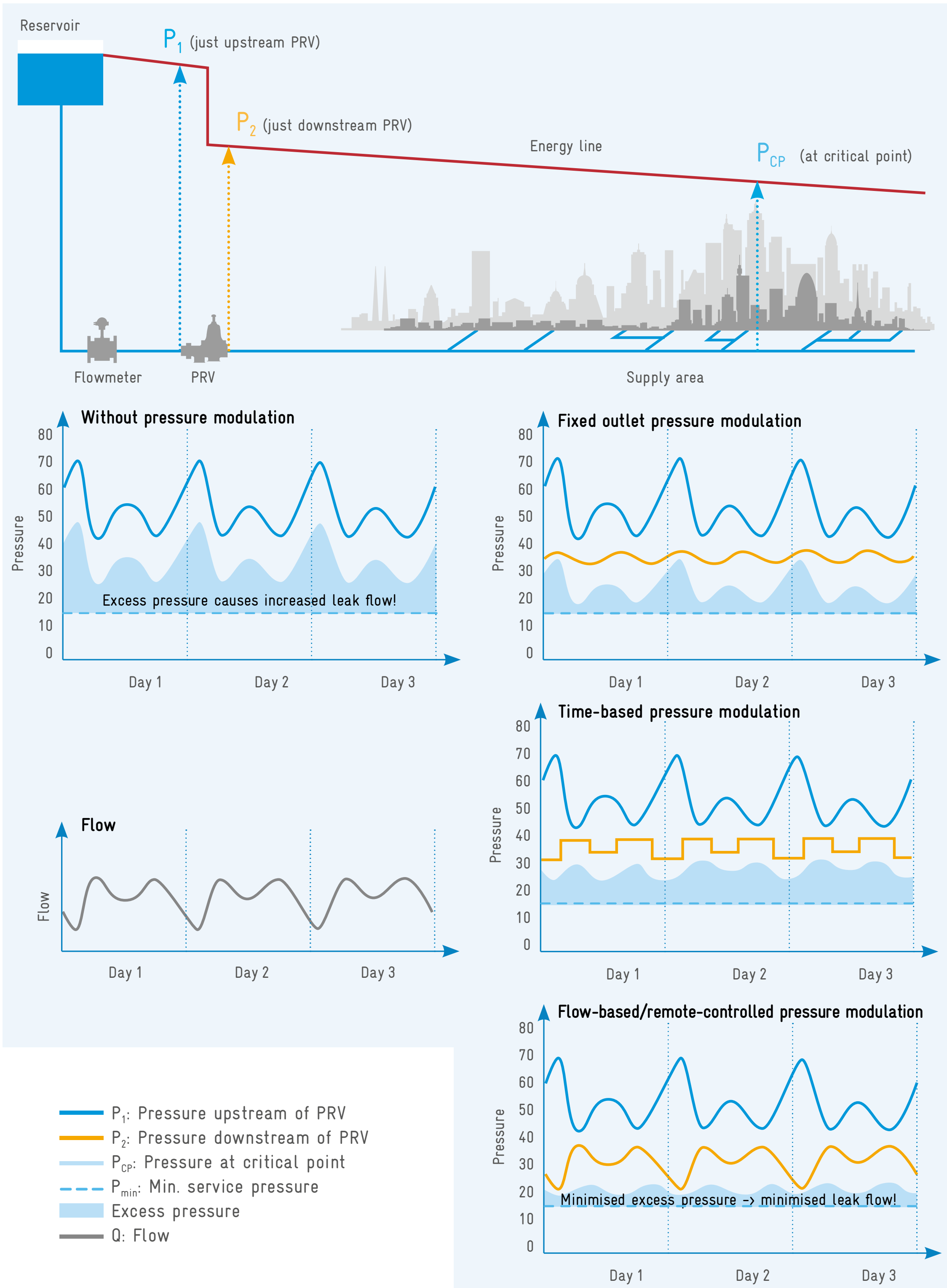
Figure 2.6 Typical PRV installation with a bypass and flow meter (Source: VAG-Armaturen)



There are four basic ways of operating the PRV and modulating the system pressure: [22]

- **Fixed outlet:** the most basic pressure control system where the PRV's outlet pressure is maintained at a chosen level at all times.
- **Time-based pressure modulation:** the PRV's outlet pressure is modulated according to the time, usually to reduce pressure during night time when flow rates are low.
- **Flow-based pressure modulation:** different outlet pressures can be set for different flow rates in order to maintain the minimum required pressure in the zone during peak flow or to open the PRV when a threshold flow is exceeded (e.g. fire flow).
- **Remote-controlled pressure modulation:** using the most advanced type of pressure modulation, the PRV's outlet pressure is continuously adjusted via telemetry from pressure sensors at one or more critical points in the PMA where the pressure is kept stable at the desired level.

Figure 2.7 Effects of different modulation concepts on excess pressure at the critical point



Alternatively, in networks with direct pump infeed, variable speed pumps with intelligent control systems can be used to reduce excessive pressures during off-peak periods of the day.

Figure 2.7 illustrates the effects of these modulation concepts on excess pressure at the critical point in a pressure management area. The critical point of a network marks the spot of lowest pressure in a zone. If minimum service pressure can be ensured at the critical point, pressure will be sufficient at all other locations in the zone. The existence of excess pressure at the critical point implies that pressure management could reduce avoidable water losses.

Flows into the PMA and supply pressure are constantly monitored and available for further review and analysis. Underground engineering is required to install the PRV and measuring devices, but the initial investment is very small compared to the large potential savings. A bypass pipe and a local control cabinet usually enable the system operator to override the control device mechanically at any time.

In addition to the basic pressure management installation, several other optional functions are available: secure cellular technology can be used to transfer data to a control room where the operator can follow the PRV's operation online. Failures can be sent to the responsible service team in the form of a text message alert, significantly reducing operation and maintenance efforts.

2.2.3 Benefits of pressure management

Pressure management can be an immediate and cost-effective solution for decreasing real water losses in a distribution network, even at low initial pressures. However, leakage reduction is not the sole benefit, as *Table 2.2* illustrates:

Table 2.2 Benefits of pressure management [47]

Pressure management: reduction of excess average and maximum pressures						
Conservation benefits		**Water utility benefits**			**Customer benefits**	
Reduced flow rates		**Reduced frequency of bursts and leaks**				
Reduced consumption	Reduced flow rates of leaks and bursts	Reduced repair costs at mains and services	Deferred renewals and extended asset life	Reduced cost of active leakage control	Fewer customer complaints	Fewer problems on customer plumbing and appliances

Supplementary materials 2.1

Checklist for implementation of pressure management

It also offers water conservation benefits because some types of water consumption will decline due to the reduced average zone pressure, for example from taps, showers and garden irrigation systems. A study by the IWA Water Loss Task Force found that pressure reduction results in a significant decrease in new pipe breaks and bursts. [79] Further benefits include deferred replacements and the extended service life of pipes, joints and fittings as well as fewer customer plumbing and appliance problems. All of these positive effects of pressure management usually result in high water savings and thus have very short payback times, as illustrated by figures from four large pressure management installations in Cape Town, South Africa which are shown in *Table 2.3*:

Table 2.3 Summary of savings from four Cape Town installations [56]

Area	Water savings (m^3/year)	Construction costs (USD)	Value of savings (USD/year)
Khayelitsha	9.0 million	335,000 (in 2001)	3,352,000
Mfuleni	0.4 million	212,000 (in 2007)	170,000
Gugulethu	1.6 million	188,000 (in 2008)	603,000
Mitchells Plain	2.4 million	967,000 (in 2009)	904,000
Total	**13.4 million m^3/year**	**USD 1,702 million**	**USD 5,029 million/year (± 600,000)**

Besides these positive effects, pressure management may generate additional, indirect benefits:

- an increased number of households with access to public water supply
- an increased duration of water supply (hours/day)
- equal and fair water supply distribution considering social constraints
- reduced production costs and energy consumption.

However, water utilities should bear in mind that pressure management only alleviates the impacts, but does not cure the causes of water loss. Therefore, pressure management should always be seen as one component of a set of measures required for successful, long-term water loss reduction. Pressure management may be a good starting point for water utilities with high levels of leakage due to the relatively high savings and the short payback periods.

3 Understanding water losses

3.1 Objectives

Having finished with this chapter, the reader should be able to:

- use water loss terminology without ambiguity
- understand the significance and scale of problems related to water losses
- distinguish the various impacts of leakage
- comprehend the hydraulic context
- identify the most important reasons and factors behind real water losses.

3.2 Definitions and terminology

Setting up a water balance at regular intervals provides the basis for assessing water losses. In the past, a wide variety of formats and definitions were used for such calculations. The International Water Association (IWA) formed a task force on performance indicators and water losses in order to achieve internationally comparable figures. An international best practice approach to calculating water balances was published in 2000. [48] A steadily increasing number of countries and water utilities around the world has since recognised and adopted this water balance. Water utilities are advised to follow the IWA terminology, particularly with regard to national and international benchmarking.

The components of the standard water balance are illustrated in *Table 3.1*. The components of the water balance should always be calculated and expressed as volumes (usually in m³) over a given period of time (usually per year). In a second step, they can be converted into performance indicators *(see Chapter 4.3.6)*.

Table 3.1 Standard terminology for the water balance according to the IWA [48]

<table>
<tr><td rowspan="10">System input volume Q_I</td><td rowspan="5">Authorised consumption Q_A</td><td rowspan="3">Billed authorised consumption Q_{BA}</td><td>Billed water exported</td><td rowspan="3">Revenue water</td></tr>
<tr><td>Billed metered consumption</td></tr>
<tr><td>Billed unmetered consumption</td></tr>
<tr><td rowspan="2">Unbilled authorised consumption Q_{UA}</td><td>Unbilled metered consumption</td><td rowspan="7">Non-revenue water</td></tr>
<tr><td>Unbilled unmetered consumption</td></tr>
<tr><td rowspan="5">Water losses Q_L</td><td rowspan="2">Apparent losses Q_{AL}</td><td>Unauthorised consumption</td></tr>
<tr><td>Customer meter inaccuracies and data handling errors</td></tr>
<tr><td rowspan="3">Real losses Q_{RL}</td><td>Leakage on transmission and distribution mains</td></tr>
<tr><td>Leakage and overflows at storage tanks</td></tr>
<tr><td>Leakage on service connections up to point of customer meter</td></tr>
</table>

The elements of the water balance are defined as:

- **System input volume:** the measured system input to a defined part of the water supply system. In systems with substantial exports of water it is also very important to determine the volume of water supplied (system input volume minus billed water exported). [48]
- **Authorised consumption:** the volume of metered and/or un-metered water taken by registered customers, the water utility and other authorised parties. It includes billed authorised consumption (such as billed metered consumption, billed unmetered consumption and water exported) and unbilled authorised consumption (such as unbilled metered consumption and unbilled unmetered consumption). This part of the water balance also comprises leaks and overflows after the point of customer metering *(see Chapter 3.6)* as well as the own requirements of the water utility, e.g. for flushing pipes or filter back-wash.
- **Revenue water** (corresponding to billed authorised consumption): the volume of water successfully delivered and billed to the customer and which thus generates revenue for the water utility.
- **Non-revenue water (NRW):** the volume which remains unbilled and therefore does not generate any revenue for the water utility. It can be expressed as the difference between the system input volume and billed authorised consumption or as the sum of unbilled authorised consumption and water losses. All elements that contribute towards NRW are highlighted in *Table 3.1*.
- **Water losses:** the volume of water lost between the point of supply and the customer meter due to various reasons. It can be expressed as the difference between system input volume and authorised consumption, and consists of apparent and real losses. Apparent losses can be subdivided into unauthorised consumption, meter inaccuracies and data handling errors. Real losses are made up of leakage from transmission and distribution pipes, leakage from service connections and losses from storage tanks.

Supplementary materials 3.1

Components of the water balance

Real losses and apparent losses are defined in *Chapter 3.4.1* and *3.5.1*. Additionally, it should be mentioned that the IWA Task Force recommends discontinuing the use of the term *unaccounted-for water* (UFW) because of widely varying interpretations of the term worldwide. [2]

3.3 Key influencing factors

Water losses occur in every water distribution network (WDN) in the world. For economic and technical reasons, it has to be accepted that real water losses cannot be entirely eliminated. Nevertheless, there has been a large increase in the knowledge and development of state-of-the-art equipment, allowing us to manage water losses within economic limits. According to the *WHO leakage management manual (2001)*, four key factors influence the degree of leakage within a utility's pipe network. These four factors are shown in *Figure 3.1*.

Figure 3.1 Key factors influencing leakage [22]

Figure 3.1 demonstrates that water loss reduction requires a holistic approach: Increased leak detection activities alone will not solve the problem if infrastructure conditions deteriorate at the same time. Furthermore, even if financial resources are available, they will not have a positive effect unless the water utility has adequate structures and takes a proactive approach towards water loss management.

3.4 Real losses

3.4.1 Classification

Real losses are water volumes lost within a given period through all types of leaks, bursts and overflows. Real losses can be classified according to (a) their location within the system and (b) their size and runtime.

(a) Location

Leakage from the transmission and distribution mains may occur at pipes (bursts due to extraneous causes or corrosion), joints (disconnection, damaged gaskets) and valves (operational or maintenance failure) and usually have medium to high flow rates and short to medium runtimes.

Leakage from service connections up to the point of the customer meter: service connections are sometimes referred to as the weak points of water supply networks, because their joints and fittings exhibit high failure rates. Leaks on service connections are difficult to detect due to their comparatively low flow rates and thus often have long runtimes.

Leakage and overflows from storage tanks are caused by deficient or damaged level controls. In addition, seepage may occur from masonry or concrete walls that are not watertight. Water losses from tanks are often underestimated and, though easy to detect, repair is usually elaborate and expensive.

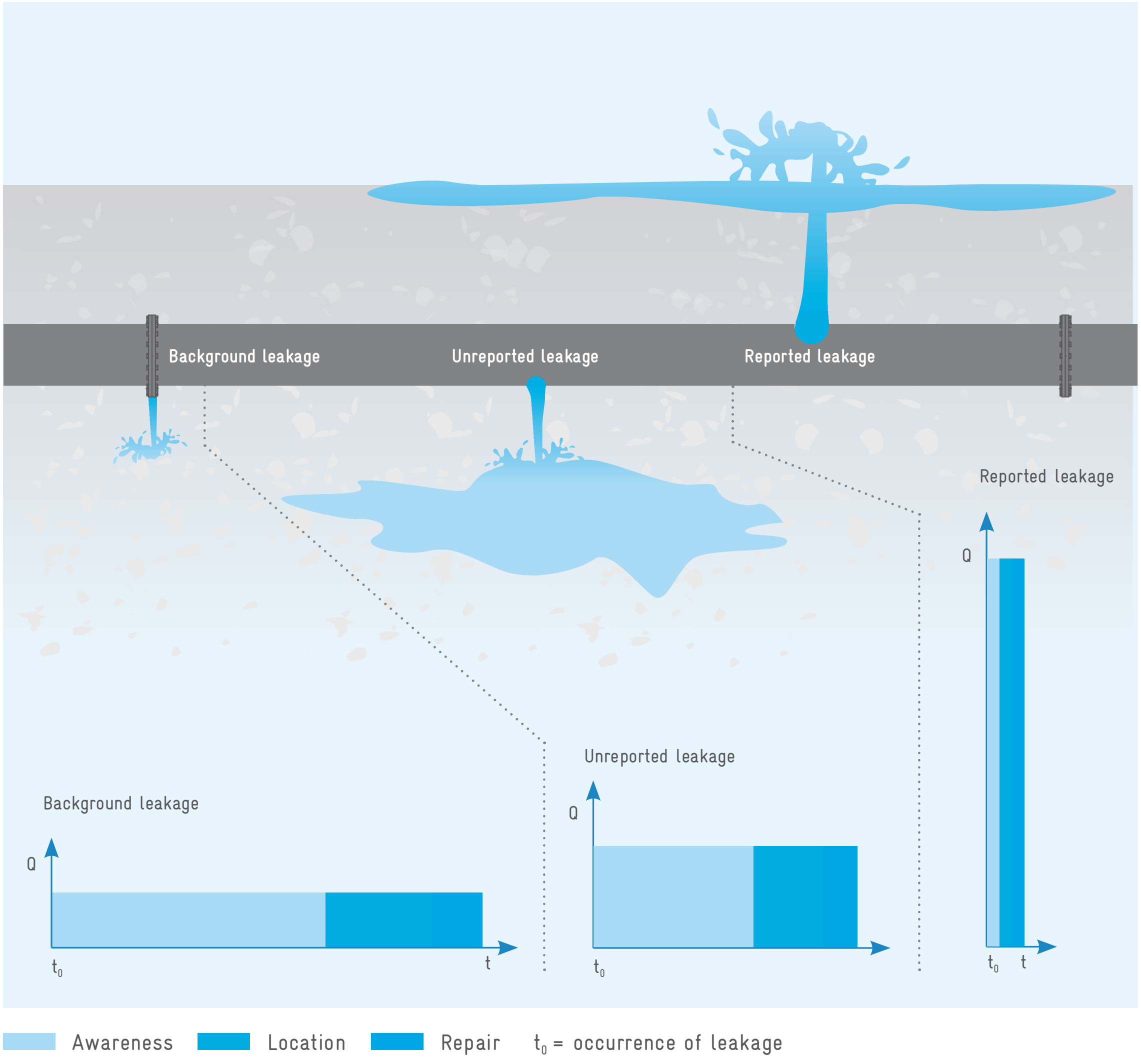
(b) Size and runtime

Reported or visible leaks primarily come from sudden bursts or ruptures of joints in big mains or distribution pipes. Leaking water will appear at the surface quickly depending on water pressure, leak size as well as on soil and surface characteristics. Special equipment is not required to locate the leak.

Unreported or hidden leaks by definition have flow rates greater than of the order of 250 l/h at 50 m pressure but due to unfavourable conditions do not appear at the surface. [22] The presence of hidden leaks can be identified by analysing trends in water consumption behaviour within a defined water supply zone. A wide range of acoustic and non-acoustic instruments is available to detect unreported leaks *(see Chapter 6.5)*.

Background leakage comprises water losses with flow rates less than of the order of 250 l/h at 50 m pressure, which do not appear at the surface. These very small leaks (seeping or dripping water from leaky joints, valves or fittings) cannot be detected using acoustic leak detection methods. Therefore it is assumed that many background leaks are never detected

Figure 3.2 Relationship between leakage rate (Q) and runtime (t) of leaks [22] [77]



and repaired but leak until the defective part is eventually replaced. Background leaks often cause a major share of real water losses due to their great number and their long runtimes.

While apparent losses can be nearly totally eliminated, a certain level of real losses will always remain in any water supply system. This amount is known as unavoidable annual real losses (UARL). The difference between current annual real losses (CARL) and unavoidable annual real losses is considered as the potentially recoverable real losses. *Figure 4.5 on page 99* provides a good illustration of the interaction between the CARL and the UARL. Real losses must be valued at the cost of producing water or at the purchase price, if water is imported.

In developed countries, real losses usually represent the most important component of water losses. However, in developing and emerging countries losses due to illegal connections, metering and accounting errors may often be of major significance to water utilities.

3.4.2 Leakage hydraulics

Real losses typically constitute a major proportion of total water losses. Leaks of different types (holes, longitudinal and circumferential cracks, leaking joints, etc.) in the distribution network's pipes are the main factor in real losses. Several field and laboratory studies have proven the high sensitivity of leakage to pressure: rising pressure will increase leakage according to the power function shown in *Equation 3.1*. Conversely, leakage decreases at reduced pipe pressure. The following explanations impart basic knowledge about the relationship between pressure and leakage. The hydraulic behaviour of leaks in pipes can commonly be described using a simplified version of the orifice equation, as illustrated in *Equation 3.1*:

Equation 3.1

$$q = c\,h^{\alpha}$$

Where:

- q Leakage flow rate
- c Leakage coefficient
- h Pressure head
- α Leakage exponent

The leakage exponent α is the outstanding factor influencing the flow rate from a leak due to its position as exponent in *Equation 3.1*. Field studies on pressure-leakage analysis have shown that α typically varies between 0.5 and 2.79 and averages 1.0. [23] [78] This means that leakage in water distribution systems is even more sensitive to pressure than traditionally assumed. Several factors have a significant impact on the range of leakage exponents:

- → The size and shape of the leak orifice, which depends on the pipe material and the type of failure (longitudinal or circumferential cracks, round holes, etc.).
- → The leak's ability to expand with rising pressure, which depends on the pipe material and the shape of the leak (round holes expand less than longitudinal cracks as pressure rises).
- → The surrounding soil.
- → The flow conditions at the leak orifice (laminar, transient or turbulent flow), which depends on the Reynolds number and the shape of the orifice.

The pipe material has a big influence on the pressure-leakage relationship. Water pressure causes stresses in the pipe walls. Depending on material properties (e.g. the modulus of elasticity), pipes made out of different materials will fail in certain characteristic ways and react differently to variations in pressure. Increasing the internal pipe pressure produces two effects: fissures and small cracks that do not leak at low pressure may open and start leaking once pressure rises. Consequently, background leakage from small leaks can be significantly influenced by changes in system pressure. Furthermore, the area of existing leaks may increase and result in a rise in the leakage flow rate. This is also dependent on the shape of the leak and its ability to expand with rising pressure. According to *Thornton* and *Lambert*, the leakage exponent α is usually assumed to be 1.5 for background leakage and leaks from splits in flexible pipes (e.g. PE, PVC); and 0.5 for leaks from rigid pipes (e.g. steel, cast iron, AC). For networks, α will usually range between 0.5 and 1.5 depending on the types of materials and the Infrastructure Leakage Index (ILI). [78] A linear relationship (α=1.0) between pressure and the leakage rate can be assumed for large water supply networks. [48] [78]

According to *Morrison et al. (2007)*, the efficiency of pressure management can be expressed using *Equation 3.2*. [58] The effect of reduced pressure on the leakage rate for networks with values of α between 0.5 and 2.5 is illustrated in graphic form in *Figure 3.3*.

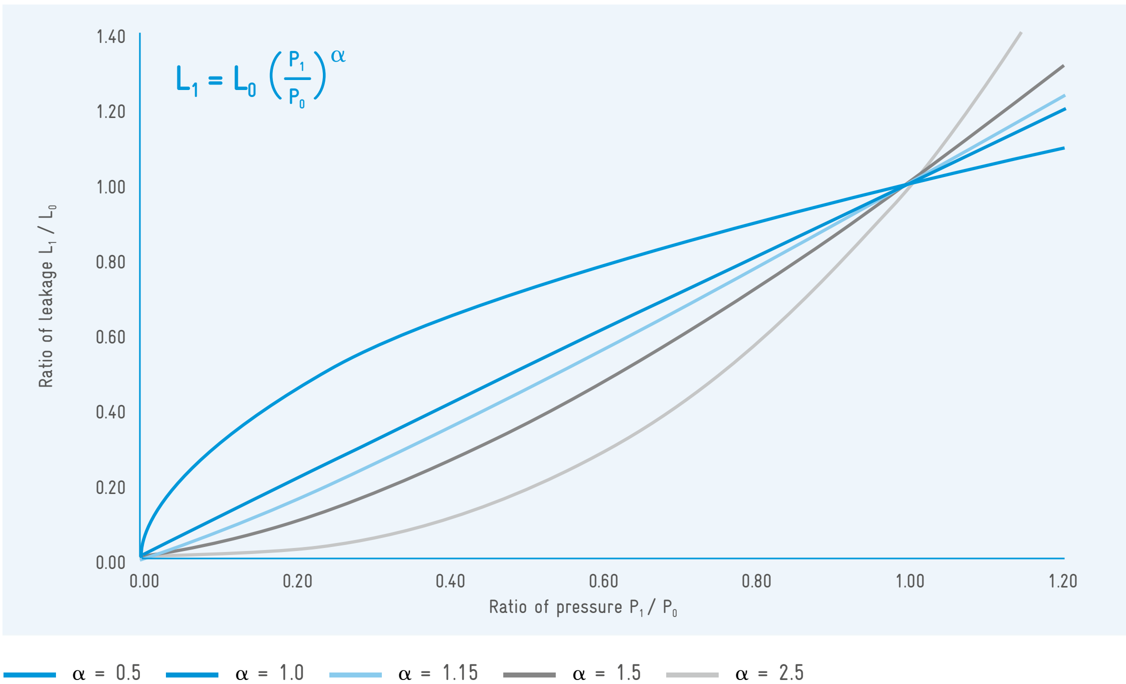
Equation 3.2

$$L_1 = L_0 \left(\frac{P_1}{P_0}\right)^{\alpha}$$

Where:

- L_0 Initial leak flow rate at pressure P_0
- L_1 Leak flow rate at adjusted pressure P_1
- P_0 Initial average zone pressure
- P_1 Adjusted average zone pressure
- α Leakage exponent

Figure 3.3 Interaction between pressure and leakage for different values of α [52]



One may conclude from this that the efficiency of pressure management depends on the network's material composition (the impact of pressure management increases with the proportion of plastic pipes) and the system's overall condition because of its high impact on background leakage *(see Chapter 6.4)*.

3.4.3 Causes of real losses

Pipes and fittings of different dimension, material and age are installed below ground, where they are subject to a multiplicity of factors which cannot be registered and controlled on a regular basis.

Additionally, *Lambert* and *McKenzie* specify four key system-specific factors for real water losses, namely the length of the mains, the number of service connections, the location of the customer's meter and the average operating pressure in the system (when the system is pressurised). These factors vary from system to system. [49]

The multitude of active and passive interactions between pipes and their environment frequently lead to damage and leaks. In simple terms, the assets of water distribution networks comprise (a) pipes and joints, (b) valves and fittings and (c) storage tanks and pumps. The causes and factors influencing water losses thus can be classified according to the type of asset.

(a) Defective pipes and joints

Material, condition and age of the pipe

Material: besides material failures caused during manufacturing (insufficient wall thickness, absence of corrosion protection on steel pipes, poor reinforcement cover on concrete pipes), damage is also brought about by inappropriate use of certain materials: soft water (especially untreated water from dams) with a high carbonic acid (CO_2) content and low calcium concentrations, or with high sulphate concentrations are known to affect concrete aggressively. Reinforced concrete pipes as well as the internal and external cement mortar lining of cast iron pipes are affected.

Condition: all metallic pipes are exposed to physical and electro-chemical corrosion. Corrosion will reduce the wall thickness and decrease the pipe's ability to withstand water pressure and external stress. The most common causes of corrosion are aggressive water and soil as well as stray current.

Age: many factors influencing leakage are age-dependent. Consequently, the age of a pipe section can appear to be the most significant factor for leakage. Nevertheless, age is not necessarily a factor, if the pipe has been carefully designed and installed, maintenance is carried out at regular intervals and external conditions are favourable.

Design and installation, workmanship

Design: mistakes made during the planning phase may influence leakage from pipes, such as the incorrect material choice, insufficient dimensioning for the actual pressure, inadequate corrosion protection measures or incorrect alignment (e.g. along slopes prone to landslides or adjacent to tree roots).

Storage and laying of pipes: improper storage may damage pipes even before installation. Grass roots can penetrate the bituminous coating of steel pipes. Dragging PE pipes over concrete surfaces or stones will cause chamfers which are more susceptible to future leakage. Extended sunlight exposure causes PE pipes to become brittle. Heavy machinery used for transport and installation may also cause damage.

Bedding: the selection of inappropriate material for pipe bedding is a frequent cause of damage: Coarse or rocky bedding material spoil external coatings on steel or cast iron pipes and support corrosion. Longitudinal and spiral cracks may appear in PE and PVC pipes as a result of stony bedding materials. Insufficient backfill and compaction of the pipe trench may cause subsidence. These uncontrolled soil movements can also trigger socket disconnection or pipe ruptures.

Joints: unprofessional execution of pipe joints is a further reason for leakage. Welded steel pipes often lack proper internal and external corrosion protection along the weld seam. If unskilled or poorly trained welders execute the relatively new technique of welding PE pipes, it frequently contains defects due to insufficient heating and pressing of the pipe ends. Leakage can also occur if socket pipes exceed the maximum permitted angular bending or if water hammer and high pressures affect joints that are not force locked.

Pressure

High pressure: increasing pressure will result in a higher flow rate from existing leaks and an augmented occurrence of new pipe bursts and leaks. As pressure mounts, leakage rates rise to a much larger extent than would be predicted by the theoretical square root relationship *(see Equation 3.1 on page 52)* between pressure and leakage rates. Aged valves and fittings may lack sufficiently robust dimensioning for high pressures.

Poor pressure: poor pressure may complicate leak detection efforts because the water is less likely to reach the surface. Furthermore, decreased noise levels from the leak impede acoustic leak location methods and may cause longer leak runtimes.

Pressure variations: marked variations in pressure within the system may lead to material fatigue and thus to leakage, mainly in plastic pipes.

Pressure surges: pressure surges (water hammer) mainly arise from inappropriate control mechanisms and can cause pipe fractures, disconnect joints and damage valves and fittings, hence leading to leakage.

Table 3.2 provides insight into the influence of pressure on leakage flow rates. The factors in *Table 3.3* serve for the conversion of these flow rates to system pressures that differ from 50 m.

Table 3.2 Leakage flow rate for circular holes at 50 m pressure [33]

	Orifice		Leakage flow rate		
	[mm]	[l/min]	[l/hour]	[m^3/day]	[m^3/month]
	0.5	0.33	20.00	0.48	14.40
	1.0	0.97	58.00	1.39	41.60
	1.5	1.82	110.00	2.64	79.00
	2.0	3.16	190.00	4.56	136.00
	3.0	8.15	490.00	11.75	351.00
	4.0	14.80	890.00	21.40	640.00
	5.0	22.30	1,340.00	32.00	690.00
	6.0	30.00	1,800.00	43.20	1,300.00
	7.0	39.30	2,360.00	56.80	1,700.00

Table 3.3 Conversion factors for Table 3.2 [33]

Pressure	10	20	30	40	50	60	70	80	90	100
Conversion factor	0.45	0.63	0.77	0.89	1.00	1.10	1.18	1.27	1.34	1.41

The values presented in *Table 3.2*, which have been confirmed in experiments, impressively illustrate the capability and high potential of pressure management to reduce the leakage flow rate in water distribution networks by means of pressure reduction. It is equally important to understand that small leaks with relatively small flow rates may cause the highest share of water losses due to their long or even unlimited runtimes. It is therefore essential to manage and minimise the duration of all leaks and bursts, even the smallest ones.

Soil and groundwater

Soil type: the prevailing soil type has significant effect on the runtime of leaks. While water escaping into cohesive soils (e.g. clay or silt) may soon appear at the surface, leaks into non-cohesive soils (e.g. sand or gravel) tend to drain away below ground, making leaks more difficult to detect.

Soil aggressiveness: most non-cohesive soils are not aggressive. Cohesive soils may negatively affect the external corrosion of metallic pipes due to differing levels of dissolved salts, oxygen, moisture, pH and bacterial activity.

Soil movement: soil movement is caused by changes in the temperature and moisture content (changing groundwater levels cause cohesive soils to contract or expand), heavy frost as well as subsidence prompted by incorrect pipe bedding, mining activities or earthquakes. Construction work, increased surface loads or pipe repair works may also trigger soil movement. Soil movement may cause pipe joints to disconnect and pipes to rupture.

Traffic

Traffic load: many pipes that were originally laid underneath pavements are now situated under the roads as traffic and road widths have increased. More vehicles and the high axle loading of modern trucks place an additional burden on the pipes.

Pavement: the water outlet may appear far away from the damage due to concrete and tarmac pavements, thus hampering leak location efforts.

Stray current: 1 ampere erodes approximately 10 kg of iron each year. Stray currents from DC-powered railway systems (trams) and reinforced concrete foundations thus aggravate the external corrosion of metallic pipes. [62]

Third-party influence

The absence of infrastructure documentation (e.g. as-built drawings) or improper execution of construction work may damage pipes, either directly through excavators or indirectly through vibrating construction machines or heavy vehicles. Damage may be detected instantly or after a delay, making the cause harder to detect.

Other factors

There are numerous other factors, e.g. the number of valves and service connections (known as the weak points within the distribution system) per kilometre of pipe, the length and diameter of the mains, the average length of service connections, the depth at which the pipes were laid as well as background leakage from joints, fittings and valves. The operational management of the system also influences leakage, e.g. in terms of water from different sources being mixed within the pipe system (risk of corrosion), the percentage of time the system is pressurised and the inspection, maintenance and leak detection strategies that influence the runtime of detected and undetected leaks. [48]

(b) Defective valves and fittings

Leaks from valves and fittings include breakage, deformations or material failures at the valve body as well as leaking gaskets at joints, bonnets or stems. Rough handling or an absence of maintenance often causes these leaks. Defective valves and fittings may contribute significantly to real water losses in spite of rather low leak rates. These deficits often remain undiscovered for a long time without a regular servicing programme. Considerable water losses may also occur from defective fire hydrants and public water standpipes.

(c) Defective storage tanks and pumps

Water losses from storage tanks are caused both by structural damage and by operational failures, such as faulty or lacking system controls which may result in overflow. Structural damage involves cracks, holes or delamination at tank walls or floors, leakage due to inferior concrete quality, as well as sealings and pipe penetrations that are not watertight. Water losses from tanks are often underestimated and, though easy to detect, repairs are usually elaborate and expensive. Water losses from pumps are usually caused by defective pump shaft seals. The amount of leakage is negligible in most cases, but flooding pump chambers and electric equipment is a nuisance and should be avoided by undertaking proper maintenance.

3.4.4 Impacts of real losses

The main objective of water supply systems is to provide all customers with drinking water of adequate quality and quantity, with sufficient pressure and at any time. [61] In many cases, leakage presents the biggest barrier to these objectives. The negative effects of leakage can be divided in (a) economic impacts, (b) technical impacts, (c) social impacts and (d) environmental impacts.

(a) Economic impacts

Water lost on its way to the consumer incurs exploitation, treatment and transportation costs without generating any revenue for the utility. The lost amount of water must be provided again in order to meet customer demand. Consequently, the production capacities of the technical installations must be increased.

Repairs to fix detected leaks are expensive in terms of the costs and personnel required and usually interrupt service to customers.

Finally, pipe bursts, leaks and overflows may cause considerable damage to infrastructure: the surrounding soil is hollowed out and eroded, making roads, rails or buildings collapse. Flooding endangers basement garages or engineering rooms containing expensive equipment. Large compensation payments may be imposed if the water utility is held liable for damages. *Table 3.4* illustrates the possible dimensions of such economic impacts for a water utility.

Table 3.4 Potential economic impacts of leakage (city of Zurich, Switzerland) [70]

Extent of damages	Description	Potential costs
Catastrophic	Fatal casualties or permanent health problems	› USD 10 million
Critical	Injury to persons, infrastructure damages and production interruptions, negative publicity	› USD 5 million
Significant	Supply disruption for the population and clients, local supply failures	› USD 1 million
Minor	Short-term disruption to supply and infrastructure, possible media coverage	› USD 0.3 million
Insignificant	Temporary supply disruptions	› USD 0.1 million
Imperceptible	No direct disruption, limited local impacts	‹ USD 0.1 million

(b) Technical impacts

Leaking drinking water pipes can increase the loads on municipal wastewater and/or stormwater collection systems due to infiltration, leading to over-designed sewer pipes. Consequently, wastewater treatment plants may receive additional water, which generates additional treatment costs.

Extensive leakage may lessen the coverage of existing water demand so much that the system can no longer operate continuously. Intermittent supply will cause further technical problems by air intruding into the pipes (risk of water hammers, damage to water meters, measurement errors, etc.) and polluted water (risk of bacterial infection spreading contagious diseases). Costly supply alternatives must be kept available, such as water tanker trucks.

In the long term, intermittent or unreliable supply will tempt customers to install roof tanks, which in turn hamper the restoration of continuous water supply. The connection between intermittent supply and the level of leakage means that water losses are generally higher in intermittently operated systems than in continuously operated systems. It must be emphasised that intermittent supply should never be perceived as a technical solution, but as an obstacle to combating water losses.

(c) Social impacts

Supply failures, such as low pressure and service interruptions to the point of intermittent supply, are the most common impacts on the customer. These inconveniences will lead to customer dissatisfaction and complaints, and may negatively affect the customers' willingness to pay their water bills. Poor supply in combination with frequent (visible) pipe bursts will affect the utility's reputation and may trigger bad publicity.

The potential health risks from sewage or other pollutants infiltrating pipe systems with low pressures or intermittent supply are even more serious. Contaminated water may cause outbreaks of water-borne diseases, such as cholera, typhus, hepatitis A or diarrhoea.

(d) Environmental impacts

Sustainable management requires that all natural water resources be handled economically. Unpolluted water is already scarce in many regions, but even regions with abundant amounts of water do not have infinite resources. Compensating for water losses by further increasing water extraction places additional stress on superficial and subterranean water bodies that sound water supply systems would avoid. [62]

In addition, pumping and chemical treatment of water lost through leaks wastes energy and thus causes needless carbon dioxide emissions. High leakage may often be responsible for more than 25% of a water utility's energy consumption.

Additional substantial amounts of energy may be required for decoction as well as for transporting potable water in bottles or tankers in the event that intermittent supply is lowering water quality. Intermittently supplied systems incur high energy costs because pressure is lost every time the system drains down and has to be refilled. Finally, more energy is required for long-distance pumping or complex treatment technologies, such as desalination or wastewater re-use if existing water resources no longer suffice. [65]

3.5 Apparent losses

3.5.1 Classification

Apparent losses are losses that are not due to physical leaks in the infrastructure, but are caused by other factors. Apparent losses can be grouped into the following categories based on their origin:

- meter inaccuracies due to broken or incorrect customer and bulk water meters
- data handling and accounting errors and
  poor customer accountability in billing systems
- unauthorised consumption due to water theft and illegal connections.

3

Summarising the above, apparent losses comprise all water that is successfully delivered to the customer but which is not metered or recorded accurately and thus causes an error in the amount of customer consumption. In water supply networks without consequent, system-wide metering and with numerous illegal connections, apparent losses may represent significant amounts of water. Apparent losses are creating production costs without generating revenue for the utility. Thus, apparent losses must be valued at the retail cost of water and are therefore in many cases the most expensive losses that a water utility will encounter. Reducing apparent water losses can be achieved in many cases at relatively low costs and is therefore usually a good starting point which pays off quickly to the water utility. [77]

3.5.2 Reasons for apparent losses

Apparent water losses are caused by (a) water meter inaccuracies, (b) data handling errors and (c) any form of unauthorised consumption. Apparent losses should not be underestimated, because they do not generate revenue for water that has already been produced, treated, transported and delivered to the customer. Reasons for apparent losses can be grouped as described *on the next page:*

(a) Meter inaccuracies

Metering losses are frequently the most common form of apparent losses. Experience shows that a small percentage of water is not metered or metered incorrectly due to measuring errors or creeping losses in water meters. This affects both customer meters and bulk water meters, and may be caused by selecting unsuitable meters, oversized meters, incorrect installation and uncalibrated meters as well as many meters' deteriorating performance over time.

(b) Data handling errors

Meter-reading personnel may make meter-reading errors. Water consumption data may get lost or changed due to systematic errors in data processing and billing procedures. Unmetered consumption (own needs and free supplies for fire fighting, watering of greens, street-cleaning, etc.) may be underestimated while unmetered production may be overestimated. Flat-rate tariffs may cause excessive domestic water consumption that by far exceeds the budgeted amount.

(c) Unauthorised consumption

Unauthorised water extraction represents a considerable source of losses in many countries and appears in many different ways, for example illegal connections, vandalised, manipulated or bypassed customer meters, illegal water abstraction from fire hydrants as well as bribery and corruption of meter-readers or other utility personnel.

3.6 Wastage

Water wastage is not counted as a water loss component in the IWA water balance because it occurs after the point of customer metering. Nevertheless, wastage can represent a significant proportion of metered or unmetered consumption: it can be broken down into deliberate wastage, e.g. vandalism or running customer taps, and into household losses caused by defective plumbing or running toilets. The latter can be significantly reduced by replacing subsidised flat-rate tariffs with an effective policy of household metering which creates incentives to repair defective plumbing. [22]

Furthermore, wastage may occur within the water utility itself through excessive or negligent usage of water for operational purposes, e.g. pipes flushing or filter rinsing, and will thus increase the amount of unbilled authorised consumption.

Water wastage can pose a serious economic problem for water utilities that have to import or buy water from a bulk water supplier, and thus have to pay the full cost for every (unmetered) cubic meter wasted. In regions with scarce water resources or intermittently supplied zones, reducing wastage may help to improve supply security. [68]

Awareness programmes aimed at both utility workers and the public should teach them to value water and propagate simple no-cost or low-cost water conservation techniques (turning taps off fully, replacing leaking hoses and worn tap washers, etc.) which may rapidly yield considerable results.

3.7 Summary and next steps

This chapter aims to impart fundamental knowledge about water losses.
The contents of *Chapter 3* of this technical manual shall enable the reader to:

- ☑ Employ clear terminology and definitions for all components of water losses and non-revenue water.
- ☑ Know the components of the IWA standardised water balance.
- ☑ Identify the key factors influencing water losses.
- ☑ Classify real water losses accoring to their location, size and runtime.
- ☑ Understand leakage hydraulics and the impact of pressure on leak flow.
- ☑ Know all potential causes for pipe bursts and breaks.
- ☑ Understand the economic, technical, social and environmental impacts of water losses.
- ☑ Know the causes and impacts of apparent losses.

This knowledge provides the basis for developing a tailor-made water loss reduction strategy, which will be described in *Chapter 4*.

3

4 Developing a technical strategy for water loss reduction

4.1 Objectives

At the end of this chapter, the reader will know the principal methods to

- assess and quantify the present status of water losses
- determine and analyse relevant performance indicators
- set leakage targets
- design an appropriate water loss control programme.

The reader should be able to perform the described methods independently after completing the supplementary materials. The definitions, terminology and performance indicators mentioned in *Chapter 4* are largely based on the work of the IWA Water Loss Task Force. More information about this subject can be found in *Alegre et al.*, *Lambert* and *Hirner.* [2] [48]

4.2 The need for water loss management

Water loss reduction should be the aim of every water utility since it leads to improved economic and ecological efficiency and better service for clients. [77] Before developing a water loss reduction strategy, decision-makers should be aware of why it makes sense to provide financial and personnel resources to reduce water losses. From the perspective of a water utility, there are at least ten reasons that may justify increased expenditure on water loss management:

→ **Operating cost efficiency:** a well-maintained water distribution system will require fewer repairs, lower production costs and prevent compensation payments.

→ **Capital cost efficiency:** a lack of maintenance and intermittent operation increase wear and tear on pipes, valves and meters. Improved supply will extend the service life of the system components and lead to lower fixed costs for the water utility in the long run.

→ **Improved metering and billing:** fewer leaks and an improved supply situation may also have positive effects on apparent water losses because air inside the distribution system can cause metering errors.

→ **Reduced health risks:** sewage and other pollutants can infiltrate the pipe system through leaks and trigger water-borne diseases in low-pressure systems or in the case of intermittent operation.

→ **Increased security of supply:** a well-maintained system with fewer leaks and bursts will increase the supply guarantee.

→ **Less infrastructural damages:** leakage might create voids below ground which can lead roads and buildings to collapse.

→ **Reduced loads on sewers:** infiltration of water lost to sewers places an additional load on sewer pipes and wastewater treatment plants.

- **Improved consumer satisfaction:** in addition to poor water quality, inadequate quantity and health risks, leakages also decrease the pressure at customers' appliances. Enhancing the supply service will improve customer satisfaction and willingness to pay.

- **Publicity and willingness to pay:** fewer bursts, increased security of supply and hygienic conditions will enhance the public's perception of the water utility. This may also positively affect the consumers' willingness to pay.

- **Reduced ecological stress:** finally, the development of a water loss reduction strategy makes sense from an ecological point of view. In the case of scarce or over-exploited water resources, water losses should be reduced to decrease the stress on these resources.

4.3 Analysis of the present status

4.3.1 Preliminary system diagnosis

A certain level of leakage is unavoidable, even in the best-maintained and operated water distribution system. Thus, a water utility should ascertain two characteristics of their system to implement a successful and sustainable water loss reduction programme: the current leakage status and the envisaged economic level of leakage.

Consequently, current water losses must be understood and assessed using a diagnostic approach before an appropriate water loss reduction strategy can be developed. It is helpful to perform the diagnosis incrementally with assistance of a checklist like the one shown in *Table 4.1*.

Table 4.1 Diagnosing the existing system, based on [22]

Question	Available methods	Chapter
Do we know our system?	GIS based network register and hydraulic modelling	5.5, 5.6
How much water is lost?	Water balance calculation	4.3.2
Where is it lost?	Metering (permanent or temporary)	4.3.2, 5.8
How to determine the losses?	Loss assessment methods	4.3.4, 4.3.5
Why is it lost?	Review of the network and operational practice	6.3, 6.4, 6.5

4.3.2 Determining the water balance

A water balance aims to track and account for every component of water that is added to and subtracted from a water supply system within a defined period of time. A water balance thus seeks to identify all components of consumption and losses in a standardised format. [77] A clearly defined water balance is the first step in assessing non-revenue water and managing leakage in water distribution networks. The terminology that is used for a water balance was introduced in *Chapter 3.2*. Abbreviations of the water balance terminology are shown in *Table 4.2*.

Table 4.2 Water balance terminology (abbreviated)

<table>
<tr><td rowspan="4">System input volume Q_I</td><td rowspan="2">Authorised consumption Q_A</td><td>Billed authorised consumption Q_{BA}</td></tr>
<tr><td>Unbilled authorised consumption Q_{UA}</td></tr>
<tr><td rowspan="2">Water losses Q_L</td><td>Apparent losses Q_{AL}</td></tr>
<tr><td>Real losses Q_{RL}</td></tr>
</table>

When elaborating the water balance calculation, it is extremely important to keep in mind that the accuracy of water loss volumes depends on the accuracy and quality of data used in the calculation. Hence, reliable metering of all water volumes entering and leaving the supply system is a fundamental requirement. Validating data also plays a key role in assessing water loss volumes. Designing a worksheet or spreadsheet to perform the water balance calculations is recommended. Commercial software is also available to support collection of the necessary data and to perform calculations. A number of techniques for calculating a water balance exist, and should be combined in order to achieve reliable results. [20] The most important techniques are (a) the top-down annual water balance and (b) the bottom-up real loss assessment.

(a) The top-down annual water balance

The IWA developed the top-down annual water balance as a best practice method. The top-down method requires that bulk and customer water meters are installed and read for the period of at least one year. This method aims to determine the overall annual real losses in m^3/a. The standard procedure according to the German Technical Association for Gas and Water can be applied as follows. [13]

Step 1

The system input volume Q_I should be ascertained using annual measurements from all bulk water meters. The accuracy of installed bulk meters should be determined via field tests, e.g. through volumetric tests or portable insertion or clamp-on flow meters. An appropriate estimate of the quantities has to be made if system input volumes are not metered. Sample surveys can improve appraisals. The total annual volume can then be estimated in consideration of annual fluctuation curves. Bulk water meters for water exports have to be identified and checked (these are the inputs into other systems) in order to calculate the amount of water supplied to the system.

Supplementary materials 4.1

Annualising water meter data

Step 2

All customers registered in the billing records (households, commercial and industrial consumers, etc.) have to be identified to determine the **billed authorised consumption** Q_{BA}. Annual consumption can be determined by means of meter readings on the reference date and by annualising metered consumption appropriately.

A proper estimate has to be made for billed customers without water meters. It is not recommended to simply assign consumption figures of metered users, because metered tariffs usually create different consumption behaviours than flat-rate tariffs. Therefore, average unmetered domestic consumption should be determined using individual household monitors (IHMs) for a random sample of users. An alternative method is to use small area monitors (AMs) if the area under investigation is not subject to large volumes of undetected leakage. [89]

Supplementary materials 4.2

Determining unmetered consumption

Step 3

Unbilled authorised consumption Q_{UA} has to be determined by means of an appropriate estimate. First, all consumers have to be identified. These might be households, municipal buildings, parks, fire services, water tankers or slum areas. An estimate of the annual consumption has to be made for each consumer group. One method can be to utilise figures from comparable customers or literature. In some cases, it makes sense to take samples in a field survey. Finally, the volume used by the water utility for operational purposes (mains cleaning, flushing, etc.) has to be identified. A qualified estimate should be made if measured values are not available.

Step 4

The **authorised consumption** Q_A can now be calculated by adding Q_{BA} and Q_{UA}. The total water losses Q_L can then be derived from Q_I - Q_A.

Step 5

Estimating **apparent losses** Q_{AL} is rather difficult and is subject to a high degree of uncertainty. Apparent losses should be broken down into their components to achieve a suitable estimate. Firstly, the number of illegal connections has to be estimated. This can be done either by consulting past records or by conducting a house-to-house survey within a sample zone. Without specific data, *Thornton* recommends using 0.25% of the system input volume as an initial approach. [77] Secondly, the losses due to data transfer and handling errors and metering inaccuracies have to be estimated. The number of broken water meters should be recorded during meter readings. Volumes can be appraised by using per capita estimates.
In Germany, apparent losses are estimated to range from 1.5 to 2.0% of the system input volume. [13] For developing countries, the IWA recommends utilising 5% of the billed metered consumption as an initial estimate until a more detailed appraisal is available. According to *Lambert (2010)*, apparent losses usually will exceed 5% in systems with customer storage tanks. It is always advisable for each water utility to assess and quantify the components of apparent losses within its own system, rather than using a percentage of the system input volume which is based on figures from other utilities. [44]

Step 6

Finally, the real water losses Q_{RL} can be derived by subtracting the apparent losses Q_{AL} from the overall water losses Q_{L}.

Supplementary materials 4.3

Water balance calculation

One disadvantage of the top-down water balance is that the procedure is subject to errors and uncertainty. The lower the number of permanently installed and regularly checked bulk and customer water meters, the lower the level of accuracy will be. Results improve with years of experience and increasing quality and quantity of the input data. [77] Many calculations using the top-down approach have shown that confidence limits of less than ± 15% of calculated real losses are difficult to achieve, even in well-managed systems with low leakage and reliable metering. [46]

A bottom-up analysis based on night flow measurements is recommended as an accompaniment to the annual water balance in order to develop an appropriate water loss reduction strategy. [20]

Each water utility should perform a top-down water balance on an annual basis. Nevertheless it has to be considered that the annual water balance is a retrospective approach which cannot provide an early warning system for identifying new leaks and bursts. Therefore, it is recognised best practice to combine water balance calculations with night flow measurements on a continuous or as-needed basis in order to initiate active leakage control and to limit the runtime of new leaks and bursts. [46]

(b) The bottom-up assessment of real water losses

The bottom-up assessment is a useful tool for crosschecking the real loss volumes obtained from the top-down water balance and the component analysis. It involves independent field test data acquired in discrete areas of the water distribution network. This is usually based on a minimum night flow (MNF) analysis *(see Chapter 4.3.4)* and takes into account diurnal variations in system pressure. MNF measurements should be executed in those seasons and days of the week when exceptional night use (e.g. for garden irrigation) is minimal in order to obtain reliable results. A MNF analysis for the entire distribution system provides an independent determination of the real loss volume that can be used to control the results of the water balance calculation. Ideally, the two volumes should balance, but experience has shown that they usually do not match exactly due to respective cumulative errors.

A further advantage of the bottom-up assessment is that areas of high real losses can be identified and prioritised within the water loss reduction strategy. Another positive by-product of collecting field test data during the bottom-up assessment is that the system information required to determine background leakage and the pressure-leakage relationship is acquired. [20]

4.3.3 Reliability of water balance calculations

As discussed in the previous chapter, the results of a water balance calculation will only be as good as the data used to generate it. In general, a water balance is not only based on measurements, but also on estimates of water production, consumption and losses. Hence, the resulting volumes of non-revenue water, real and apparent losses will always be subject to a greater or lesser degree of error. Errors in ascertaining real and apparent loss volumes will influence the economic analysis of options and may lead to an inappropriate water loss reduction strategy. Therefore, it is important for all measured data and all necessary estimates to be as close to real conditions as possible so that valid and useful results can be achieved. Data source reliability and data accuracy should therefore always be critically assessed. [2]

Accuracy bands

Reliability describes the extent to which a data source yields consistent, stable and uniform results each time over repeated measurements under same conditions.

Accuracy relates to measurement errors in input data and the closeness of observations, computations or estimates to the true value. In practice, no detailed information will be available about data accuracy and reliability, but water utilities will be able to provide competent guesses about the accuracy band of certain input data. [2]

4

Table 4.3 Example for the relationship between data origin and data accuracy

Data origin	Description	Accuracy bands
Measured volumes	System input, metered consumption, metered export	± 0.1 to 2.0%
Estimated volumes	Unmetered consumption, apparent losses	± 5 to 50%
Derived volumes	Non-revenue water, real losses	Depends on accuracy of measured and estimated input data

95% confidence limits

The use of 95% confidence limits has been established as a procedure to rate the degree of uncertainty of single components of the water balance. These 95% confidence limits come originally from the uncertainty calculation and are based on normal distributions, which all share the following property: 95% of the observations fall within the range of ± 1.96 standard deviations (σ) around the mean value. [77]

In practice, the use of 95% confidence limits means that calculations based on approximate data have wider confidence limits than calculations made with more reliable data. [46]

For each measured or estimated component of the water balance, accuracy bands (± ...%) have to be defined within which the real value lies with a probability of 95%. The more accurate the data, the smaller the lower and upper limits of the accuracy band will be.

Supplementary materials 4.4

Use of 95% confidence limits

Furthermore, the variance (variance V = σ^2) can be determined for each component of the water balance on basis of the 95% confidence limits. Components with a large variance will have the biggest impact on the accuracy of derived volumes. The derived volumes of the water balance will then have an accrued level of uncertainty based on variances in the respective input data.

The use of 95% confidence limits helps to identify components with a large variance and hence the biggest impacts on the accuracy of the water balance's final results. Once identified, measures should be taken to improve the accuracy of components with the greatest impact, e.g. by installing additional metering devices.

As *Table 4.4* demonstrates, inaccuracy in derived volumes builds to significant values that might affect leakage management strategies, even in systems where system input and consumption volumes are metered.

Table 4.4 Example for the determination of accuracy bands [52]

	Data origin*	Volume [m³]	Accuracy Band [%]		Standard deviation σ	Variance V = σ^2
System input Q_I	(M)	1,996,139	± 1.0	→	10,184	103,721,650
Revenue water Q_{RW}	(M)	1,801,146	± 0.2	→	1,838	3,377,891
Non-revenue water Q_{NRW}	(D)	194,993	± 10.4	←	10,349	107,099,541
Unbilled authorised consumption Q_{UA}	(E)	30,000	± 20.0	→	3,061	9,371,095
Water losses Q_{WL}	(D)	164,993	± 12.8	←	10,792	116,470,637
Apparent losses Q_{AL}	(E)	32,999	± 50.0	→	8,418	70,862,896
Real losses Q_{RL}	(D)	131,994	± 20.3	←	13,687	187,333,533

* With: (M) = metered, (D) = derived, (E) = estimated volumes.

4.3.4 Assessing and quantifying real water losses

This chapter will deal with the question of how to determine real losses. This step must be taken before the issues of where and how much water is lost can be settled. The system components have to be established using system maps, hydraulic models or the network register before this process can begin.

In general, leakages that lead to real losses can occur in (a) storage tanks; (b) transmission mains and (c) the distribution network *(see Chapter 3.4)*. The majority of leakages occur within the distribution system. Therefore, losses at tanks and transmission mains are usually of minor importance. Nonetheless, the search for real losses may start at these points since they can be measured with little effort.

(a) Assessing losses from storage tanks

Fissures or cracks in the construction, pipe penetrations that are not watertight and leaking pipes in the valve chamber are the typical reasons for leaks from a tank. Conducting a volumetric or drop test is a common method of identifying losses from storage tanks. To perform the test, the supply from the tank has to be interrupted; therefore, this test is best done during night hours. If possible, the disconnected areas should be supplied by a second tank chamber or by rearranging zone boundary valves. The tank should first be filled to its maximum level, before closing the inlet and outlet valves. Fluctuations in the water level are observed over a period of 4 to 12 hours. The exact duration depends on local supply criteria. In general, a long testing period delivers the most reliable results. The tank's leakage rate can be derived by dividing volume of water lost by the duration of the test.

Supplementary materials 4.5

Drop test calculation

(b) Assessing losses from the transmission mains

Transmission mains usually have only few branch connections, making it relatively easy to determine potential water losses. If bulk water meters are not installed at the transmission mains, flow measurements can be performed using portable flow meters. The flow rate should be measured simultaneously at the upstream and the downstream end of a pipe section. Reasonable results require steady flow conditions, fully filled pipes and that all lateral connections to the secondary network can be closed. The result of these measurements will give a good idea of the overall losses along the entire transmission mains. More detailed measurements should be taken if real water losses are high and have to be narrowed down further, e.g. by gradually analysing shorter pipe sections.

In the long run it makes sense to install permanent bulk water meters at the transmission mains. All sources and delivery points should be equipped with water meters in order to monitor water production and distribution continuously and control water losses at the transmission mains.

(c) Assessing losses in the distribution network

Measuring losses within the distribution network is more difficult since it usually has a more complex structure. Measurements can be best performed if supply arrangements can be temporarily changed and the supply area can be separated into discrete zones with designated boundaries. In this case, portable flow meters can be installed at the entry (and exit) points of the discrete areas. The choice of measurement method to pinpoint the locations of the leak should be based on the type of supply and on the design characteristics of the supply and distribution system, e.g. if supply is continuous or intermittent. [22]

Supplementary materials 4.6

Minimum night flow (MNF) analysis

The following methods can be used to measure leakage:

Minimum night flow analysis (in systems with continuous supply)

The minimum night flow (MNF) method is suitable for systems that are operated continuously. This method is based on the assumption that authorised consumption drops to a minimum during night hours (usually between 2 and 4 am). Therefore, real losses represent the maximum percentage of the flow. The amount of water fed into a discrete zone during this time period is continuously measured and the share of legitimate consumption and losses is analysed according to *Equation 4.1*:

Equation 4.1

$$Q_{in} = Q_{dom} + Q_{bulk} + Q_{trans} + Q_{loss}$$

Where:

Q_{in}	[m³/h]	System input
Q_{dom}	[m³/h]	Domestic night consumption
Q_{bulk}	[m³/h]	Non-domestic night consumption
Q_{trans}	[m³/h]	Transfer of water to neighbouring zones
Q_{loss}	[m³/h]	Water losses

Legitimate consumption consists of domestic night consumption Q_{dom} (mainly for flushing toilets) and non-domestic night consumption Q_{bulk} (administrative, industrial, commercial or agricultural users) which may represent a large percentage of minimum night flow. While a pilot study can estimate or ascertain domestic night consumption, it is important to identify bulk consumers and determine their night consumption. Water exports and transfers to neighbouring zones Q_{trans} also have to be measured or must be ceased during the MNF assessment. In order to determine the daily water losses from the assessed zone, the ratio of night and day zonal pressures must be taken into account by calculating the night to day factor (NDF). Pressure profiles at the average zone point (AZP) must be measured

Equation	
4.2	$$Q_{loss,d} = NDF \times Q_{loss}$$
4.3	$$NDF = \sum_{i=0}^{24} \left(\frac{P_i}{P_{MNF}}\right)^{\alpha}$$

Where:

$Q_{loss,d}$	[m³/d]	Daily real loss volume
NDF	[h/d]	Night to day factor
Q_{loss}	[m³/h]	Average minimum night flow rate
P_i	[m]	Average pressure at AZP during 24 hours
P_{MNF}	[m]	Average pressure at AZP during MNF conditions
α	[-]	Leakage exponent

and the system's leakage exponent α *(see Chapter 3.4.2)* must be ascertained in order to calculate the NDF. The volume of daily real water losses $Q_{loss,d}$ can then be determined according to *Equation 4.2* and *4.3*.

Typical values for the NDF range from 20 or less in gravity-fed systems to over 30 hours per day in pressure management areas with flow-modulated systems.

The measurement can be taken either for the overall system or for discrete zones separated by closing off boundary valves. Smaller zones will produce more accurate results because the size of the zone and the number of connected inhabitants have an effect on the simultaneity of water abstractions. Flows can either be measured at one or several points within the zone. Taking measurements at several points will make the determination of real losses more precise. System inflow into small zones directly supplied by one or more tanks can easily be determined using the tank drop test described above. The only difference is that the outlet valve is left open. Otherwise, flow rates should be measured by utilising portable flow meters and the acquired data should be logged and stored in electronic format for further processing.

Supplementary materials 4.7

Determination of real losses in intermittently supplied systems

Stop tap method (in systems with intermittent supply)

Intermittently supplied systems have to be treated with special attention since they are only operated at low pressures and for short periods of time. Since customers in intermittent systems commonly use private storage tanks, tank filling distorts the night flow characteristics. Conventional methods, such as the

MNF analysis, can therefore not be used to assess leakage. The stop tap method offers an alternative. This method has to be applied in small, isolated areas that can be created by closing boundary valves. As a next step, all customer connections have to be closed in order to prevent the filling of private tanks. The system is then pressurised, and losses can be measured as described before. This approach will give an idea of where losses are located, but a proper water balance still cannot be developed since the operation mode is not in line with normal conditions *(see Chapter 3.4.2)*. One disadvantage of this method is that considerable volumes of water will be lost at the leak points and all leaks cannot be identified during the short testing period. Further, customers are without supply for several hours.

Mobile tanker method (in systems with intermittent supply)
This method relies on an extra water source, which is used to supply the area during the testing period. It was developed to overcome the difficulty of diverting supply to small, isolated areas. Additionally, normal operation is not disturbed and the amount of water lost can be limited. Water is fed into the system from an ordinary street tanker. [22] The desired test pressure is maintained using a mounted pump. Again, customers cannot be supplied with water during the testing period.

Continuous measurement
The best method to determine real water losses in the distribution network is the constant arrangement of the network into discrete zones, with permanent bulk water meters installed at all entry points and customers meters at households. The water utility will obtain a good overview of the condition of its water supply system and can detect pipe breaks almost instantaneously by continuously monitoring the system input and regularly reading customer meters.

The methods described so far are suitable for assessing and quantifying water losses in zones or networks. This step will allow the water utility to gain an overall picture of the present situation and to prioritise countermeasures for zones where losses are most drastic. Once we know that water losses exist in a zone, the leaks still have to be detected. The methods and instruments for leak detection are described in *Chapter 6.6*.

4.3.5 Assessing and quantifying apparent water losses

As *Chapter 3.5.2* outlined, apparent losses are non-physical losses caused by (a) water meter inaccuracies, (b) data handling errors and from (c) any form of unauthorised consumption (water theft and illegal use). Quantifying apparent losses in a distribution network is a difficult task which has to be based mostly on assumptions and estimates. These assumptions should be drawn up separately for each of the three main sources of apparent losses, as described below. [77] Although the assumed volumes of apparent losses will be subject to errors and thus approximate to some degree, this step is required to determine the water balance. [48]

(a) Assessing meter inaccuracies

Apparent losses due to meter inaccuracies can be estimated by selecting a representative group of domestic meters while taking into account the different meter types, brands, sizes and age groups, and checking them on a test bench. Large bulk meters can also be tested on-site and in operation by means of calibrated portable flow meters. The average meter inaccuracies (percentage of over-registration or under-registration) for each group of meters can then be applied to the whole meter park. [77]

(b) Assessing data handling errors

Errors caused by data handling mistakes can be detected and quantified by means of standard database software. Meter reading errors can be reduced by continually training meter-readers and by introducing standardised working routines.

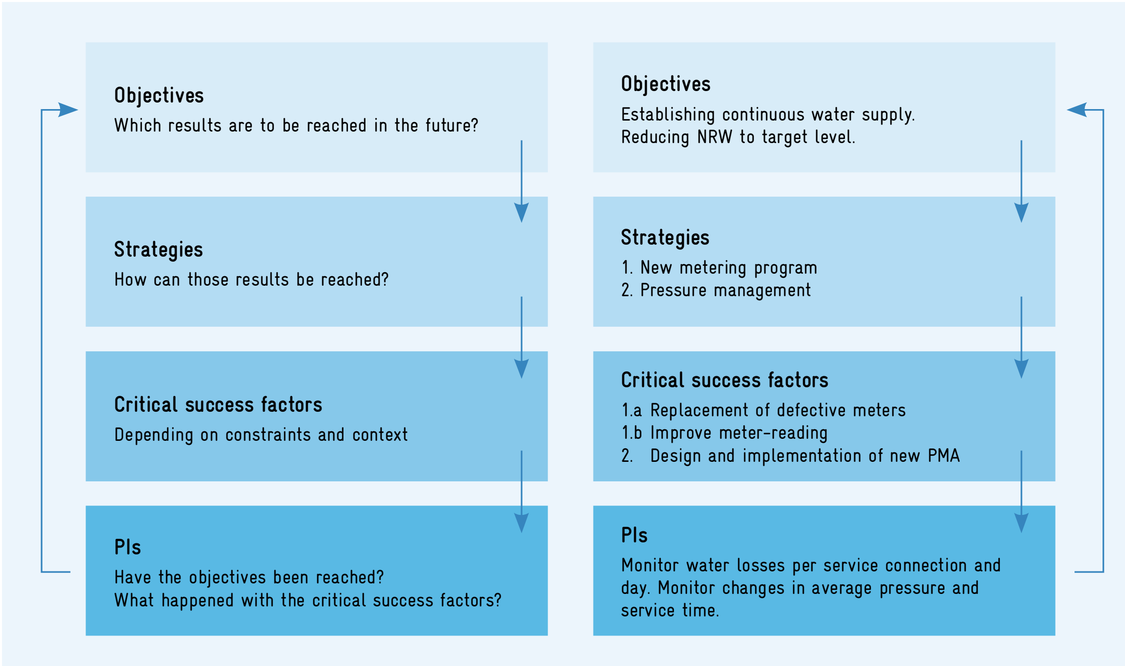
(c) Assessing unauthorised consumption

The water utility needs to estimate the number of illegal connections in order to quantify unauthorised use of water, e.g. by conducting a house-to-house survey in a pilot zone. The estimated number of illegal connections then has to be multiplied by the typical household size and per capita water consumption. Illegal connections that are accidentally discovered by water utility workers should thus always be registered. The number of broken, bypassed or manipulated meters should also be taken into account based on information from meter-readers or other utility personnel. [22]

4.3.6 Calculation and analysis of relevant performance indicators

The establishment of a standardised water balance provides the water utility with reliable figures for the amount of real and apparent losses in their water supply system. Different performance indicators (PIs) should then be calculated and analysed to determine whether these losses are comparatively high or low. [45] However, performance indicators are not solely tools for national or international benchmarking between water supply utilities, and should never be a goal in themselves: performance indicators help to extract necessary information from huge amounts of data and are a useful tool for decision-making processes. As a first step, it is important to define precise and clear objectives and to determine most suitable strategies for accomplishing them. Appropriate performance indicators should then be selected and the necessary input data collected.

Figure 4.1 Use of performance indicators in decision-making processes: general approach (left) and example (right). Based on [2]



The following sections offer a short introduction into the main performance indicators for water losses. Reading the IWA best practice manual on Performance Indicators for Water Supply Services is strongly recommended for performance indicators covering the entire spectrum of water supply. These indicators are typically broken down into (a) financial and (b) technical performance indicators. [2]

(a) Financial Performance Indicators

Once the system input is known and the respective shares of revenue and non-revenue water have been determined, a simple financial performance indicator (PI) should be calculated for each component of the three major constituents of non-revenue water as shown in *Equation 4.4*.

Unauthorised consumption and apparent losses should be rated at the average sales price of water as they represent volumes of water that have been delivered to the consumer. Real losses can generally be rated at the average production costs or with the purchase price (if water is imported from another water utility) or even at the costs of exploiting alternative sources (e.g. desalination) if there are shortages of water. The ratio between the components of annual losses L_A and the annual cost of running the water supply network provides a good overview of the extent of water losses. [48]

Equation 4.4

$$L_A = (Q_{UAC} + Q_{AL}) \times C_{SP} + Q_{RL} \times C_P$$

Where:

L_A	[USD]	Annual losses
Q_{UAC}	[m³]	Volume of unbilled authorised consumption
Q_{AL}	[m³]	Apparent losses
Q_{RL}	[m³]	Real losses
C_{SP}	[USD/m³]	Sales price
C_P	[USD/m³]	Production cost

(b) Technical Performance Indicators

It is a widely accepted fact that a percentage water loss rate (water loss rate [%] = annual real water losses Q_{RL} / system input Q_I) is not a suitable technical performance indicator because it does not consider the length of the distribution network, the number of service connections and the system pressure. Therefore, indicating specific water losses in proportion to the network length is recommended, as shown in *Equation 4.5*. [13]

International experience shows that the greatest proportion of losses occurs at service connections rather than from the mains, except in areas with low connection density. Therefore, the water losses can be calculated proportionate to the number of service connections, as shown in *Equation 4.6*:

4.5

$$Q_{SL} = \frac{Q_{RL}}{L_N \times 365}$$

4.6

$$Q_{SCL} = \frac{Q_{RL}}{N_C \times 365}$$

Equation

Where:

Q_{SL}	[m³/km/d]	Specific water losses
Q_{RL}	[m³/a]	Annual real water losses
L_N	[km]	Network length (without service connection pipes)
Q_{SCL}	[m³/conn/d]	Water losses per service connection and day
N_C	[-]	Number of service connections

Both PIs are only comparable between water supply systems of similar size and structure. It is therefore recommended to express water losses based on each km of the mains *(see Equation 4.5 on the previous page)* for rural networks with less than 20 service connections per km. *Equation 4.6 on the previous page* should be used for densely populated areas with more than 20 connections per km. [53]

Lambert et al. introduced an auditable component-based methodology for calculating standardised technical performance indicators for assessing and comparing real water losses, which allows comparing systems of different size and structure. [45] This PI takes into consideration the five local key factors with major impact on real water losses: the length of the mains, the average operating pressure, the number of service connections, the location of customer meters and the continuity of supply. This method is described in the following sections.

Current annual real losses (CARL)

The IWA WLTF developed the current annual real losses (CARL) equation, which has been adopted by several national technical associations and utilities around the world over the past ten years. The CARL is also valid for water distribution networks with intermittent supply, when taking into account the number of days when the system is pressurised. The CARL is defined as:

Equation 4.7

$$CARL = \frac{Q_{RL} \times 10^3}{N_{dwsp}}$$

Where:

CARL	[l/day w.s.p.]	Current annual real losses
Q_{RL}	[m³/a]	Annual real water losses
N_{dwsp}	[-]	Number of days when system is pressurised (w.s.p.)

Unavoidable annual real losses (UARL)

Real water losses exist in every large water distribution network and can never be completely eliminated. A certain minimum amount of real losses will remain, even in newly commissioned sections of a network. [77] This amount is referred to as the unavoidable real losses, which represents the volume of real losses that could be reached at the current operating pressure if there were no financial or economic limitations. Hence, the ratio between the CARL and the UARL represents the potential for reducing real water losses further. The UARL draws on factors related to the length of the mains, the number of service connections and the location of customer meters and is valid for the average operating pressure. The leakage rate from (undetectable) background losses, reported and unreported at the average pressure is calculated for each component (the mains, service connections and service pipes). This equation was developed in 1999 by *Allan Lambert* on the basis of international data sets and has since been validated by comparing its outcomes with test results from a large number of well-managed water supply systems in various countries. [45] The summarised standard equation for the UARL (in litres per day) is defined as:

Equation 4.8

$$UARL = (18 \times L_N + 0.8\ N_C + 25 \times L_P) \times P_A$$

Where:

UARL	[l/day w.s.p.]	Unavoidable annual real losses
L_N	[km]	Network length (without service connection pipes)
N_C	[-]	Number of service connections
L_P	[km]	Length of private service pipes after the property line Lfter the property line up to the customer meter
P_A	[m]	Average operating pressure

While most water utilities know the length of the mains and the number of service connections in their systems, it will be harder to obtain the length of service pipes laid on private property: LP can be assumed to be zero if the customer's meter is located near the property boundary. Otherwise, the average length of service pipes can be obtained from a number of random inspections, if detailed information is not available from the network register. [50]

The equation and its fixed parameters have been derived from statistical analysis of 27 different water supply systems in 20 countries (please refer to *Lambert et al.*, 1999 for details of the derivation of this equation). The ratio of the CARL to the UARL is called infrastructure leakage index (ILI).

Infrastructure leakage index (ILI)

The dimensionless performance indicator ILI is a measure of how well the water utility is implementing its leakage management strategy and infrastructure management. The ILI is defined as:

Eqt. 4.9

$$ILI = \frac{CARL}{UARL}$$

Figure 4.5 on page 99 offers a good insight into the interrelationship between the four components of leakage management and the ratio of the CARL to the UARL. The combination of all leakage management measures allows the volume of current annual real losses to be reduced up to the UARL, which is the lowest technically feasible volume of real losses at the current operating pressure. It is important to bear in mind that the ILI is purely a technical performance indicator which does not take into account any economic considerations. Hence, an ILI of 1.0 (the CARL = the UARL) need not be profitable from an economic point of view, e.g. if the marginal cost of water is very low. [50]

Supplementary materials 4.8

ILI calculation

Ten years' experience with the ILI show that it can be applied for benchmarking at international, national, city or system-wide levels in networks that meet the following requirements: [50]

- → number of connections: Nc > 3,000
- → average pressure: PA > 25 m
- → connection density: no lower/upper limit.

After calculating the ILI for a water supply system, an initial assessment of its condition and an immediate description of the actual water loss management performance can be obtained by using the World Bank Institute's banding system shown in *Table 4.5*:

Table 4.5 World Bank Institute's banding system for developed and developing countries [53]

WBI band	ILI range		Guideline description of real loss management performance categories
	Developed countries	Developing countries	
A	< 2.0	< 4.0	Further loss reduction may be uneconomic unless there are shortages; careful analysis needed to identify cost-effective leakage management
B	2.0 to < 4.0	4.0 to < 8.0	Possibilities for further improvement; consider pressure management, better active leakage control, better maintenance
C	4.0 to < 8.0	8.0 to < 16.0	Poor leakage management, tolerable only if plentiful cheap resources; even then, analyse level and nature of leakage, intensify reduction efforts
D	8.0 or more	16.0 or more	Very inefficient use of resources, indicative of poor maintenance and system condition in general, leakage reduction programs imperative and high priority

Pressure management index (PMI)

The pressure management index is a relatively new index which is intended as a support tool for assessing the scope and potential efficiency of pressure management. Like the ILI, the PMI is the ratio between current average zone pressure P_A and the minimum acceptable pressure P_{min}. In this case, P_A is the average pressure across the system *(as in Equation 4.8 on page 85)* which should be weighted by service connection location and also consider seasonal variations. P_{min} should be related to the minimum standard of service. The minimum standard of service will vary from country to country and is usually prescribed by standards, regulators, the government and/or trade associations. It usually ranges between 5 and 25 metres, depending on the height of the buildings and local fire fighting requirements. A safety margin P_{safety} should be added to P_{min}. [83] Thus, the PMI can be described as:

Equation 4.10

$$PMI = \frac{P_A}{P_{min} + P_{safety}}$$

Where:

PMI	[-]	Pressure management index
P_A	[m]	Current average zone pressure
P_{min}	[m]	Minimum standard of service
P_{safety}	[m]	Safety margin (usually 3 - 5 m)

It has to be considered that the PMI takes account of neither the feasibility of further pressure management measures, nor the costs involved. Nevertheless, it can be a useful tool for estimating the water loss reduction potential by means of pressure reduction. The PMI is also incorporated in the process of leakage target level setting *(see Chapter 4.4.3)*.

4.3.7 Evaluating potential savings

Every water utility must develop a water loss reduction programme based on its current operating budgets. Leakage control can be expensive. Therefore, water utilities should aspire to strike an economic balance between the costs of leakage and the benefits that will result from active leakage control (ALC). Before the economic level of leakage (ELL) can be determined, the water utility should develop a clear and distinct cost structure.

A water utility's costs can be divided into day-by-day operational costs and fixed capital costs. *Table 4.6 on the next page* shows the different elements in a water utility's cost structure.

Labour, energy and capital are the most important production factors for a water utility. A water loss reduction programme can reduce most of these costs, with the electricity cost normally the most receptive item.

Table 4.6 Typical cost structure of a water utility

Operational expenditure (running cost) OPEX	Capital expenditure CAPEX
→ labour (internal manpower) → cost of imported water (raw/treated) → electrical energy cost → abstraction and treatment cost → material cost → transmission, storage and distribution cost → meter management cost → cost of active leakage control → cost of outsourced services	→ depreciation → net interest (difference between interest expenses and interest income)

In general, electricity costs can vary enormously depending on the local conditions facing a water utility. According to the international platform for water utility benchmarking IBNet *(www.ibnet.org)*, data from more than 2,500 water utilities worldwide showed that electricity costs make up an average of about 23% of operating expenses, while labour costs swallow up 36%. In times of rising energy prices, it can be assumed that the ratio of energy costs will even increase over the coming years.

The sum of operational and capital cost factors constitutes the water utility's total costs. A water utility that follows a policy of cost recovery will calculate its production costs by dividing the overall cost by the amount of water produced. Production costs are defined as:

Equation 4.11

$$C_P = \frac{(CAPEX + OPEX)}{Q_1}$$

Where:

C_P	[USD/m³]	Production cost
Q_1	[m³/a]	System input volume
CAPEX	[USD/a]	Capital expenditure per year
OPEX	[USD/a]	Operational expenditure per year

Once the average cost of producing one cubic meter of drinking water has been determined, the annual potential savings from reducing real water losses can be roughly determined as:

Equation 4.12

Apparent loss reduction potential		Real loss reduction potential
$SP_A = (Q_{UA} + Q_{AL}) \times C_{SP}$	+	$(Q_{RL} - UARL_Y) \times (C_P - C_{ALC})$

$$SP_A = (Q_{UA} + Q_{AL}) \times C_{SP} + (Q_{RL} - UARL_Y) \times (C_P - C_{ALC})$$

Where:

SP_A	[USD]	Annual saving potential
Q_{UA}	[m^3/a]	Volume of unbilled authorised consumption
Q_{AL}	[m^3/a]	Apparent losses
C_{SP}	[USD/m^3]	Sales price
Q_{RL}	[m^3/a]	Real losses
$UARL_y$	[m^3/a]	Unavoidable annual real losses (= UARL x 365 / 1.000)
C_P	[USD/m^3]	Production cost
C_{ALC}	[USD/m^3]	Costs for active leakage control measures

The costs of active leakage control are unique to each water utility and have to be determined empirically, taking into account expenses for infrastructure, personnel and materials. Active leakage control methods are described in *Chapter 6.5*.

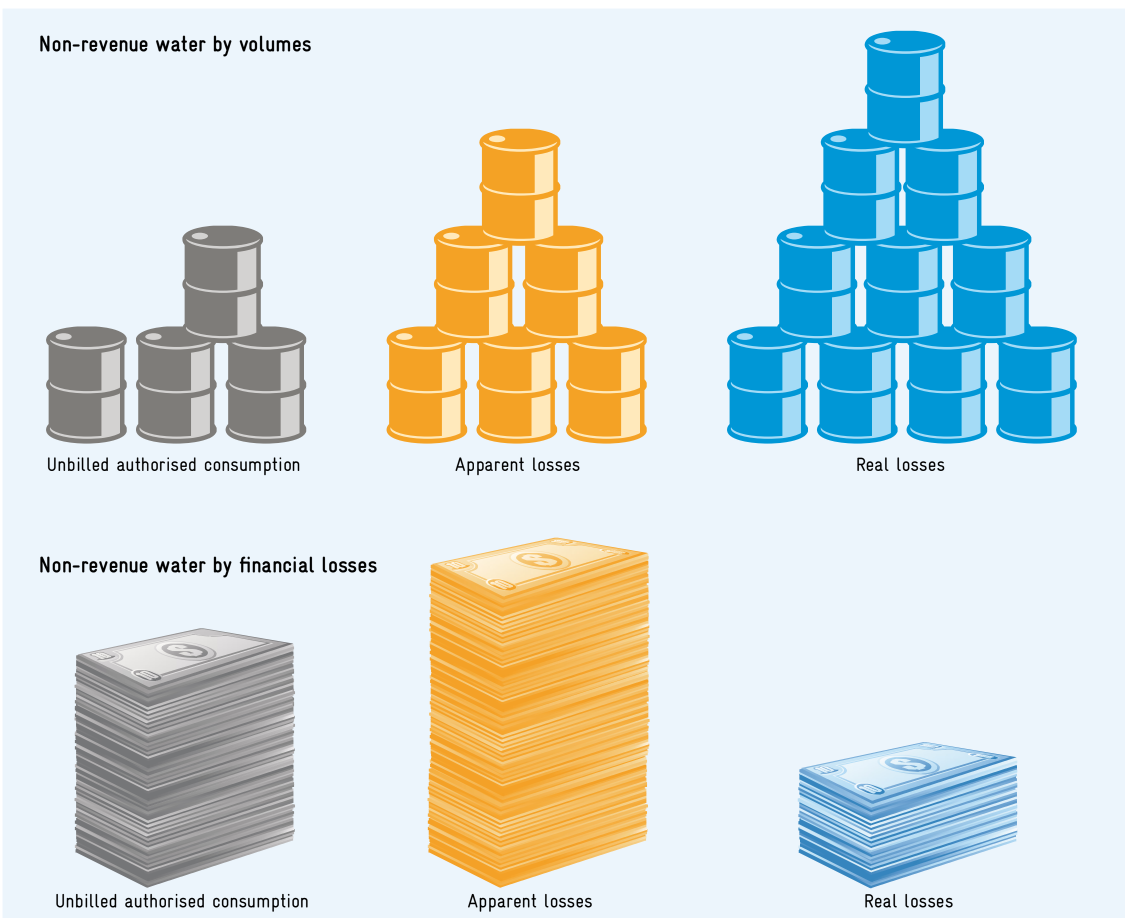
4

4.4 Identifying appropriate measures

4.4.1 Selecting methods

The detailed water balance calculation and the determination of potential savings for real and apparent losses are decisive factors when selecting the correct water loss reduction methods. Water utilities should always first set their sights on components of non-revenue water where investments will generate the highest rate of return. Therefore, it is important to compare the components of non-revenue water not only by their volumes, but also by their financial impacts. *Figure 4.2* offers an example that the highest annual water loss volumes do not necessarily incur the highest financial losses for a water utility. The recovery of apparent losses is possible at relatively low cost and will directly improve the water utility's financial position, especially at the beginning of a water loss control programme. These recovered funds can serve to finance long-term water loss control activities. [77]

Figure 4.2 Example of a possible volumetric and financial distribution of losses [26]



A set of specific counteractive measures is available for each component of non-revenue water:

Table 4.7 Methods to combat NRW

Component	Counteractive measures
Unbilled authorised consumption	→ increase the collection rate → reduce authorised consumption inside and outside the water utility → observe and reduce the number of unbilled customers
Metering inaccuracies	→ set up meter population demographics → arrange regular meter accuracy testing → introduce meter rotation and maintenance programme
Meter reading and data transfer errors	→ analyse billing records for unusual consumption patterns and missing meter readings → audit samples of suspect accounts [77] change from manual to automatic meter reading (AMR)
Data handling errors	→ flowchart the billing system process → conduct a billing process analysis [77] → introduce the use of computerised billing systems → adopt correct annualising of consumption data → improve customer account management → compile customer account demographics and search for anomalies in consumption
Unauthorised consumption	→ conduct inspections for meter tampering, bypassing and illegal connections → contain misuse of fire hydrants and other forms of illegal consumption → prevent fraud by water utility meter readers → use prepayment structures
Leakage from detectable bursts and breaks	→ conduct a campaign to repair the backlog of reported/visible pipe breaks → reduce number of bursts and leaks by: • implementing pressure management (short-term) • developing a rehabilitation strategy (long-term) → reduce runtime by: • introducing continuous network monitoring • improving active leakage control • improving speed and quality of repairs
Background leakage	→ implement pressure management → develop a long-term rehabilitation strategy

Not all of the measures specified in *Table 4.7* are appropriate for every water utility. Cost-benefit analyses should therefore be drawn up for the methods of choice.

4.4.2 Defining the economic level of leakage

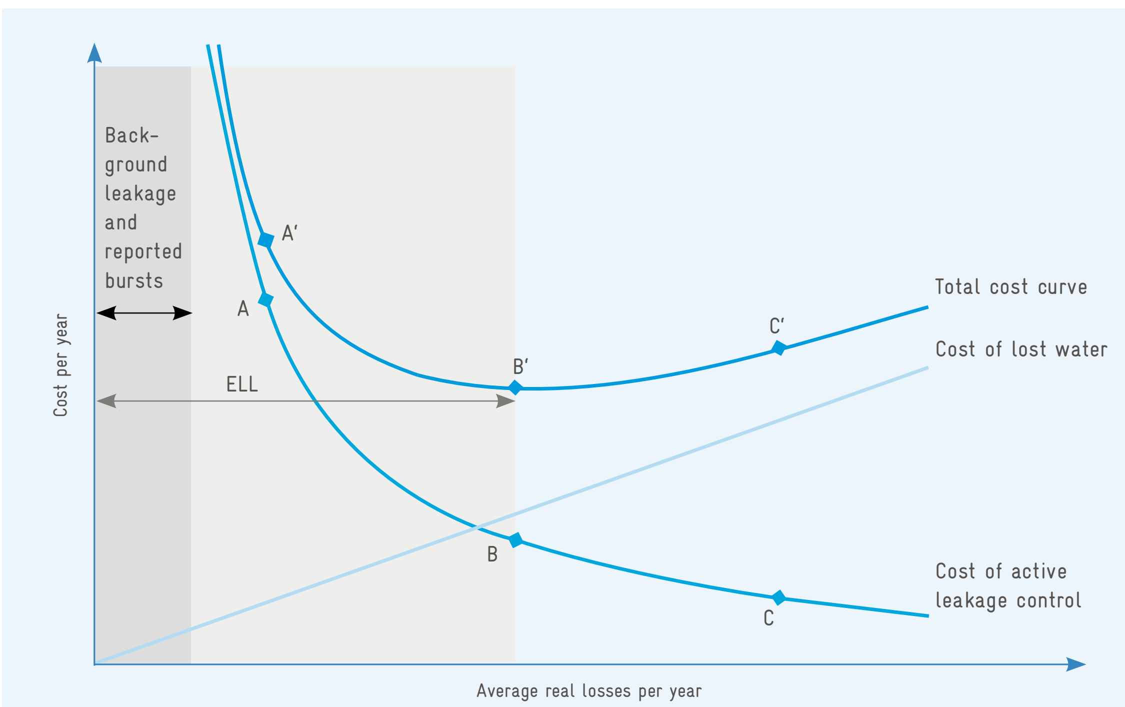
The concept of the economic level of leakage (ELL) describes the equilibrium between the costs of leakage control and their benefits, below which it is not cost effective to make further investments or to use additional resources to drive leakage down any further. In other words, the value of the water saved is lower than the cost of achieving any additional reduction in losses. [23] The ELL thus deals with the questions of what a water utility's leakage target should be and how its cost can be justified.

In theory, the most economic level is determined as follows: if the marginal cost of water is constant, the cost of lost water can be described as a function which rises linearly with an increasing level of leakage *(see Figure 4.3)*. The cumulated costs of water loss control measures are represented by a strictly decreasing convex function. This is due to the fact that the marginal cost of reducing water losses is much lower at high leakage rates than at low leakage rates. The total cost for a water utility can be calculated by adding the cost of lost water to the cost of water loss control measures.

Figure 4.3 illustrates how the cost of active leakage control increases as the level of leakage subsides and the annual cost of lost water decreases (C - B - A). The economic level of leakage occurs at the lowest point in the total cost curve *(point B' in Figure 4.3)*. [45]

In practice, determining the ELL is a rather complex and iterative process since the effects of each implemented water loss control measure are not known in advance. Further-

Figure 4.3 Determining the economic level of leakage (ELL), based on [45]



more, the cost function of the water cannot usually be described linearly because labour and capital do not show a linear increase with the level of leakage. In addition, a distinction can be made between a short-run and a long-run ELL. The short-run ELL only considers operational cost factors and can therefore be determined by comparing the cost and benefits of additional water loss control measures with the marginal cost of the water lost, e.g. active leakage control and the quality and speed of repairs. [6] Other leakage control activities will involve capital expenditure on infrastructure. A long-run ELL is required in this case, which evaluates the investment decision within a full life-cycle assessment, for example for pressure management or network rehabilitation. [38] The following procedure can be selected to determine a water utility's ELL:

Table 4.8 Determining the ELL

Step	
Determination of the current state of the water utility	→ What is the actual leakage level? → What are the actual operational costs? → What are the actual capital costs? → What is the actual amount spent on active leakage control?
Determination of the UARL:	→ The UARL indicates the potential for further water loss reduction
Assessment of the current cost structure	→ Which potential savings can be identified or estimated when analysing the operational and capital cost? → The marginal cost of the capital investment should be taken into consideration in the ELL calculation in the case of limited water resources and if new water resources or treatment capacity have to be constructed.
Selection of a number of activities	→ A number of leakage reduction activities should be chosen in accordance with the estimated potential savings. The costs and benefits of these measures should be analysed and ranked. The ones with the highest benefits should be implemented first. → The four primary activities are active leakage control, speed and quality of repairs, pressure management and infrastructure management [66]
Reassessment of the cost structure	→ The benefits of the chosen activities have to be reassessed after an appropriate time period. A period of at least every five years is recommended. The reassessment is performed by repeating the previous steps. → This process is continued until the marginal cost of any activity is equal to or greater than the marginal cost of water. At that point the economic leakage level will be achieved. → The assessment should take into account the fact that annual water losses might show random fluctuations. Therefore, the water utility leakage target should be based on the average over a number of years. → The described analysis is drawn up from the perspective of a water utility operating economically. However, a water utility also incurs environmental and social cost. Methods for including the costs and benefits of these factors are also available [80]

4.4.3 Setting targets

The previous chapters have shown that completely eliminating water losses from a water distribution network is neither feasible, nor economic. Nevertheless, excessive water losses are symptomatic of other shortcomings, such as an absence of system maintenance and control. These failings frequently result in high operational costs and produce unreliable or even intermittent supply. Every water utility should thus set a target level between these two extremes for water losses from its distribution system. [82]

These targets may be driven by water conservation issues, customer supply security, economic considerations or regulatory requirements. In any case, the target level will be a compromise between a series of competing factors, such as the available budget, human resources, technical feasibility, time constraints and even political considerations. At the early stages of a water loss control programme, targets are mainly based on assumptions which will later be supplemented by system-specific information collected throughout the process.

Unit of measure

Leakage targets require a unit of measure in order to define the initial situation and to monitor progress. The most reliable target setting value for monitoring changes over time is the absolute volume of water losses measured in cubic metres per day [m^3/d]. It is also recommended to use water loss per service connection and day [l/service connection/day] if the utility is growing in size as leakage management is being implemented over a multi-year period.

Spatial discretion

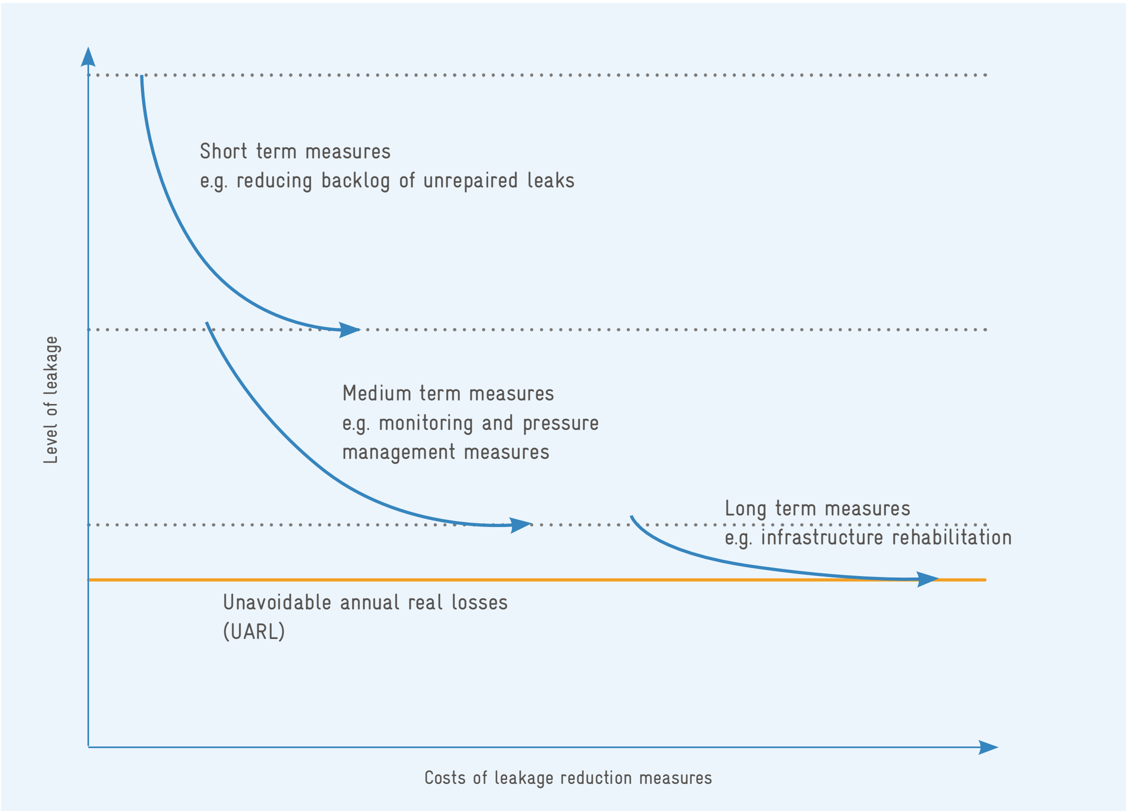
Target levels should be set for discrete zones of the water distribution network, for example for each district metered area (DMA) or pressure management area (PMA), and then aggregated the water utility's overall leakage target. With this approach, particular zones can be prioritised and progress in water loss reduction can be monitored for each zone independently.

Time-scale

Realistic time scales should be chosen for leakage targets. Leakage management is a painstaking process and there are usually no quick and easy solutions. A long-term target that is ambitious, but not unrealistic is recommended. This long-term target can be subdivided in short-term objectives of three to five years that aim to achieve a certain percentage of the long-term leakage reduction. The timescale has to provide reasonable periods for designing, setting up facilities, tendering and awarding contracts and implementing works. [81]

Leakage reduction follows the law of diminishing returns: the impact of leakage reduction measures in terms of the water saved will diminish with the advancing duration of the leakage management programme. This effect means that leakage management measures typically follow a similar pattern to the one shown in *Figure 4.4*:

Figure 4.4 Diminishing returns of leakage management measures, based on [81]



Short-term measures: leaks will be relatively easy to detect at the beginning of a leakage management programme. Moreover, a backlog of reported and unreported leaks, which may have built up in previous years, can be reduced rather quickly. Once this backlog has been detected and eliminated, more effort is required to reduce leakage by a similar volume. [81]

Medium-term measures: medium-term measures comprise the installation of DMAs, measurement and control devices and pressure management schemes. Again, at the beginning those installations will be set up which cover a large area, require a minimum of valves and accessories and have the biggest impact on average pressures.

Long-term measures: long-term measures mainly consist of replacing mains and service connections, starting with those with the highest burst frequency or the highest specific leak flow.

Calculating target levels

Many factors flow into the process of determining target levels. Therefore, each water utility must define its objective in keeping with its means and requirements. Nevertheless, the following equation is presented as an instrument for calculating targets for real losses taking into account active leakage control (which influences the ILI) and pressure management (which influences the PMI, *see* *Chapter 4.3.6*). Annual targets can be set for the ILI and the PMI. The target level of real losses TARL (usually measured in m^3/a) can then be calculated according to *Equation 4.13*:

Equation 4.13

$$TARL = CARL \times \frac{TILI}{ILI} \times \frac{TPMI}{PMI}$$

Where:

TARL	[m^3/a]	Target annual real losses
CARL	[m^3/a]	Current annual real losses
PMI	[-]	Current pressure management index
TPMI	[-]	Target pressure management index
ILI	[-]	Current infrastructure leakage index
TILI	[-]	Target infrastructure leakage index

At the end of a year, the progress made and the resources spent should be assessed and incorporated into the target for the next year. [83]

4.5 Designing and implementing a water loss control programme

4.5.1 Action plan

Chapter 3 helped the reader to understand the reasons for water losses and their negative impacts on water supply systems. This chapter has presented a number of techniques for assessing and quantifying the extent of real and apparent water losses. These techniques build upon each other and should be realised stepwise as a precondition for designing and implementing an appropriate action plan, as illustrated in *Table 4.9*.

Supplementary materials 4.9

Preparation of the action plan

Table 4.9 Steps of an action plan [81]

Stage	Objective	Measures / tools
Preparation	Understand principal reasons and factors influencing water losses	Pilot studies, literature review
	Collect information about the water supply system	Network register, hydraulic network model, measurement of flows and pressures
	Assess current level of real and apparent losses	Top-down water balance, component analysis, bottom-up water balance
	Check reliability of water balance calculations	Accuracy bands, 95% confidence limits
	Analyse potential savings	
Target-setting	Calculate relevant performance indicators	CARL, UARL, ILI, PMI
	Define economic level of leakage	ELL
	Select appropriate intervention methods	Active leakage control (ALC), DMA, pressure management, pipe rehabilitation and replacement
	Determine short-term and long-term targets	TARL
	Elaborate an investment plan	
Procurement	Provide support services, equipment, materials, IT systems	
Project execution	Deploy own personnel or contract specialised firms	
	Manage works	
	Train personnel	
Monitoring and Maintenance	Review budgets	
	Monitor leakage development, maintain facilities and equipment	Failure database, network register
	Ongoing ALC	
	Evaluate results	Water balance, network register

4.5.2 Selecting and implementing intervention methods

A suitable set of intervention methods has to be selected depending on the individual components of water losses. The correct combination of intervention methods depends on the characteristics of any given system and the cost-benefit ratio of each method which is specific to each water utility. *Figure 4.5* shows the principal intervention methods for managing real and apparent losses. Each water utility has to decide if a single method or the combination of several methods will offer the most cost-effective way of reducing water losses. [77]

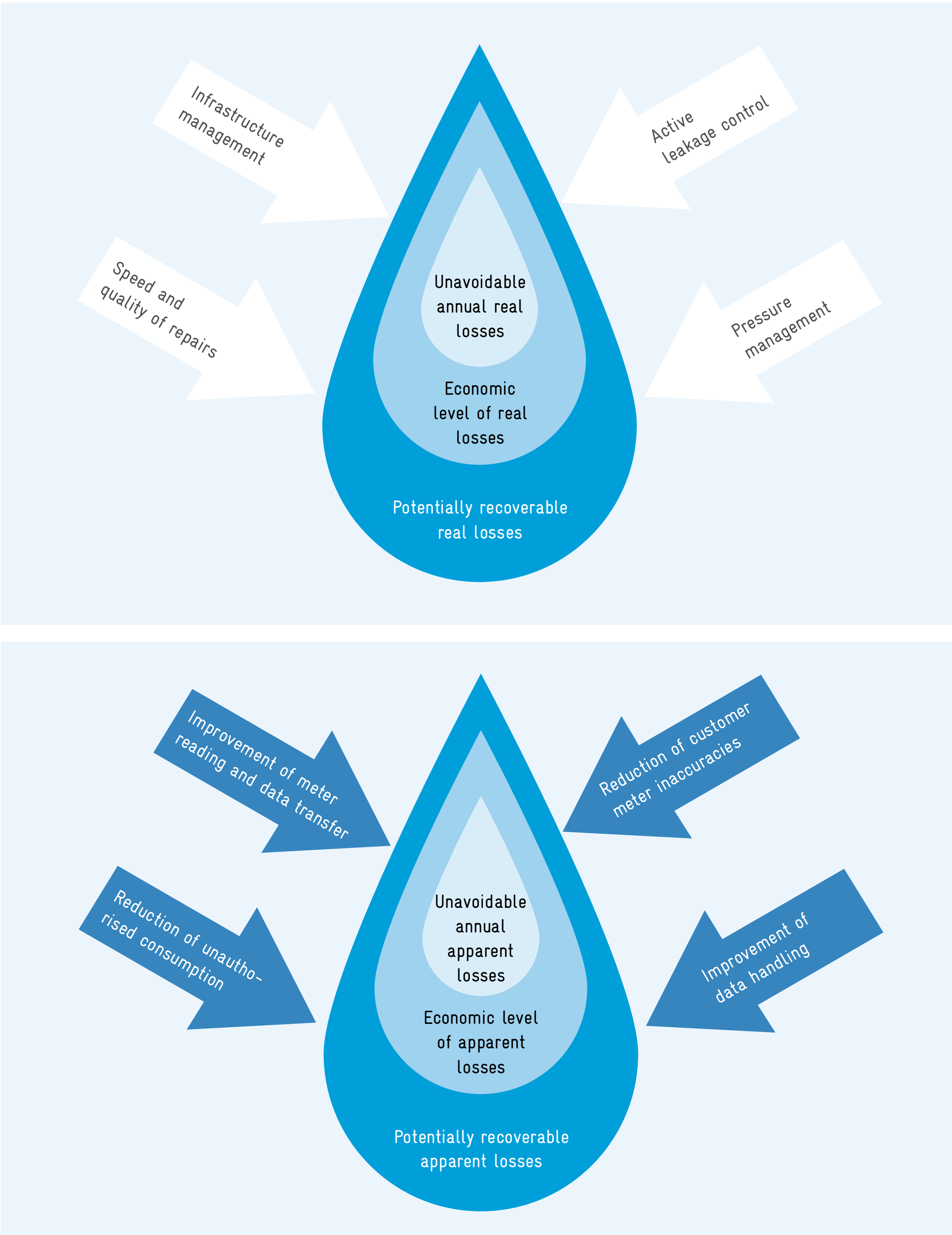
The four principal methods of reducing real water losses will be presented in detail in *Chapter 6*. Having identified the most economic methods, the utility can start putting them in place. These measures can also be partially or fully outsourced to specialised firms if the water utility lacks personnel, technical equipment or the expertise to implement them. [77]

4.5.3 Evaluating results

A sustainable reduction in water losses will not be achieved by means of an one-off set of measures: pipes deteriorate, new leaks appear, wear and tear reduces the accuracy of meters; these factors make water loss management a continuous and ever-changing challenge for water utilities. Therefore, evaluating results is essential to assess the water loss control programme and influences the planning of further measures. For instance, assessing the cost-benefit ratio of an installed pressure management scheme can serve to improve the determination of water loss reduction costs.

Analysing the efforts and results of a water loss control programme is recommended at least once per year. [77] Results achieved in a pilot zone can be extrapolated in order to design appropriate measures for the entire network.

Figure 4.5 Intervention tools for real and apparent loss reduction programmes [77]



4.6 Summary and next steps

This chapter provides methods to assess and quantify the amount of water lost in a distribution network and also shows how to implement a water loss control programme. The contents of *Chapter 4* of this technical manual will enable the reader to:

- ☑ Know the ten principal reasons motivating the implementation of water loss reduction measures.
- ☑ Set up a water balance in order to analyse the present status of water losses in a water supply system.
- ☑ Employ minimum night flow measurements and the bottom-up assessment of real losses to crosscheck the water balance.
- ☑ Use 95% confidence limits for verifying the accuracy of water balance calculations.
- ☑ Employ various methods to measure real losses in continuously and intermittently supplied water distribution networks.
- ☑ Calculate and evaluate several technical and financial performance indicators.
- ☑ Determine the economic level of leakage, set leakage targets and design a water loss control programme.

The next chapter will provide information about the basic structures that a water utility should put in place in order to achieve sustainable water loss management.


Photo: © P. Klingel, 2006

Basic data prerequisites for sustainable water loss management 5

5.1 Objectives

At the end of this chapter, the reader should be able to

- → understand the significance of information systems for efficient water loss reduction
- → comprehend the structure and functionality of geographic information systems
- → grasp the importance of a GIS-based landbase, network register, hydraulic network model, failure database and customer information system as instruments for successfully implementing leakage reduction efforts.

5.2 Information systems and water loss management

5.2.1 Information: a prerequisite for efficient water loss management

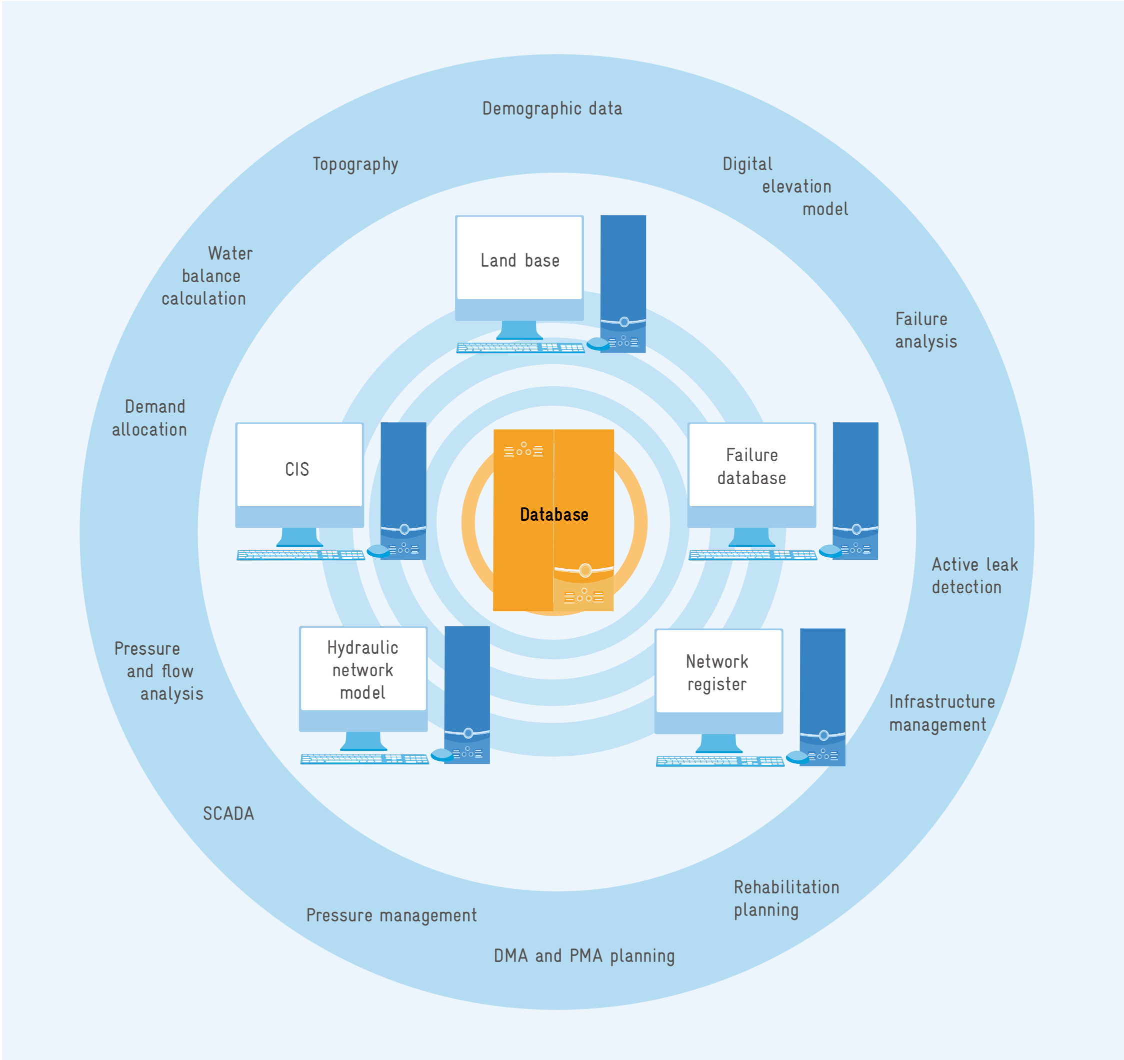
Water utility personnel in charge of detecting, locating and repairing leaks not only need adequate leak detection equipment, but also precise information which allows them to carry out their work efficiently. This information is derived from data which has to be collected, processed and interpreted via information systems. [34]

Modern water utilities collect and process large amounts of different data daily from different departments and with different purposes. For example, some departments use specific tools and information systems, such as a digital landbase, network registers, hydraulic network models, failure databases or customer information systems (CIS). Other departments might establish annual water balances or collect information about pipe rehabilitation planning, PMA and DMA zones including recording ongoing inflows and pressures as well as logging feedback from leak detection and repairs. All of this data offers valuable insights in the water supply system. Unfortunately, plenty of the collected data remains in its original department without being used additionally.

However, data collection should never become a goal in itself. Instead, water utilities should learn to appreciate the value of the collected data. Experience shows that enterprises achieve multiple benefits by creatively aggregating the wealth of available data. [67] Good decisions and careful planning always require sound data as their basis. Water utilities should not only strive to use the collected data for their specific application so as to develop an effective water loss management strategy. They should also pool the available information, combine it and foster good working relationships through interdepartmental teamwork. This approach will improve early leak detection efforts and allow the most efficient counteractive measures to be selected. *Figure 5.1 on the next page* illustrates the numerous interactions between various information systems and how they can be grouped, for example into a single GIS-based decision support system (DSS).

Each water utility should create an independent administrative unit for NRW management in order to collect and consolidate all data required for efficient water loss management. It is the duty of this unit to define its objectives and determine which data is required. It can then request and exchange available data with other departments. The water loss reduction unit itself must initiate the collection of any missing data.

Figure 5.1 Interactions between various GIS-based information systems



5.2.2 Description of relevant information systems

The following section offers a short overview of the most important information systems for decision-support and describes their significance for successful water loss management.

Landbase

The landbase is a seamless electronic map set to a known system of coordinates and covers the water utility's entire service area. It forms the basis for all other information systems. It can be set up from topographic maps in hardcopy or digital format as well as from rectified aerial photographs. Furthermore it can be complemented with digital elevation models

(DEMs), cadastral or land use data, population data, etc. *Chapter 5.4* provides detailed information about the landbase.

Output: a seamless, geo-referenced electronic map of the service area.

Further use: information from the landbase serves as the geographic basis for all other information systems

Network register

A network register is mandatory for water utilities in order to maintain overview over the several hundred or thousand kilometres of transmission mains, distribution pipes and service connections, each with their respective accessories. A GIS-based digital network register is recommended given the large amount of assets and keeping in mind that all assets have a spatial reference. The actual conditions of the water supply system should be reproduced as realistically as possible, depending on the desired level of detail. *Chapter 5.5* contains detailed information about how to establish a network register.

Output: spatial information about pipe sections, service connections, valves, fittings and other facilities of the WDN.

Further use: information from the network register may provide necessary inputs for night flow analysis and water balance calculations, hydraulic network models, failure database, demand allocation and the design of DMAs and PMAs.

Hydraulic network model

Hydraulic network models represent a critical part of designing and operating water supply systems. Network models can be used to simulate the response of an existing system under a wide range of conditions without disrupting service to customers. Simulations are thus useful to anticipate problems in existing or planned networks and are necessary to design interventions properly (e.g. installation of a pressure management scheme). The cost of simulating various different options is very low in comparison to the cost of the actual building project. [88] *Chapter 5.6* contains detailed information about the hydraulic network model.

Output: information about system-wide pressures and flows, determination of weak points and bottlenecks, allocation and fluctuations in demand.

Further use: information from the hydraulic model may serve as input for DMA and PMA planning and design as well as rehabilitation planning work.

Failure database

A failure database contains information about all breaks and damages that have occurred in a water distribution network. A database that is consistently updated and maintained provides valuable information about the ageing behaviour of different pipe materials and is useful for the identification and systematic rehabilitation of vulnerable pipe sections. Furthermore, faulty or inferior batches of valves and fittings can be identified and be replaced as a preventative measure. The failure database should receive constant input data gathered during leak detection and repairs. *Chapter 5.7* provides detailed information about the failure database.

Output: information about material characteristics, ageing and corrosion behaviour, location of damaged and leaking pipes, connections between system pressure and the frequency of new bursts and leaks.

Further use: information from the failure database may serve as input for rehabilitation planning, leak detection, minimum night flow analysis and set-up of the hydraulic network model.

Customer information system (CIS)

The customer information system and billing records form the essential foundations for calculating the water balance if water consumption is metered. Monthly or quarterly billing data for all domestic and non-domestic customers serves as the system output and can be converted into an average daily flow rate. The connection between the GIS-based network register and customer address data allows water consumption to be allocated precisely to discrete supply zones. Comparing water input and water consumption in each zone or the whole network indicates zones with high losses and can thus be used to leverage leak detection efforts. *Chapter 5.8* presents detailed information about the customer information system.

Output: information about water consumption, seasonal consumption variation, customers with special requirements and consumption allocation.

Further use: information from the customer database may serve as input for the water balance calculation, DMA and PMA design, demand allocation, leak detection and setup of the hydraulic network model.

5.2.3 Integration into an overarching GIS

The five information systems described above form the core of the decision support system (DSS) for efficient water loss reduction. Relevant data from these sub-systems should be found in an overarching GIS. This GIS should be able to exchange data with other sub-systems, which are described in detail in previous chapters and in *Chapter 6* of these guidelines:

- → water balance calculation *(see Chapter 4.3.2)*
- → customer metering *(see Chapter 4.3.5)*
- → district metered areas *(see Chapter 6.3)*

- pressure management *(see Chapter 6.4)*
- infrastructure management *(see Chapter 6.7)*
- active leak detection *(see Chapter 6.5)*.

Chapter 5.3 shall help to determine the major steps in developing and implementing an adequate GIS for a water utility, with the main focus on water loss reduction. The rapid technological progress in GIS development and the wide range of commercial GIS solutions means that this section can only provide a general discussion.

5.2.4 Defining objectives

The collection and processing of data for the GIS-based decision support system has to be objective oriented. The water loss reduction unit has to identify these objectives in clear and precise terms. Failures to define the objectives might result either in excessive or in insufficient data collection. Outlining objectives will be useful in order to answer some difficult questions: which data will be required? Which other departments have to be involved? Which data has to be collected in the field? Which external data has to be purchased? What are the software and hardware requirements? How shall existing software and hardware structures be integrated?

Table 5.1 describes the major objectives that a GIS-based decision support system should achieve in order to improve a utility's water loss management:

Table 5.1 Objectives of a GIS-based decision support system for water loss management

Objectives	Example
Control	Improved monitoring and balancing of water production, consumption and losses.
Analysis	GIS systems allow combining, querying, analysing and visualising large amounts of data from different sources.
Efficiency	Improved sharing of data between single departments or stakeholders, resulting in faster access to information and reduced data redundancy.
Planning	Detailed data basis for infrastructure management and rehabilitation planning, pressure management and other construction measures.
Operation	Optimisation of system operation, pressure management and active leak detection measures.

5

5.3 GIS basics

5.3.1 Definition of a geographic information system

A geographic information system (GIS) is a computer-based tool that manages all types of information based on geographic location. Utilising maps and reports, its purpose is to handle queries and perform statistical analysis and visualisation. GIS usually consists of four components: hardware, software, spatial data and data processing functions. GIS provides a means of sharing data and a method of visualising geographic related problems and their solutions. The purpose of a GIS is to combine diverse data from different sources in order to create new information and to provide a spatial framework for decision support. A GIS can be used for tasks such as:

- Logical query (e.g. determining all service connections that are completely within a particular supply zone or DMA).
- Proximity analysis (e.g. identifying objects sensitive to flooding within a certain distance of susceptible pipe sections).
- Network analysis (e.g. identifying all households impacted by a pipe break).
- Categorisation (e.g. combining and visualising pipe material and age with failure frequency).
- Visualisation (e.g. displaying all customer water meters which are due for routine replacement).

GIS should not be confused with computer-aided design (CAD) systems. CAD is mainly used for planning and designing technical objects, and CAD drawings may appear similar to GIS maps at first sight. Unlike CAD drawings, GIS features are not simply points and lines but have spatial reference and attributes associated with them. Furthermore, additional information can be linked to spatial objects based on their spatial reference. [88]

5.3.2 Level of implementation

A GIS integrating the five sub-systems - the landbase, hydraulic network model, network register, failure database and customer database - is recommended for optimal performance. The five sub-systems may also be run independently depending on the user's needs. GIS can generally be implemented at one of four levels:

- **Project level:** supporting a single project objective.
- **Department level:** supporting the needs of one department.
- **Enterprise level:** inter-departmental sharing of data that meets the needs of two or more departments.
- **Interagency level:** sharing applications and data with external users. [88]

Decentralised GIS solutions at project or department level are usually less expensive than centralised data management solutions requiring hefty hardware and software investments. Nevertheless, decentralised data management often leads to work redundancy and data islands: the same piece of information is produced and stored by different departments within a utility without being linked. [88]

A GIS at company level will be more appropriate for most water utilities given this factor and the many different aspects involved in water loss management. A client-server architecture is the preferred configuration for an enterprise-level GIS, as illustrated in *Figure 5.2*.

Figure 5.2 Client–server architecture for an enterprise-level GIS, based on [93]

5

5.3.3 GIS user requirements

The success of GIS implementation in a utility depends highly on the people who build, maintain and use the GIS. The user's technical skills and knowledge are just some factors to be considered, while non-technical factors often are more important. It is imperative that end users in all involved departments feel that their needs and wishes were considered during project implementation to reap the full benefits of an enterprise-level GIS. The GIS will not be accepted unless the qualified end users were actively involved in creating the system. [76] A utility's GIS department should strive to create awareness of the benefits of the GIS system and should constantly transfer know-how and experience to other departments. [72]

It is equally important to inform the departments involved about the demands and capabilities of the system in order to avoid unrealistic expectations. The introduction of a GIS will typically result in some work process changes that are necessary to interface different existing and new systems. Therefore, end users must show some degree of flexibility to adjusting existing work processes. Clear lines of responsibility and accountability should be established for all concerned utility personnel. A system administrator should be appointed to coordinate works with the system provider on the one hand and with the utility’s end users on the other hand. [76]

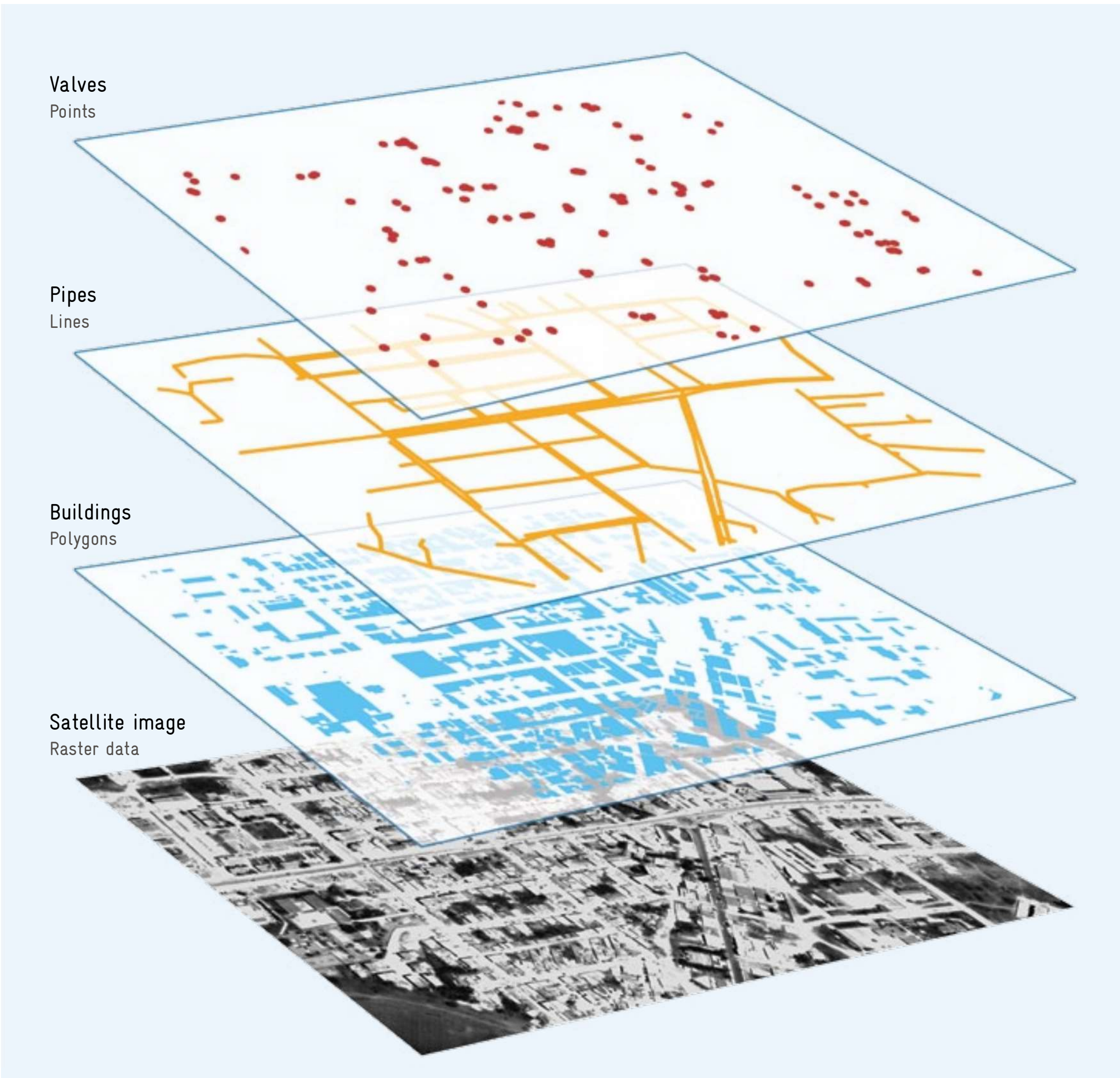
5.3.4 Types of data

Geographic data can be divided into four main categories depending on their specific characteristics: vector data, raster data, triangulated irregular networks and object information, as specified below:

- → Vector data is used to represent spatial objects with well-defined shapes as an ordered set of coordinates (spatial reference). Vector data can be classified into points, lines and polygons. A set of describing (non-spatial) attributes can be allocated to each spatial object.
- → Raster data is used to represent areal data. For this purpose, areal data is divided into a grid or raster of square cells of uniform size. A set of describing attributes can be allocated to each cell.
- → Triangulated irregular networks (TINs) are used to model three-dimensional surfaces. They consist of a set of nodes with elevation information which are interconnected with a network of edges. These edges build a set of triangles that form the surface of the TIN. The elevation of any point can be interpolated within the TIN.
- → Object information is descriptive information which has no spatial reference by itself. Object information is usually stored in relational databases and can be linked to vector or raster data. [93]

Figure 5.3 illustrates the application of different types of geographic data: pipes are represented by lines, buildings by polygons, valves by points, descriptions as object information and the background satellite image is stored as raster data.

Figure 5.3 Representation of different types of data in a GIS



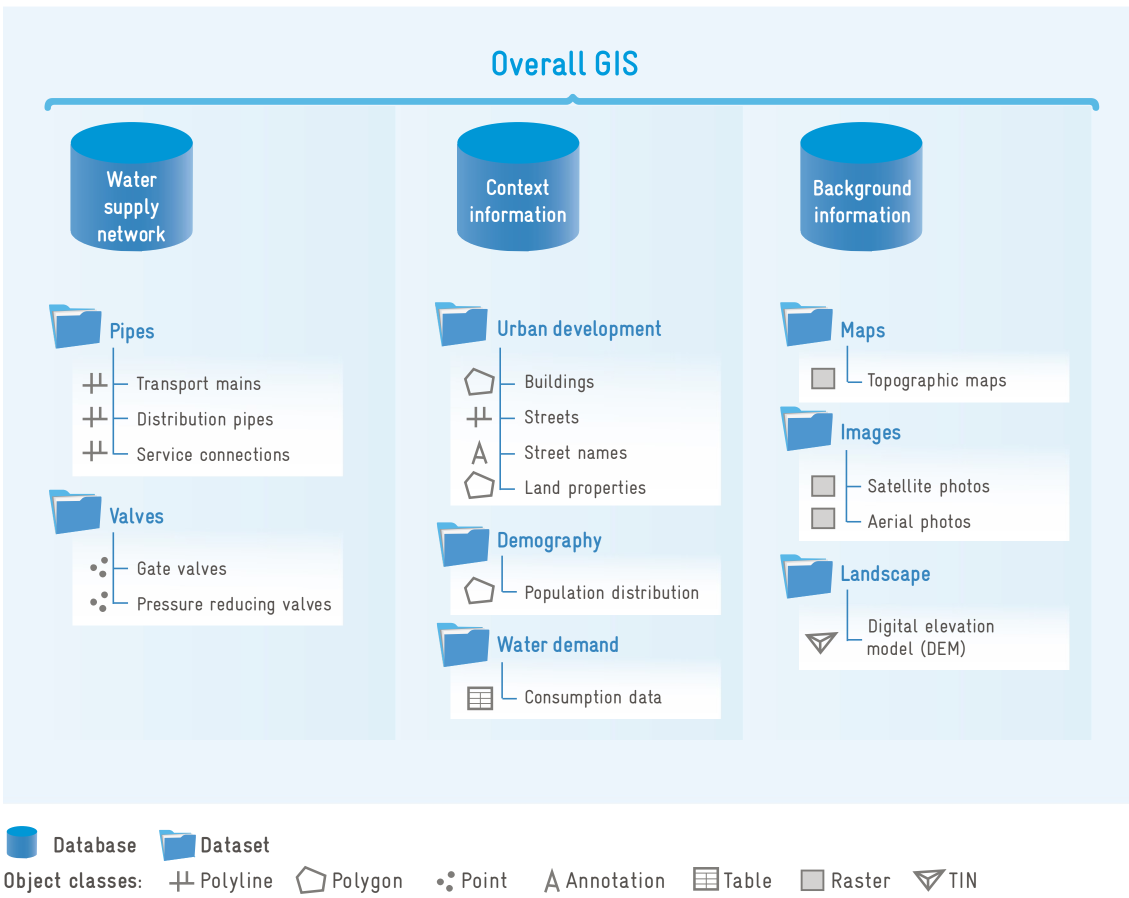
5.3.5 GIS data structure

All data contained in a GIS can be tied to a geographic location. For example customer water meters, distribution pipes or the boundary of a discrete supply zone all have in common that they can be located at an exact geographic position. There are numerous commercial solutions which use different data formats for structuring and storing data.

Relational databases are the most convenient data structure for storing all kinds of spatial, topological and attribute data.

Relational databases can be used to organise data into broad categories of related data. At an enterprise level, different departments may have responsibility for different data sets. In this case, the databases may also echo the utility's organisational structure. Geographic data can be stored inside a relational database as single object classes or can be combined to create sets of related data. *Figure 5.4* illustrates one example of a possible GIS structure.

Figure 5.4 Structure of a GIS based on databases, data sets and single object classes [93]



Creating a collection of various data set types is usually the first step in setting up a GIS. The original set of databases can be continuously enhanced by adding data sets and advanced capabilities in order to cope with the users' requirements.

5.3.6 Data collection, conversion and integration

Input data for setting up the GIS typically has to be collected from various different sources of information: different utility departments, administrative boards and agencies, private consultants, engineering offices and others. Common forms of input data for water supply systems include paper network maps, as-built drawings, field measurement data, existing digital data from CAD and GIS systems, but also reports, spreadsheets and photographs. Different data-conversion methods have to be employed depending on the available input data: paper plans and maps can be digitised (tablet digitising) or scanned and vectorised on-screen (heads-up digitising). Specialised software is available that can convert existing digital data, e.g. CAD drawings, into the required data format. Hardcopy reports and tables often have to be digitised via keyboard entry. [72]

Other types of data, such as consumption records from the CIS or system pressures and flows from the SCADA system, can be transferred into an existing GIS system on a periodic basis. For instance, visualising actual information about water production and consumption in the GIS may help to recognise trends in the water loss situation in discrete areas.

The process of data collection, conversion and integration into the GIS is laborious and expensive. *Shamsi* reports that data collection and entry costs can be up to 80% of total project costs in some GIS projects. [75] Therefore, a thorough understanding of the GIS data requirements is essential before starting the data collection and conversion process.

After GIS set-up, water utilities should consider establishing ground truth, e.g. by checking the quality of GIS information in several field visits. It is subsequently important that the database is maintained and kept up-to-date. All changes to the system have to be recorded and integrated into the existing GIS.

5.4 Landbase

5.4.1 Input data for the landbase

Each water utility GIS must use some kind of landbase as background information and a spatial reference for its information systems and for other planning and management purposes. These might include the network register, hydraulic model and/or failure database. Setting up the landbase consists of acquiring, digitising and geo-referencing topographic maps and aerial or satellite photography which form the backbone for all other data. Distinctive points have to be measured in the field and serve as reference points for geo-referencing maps and photographs. Other useful data may be used to complement the landbase:

- cadastral mapping data (land plots)
- land use information
- infrastructure and transportation system data
- administrative limits
- population distribution
- location of administrative, commercial and industrial entities
- digital elevation models
- information about soil, vegetation, hydrographic and other environmental data.

Developing the landbase requires careful planning and vast amounts of data and is therefore a rather long and expensive process. Costs can be reduced significantly if the landbase is set up in cooperation with other potential users, for example the municipal transportation authority, energy, gas or telecommunication providers.

5.4.2 Contents of the landbase

The minimum requirements for the contents of the landbase are as follows:

- representation of all buildings adjoining roadways and pipe alignments
- all other significant structures (dams, bridges, etc.)
- roads, kerb sides, walkways, rails
- land plots.

Additional items might include the position of rivers, lakes, channels, trees and other structures.

5.4.3 Data quality considerations

It is very important to set up the landbase with a high degree of accuracy and correctness because carelessness at this initial stage may cause numerous and very costly problems later. For example, the accuracy of the map will be very low and deviations of several meters may arise between real-world positions and positions indicated in the map in the event that some of the data has not been geo-referenced carefully to the chosen projection. Water supply system facilities captured at a later stage using a high-precision, differential global positioning system (GPS) will be displayed at the incorrect location. Ultimately all facilities will have to be shifted in the GIS to match the (incorrect) spatial reference – a labour-intensive and time-consuming undertaking. [88]

The following issues should therefore be considered in order to produce a highly reliable landbase: (i) map projection type and coordinate system, (ii) accuracy (sub-metre precision or ± ... metres), (iii) scale of maps and aerial photographs and (iv) actuality of the used data.

For the same reason, the quality of sources has to be considered: data from a 1:25,000 scale topographic map specified as having 90% of its features within 15 m of their correct location will not allow detailed planning work. Elevation information from a DEM with an average elevation error of ± 5 m can be used neither for hydraulic model calibration, nor to design a correct pressure management scheme.

Once converted into a GIS environment, map data is no longer scaled and new maps of any desired output scale can be produced. However, the produced outputs can never be more accurate than the original data source from which the data was acquired. [75] Therefore, the GIS' user should always be aware of the scale and quality of its source data. Map magnifications exceeding the ratio of 1:2 should be avoided. [17]

The following standardised map scales are recommended as input for the landbase:

Table 5.2 Recommended map scale for setting up the landbase

Object	Scale
Topographic maps for large-scale, cross-regional supply systems	1:10,000 to 1:50,000
Topographic maps as background info for urban areas	1:2,000 to 1:10,000
Aerial photographs, satellite photographs	1:2,000 to 1:10,000
Cadastral maps for detailed planning in urban areas	1:250 to 1:1,000

Proper documentation of the landbase set-up process is essential: The landbase needs to be traceable to a known source, so that its accuracy and precision is known. High accuracy will lead to rising development costs. The utility should therefore always keep in mind the planned objectives of the GIS when setting up the landbase. [9]

5.5 Network register

5.5.1 Objectives

One of the future challenges facing water utilities worldwide will be the sustainable management and the conservation of value of their capital assets. The pipe network usually represents 60 to 80% of a water utility's capital assets. [42] A digital GIS-based network register is a powerful system that enables water utilities to:

- → have instant access to necessary information
- → reduce time-consuming paper-based processes
- → improve maintenance and operation efforts
- → facilitate leakage management
- → identify system deficiencies
- → accelerate emergency repairs
- → facilitate long-term rehabilitation and extension planning.

It has to be considered that setting up an entire network register is a multi-stage process which frequently takes three to five years for large water distribution networks. [5] Numerous engineering firms offer services covering the entire implementation cycle, including hardware and software set-up and installation, data conversion, document scanning, updating and mapping.

After initial set-up, the system has to be continuously updated: new pipe extensions or reallocations, rehabilitation measures and leak repairs have to be measured and allocated in the correct position. Additional object information should be linked, e.g. the construction date, material, dimension, corrosion protection, type and reason for damage and the names of the personnel or subcontractors involved. [60]

5.5.2 Input data for the network register

Utilities maintain a core set of records detailing their networks' physical assets which may serve as input for the network register. These typically consist of:

(a) System maps of various scales and detail

Electronic or hardcopy system maps can be merged into one seamless electronic map database. They constitute the basis for the network register and the hydraulic model.

(b) Detailed documents

Paper records showing the as-built location, size and selected parameters of pipes, valves, pumps, service connections, meters, etc. can be scanned and linked to their respective asset in the map database.

(c) Reports about failures, inspections, repairs

Reports, photo documentation or even CCTV inspection videos provide additional information about assets and can be linked to spatial objects.

(d) Continuous measurements

SCADA measurements, consumption patterns, water quality data.

As always, it is important to keep in mind the quality of the input data: pipe location can be measured in the field (very exact: during construction in the open ditch; less exact: on the surface, from street cap to street cap) or be constructed (exact: from CAD design drawings; less exact: from hand-drawn sketches) or even be guessed (e.g. based on oral statements). The origin of the data and the level of accuracy should be documented in metadata. [25]

In the interests of readability, the accuracy of all network elements should be adjusted to the scale of the desired output maps. The following standardised output map scales are recommended depending on the degree of development and the amount of pipes: [17]

Table 5.3 Recommended output map scale for the network register

Degree of development	Scale
Densely developed urban areas with a large amount of pipes	1:250
Medium developed areas with an average amount of pipes	1:500
Sparsely developed rural areas	1:1,000

5

5.5.3 Data structure

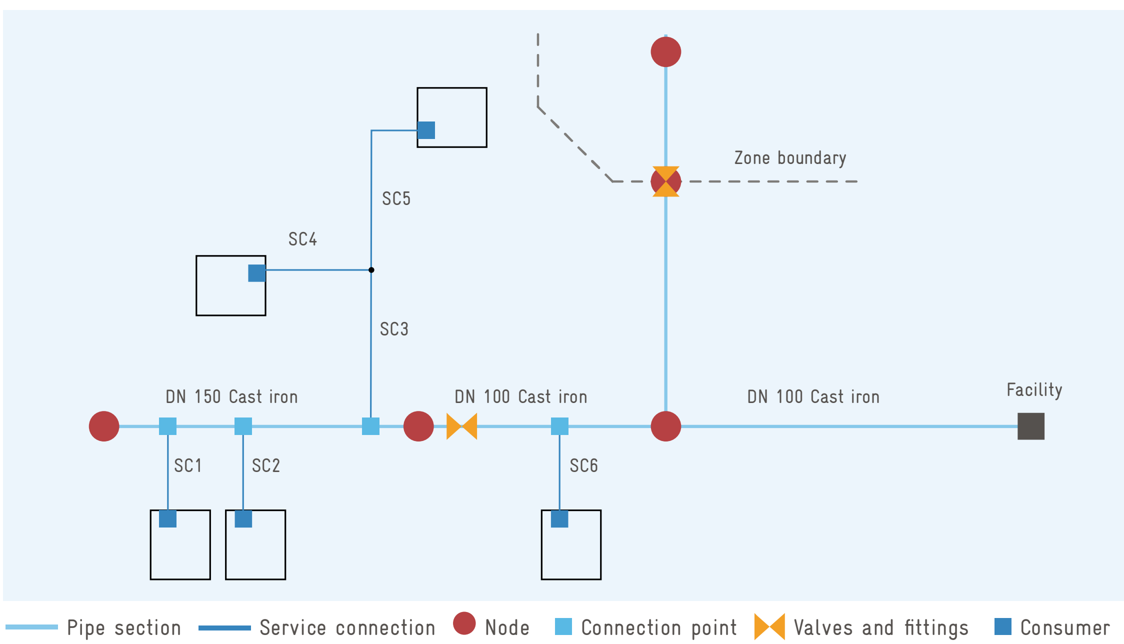
In 1996, the DVGW developed a catalogue of requirements called GAWANIS. [15] GAWANIS is primarily intended to support water utilities in developing a digital network register catering to their specific needs. It recommends a standardised data structure which can be summarised as follows:

- The whole distribution network has to be divided into discrete pipe sections with identical attributes (material, diameter, etc.). A new pipe section has to be established if one attribute changes along a pipe alignment. In the same way, a new pipe section has to be created at every branch. A node has to be located at the start and end point of every pipe section. Pipe sections can be divided automatically at zone boundaries or administrative limits.

- → Service connections form a separate object class. One or more service connections can be connected to a pipe section. Where the service connection is connected to the pipe section, a connection point has to be set. A service connection is not seen as a branch and therefore does not divide a pipe section into two. Service connections can be branched and can supply various consumers. A new service connection has to be defined at branches.
- → Locating valves and fittings does not require that a pipe be divided into two pipe sections. Yet, a pipe can be divided into two pipe sections at a valve if necessary (e.g. at boundary valves).
- → Facilities comprise all plants that produce, convey, store and treat water within the system, for example wells, pumps, tanks and treatment plants. Each network has to begin or end at a facility.

Figure 5.5 illustrates the standardised data structure.

Figure 5.5 Standardised data structure for distribution networks, based on [15]



The typical attributes of the network elements specified above are described in *Table 5.4.* These attributes can be extended to suit the needs of each water utility. A descriptive text can be added to each element in order to provide additional information.

Table 5.4 Pipe network elements and its attributes

Element	Obligatory attributes	Additional attributes
Pipe section	ID, length, nominal diameter, material	Inner/outer diameter, wall thickness, date of construction, manufacturer, nominal pressure, roughness, supply zone, street name, etc.
Service connection	ID, length, diameter, material	Date of construction, manufacturer, etc.
Node	ID, x, y coordinates, surface elevation	Pipe cover, etc.
Facility	ID, type, capacity	Status, date of construction, manufacturer, etc.
Connection point	ID, type	Date of construction, manufacturer, etc.
Consumer	ID, address, meter ID	Date of installation, status, etc.
Valves	ID, type, nominal diameter	Dimensions, date of installation, manufacturer, function, status, etc.
Fittings	ID, type, nominal diameter	Dimensions, date of installation, manufacturer, nominal pressure, etc.

5.5.4 Network register and leakage

A GIS-based network register enables water utilities to produce reports automatically that group their leaks based on service area, pipe material, cause of damage, leak size, leak type and leak repair status. This information helps to schedule leak repair and pipe replacement projects more effectively. Graphic visualisation of the results helps to reveal leakage hotspots, prioritise repairs, identify problematic materials and effectively deploy leak repair crews. [67]

Supplementary materials 5.1

Network register set-up

5.5.5 Linking network register and hydraulic model

Hydraulic calculations of water supply systems are indispensable for analysing system capacity. Until the 1990s, software and hardware constraints meant that most analyses of water supply systems were simplified or incomplete. Since then, computing power has improved enormously, allowing very large, very detailed networks of high complexity to be modelled. [5] In the specific case of water loss reduction, hydraulic network models can be very useful tools to design DMAs and PMAs. Linking a hydraulic model to a GIS-based network register will facilitate and accelerate the model-building process tremendously. Two different approaches are typically taken:

(a) Connection via an interface

In this case, data input and editing is only performed in the network register. An interface has to be created which exports the data in the precise form required by the hydraulic model, usually an ASCII or database file. Modelling software is used to simulate, visualise and analyse results.

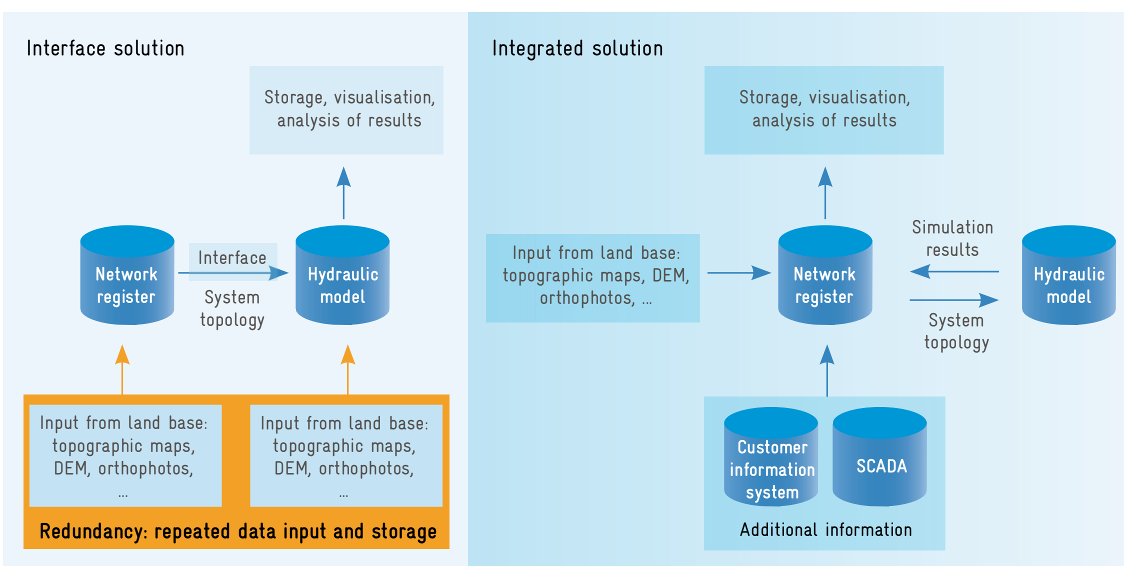
This solution usually requires some reworking measures to complete the model, because some elements are handled differently in each system, e.g. pumps or tanks. Redundant data storage may be required, e.g. for the background map.

(b) Integrating the hydraulic model

Integrating the hydraulic model into the network register accelerates the whole process. The topology of the hydraulic model is updated automatically upon any changes to the network register and sources of possible data handling errors are reduced. Additional information (e.g. pump curves, demands at each service connection, pressures, flows and status of valves from SCADA) are directly available from the respective model element. In the same manner, simulation results are directly stored, visualised and analysed at their location in the network register.

This integrated solution will require greater efforts at first because both systems have to be harmonised with each other. In the long run, the integrated system is more efficient because it allows more frequent calculations to provide planners with a sound basis for decision-making. [5]

Figure 5.6 Linking the hydraulic network model to the network register



5.6 Hydraulic network model

5.6.1 Definition and objectives

The term hydraulic network model describes the use of a mathematical representation of a real water supply system. Hydraulic network models are used to simulate the behaviour of existing or planned systems under a wide range of conditions without disrupting service to the customer. They also offer a valuable tool for making the operation and management of water distribution networks more efficient.

Taking into account the specific requirements of efficient water loss management, hydraulic network models may be employed to put in place the following measures successfully:

- System capacity verification: analysis of pressures and flows.
- Zone boundary selection for district metered areas (DMAs) and pressure management areas (PMAs).
- Specific applications for planning pressure management: dimensioning valves and meters, revising fire flow conditions, detecting shortcomings of pressure and water quality.
- Analysing system vulnerability, supply security and emergency response in the event of pipe breaks.

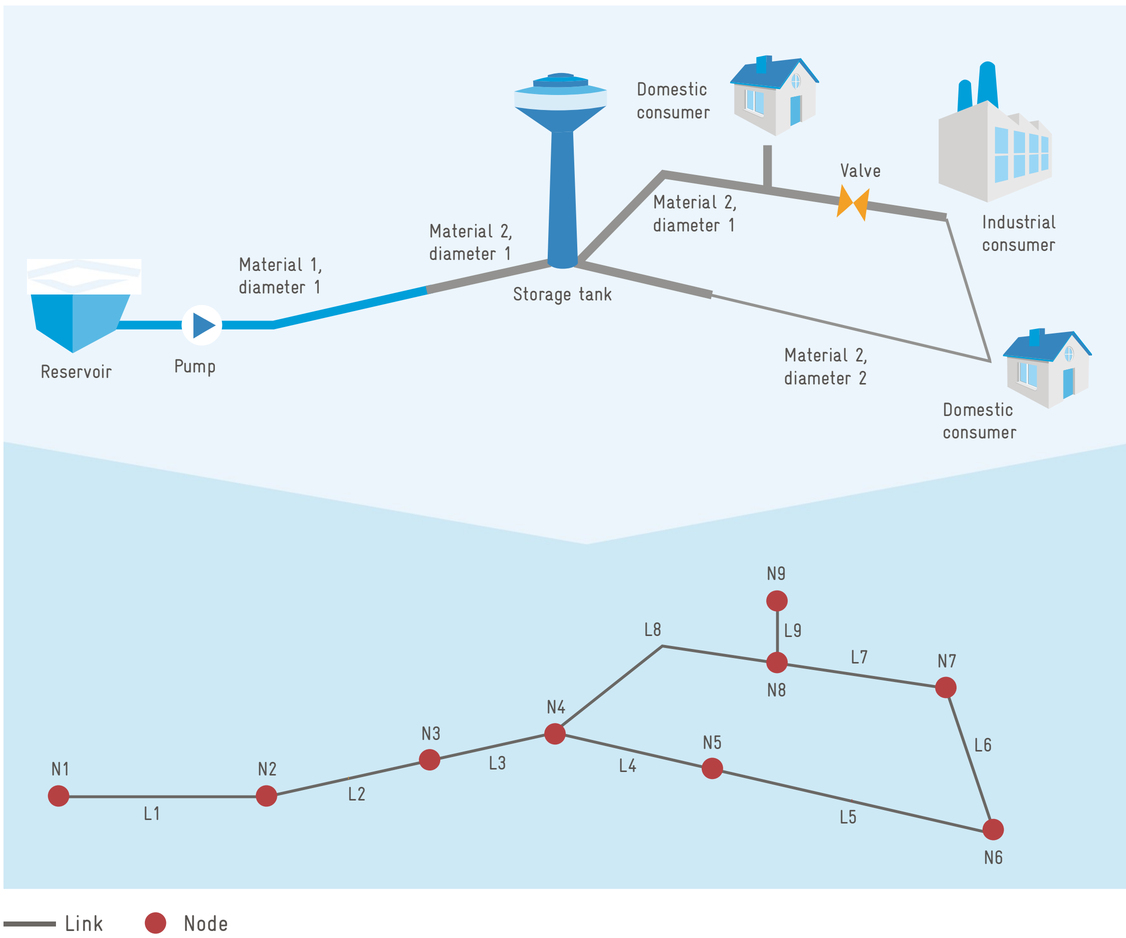
5.6.2 Foundations of hydraulic modelling

The user should understand the mathematical and hydraulic principles employed in hydraulic modelling software to allow the results to be interpreted correctly. Nevertheless, the fundamental process for model set-up and the required input data will only be described in detail within this manual. For more information about hydraulic principles, please refer to *Walski.* [88]

Topology of a water distribution network

A water distribution network can be described as a digraph (or directed graph) which is composed of a finite set of nodes and links. A start node and an end node have to be allocated to each link. This digraph forms the backbone of every mathematical model. Each link represents a homogeneous section of a pipe. Valves and pumps are also represented by a link. The nodes designate physical changes in a pipe section, for example changing material, changing diameter or pipe branches. Nodes are also used to model points where water enters and leaves the system as well as for tanks, consumers and end points of pipes. The physical and non-physical characteristics of all system components (pipe diameter, material, pump curve, minimum and maximum tank water levels, etc.) are assigned to the links and nodes as attributes. [11] *Figure 5.7* represents a simplified water distribution network as a digraph.

Figure 5.7 Representation of a simplified water distribution network as digraph



Data structure

Most modelling software products organise their data in a set of tables or databases with a hierarchical structure. The tables of nodes and links with their respective attributes form the first level of this structure. More complex attributes are usually stored in secondary and tertiary tables of this structure and can be assigned to nodes and links via their unique IDs. [40] *Figure 5.8* shows the hierarchical data structure for the simplified distribution network illustrated in *Figure 5.7*.

Figure 5.8 Hierarchical data structure of a water distribution network

Nodes

ID	x	y	Type
N1	0.0	0.5	Reservoir
N2	2.5	0.5	Intermediate node
N3	4.7	1.0	Intermediate node
N4	6.5	1.3	Storage tank
N5	8.3	1.0	Intermediate node
N6	11.7	0.0	Demand node
N7	11.3	2.0	Demand node
N8	9.0	2.3	Intermediate node
N9	9.0	3.0	Demand node

Demands

ID	Demand	Pattern
N6	35	DOM
N7	160	IND
N9	20	DOM

Patterns

ID	Time	Factor
DOM	01:00	3.5
IND	01:00	2.0

Tanks

ID	Diameter	Min. level	Max. level
N4	12.0	1.0	4.0

Links

ID	Startnode	Endnode	Length
L1	N1	N2	2.1
L2	N2	N3	2.1
L3	N3	N4	1.7
L4	N4	N5	2.0
L5	N5	N6	3.1
L6	N6	N7	1.9
L7	N7	N8	2.3
L8	N4	N8	3.2
L9	N8	N9	1.8

Pipes

ID	Diameter	Material	Type
L1	1	1	Pump
L2	1	1	
L3	2	1	
L4	2	1	
L5	2	2	
L6	2	2	
L7	2	1	Valve
L8	2	1	
L9	2	1	

Pumps

ID	Pump curve	Speed
L1	Curve1	2,900

Valves

ID	Valve type	Status
L7	TCV	open

Tables of links usually define the topology of a network by establishing their start and end nodes. The coordinates and elevations of its nodes determine a network's spatial position. Relational databases are convenient for model data handling, but software products are also available that can store data in tabular lists in simple text files.

Model parameters

The attributes of nodes and links can be subdivided into given parameters and variables. The given parameters of a hydraulic network model might include all system components (pipes, pumps, tanks), water supply and abstraction points as well as system controls. Node pressures, flow rates and flow velocities, changes in the tank water level, quality and other attributes are variables calculated by the model. The quality of input parameters directly impacts the quality and accuracy of the simulation results. It is thus essential to adjust the quality of input parameters to the desired tasks of the model and to strike a balance between data acquisition efforts and the informative value of the model's results.

The model parameters for data acquisition efforts and quality can be classified as follows:

- → Parameters which can be directly and accurately measured (e.g. the location of the pipe network, tank geometries, pump characteristics and system controls).
- → Parameters which can be directly measured, but with insufficient accuracy (e.g. domestic consumers' water consumption).
- → Parameters which cannot be measured directly (e.g. pipe roughness, inner diameter, water losses). [11]

The last group of model parameters can be determined through model calibration which is described in the following section.

Model calibration
Model calibration describes the process of comparing real, measured system conditions with model results simulated under the same boundary conditions. The model has to be adjusted until discrepancies between reality and simulated results are minimised. The calibration process usually involves the parameters of pipe roughness, water consumption, water losses and system controls, with greatest importance attached to the pipe roughness. [88]

In most cases, the integral roughness of the network is determined. This factor comprises not only the real pipe roughness, but also local head loss, reduced inner diameters due to incrustation and sedimentation as well as unknown factors (e.g. partly closed valves or incorrect information about diameters). Fire flow tests are used in order to ascertain the flow and pressure data: these tests usually consist of selecting and isolating a measuring pipe section where flow is induced by opening a hydrant. Flow and pressure measurements are taken simultaneously when the pipe section reaches steady flow conditions. [4] SCADA systems are also a good source of data for model calibration.

5.6.3 Input data

Input data for hydraulic network models can be classified into four main groups, which can ideally be obtained from the water utility's related information systems: [4]

- → **Geographical information** can ideally be obtained from the utility's landbase and comprises topographical maps, cadastral data, aerial photography, digital elevation models and other background information which is useful to determine the physical location of the model.
- → **Facilities data** should be contained in the network register and include all information about pipes, pumps, valves, storage tanks and other physical elements of the water distribution network.

- → **Operational data** is important to establish controls and boundary conditions in hydraulic network models. They comprise pressures, flow rates, tank water levels, valve settings as well as information about pumps' status and control. Operational data can usually be obtained from the utility's SCADA system.
- → **Demand data** or water consumption data and information about their spatial allocation should be available from the customer information system.

Water utilities should be aware that collecting input data for model set-up is not a one-time activity, but a permanent process. The model must be constantly updated to achieve accurate simulation results in the long term.

5.6.4 Model set-up

The following will illustrate the major steps required when setting up an operational hydraulic network model.

Defining model objectives

The water utility has to decide on the objectives of the hydraulic network model prior to data acquisition and model set-up. The demands on the model output define the accuracy, completeness and level of detail needed, and thus influence the efforts and expense of the modelling process.

Data acquisition and data preparation

Data has to be acquired and prepared from various sources in order to develop and maintain a model that represents the physical water distribution network with a degree of accuracy which is adequate to meet the defined objectives. Good engineering judgement has to be used to determine the quality of the data and its impacts on the model outputs. [4] The quality, quantity and nature of the available data vary from case to case, which makes this step time consuming and hard to predict.

Model set-up and calibration

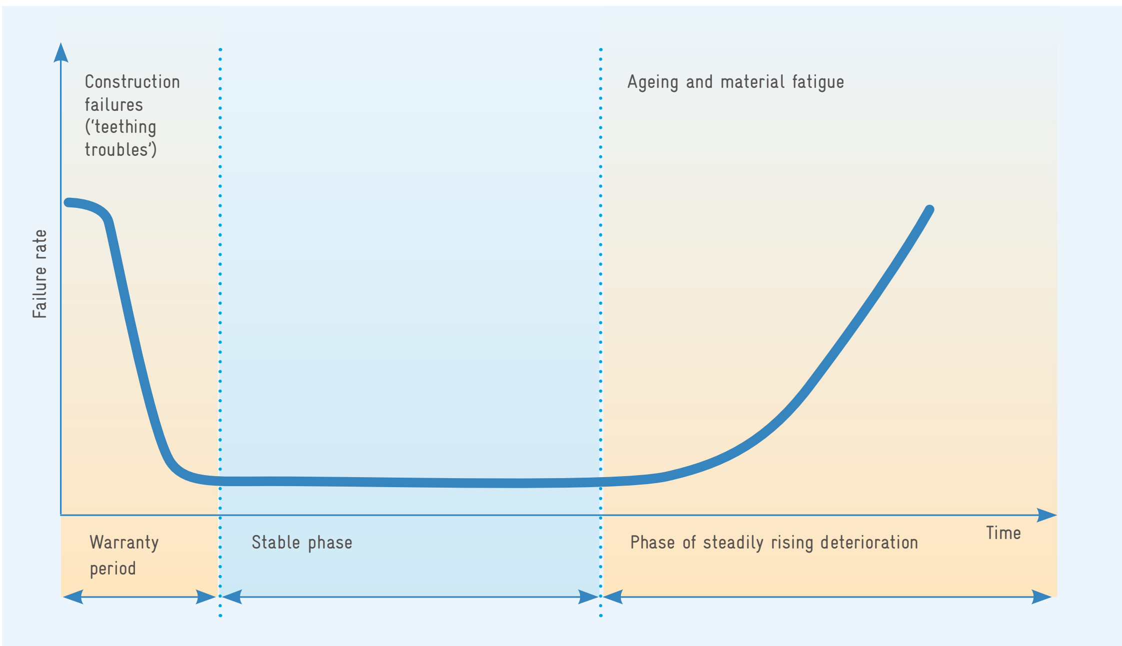
This step involves abstracting physical and non-physical data from the water supply system and transforming it into the digraph of nodes and links. Additionally, the general simulation parameters have to be set up. The calibration and verification of the model is an iterative process after which the model is ready for utilisation.

5.7 Failure database

5.7.1 Objectives

Failures occur during the entire useful life of a water distribution network. Consequently, failures can be defined as a local impairment to serviceability which generally involves leakage. Experience shows that failures accumulate at the beginning (construction failures) and the end (material fatigue, corrosion) of the useful life of a discrete pipe section, as illustrated in the *bathtub* curve shown in *Figure 5.9*. [43]

Figure 5.9 Typical behaviour of the failure rate in pipes, based on [43]



The curve shows failures as a function of age: teething troubles due to poor-quality materials and installation work dwindle at the outset. They are followed by a longer period of maturity with a fairly low failure level when failures are neither frequent, nor serious, and will be remedied through spot repairs. At the end of the curve, failures increase rapidly when the system is ageing in the proper sense of the word. When failures approach a critical failure rate, this is a warning sign and the water utility has to prepare itself for the fact that rehabilitation is near and the service life of the pipe will soon end. The old pipeline needs to be relined or replaced in due time. [32]

Assessing the overall condition of a water distribution network is difficult, because most system elements are installed below ground. Statistical analysis and graphic visualisation methods in a failure database allow water utilities to identify spatial, temporal or material-specific build-ups of failures and combinations thereof.

This knowledge is essential for systematically planning rehabilitation measures, selecting suitable materials and putting in place inspection and maintenance routines. The interpretation of failure data supports the planning process when it comes to choosing:

- pipe material
- corrosion protection
- pipe connections
- type and manufacturer of valves and fittings
- execution of construction works.

Pipe and valve failures are directly associated with water losses and the cost of repairs within a water distribution network. The failure rate for selected materials used in a water distribution network is easy to calculate. Calculating the failure rate on an annual basis may offer an indicator for the actual condition of the network. Temporal variations in the failure rate can be used to assess the impacts of measures, such as pressure management or rehabilitation strategies.

5.7.2 Collecting failure data

All failures within the water distribution network should be systematically recorded by means of standardised data sheets in hard copy or digital format. Failures that cause leaks should always be logged. Failures that do not involve leakage may also be registered in order to gain a broad overview of the weak points in the network. Skilled utility personnel should perform data entry directly on-site. The standardised data sheet should have a general heading, which provides space for entering the address or geographic position, date, time and name of the informant. Other information should be grouped in thematic blocks detailing the (a) type of damaged asset, (b) kind of failure, (c) cause of failure and (d) asset-specific data. [12]

Supplementary materials 5.2

Failure data collection

(a) Type of damaged asset

This category specifies the part of the network where the failure has occurred. A distinction can be made between the transmission mains, distribution mains, and service connections. The failure can be situated at pipes, pipe connections, valves (different sub-types), hydrants or fittings.

(b) Kind of failure

The kind of failure could be ruptures, fissures, holes as well as connections that are not watertight and defective valves. This section should also show if the failure caused leakage.

(c) Cause of failure

An attempt should be made to identify and document the cause of the failure. This might be corrosion, material failure, construction failure, soil movement or third-party influence, for instance.

(d) Asset-specific data

Some additional asset-specific data must be gathered about the damaged part: the data sheet should provide boxes where the personnel can tick the nominal diameter, material, inner and outer corrosion protection and the type of connection used in the part in question. If available, information about date of construction and the executing construction company can be added.

Taking high-resolution digital photos of the recorded damage and linking them to the failure database is recommended. Furthermore, it can be useful to store information about the cost of repair and the repair methods selected. [71]

5.7.3 Failure analysis

Present-day data processing tools offer manifold possibilities for statistical analysis and visualisation of failure data. One option is to link information from the failure database to the network register. This step can be taken via a data exchange interface between both systems or by directly integrating failure data into the network register. Relationships between pipe data and failure data can be analysed using common GIS tools. This implies advantages for both information systems:

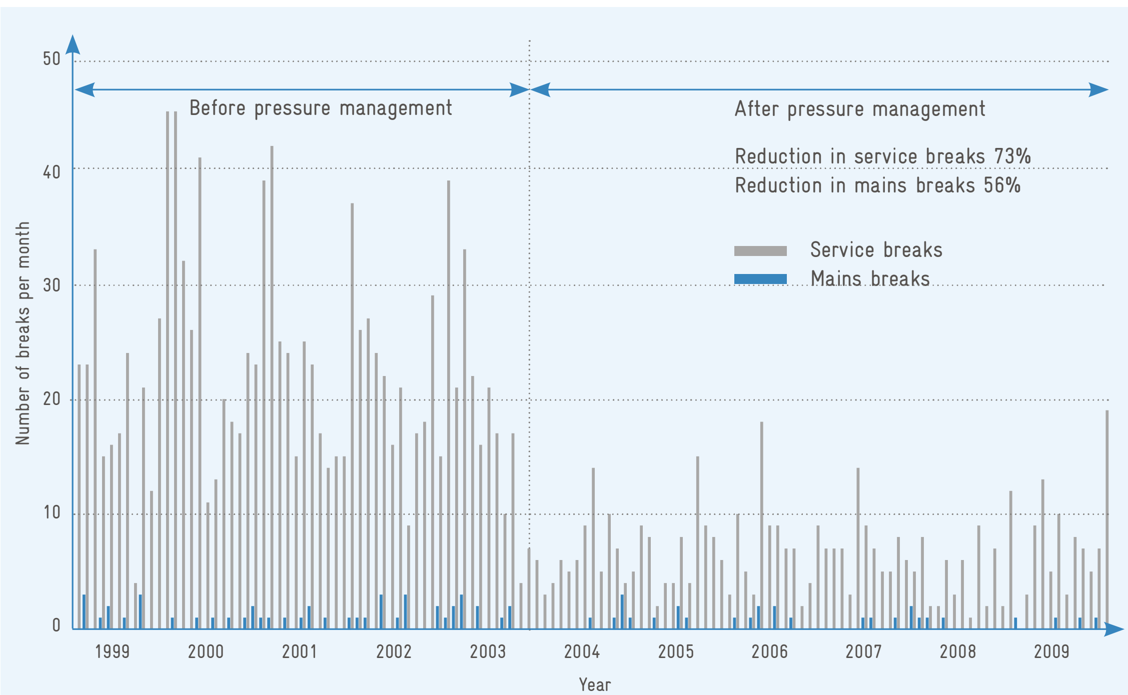
- → Information for the failure database is usually obtained on-site where visible pipe characteristics can easily be found. Existing network register data about the diameter, material and external corrosion protection can thus be crosschecked, corrected and supplemented.
- → Other information may be easier to source from the network register, for example the date of construction or internal corrosion protection.

Failures can be analysed in detail, for example relating to a certain material, diameter or period of construction, by combining all available data. Failures can be analysed according to their spatial allocation by calculating the number of damages per pipe section, street or pressure zone. [12] This classification will help water utilities to detect relationships between the failure rate and traffic load, system pressure or soil characteristics. The correct interpretation of these results will help to find an optimal strategy for operating, maintaining and rehabilitating the network.

5.7.4 Connection between the failure rate and system pressure

Information recorded about failures should always be linked to data on measured pressures at the time of the failure due to the significant influence of pressure transients (water hammer) as well as excess pressure on the appearance of new breaks and bursts. Many bursts are caused by lack of appropriate pressure management, and there are numerous studies showing how new bursts can be drastically reduced by pressure management *(see Chapter 6.4)*. This will result in additional savings for water utilities by virtue of fewer inspections, repairs, leakage detection costs and increased service life. *Figure 5.10* illustrates how managing pressure can reduce breaks on mains and service connections based on information from *Joshua May (Gold Coast Water, Australia)*.

Figure 5.10 Influence of pressure management on break frequency, based on [54]



5.8 Customer information systems (CIS)

5.8.1 Objectives

Nowadays, virtually all water utilities of a certain size have electronic customer information systems (CIS), which usually consist of several subsystems, such as customer databases, meter databases and electronic billing systems. Traditionally, these systems fulfil a key role in administering water utilities' revenues and are therefore managed by the accounting department. Customer information systems' accounting function often means that their significance and potential for decreasing NRW is neglected. [35]

Experience shows that NRW resulting from unbilled authorised consumption is often not caused by a lack of metered connections or meter accuracy, but rather by shortcomings in the management and coordination of meter reading and in the timeliness and accuracy of the customer database. [77] Exhaustive and constantly updated customer information systems that link customer accounts and entities, such as plots, properties, connections and meters, as well as their geographical location are thus crucially important for sustainable water supply management. [27] Customer information systems may yield the following benefits for water loss reduction:

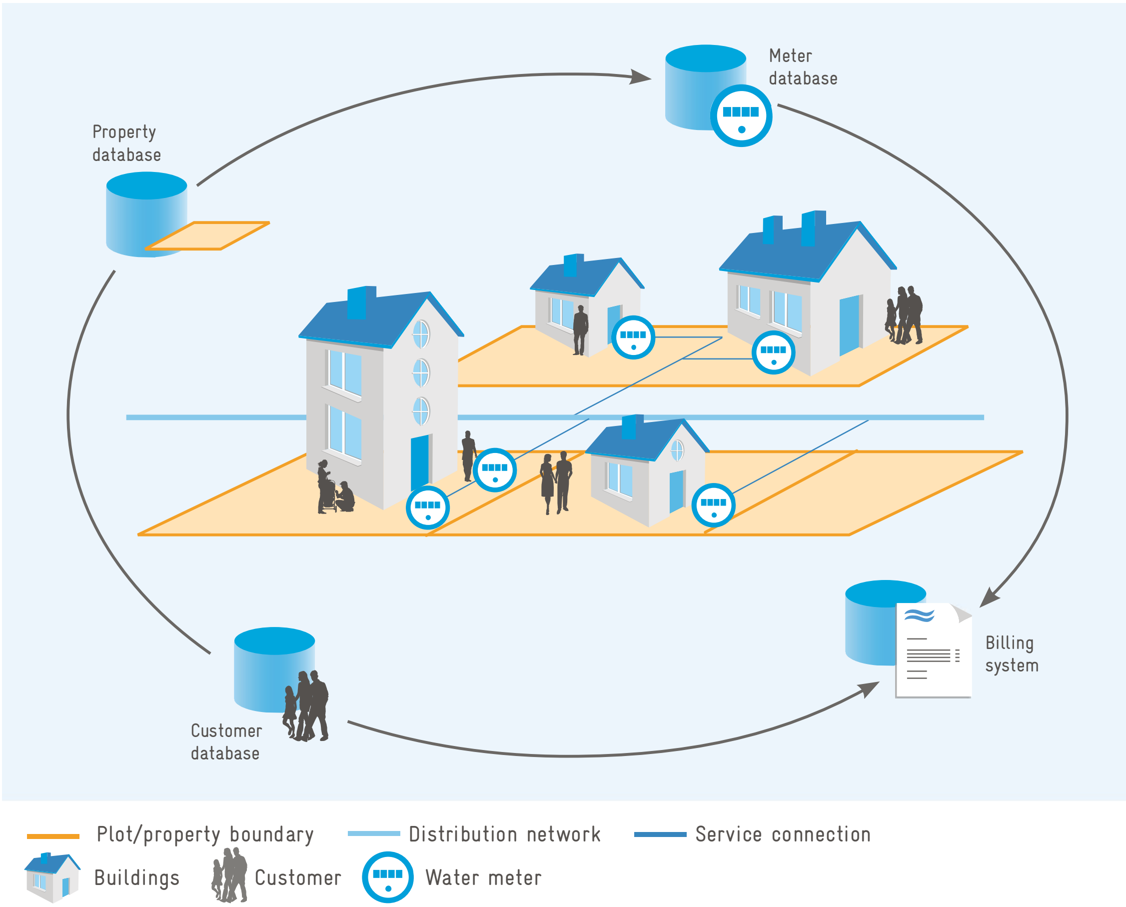
- reducing apparent losses and NRW
- increasing the efficiency of water meter readings, maintenance and replacement
- improving the quality of input data for water balance calculations
- providing precise demand allocations for hydraulic modelling
- DMA and PMA planning.

5.8.2 CIS components

The main components of water utilities' customer information systems are usually: (a) the customer database, (b) the property database, (c) the meter database and (d) the billing system. Ideally, these four components are interconnected and linked to the utility's GIS. Operating these main components as completely separate entities usually leads to redundant work and increased apparent water losses, and should thus be avoided.

The following section describes the contents and functions of the different information systems:

Figure 5.11 Connections between the major CIS components



(a) Customer database

The customer database contains information about all of a water utility's customers, be they private persons, enterprises or public institutions. Each customer is identified by a unique ID that links the client to the property and meter databases and the billing system. The customer database provides information about:

- → name, account number and address (spatial location can be linked to GIS)
- → water meter ID
- → property tenant.

(b) Plot and property database

The plot and property database contains data associated with each plot of land supplied within a water utility's service area. It forms the basis for commercial and engineering functions, such as tariff assignment, billing and demand analysis. The ID links properties to the customer and meter databases and to the billing system. This database provides information about:

- → location of the property (linked to the GIS)
- → type of development (residential, commercial, administrative, industrial, informal)
- → property owner
- → service connection to each property.

(c) Meter database

The meter database includes all relevant information related to a water utility's meter park. The meter ID, serial number, size, type, age, location and the mode of meter reading (manual/automatic) should be logged for each water meter. The meter database:

- → collects input data from all manual and automatic meter readings
- → checks the accuracy of readings (very high/low consumption, negative consumption)
- → records the condition of the meter (tampered, leaking, damaged or inaccessible)
- → provides the billing system with acceptable meter readings
- → generates meter reading walk routes (and maps, if GIS-based)
- → produces meter maintenance schedules for the operation and maintenance department.

(d) Billing system

The billing system should ensure that all customers are billed accurately for the actual amount of water that was supplied. This system should be used to obtain a high level of billing coverage by ensuring that all consumers of water get billed, whether metered, unmetered or illegally connected in order to reduce unbilled authorised consumption. Furthermore, the billing system may help to reduce apparent losses by improving the integrity of processed data. The billing system:

- → collects and finalises all acceptable meter readings
- → generates estimates for meters which are not readable
- → calculates the consumption of each meter
- → generates charges according to the respective tariff structure
- → consolidates customers' actual charges and previous transactions
- → produces customer statements

- identifies debts and creates reminders for debtors
- accounts for all incoming payments. [92]

Data accuracy is the foundation for all of these information systems. Data is quite often incomplete, questionable or even non-existent or data from different sources is inconsistent and does not match. In this case, great efforts have to be made to validate data.

5.9 Summary and next steps

Water utilities are unable to manage highly complex water supply systems and run the risk of wasting efforts and financial resources as well as reduced revenues without valid data and without proper decision support systems.

The contents of *Chapter 5* of this technical manual shall enable the reader to:

- ☑ Understand that information is the key for successful water loss reduction.
- ☑ Employ GIS as an instrument to exchange information and for various departments of a water utility to work together.
- ☑ Become acquainted with the typical structure and functioning of GIS.
- ☑ Know which input data is required to set up a digital landbase and how to procure it.
- ☑ Understand the importance and benefits of a network register and a hydraulic model for efficiently managing water supply systems.
- ☑ Set up and employ a failure database and a customer information system.

By implementing these information systems, water utilities create the necessary basis for successful practical water loss reduction measures which will be described in *Chapter 6*.

5

Photo: © J. Baader, 2008

Methods and instruments for reducing real water losses

6

6.1 Objectives

At the end of this chapter, the reader will know the principal methods to:

- → Design and implement district metered areas for improving control over water distribution, consumption and losses.
- → Understand the technical aspects of pressure management, choose the most appropriate use case for different local conditions and develop a typical project implementation plan for pressure management.
- → Choose the appropriate methods and instruments for leak detection and location.
- → Improve the efficiency of pipe repairs and infrastructure rehabilitation management.

6.2 Taking action against real water losses

6.2.1 Scheduling interventions

The condition of water distribution networks constantly deteriorates without sufficient maintenance and rehabilitation measures. To the same extent, real water losses steadily rise without adequate intervention strategies on the part of the water utility. When scheduling interventions, water utilities usually combat real water losses with one of the following approaches: (a) the outage strategy, (b) the pre-emptive strategy and (c) the inspection strategy. [13] [22]

(a) Event-driven maintenance: outage strategy (passive leakage control)

Action is taken only to combat failures that have already occurred. Visible pipe bursts or drops in pressure due to a major leak are usually reported by customers or noted by the water utility's personnel. The outage strategy is mostly encountered in water utilities without adequate water loss management. Overall losses are usually high because no efforts are made to locate and repair hidden leaks and reduce background leakage. Event-driven maintenance impedes sustainable water loss management.

(b) Interval-oriented maintenance: pre-emptive strategy (pro-active leakage control)

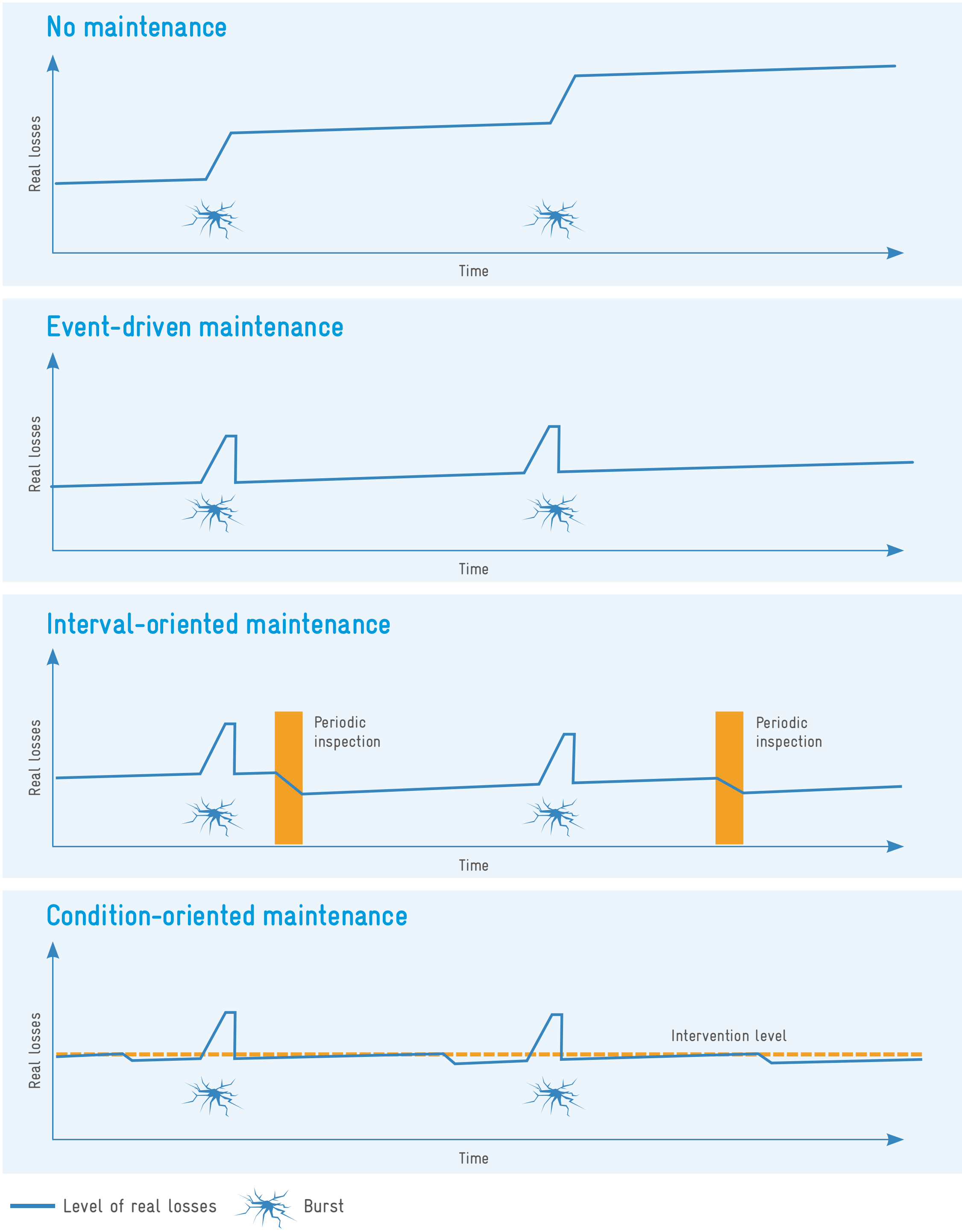
Inspections and maintenance are executed at defined time intervals. Short inspection cycles are required at high levels of leakage. Low failure rates and low levels of leakage allow for longer time lags. The pre-emptive strategy is labour-intensive, because all parts of the network have to be inspected, irrespective of their actual condition.

(c) Condition-oriented maintenance: inspection strategy (pro-active leakage control)

The condition of the network and the actual level of leakage are continuously monitored through regular inspections and ongoing flow measurements. Action is taken as soon as the level of leakage exceeds a defined critical value or according to an economic intervention strategy based on the value of accumulated real losses since the previous intervention. Regular inspections can therefore be carried out at longer intervals. The inspection strategy is the most target-oriented and efficient intervention method for reducing water losses.

Figure 6.1 on the next page illustrates in graphical form the impact of these strategies on the dynamics of real water losses.

Figure 6.1 Comparison between different intervention strategies to combat real losses



Furthermore, there is a connection between the scheduling of measures to counteract water losses and the appropriate methods which a water utility can choose: condition-oriented maintenance, for example, is only feasible if the water distribution network has been divided into discrete sectors (DMAs) where all inflows and outflows are continuously measured and analysed.

6.2.2 Choosing appropriate intervention methods

As *Chapter 3.4* describes, many different factors influence the occurrence and extent of real losses in a water distribution network. Before deciding which intervention methods are appropriate, a water utility thus has to understand which factors are contributing towards the real losses in its particular system. A single method or a combination of different methods will constitute the most efficient and economical instrument for water loss reduction, depending on the local situation. [77]

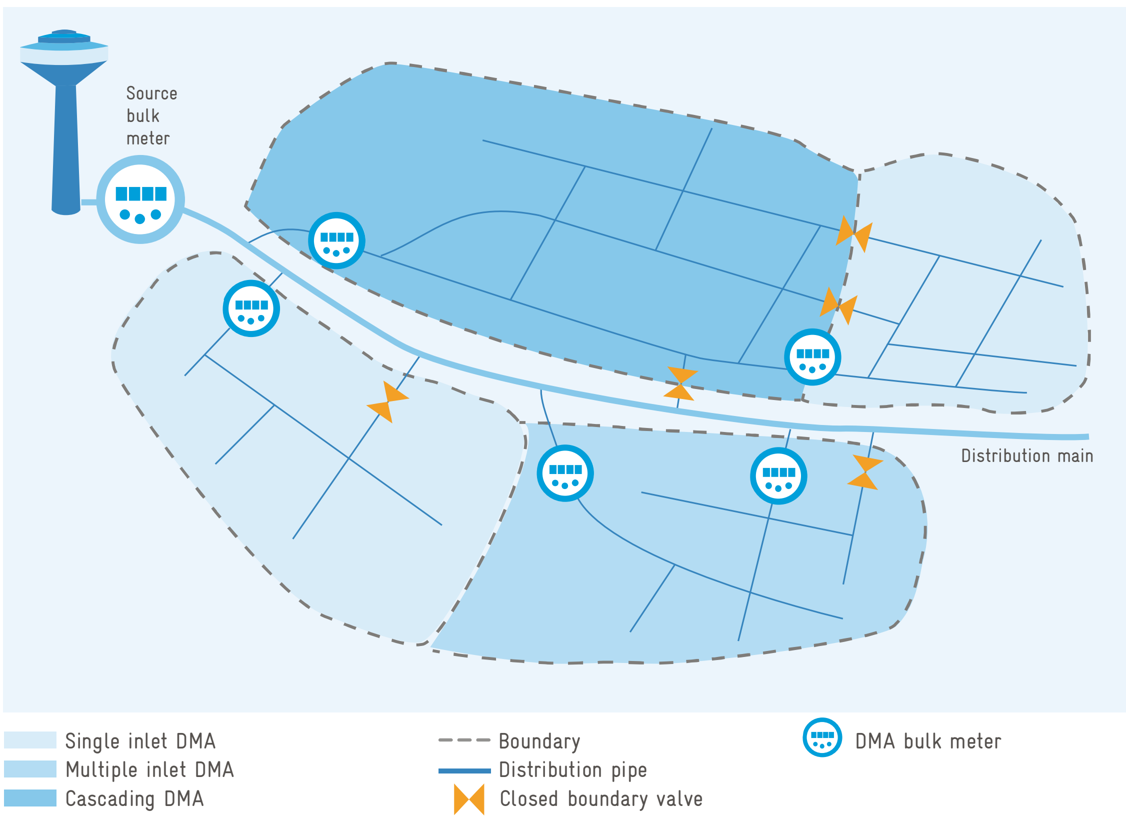
The IWA Water Loss Task Force defined the four principal methods of combating real water losses as follows: pressure management, active leak detection, the speed and quality of repairs and infrastructure rehabilitation management. [69] Additionally, subdividing water distribution networks into DMAs can be seen as a method and a prerequisite because it is essential for continuously monitoring leakage and required for installing pressure management schemes. These five principal methods are described in the following chapters, with a special focus on pressure management in *Chapter 6.4*.

6.3 District metered areas (DMAs)

6.3.1 Definition and purpose of DMAs

A district metered area (DMA) is defined as a discrete area of a water distribution network. It is usually created by closing boundary valves so that it remains flexible to changing demands. However, a DMA can also be created by permanently disconnecting pipes to neighbouring areas. Water flowing into and out of the DMA is metered and flows are periodically analysed in order to monitor the level of leakage. [58] DMAs can principally be categorised into three different types: single inlet DMAs, multiple inlet DMAs and cascading DMAs, as illustrated in *Figure 6.2*:

Figure 6.2 Typical layout of DMAs, based on [22]



Subdividing large water distribution networks into a limited number of DMAs has the advantage that new, hidden leaks can be located much earlier (reduced awareness time) and much more precisely (reduced location time). Water utilities can immediately determine sudden exceptionally high flows into an area if inflows and outflows of a DMA are monitored on a regular basis *(see Chapter 6.5.2)*. As a result, the awareness, location and repair times for new leaks are significantly reduced. Furthermore, the level of leakage can be quantified for different areas, and leak detection and repair activities can be efficiently directed to problem areas. [7]

In addition to offering these advantages, DMAs can also be upgraded to pressure management areas (PMAs) by installing pressure reducing valves (PRVs) at their inlet points. Pressure management reduces the flow rate of undetected leaks and background leakage and diminishes the number of new pipe bursts *(see Chapter 6.4)*. In summary, it can be stated that:

- a DMA is a discrete area where inflows and outflows are measured, but without active pressure management
- a PMA is a discrete area with active pressure management where inflows and outflows are usually measured.

Creating DMAs may also be the first step in counteracting intermittent supply: DMAs facilitate to find and repair the major leaks and thus may allow reducing periods of supply interruption. Another benefit of DMAs is the ability to conduct locally limited NRW assessments by comparing net input volumes into the DMA with customers' billed consumption in the same period of time. [7]

6.3.2 DMA design

Designing DMAs requires in-depth knowledge of the water supply system. The existence of a complete, up-to-date network register and topographical information is indispensable. Furthermore, water consumption patterns and operational data about flows and pressures should be available. For complex networks, a calibrated hydraulic model may be required to determine the impacts of sectorising upon service pressures and to detect potential bottlenecks, redundant pipes and zones endangered by stagnation. The following general rules should be considered when designing DMAs. [58]

- DMAs should not include trunk mains or storage tanks. If unavoidable, flow meters must be installed to control water inflows and outflows. Their design should separate the DMAs from the trunk system as far as possible, thus improving control over the former without affecting the flexibility of the latter.

- → Each DMA should preferably be supplied through a single, metered supply point. It may be necessary or useful to supply one DMA via two inlet valves equipped with flow meters to comply with fire fighting requirements. All flow meters have to be correctly sized and installed in accordance with manufacturer instructions. Both flow meters and PRVs need to be sized to measure and control predicted low flows after pressure management and leak detection. Therefore, they usually have to be downsized compared with the main's actual diameter. Metered flow data should be transferred to the control room through telemetry, if possible.
- → DMA boundaries should be created by closing boundary valves. DMA boundaries should follow natural boundaries (e.g. rivers, railway lines, major roads). The number of valves to be closed should be minimised. Boundary valves have to be clearly marked or equipped with special devices to avoid them being accidentally opened by (unauthorised) utility personnel.
- → Variations in ground elevation should be minimal across the DMA. The future implementation of pressure management systems should be kept in mind when planning a DMA.
- → The types of consumers (domestic, industrial, commercial or critical customers such as hospitals) and their respective water supply requirements should be assessed.
- → Legal regulations governing minimum pressures, local constraints due to topography and height of buildings as well as fire fighting requirements have to be respected. The boundary can be left open if closing valves at a certain point would generate pressure problems, but flow meters have to be installed to control inflows and outflows.
- → Closing boundary valves to create DMAs will increase the number of dead-end pipes. DMAs should thus be designed in such a way that prevents water quality problems related to stagnation. Hydraulic network models help to identify and avoid potential zones of stagnation.
- → Pressure management plays a key role in leakage management and, where possible, should be incorporated into the process of reconfiguring the system when designing DMAs.

Water utilities have to consider hydraulic, practical and economic factors when they are planning to subdivide their network into discrete DMAs. Regarding the size of DMAs, installation and maintenance costs per connection are generally higher for small zones because a larger amount of valves and meters is required. However, smaller DMAs have the advantage that the presence of new leaks will be discovered earlier.

Furthermore, it is possible to distinguish even small leaks from customer night use and background leakage, and the location of a leak within the DMA can be carried out faster. Therefore, small DMAs can economically achieve a lower level of leakage than large DMAs. In its DMA Guidance Notes, the IWA recommends that DMAs in urban areas should have between 500 and 3,000 service connections. [58] According to the German Technical Association for Gas and Water (DVGW), the total length of distribution pipes within a DMA should range from 4 km up to a maximum of 30 km, depending on the desired accuracy of water loss control. [13]

Supplementary materials 6.1

Planning of DMAs

DMA implementation is also feasible and useful in water distribution networks with intermittent supply, although it is more difficult to determine the level of leakage if customers store water in private tanks. Average consumption can be calculated per service hour and can be compared with inflow into the DMA provided that reliable customer consumption data is available.

6.3.3 DMA implementation

Once the limits of a new DMA have been determined, a site survey should be executed and existing boundary valves must be closed and tested for tightness. Testing the valves is essential because one leaky valve will distort the leak assessment not only in the actual DMA, but also in the neighbouring DMA. Defective valves have to be replaced. A new valve has to be installed at boundaries without valves.

An appropriate flow meter has to be designed and installed for the inlet point. When dimensioning the flow meter, the existing pipe diameter, the expected flow range, admissible head loss at peak flow and reverse flow requirements have to be taken into consideration. The accuracy and repeatability of measurements, installation and maintenance costs as well as operational conditions (continuous or intermittent supply) also play an important role. [22]

Once all valves have been closed and tested, a zero pressure test should be performed (preferably during a period of low consumption and after having informed customers) in order to verify that the DMA is completely isolated. Several pressure gauges have to be installed throughout the DMA. The inlet valve to the DMA then has to be closed while observing the pressure in the zone. Consumption can be simulated by opening a hydrant. If the pressure drops to zero, it indicates that the boundaries of the DMA are tight. If pressure does not drop or if it rises again after the hydrant is closed, it is highly probable that a boundary valve is not completely closed or that there is an unknown connection to an adjacent zone. The area of the potential inlet can be localised by assessing the pressure head (ground elevation plus pressure at gauge) throughout the DMA. [58]

After installation and testing, an assessment should be performed to establish whether all flow meters are working correctly and whether customers in the district face any pressure or supply shortages.

6.3.4 Operation and management

Like all other leakage reduction methodologies, implementing district metered areas is not a quick fix, but requires long-term commitment on the part of a water utility's management and operational personnel. If designed and implemented correctly, a DMA can be one of the most effective measures to reduce water losses. [59] Once the DMA has been set up, initial work has to be conducted, such as determining leakage and eliminating the backlog of detected and undetected leaks. In the long run, water utilities have to institute and maintain routine operations and should check the capability and potential of implementing pressure management.

Determining the level of leakage

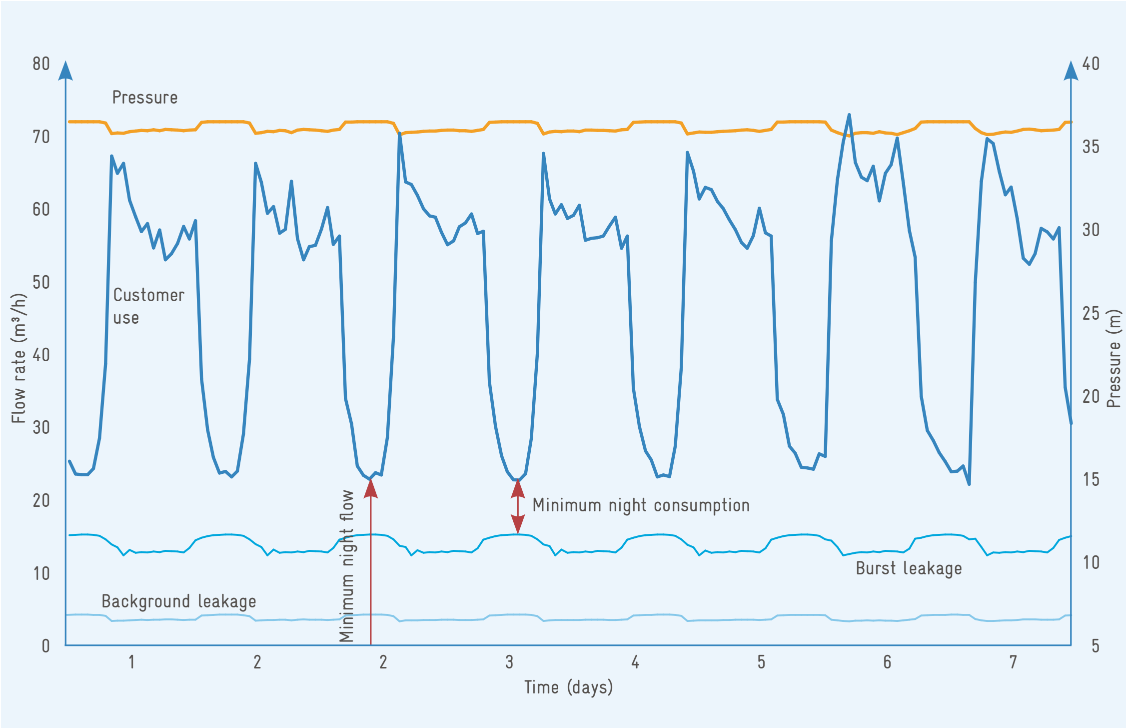
Leakage in a DMA can be calculated as the difference between total inflows and customer consumption within the same period of time. The system input can be measured directly after flow meters have been installed at all inlet (and outlet) points of a DMA. Flow measurements can be transferred to the utility's control room as real-time data using SCADA systems. Real-time data allows immediate reactions to new leaks, but is also the most costly method of monitoring leakage trends in DMAs if SCADA is not required for other uses, such as pressure management. Flow meters can also be read daily or weekly via the GSM network or manually because most new leaks emerge slowly and have low flow rates at first. [77]

The most common method of determining the level of leakage in a DMA is to analyse the period of minimum night flow (MNF), which usually occurs between 2 am and 4 am in urban areas. The MNF should be the one-hour minimum of the aggregation of all recorded inflows and outflows of the DMA. [22] Customer consumption is at its minimum during this period, and leakage thus represents the maximum percentage of net inflow into the DMA *(see Figure 6.3)*. Unreported leaks and (undetectable) background losses make up the total leakage. Several procedures are available for estimating the amount of background leakage *(see Supplementary Material 3.2)*.

Eliminating the backlog of undetected leaks

After installation of a new DMA, an intensive leak detection and repair campaign has to be undertaken to determine and eliminate the backlog of visible and hidden leaks in the district. As a consequence, inflow into the DMA should only consist of customer consumption and (undetectable) background leakage. The resulting flow pattern should be recorded as a reference value for setting leakage targets.

Figure 6.3 Relationship between the flow rate, pressure and leakage components, based on [58]



Implementing and maintaining routine operations

Key information for each DMA should be recorded and drawn in system maps. This information (for example about zone boundaries, flow meter locations, household and other consumers' records) should always be kept up-to-date. It is important to check regularly that all boundary valves are marked, closed and drop-tight for the purpose of DMA maintenance. Records of pipe flushing or boundary valves being opened for operational reasons should be kept and supervision personnel should be told not to include the resulting flows in the leakage analysis. Flow meters should be properly maintained to ensure a high level of data accuracy. Customer complaints about low pressure, service interruption and water quality problems should be monitored to identify potential shortcomings on the part of the DMA.

Checking pressure management capability

Leakage in a DMA will always be composed of detectable pipe bursts (flow rates greater than 250 l/h at 50 m pressure) and background losses (seeping or dripping water from leaky joints, valves or fittings) which are not detectable with acoustic leak detection methods. Assessing whether installing a pressure management scheme would be an economical option for further reducing leakage levels is advisable, especially if background losses are significant.

6.4 Pressure management

6.4.1 Definition and purpose of pressure management

As already widely explained in this technical manual, excessive water pressure can aggravate the risk of new water main breaks. The pressure-leakage relationship also means that high pressure can cause excessive leakage flow rates. Conversely, reducing the water pressure in a pipe network can decrease leakage.

Pressure management thus comprises the adjustment and control of water pressure in water supply systems to an optimum level. The implementation of a pressure management system can be profitable not only in existing water distribution networks, but also in newly planned networks. *Thornton et al.* generally defined pressure management as *the practice of managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to legitimate uses and consumers, while reducing unnecessary excess pressures, eliminating transients and faulty level controls all of which cause the distribution system to leak unnecessarily.* [78]

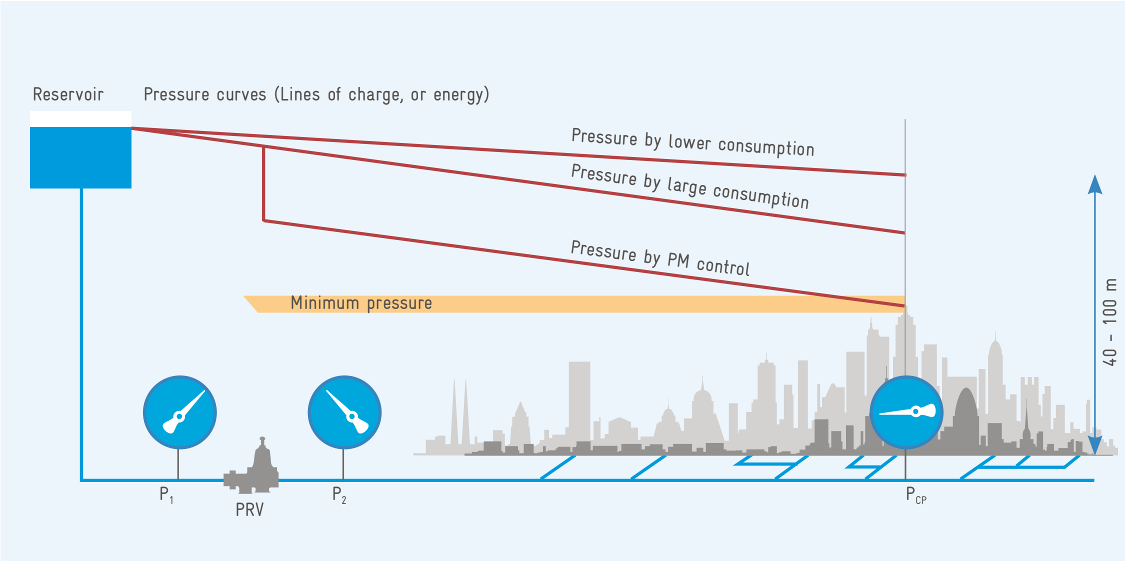
When reducing pressure, the minimum required supply pressure must always be ensured at the critical point in the network. It should be noted that the location of the critical point within a network might alter depending on variations in consumption behaviour or due to changing system structure. The water utility itself, water authorities or local legislation usually define the minimum supply pressure. Furthermore, negative pressure must always be avoided, for example during peak consumption or fire flow conditions.

The minimum supply pressure depends on the height of buildings, local legislation and customers' requirements. In Germany for example, 15 m pressure has to be guaranteed at all points in the network at all times. Maximum pressures, especially in low consumption periods at nighttime, are usually much higher, often up to 60 m or more. This signifies a great potential for reducing pressure and thus water losses.

The following section explains the principles behind the idea of pressure management. *Figure 6.4* shows a sketch of a typical pressure management area (PMA) with single inlet and one pressure regulating valve (PRV). In the sketch, P_1 refers to the pressure upstream of the PRV, P_2 refers to the pressure downstream of the PRV and P_{CP} refers to the pressure at the critical point, namely the point of lowest pressure within the PMA. The critical point can be located anywhere in the PMA and depends on topography, pipe diameters and water consumption behaviour within the network.

The red lines in *Figure 6.4* represent a simplified distribution of pressure within the network, from the input (P_1) to the critical point (P_{CP}). Energy head loss in the pipes decreases the pressure between P_1 and the critical point. Without pressure management, pres-

Figure 6.4 Simplified view of pressures within a distribution network



sure at the critical point will vary throughout the day: high consumption during the day time will cause high pressure losses, while flow velocities and thus pressure losses are at a minimum during the night time. However, pressure management can reduce pressure at the critical point to the minimum required pressure and also keep it at a constant level throughout the entire day by employing different PRV modulation strategies.

To put it simply, pressure management not only reduces pressure variations, but also eliminates superfluous pressure from the network and thus lessens leak flow rates and real water losses.

This objective can be approached using different technical solutions described in this chapter. However, its attainment is not always straightforward, as it involves different stages and data analysis prior to designing a pressure reduction scheme. Every PMA is different and has its own specific constraints. Therefore, each implementation project needs to be customised. The next section explains different pressure management concepts.

It should also be mentioned that PRVs are not the only pressure management tool. Speed-controlled pumps can also be utilised to manage pressure in cases where a pump feeds directly into a distribution network.

Chapter 6.4.2 introduces different concepts for the control (modulation) of pressure management systems. *Chapter 6.4.3* describes various types of PRVs and *Chapter 6.4.4* explains the different kinds of PMAs. *Chapter 6.4.5* presents a step-by-step approach to planning and designing a pressure management system. *Figure 6.5 on the next page* summarises the different available pressure management concepts and components.

Figure 6.5 Classification of the different concepts and components for pressure reduction

- **Modulation location**
  - Local point modulation
  - Critical point modulation
  - Section 6.4.2
- **Modulation type**
  - Fixed outlet pressure
  - Time-based pressure
  - Flow-based pressure
  - Section 6.4.2
- **Valve type**
  - Diaphragm (membrane) valve
  - Plunger (needle) valve
  - Section 6.4.3
- **Inlet & PMA type**
  - Single inlet PMA
  - Multiple inlet PMA
  - Dynamic PMAs
  - Micro & macro PMAs
  - Section 6.4.4

6.4.2 Modulation concepts

The term modulation describes the methods by which PRVs are controlled in a pressure management system. Modulation concepts can be divided according to the modulation type (which comprises different control modes for PRVs) and modulation location (which defines if pressure is controlled directly behind the PRV or at a discrete point in the water distribution network). Both of these concepts are described in the following sections. *Chapter 6.4.5* explains how these elements can be combined to create customised solutions tailored to different local conditions and requirements. It should be noted that all types of modulation are flexible and can be adapted or upgraded by simply changing the settings of the programmable logic controller (PLC) of a PRV.

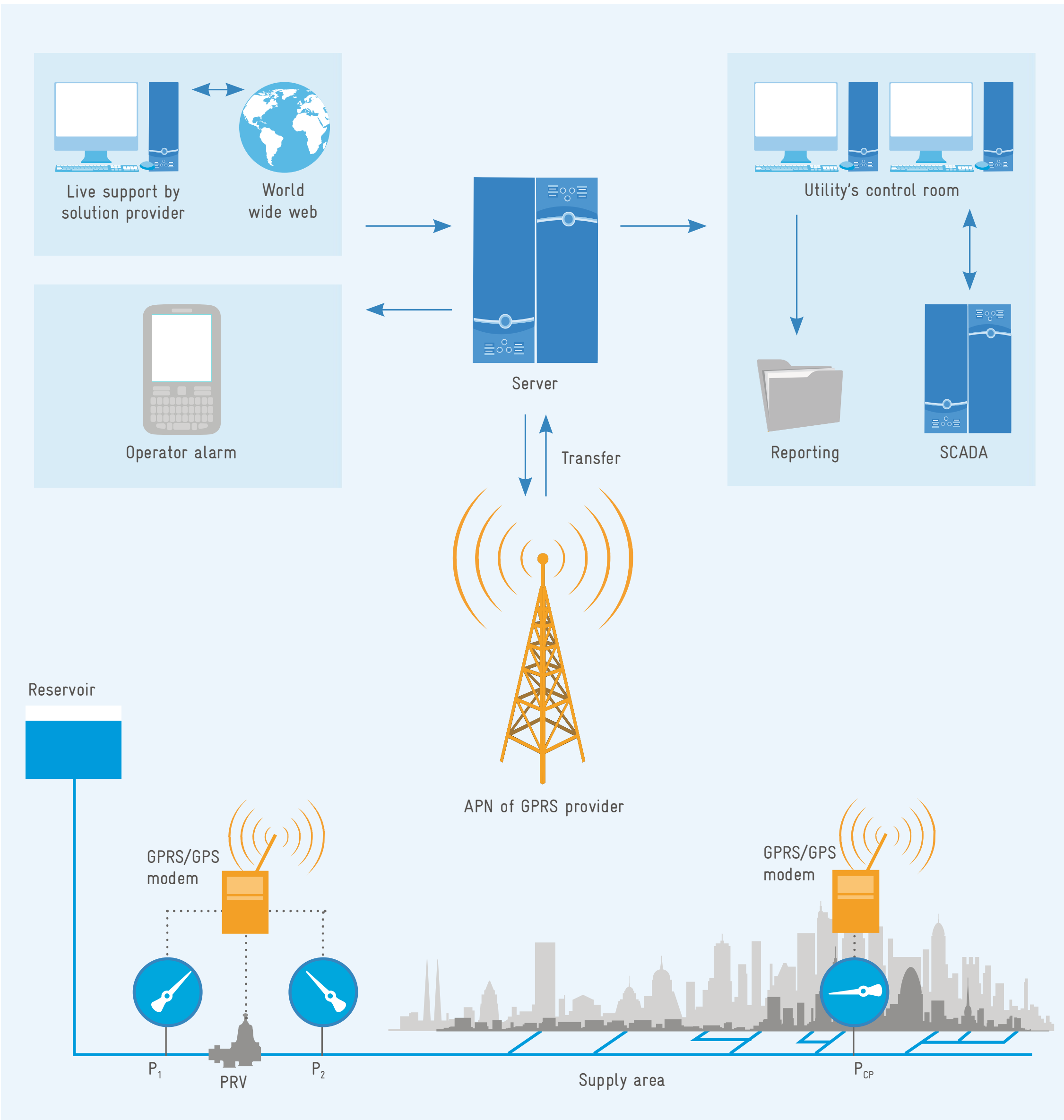
(a) Modulation location

Local point pressure modulation – This technique is the simplest way to reduce pressure. It consists of modulating pressure at the inlet of the PMA by installing a PRV in order to set P_2 to constant or pre-defined values. Pressure sensors are only required at P_1 and P_2 and communication between sensors and the PRV is simple. This type of modulation requires the lowest investment, but pressure cannot be reduced to an optimum due to the higher security margin needed to ensure service pressure at P_{CP}. Leak flow reduction is therefore limited. This technique is often coupled with time modulation, which is explained in *Section (b)*.

Critical point pressure modulation – Using critical point modulation (also referred to as remote node-based modulation), a pressure sensor at the critical point continuously monitors P_{CP} and communicates information to the PRV at the inlet of the PMA. This PRV continuously adjusts P_2, so that P_{CP} stays as close as possible to the desired value (e.g. the minimum supply pressure of 20 m). This technique produces better results than local point modulation, but also requires additional investments for the P_{CP} pressure sensor and communication devices. Radio transmission or a GPRS/GSM modem with a SIM card using the internet can be used to communicate the results, as shown in *Figure 6.6*. A typical system also allows live monitoring and control of the PMA.

The location of the critical point within a PMA may alter due to changes in the structure of the zone (additional inlet point, changed boundary valves, decommissioning of pipe sections, etc.) or due to changed water consumption behaviour. The pressures within the network should therefore be monitored regularly. The effects of different types of pressure modulation are represented in *Figure 6.7 on the next page*, showing P_1, P_2, P_{CP} and the flow Q for a system without pressure modulation and two systems with local point and critical point modulation. As *Figure 6.7* shows, the pressures at P_1 and P_{CP} are inversely connected to the

Figure 6.6 Communication in a remote control system



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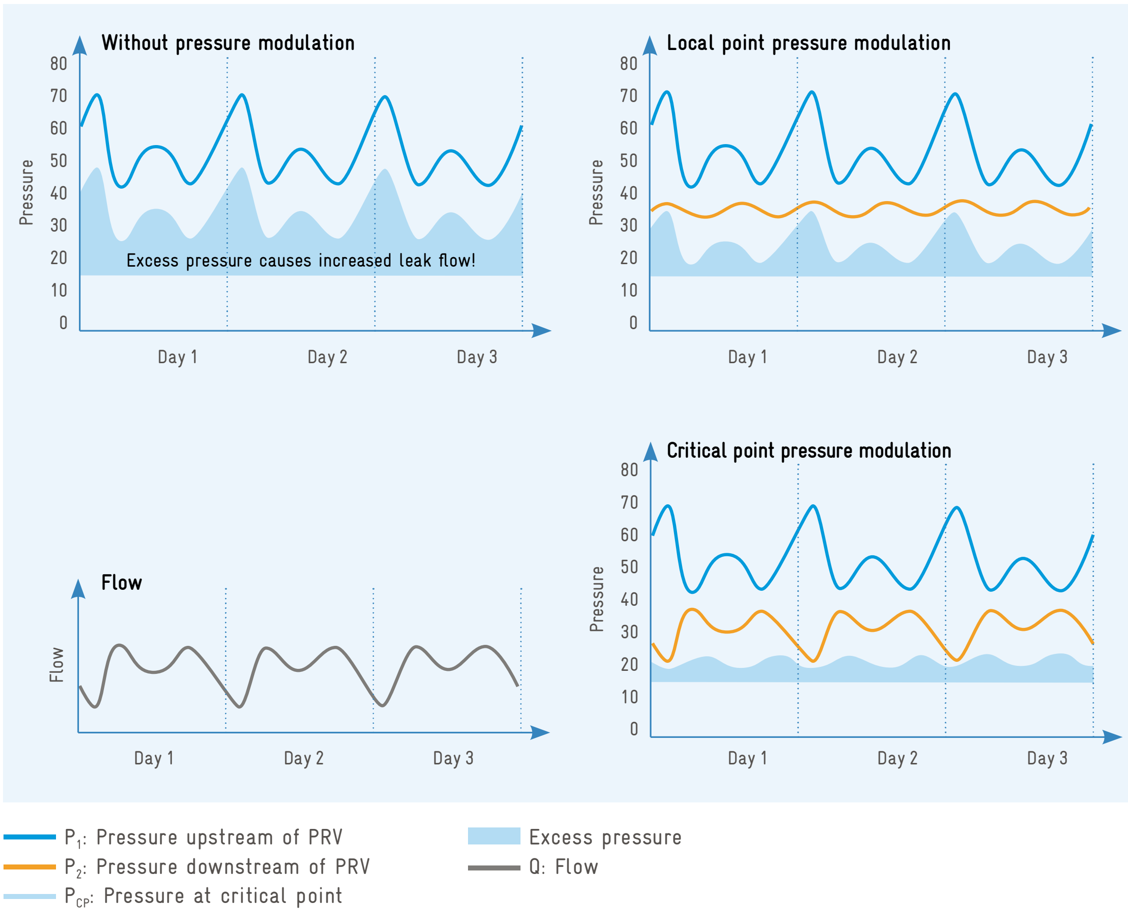
consumption pattern where there is no pressure management. In the case of local point pressure modulation, P_2 is set to a defined value, which implies decreased pressure at the critical point. Yet, pressure P_{CP} at the critical point still varies due to changes in the consumption pattern. In the case of critical point modulation, pressure P_{CP} is kept almost constant at the desired level, while P_2 downstream of the PRV is continuously modulated.

Figure 6.7 Different modulation concepts and their effects on pressure



(b) Modulation type

Fixed outlet pressure modulation – A fixed outlet pressure regulating valve (PRV) sets the downstream pressure P_2 to the desired value. The valve is then continuously actuated to maintain this pressure. P_2 has to be set in such a way that the minimum level of service is still guaranteed at the critical point at maximum demand. The disadvantage of this type of modulation is that the pressure in the network rises during periods of minimum demand without effectively being able to apply further control. [8] Nevertheless, fixed outlet pressure modulation is effective for PMAs with low head losses between P_2 and P_{CP} and rather uniform consumption patterns without significant daily or seasonal variations. [77]

Time-based pressure modulation – Time-based pressure modulation allows higher downstream pressure P_2 to be set for daytime and lower pressure at night when consumption decreases. However, time-based modulation can also be more complex: a pressure pattern with different set points can be determined by analysing normal water consumption and its relationship to pressure at P_{CP} over a period of time. This pressure pattern indicates the desired outlet pressure P_2 at different times of the day. The PLC will then modulate the PRV in such a way that downstream pressure P_2 is maintained until the next time step. [64] *Figure 6.8* shows an example of the time-based pressure modulation concept.

It is important to notice that the controller cannot force a PRV to change the pressure instantaneously. Instead, the valve opening has to be adjusted to the new setting smoothly over a period usually lasting several minutes. [64]

Figure 6.8 Time-based pressure modulation

Setting	Time (hh:mm)	Pressure (m)
Set 1	0:00	25
Set 2	5:00	30
Set 3	7:00	40
Set 4	12:00	38
Set 5	20:00	30

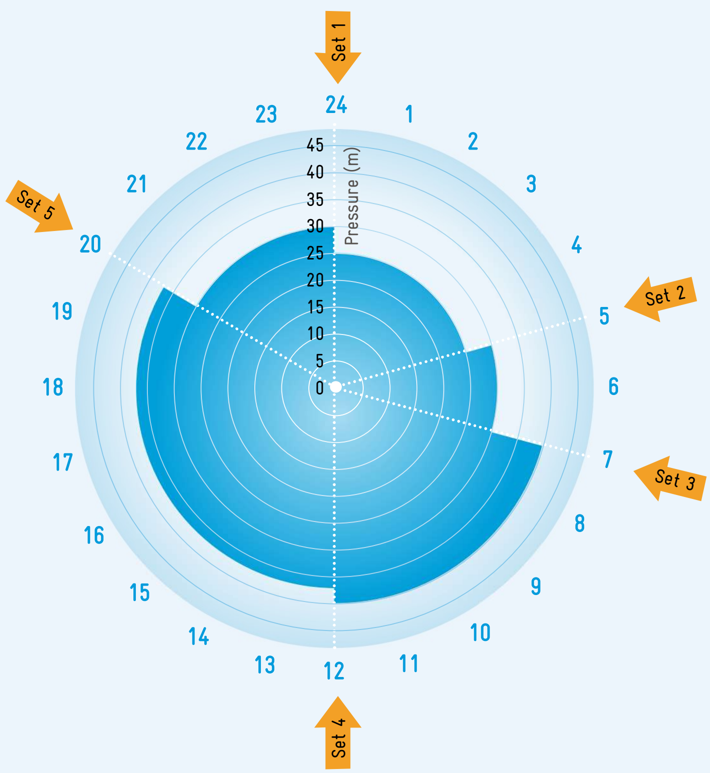
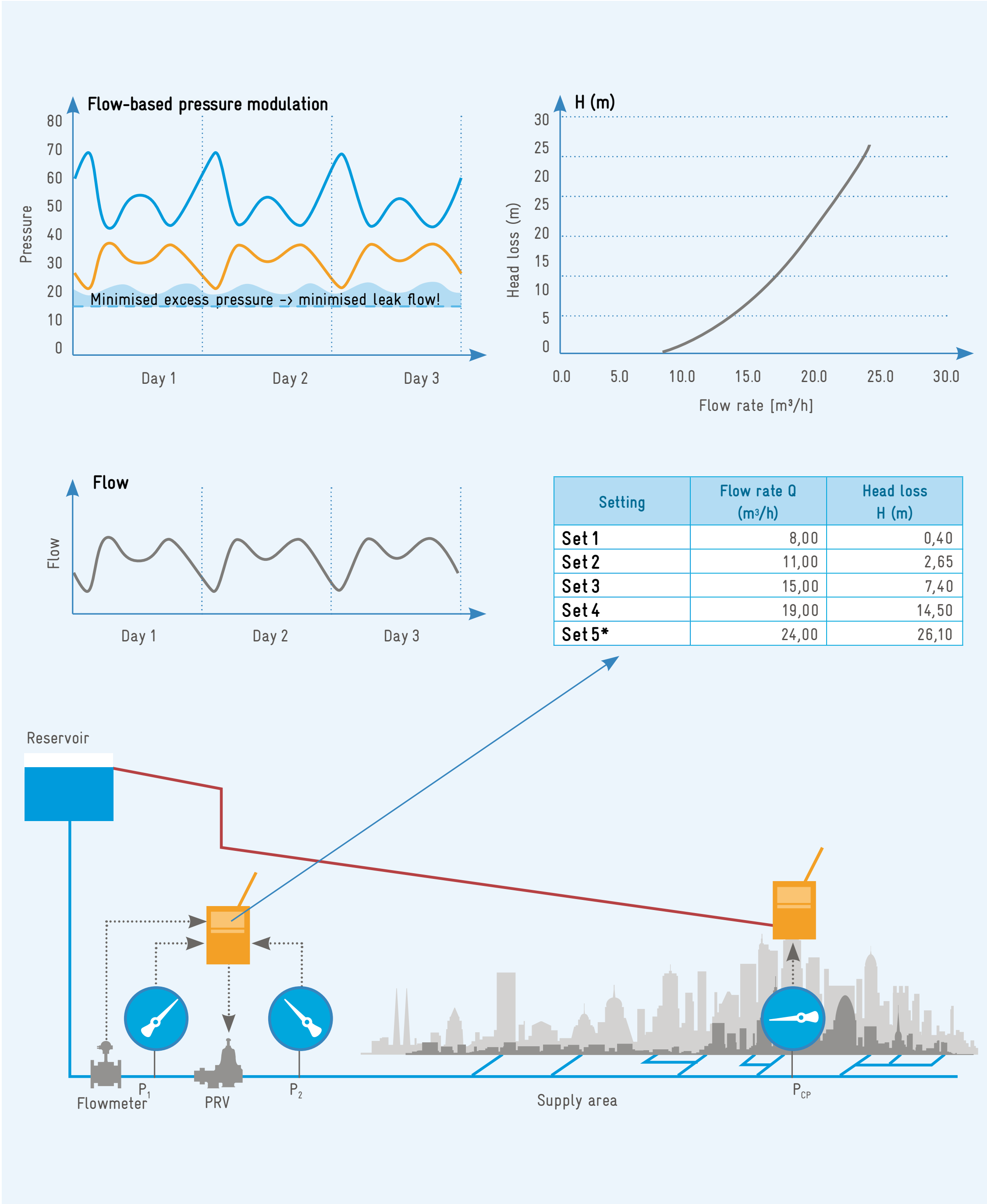


Figure 6.9 Flow-based pressure modulation



Setting	Flow rate Q (m³/h)	Head loss H (m)
Set 1	8,00	0,40
Set 2	11,00	2,65
Set 3	15,00	7,40
Set 4	19,00	14,50
Set 5*	24,00	26,10

P_1: Pressure upstream of PRV
P_2: Pressure downstream of PRV
P_{CP}: Pressure at critical point
P_{min}: Min. service pressure
Excess pressure
Q: Flow

* flow – head loss relationship for fire flow conditions

Flow-based pressure modulation – Flow-based pressure modulation requires the installation of a flow meter at the inlet to the PMA which continuously monitors flow into the zone. The PRV controller then compares measured flow rates with the specific flow rate/head loss relationship of the PMA which has to be determined beforehand by the water utility. The PRV's valve opening is then actuated accordingly.

Figure 6.9 shows how such a flow rate/head loss relationship typically looks. In this example, the first four settings represent the normal daily flow pattern, which ranges between 8 and 19 m^3/h. For these flow rates, the head loss between P_2 and the critical point (P_{CP}) has been determined as 0.4 to 14.5 m. The PRV's outlet pressure P_2 is now set to a value which ensures minimum service pressure at the P_{CP}. The outlet pressure P_2 is set to higher values in the case of exceptionally high flow rates, e.g. fire flow. [64] The better the relationship between flow rate and head loss is known, the more precisely the PRV settings can be defined in order to ensure smooth system pressure control. *Chapter 6.4.5* (typical use cases) will explain the different options for combining the modulation location and type.

6.4.3 Types of pressure regulating valves (PRVs)

The two most common types of PRVs on the market are diaphragm valves *(Section a)* and plunger valves *(Section b)*. This section explains the functionality of the different valve types and exemplifies their most important characteristics, advantages and disadvantages in order to determine which type is the most suited to specific needs *(Section c)*.

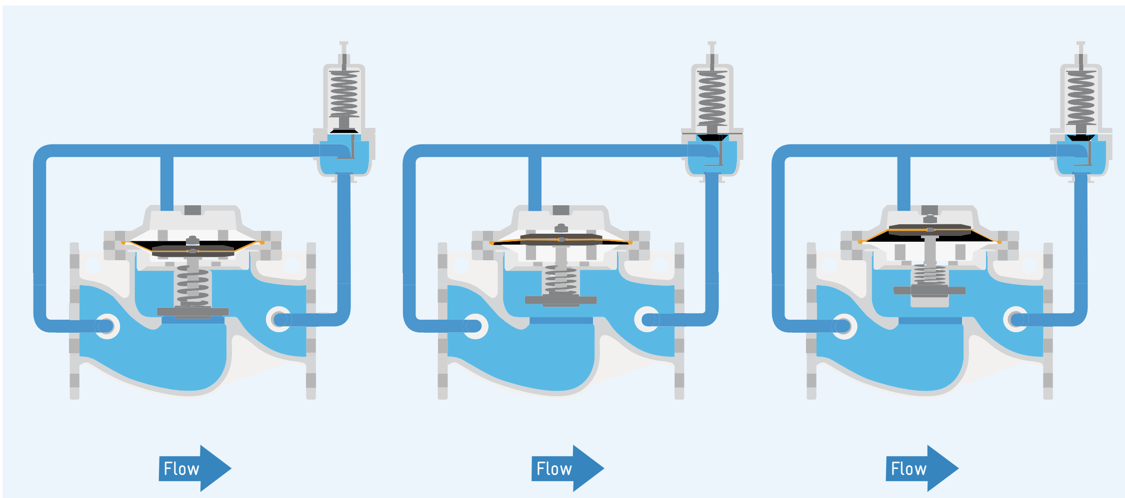
(a) Diaphragm valves

Diaphragm valves, also called membrane valves, generally consist of a hydraulically operated main valve and a pilot circuit. Different subtypes of diaphragm valves are available, such as globe type, Y type or direct sealing valves, which vary in shape, flow characteristics and actuator mechanisms.

The main valve consists of three major parts: the body, cover and diaphragm assembly. The diaphragm assembly is the only moving part in the main valve. The diaphragm, usually made out of synthetic rubber, is clamped between the body and the cover in order to separate the control pressure from the line pressure. When the pilot valve's orifice opening decreases, more water is forced into the space between the cover and the diaphragm, and the valve is modulated to its closed position, and vice-versa. The valve's outlet pressure can be adjusted simply by turning a screw at the pilot valve until the desired fixed pressure is reached. The PRV has so far been operated hydraulically and neither external power supply nor batteries have been required.

A battery-powered PLC has to be installed if a diaphragm valve is supposed to be operated by time-based or flow based modulation. The exact control pattern is determined by a table of values, which stipulate the desired outlet pressure for a specific time of the day or for a given flow. The PLC then actuates miniature solenoid valves on the tubes of the pilot circuit. This action transfers small amounts of water around the pilot circuit, altering the pressure on the actuator of the pilot valve and hence the position of the diaphragm until the desired outlet pressure is reached. [64]

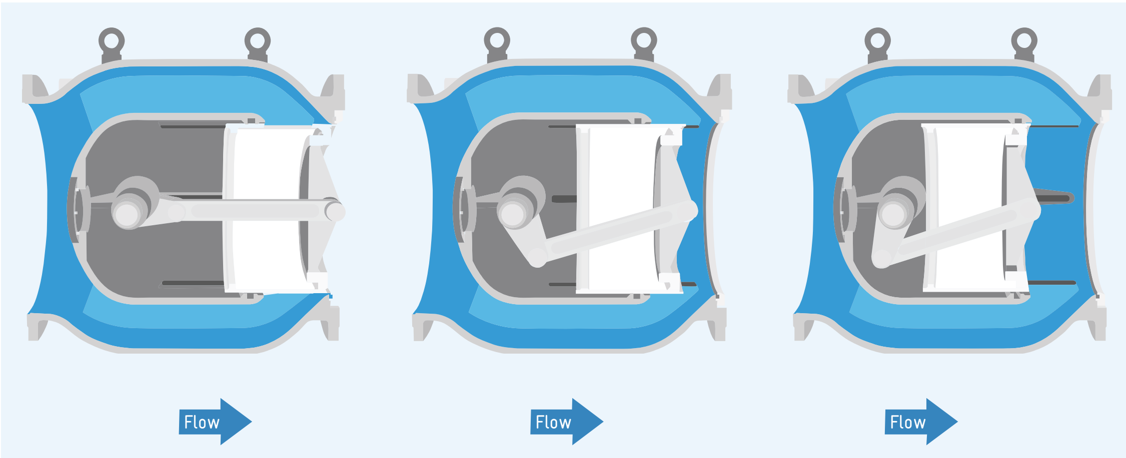
Figure 6.10 Functionality of a diaphragm valve: closed (left), 50% open (centre) and fully open (right) (Source: VAG Armaturen)



(b) Plunger valves

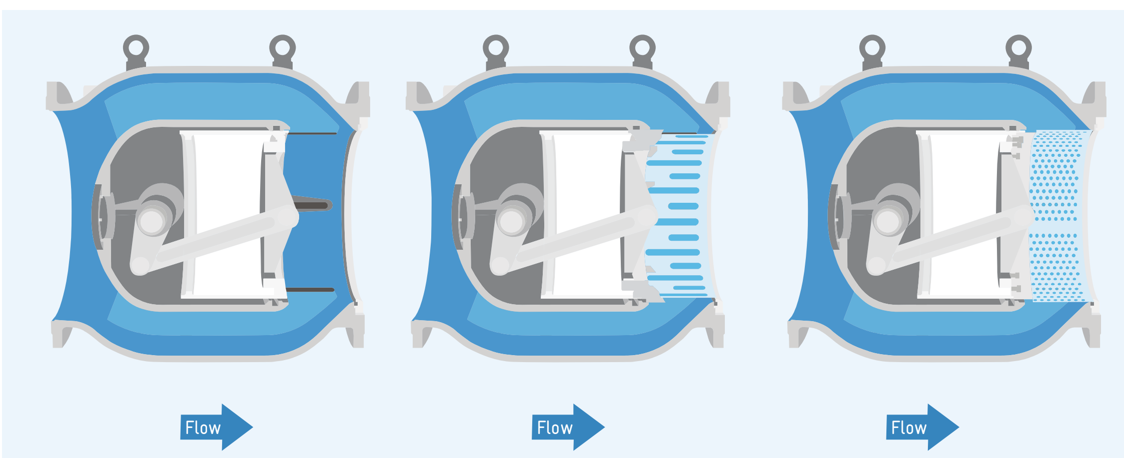
Plunger valves, also known as piston valves or needle valves, are equally suited to reducing and controlling pressures and flow rates in a safe and reliable manner. Unlike diaphragm valves, which are actuated hydraulically, plunger valves require external actuators that are powered manually, pneumatically or electrically. Pressures and flow rates are controlled by varying the valve's inner cross section. Therefore, plunger valves usually consist of the valve body and an axially guided sliding plunger. The linear movement of the plunger results from the conversion of the rotary movement of the external actuator. This ensures a symmetrical ring-shaped cross section in every position, as illustrated in *Figure 6.11*.

Figure 6.11 Functionality of a plunger valve: closed (left), 50% open (centre) and fully open (right) (Source: VAG Armaturen)



Different cylinders mounted on the plunger and different outlet sections are used to adapt the plunger valve optimally to its intended use. The cylinders divide the flow into individual water jets which hit each other downstream of the plunger in the pipe's central line in order to dissipate energy without risk of cavitation. Examples of various cylinders and their function are shown in *Figure 6.12*.

Figure 6.12 No cylinder (left), slotted cylinder (centre) for standard applications and multiple orifice cylinder (right) for high pressure differences (Source: VAG Armaturen)



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As mentioned before, an external actuator sets the plunger valve in motion. The desired pressure downstream of the PRV (P_2 or P_{CP}) is set as the nominal process value. Pressure sensors at P_2 or P_{CP} then report the actual pressure to the valve's position controller, which determines if the actuator has to open or close the valve in order to deliver the desired pressure. A tolerance margin avoids permanent opening and closing of the valve.

(c) Comparison between diaphragm and plunger valves

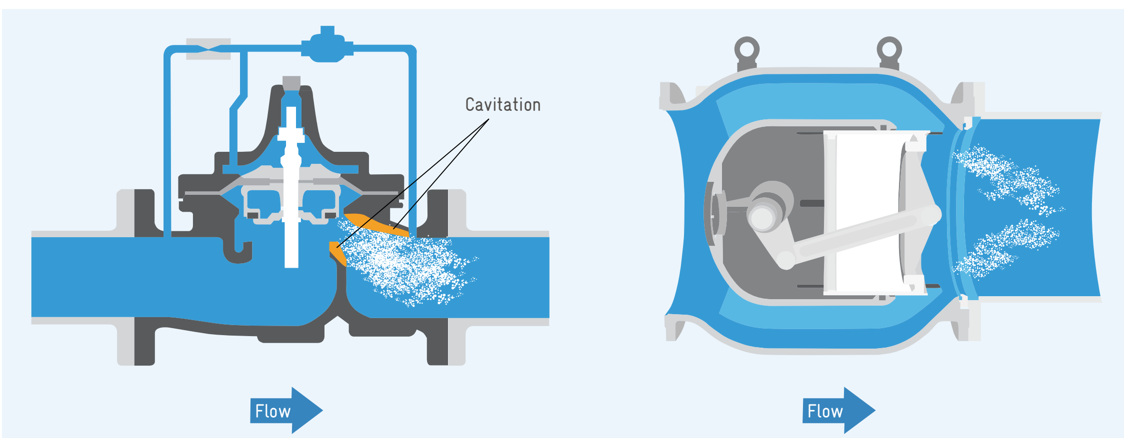
This section presents the differences between plunger and diaphragm valves, their respective advantages and disadvantages as well as different aspects to be considered when choosing one type of valve.

Cavitation behaviour – The dynamic process of the formation and implosion of cavities in fluids is known as cavitation. Cavitation can occur when high flow velocities decrease the local hydrostatic pressure below a critical value which corresponds to the fluid's vapour pressure. As a consequence, small gas bubbles are formed which collapse when they reach zones of higher pressures. The implosion of the bubbles creates high local pressure peaks which can reach several thousand bars. [90] This may cause severe problems, such as loud noise, strong vibrations, throttled flow, erosion or even total destruction of the affected pipe or valve components.

Control valves are particularly susceptible to cavitation. Pressure may drop to critical values in the reduced cross section of the constriction due to increased flow velocity. Behind the constriction, pressure mounts again and the gas bubbles collapse. The surface of the pipe wall in this area may be damaged significantly by the impact of the striking jet of water and by the shock wave from the imploding bubbles.

In plunger valves, the ring-shaped cross section allows for a symmetrical flow profile and for the water jet to be located downstream of the constriction in the centre of the pipe. This

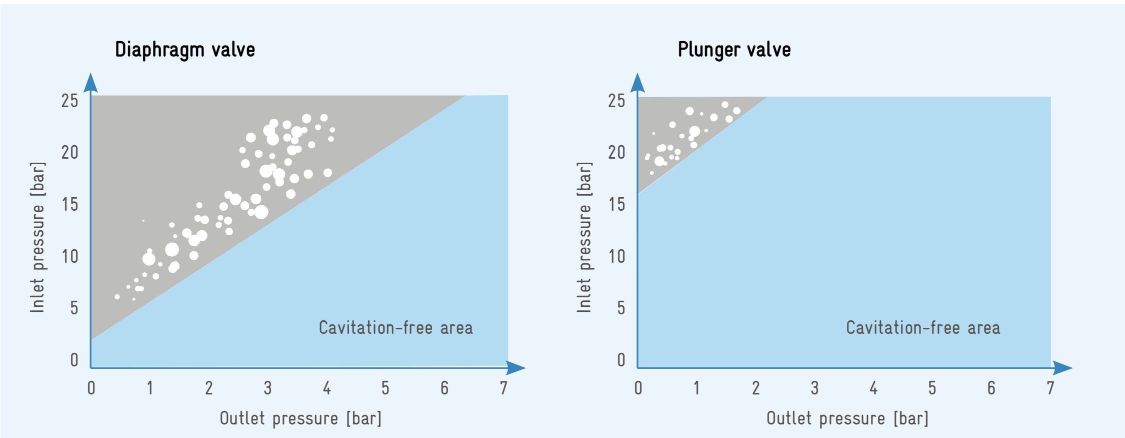
Figure 6.13 Flow characteristics and cavitation in diaphragm valves (left) and plunger valves (right)



allows an intensive impulse exchange with the surrounding water and also protects the pipe walls because the gas bubbles concentrate in the centre of the pipe, as illustrated in *Figure 6.13*.

The risk of cavitation in plunger valves can be minimised by using adequate cylinders, even in the event of significant differences between the inlet and outlet pressure. By contrast, diaphragm valves are limited to relatively small differential pressure, as illustrated by the diagrams in *Figure 6.14.* Consequently, plunger valves facilitate greater reductions in pressure. [73] Two valves can be connected in series if diaphragm valves are to be used for high differential pressures.

Figure 6.14 Cavitation behaviour of a diaphragm valve (left) and a plunger valve (right)



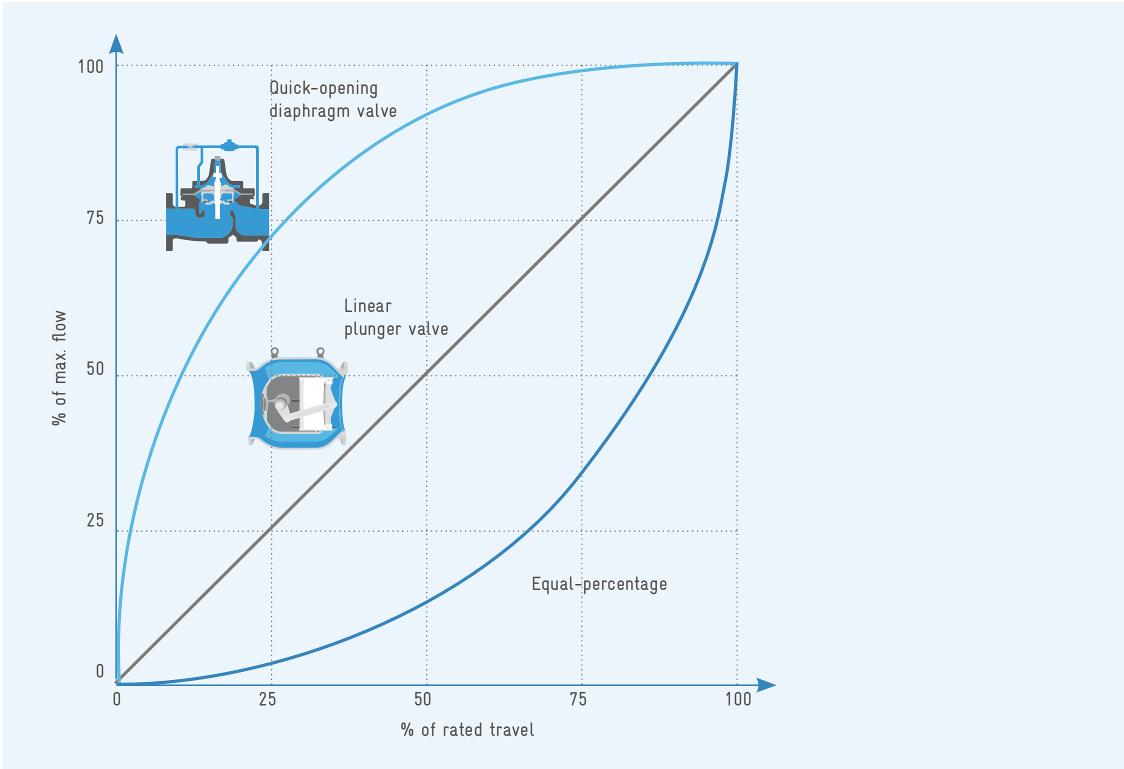
The risk of cavitation has to be considered in systems with high upstream pressure and significant pressure differentials (over 3:1 as a rule of thumb for P_1:P_2). The risk of cavitation usually is negligible in the case of upstream pressures smaller 25 m. [29]

Regulation characteristics and precision of control – The valve gain of a PRV has to be considered in order to ensure pressure regulation stability for a broad range of flow rates. Valve gain is the slope of the valve characteristic curve and is defined as the ratio of the change in flow to the change in valve travel. Typical flow characteristics of control valves can be categorised into (a) quick opening, (b) linear and (c) equal percentage, as illustrated by *Figure 6.15 on the following page*.

Diaphragm valves are typically quick opening and offer very large valve gain at low flow conditions. Small valve travels thus cause large increases in flow at the beginning of the valve opening, as shown in *Figure 6.15*. Therefore, diaphragm valves may be subject to instability under low flow conditions. These regulation instabilities may cause oscillation and unwanted pressure fluctuations within the system. [29]

Plunger valves have almost linear control characteristics due to their large stroke, as can be seen in *Figure 6.15*.

Figure 6.15 Regulation characteristics of diaphragm and plunger valves



For this reason, plunger valves demonstrate very precise regulation characteristics, even at low flow rates, and are less subject to oscillation. In practice, this means that a more precise adaptation to pressure conditions is possible throughout the entire spectrum of flow rates.

Power supply – The biggest advantage of diaphragm valves is that they are operated hydraulically and thus do not require any auxiliary energy sources. Plunger valves, on the other hand, are usually set in motion by pneumatic or electrical actuators. Therefore diaphragm valves can be more suitable for remote locations without access to power supply.

Head loss – PRVs and their equipment (e.g. flow meter, isolating valves, strainer, dismantling piece, etc.) always generate a local head loss, even when fully open. The head loss in fully open position is usually smaller than for plunger valves, depending on the cylinder used: without a special cylinder, plunger valves usually have head loss coefficients ζ ranging from 1.0 to 2.0, compared with 3.0 to 8.0 for slotted cylinders. Diaphragm valves usually have head loss coefficients ζ between 5.0 and 6.0.

Low pressure losses and high flow rates at fully open position are especially important during fire flow conditions and in systems where upstream pressure P_1 may drop to values close to the required pressure during peak flow. However, it should always be kept in mind that a PRV's original function is to reduce pressure. Consequently, head loss should not normally be considered a key selection criterion. [29]

Maintenance requirements – In general, all types of PRVs should be checked and maintained at regular intervals in order to ensure their functionality and optimum mode of operation. The DVGW recommends performing the inspections and maintenance measures listed in *Table 6.1* at intervals of one year:

Table 6.1 Yearly inspections and maintenance measures for PRVs [13]

Inspections	Maintenance measures
→ damages and corrosion → functionality of the PRV → external tightness → no flow when the valve is at completely closed position → correct outlet pressure setting	→ cleaning → corrosion protection → lubricating movable external parts
If applicable:	
→ free passage of strainer and control circuit → functionality and precision of manometers → functionality of air valves	

While plunger valves require little special maintenance, diaphragm valves need more attention. The small diameters of the control circuit mean that particles, sand or incrustations can obstruct these pipes, alter the control characteristics and eventually block the valve. Diaphragm valves thus need more maintenance work, especially when the quality of the water is low: the strainer in the main line dirt trap as well as the strainer in the control circuit filter should be checked and cleaned every three to four months. Furthermore, replacing the rubber diaphragm and all seals every five years is recommended.

Supplementary materials 6.2

Maintenance of PRVs

Investment and total lifecycle costs – Besides investment costs for a PRV, total lifecycle costs (for operation and maintenance, labour and spare parts) have to be considered. Diaphragm valves generally entail a lower initial investment than plunger valves. Besides the cost of the valve itself, the necessary installations and power supply precautions are important factors in the cost of plunger valves.

However, plunger valves may be the more economic solution for large diameters (larger than DN 400) in cases where two diaphragm valves have to be installed in parallel in order to cope with the flow range. The same applies for high pressure differentials where diaphragm valves sometimes have to be installed in series.

In terms of the total lifecycle costs, diaphragm valves usually have higher maintenance requirements (replacement of worn seals, checking and cleaning of filters, etc.), while plunger valves will require a certain amount of power for the valve's electrical actuator.

On the other hand, plunger valves offer more flexibility to changing demands because the ring-shaped cross section offers a linear control curve over a wide range of flow rates. Exchangeable cylinders also help to adapt the valve to changing conditions, while diaphragm valves usually have to be substituted completely.

6.4.4 Types of pressure management areas

Pressure management areas (PMAs) can be classified into three categories depending on the local condition and configuration as well as different inlet possibilities. Furthermore, a distinction can be made between micro and macro PMAs depending on the network length and the number of house connections within a PMA.

(a) Single inlet PMA

A single inlet pipe supplies this area with water, either on a branch pipe from a trunk main or on a gravity fed pipe behind a reservoir. The PMA is separated from neighbouring networks by closing boundary valves. A PMA can be developed by upgrading an existing DMA *(see Chapter 6.3)*.

(b) Multiple inlet PMA

A regulating system for two or more inlets into the PMA requires more complex calculations in order to guarantee constant pressure at the critical point. Different processes are possible. For example, a decision can be made to keep one inlet at a constant position and only regulate the second valve. Designing and implementing a multiple inlet PMA always requires more detailed engineering than a single inlet PMA. The use of a hydraulic model is recommended.

(c) Dynamic PMAs

Dynamic PMAs are the most evolved type of pressure management technology: both the location of the critical point and the location of the boundary and the number of inlets into the PMA can be changed to adjust the system optimally to meet actual requirements.

(d) Micro and macro PMAs

Furthermore, a differentiation can be made between macro and micro pressure management areas: a micro PMA usually consists of an independent distribution zone where pressure is controlled at one or several inlet points. A macro PMA consists of a PRV on a transmission pipe which supplies several distribution networks or micro PMAs.

6.4.5 Planning and design

This chapter presents different use cases for pressure management installations, explains typical project implementation steps and demonstrates how plunger valves and diaphragm valves are typically installed. The different modulation concepts from *Chapter 6.4.2* can be combined with different types of valves and designs of pressure management areas (e.g. local point pressure modulation + fixed outlet type + diaphragm valve + single inlet PMA). This would lead to more than 12 different possible use cases. However, in practice, the following seven typical use cases are applied.

(a) Typical use cases

These use cases shall provide guidance for finding the most suitable solution in different boundary conditions. *Uses cases 1-5* are for single PMA inlets and *use cases 6 and 7* for PMAs with more than one inlet.

- → **Use case 1:** local point modulation, diaphragm valve with fixed outlet pressure. This is the most basic pressure management solution and suitable for areas without power supply (remote locations) or frequent power failures. The installation of diaphragm valves with fixed outlet pressure is relatively inexpensive and offers quick payback times. It should be used in areas with poor or unreliable information about the network, customers and components of the water balance. It can be the first step in establishing a PMA and should always be accompanied by monitoring pressure and flow in order to better understand the network. Provisions should be made to allow for future upgrades to more advanced solutions.
- → **Use case 2:** local point modulation, diaphragm valve with time or flow modulation. This use case combines local point modulation with time-based or flow-based modulation. For example, pressure will be reduced at night or according to a pre-defined pressure/flow rate relationship. This second use case is also suitable for areas with poor or unreliable background information. It is recommended to measure inlet pressure P_1 and the flow rate for a minimum of three representative months in advance of project implementation. Power supply

(battery) is necessary (for the PRV controller), but the system also works with intermittent or insecure power supply. The pressure differential between P_1 and P_2 should not be too high in order to avoid cavitation problems. Pressure control is still basic, but typically already produces better results than *use case 1*.

→ **Use case 3:** local point modulation, plunger valve with time-based or flow-based modulation. This is the same as *use case 2*, but uses a plunger valve. Plunger valves require an external power source, but allow for a larger inlet diameter and higher pressure difference. Furthermore, maintenance costs are low.

→ **Use case 4:** critical point modulation, diaphragm valve with time-based or flow-based modulation. This use case requires communication between a pressure sensor installed at the critical point of the DMA and the PRV. The most cost-effective solution is to work with the local GSM mobile network.

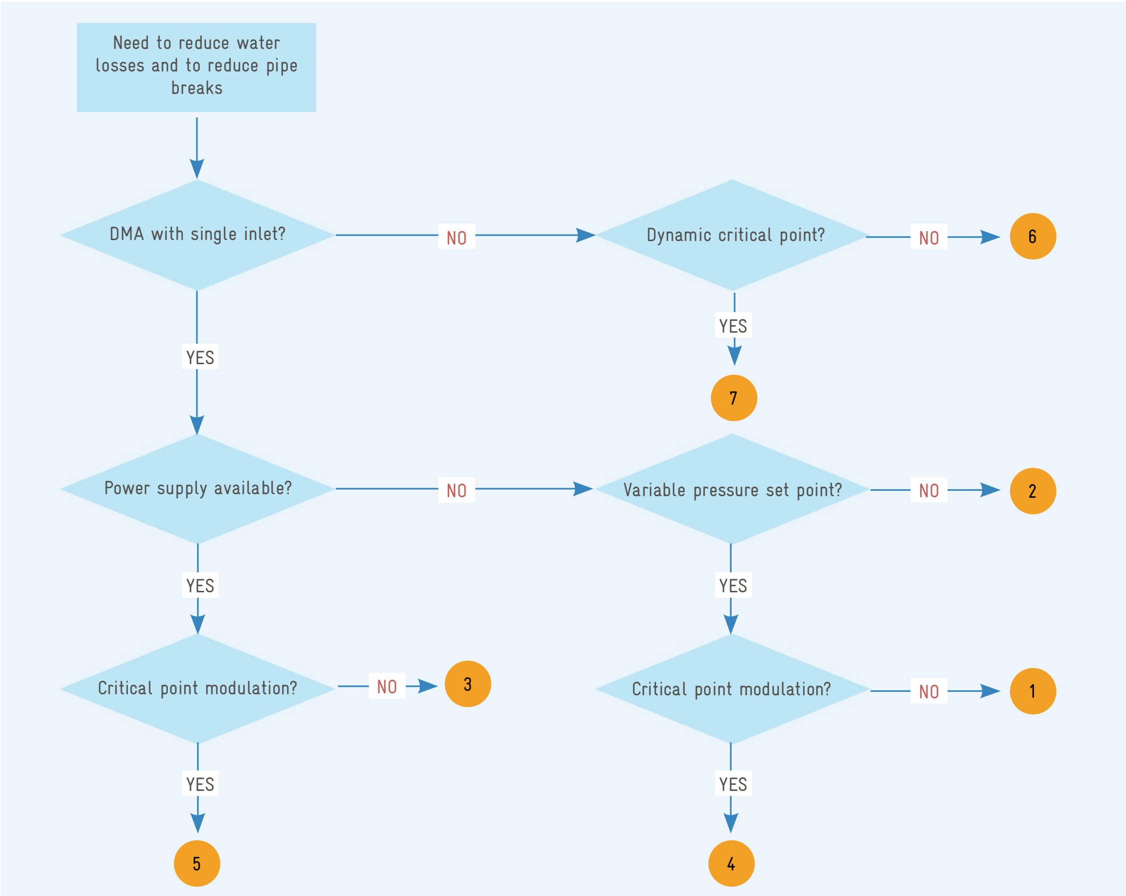
→ **Use case 5:** critical point modulation, plunger valve with time or flow modulation. This use case requires communication between a pressure sensor installed at the critical point of the PMA and one at the PRV. The most cost-effective solution is to work with the local GSM mobile network. Critical point modulation offers better options for optimisation; therefore these systems will still be cost-effective for systems with relatively low water losses. A hydraulic model of the system is recommended as it will allow optimal system design. In any case, network structure data, inlet pressure and flow measurements are absolutely necessary for correct dimensioning, and there is a need for continuous and stable power supply at both the critical point and the PRV location.

→ **Use case 6:** multiple inlet. This use case considers PMAs with more than one inlet. All concepts and components from *Figure 6.5* can be applied in accordance with hydraulic information.

→ **Use case 7:** multiple inlet, dynamic DMA. This use case involves a dynamic critical point. The critical point may vary in location throughout the day, and an optimal water distribution requires intelligent control. A hydraulic model and consumption data are a must-have and a SCADA system is recommended in the case of systems with multiple inlets. This is a high-budget solution, but offers significant optimisation possibilities. Cost-efficient results can be reached, even with low to medium water losses.

The flow chart in *Figure 6.16* illustrates the process for selecting the most suitable pressure management solution for a network or distribution zone.

Figure 6.16 Decision support flow chart for the seven typical use cases



(b) Typical stages of project implementation

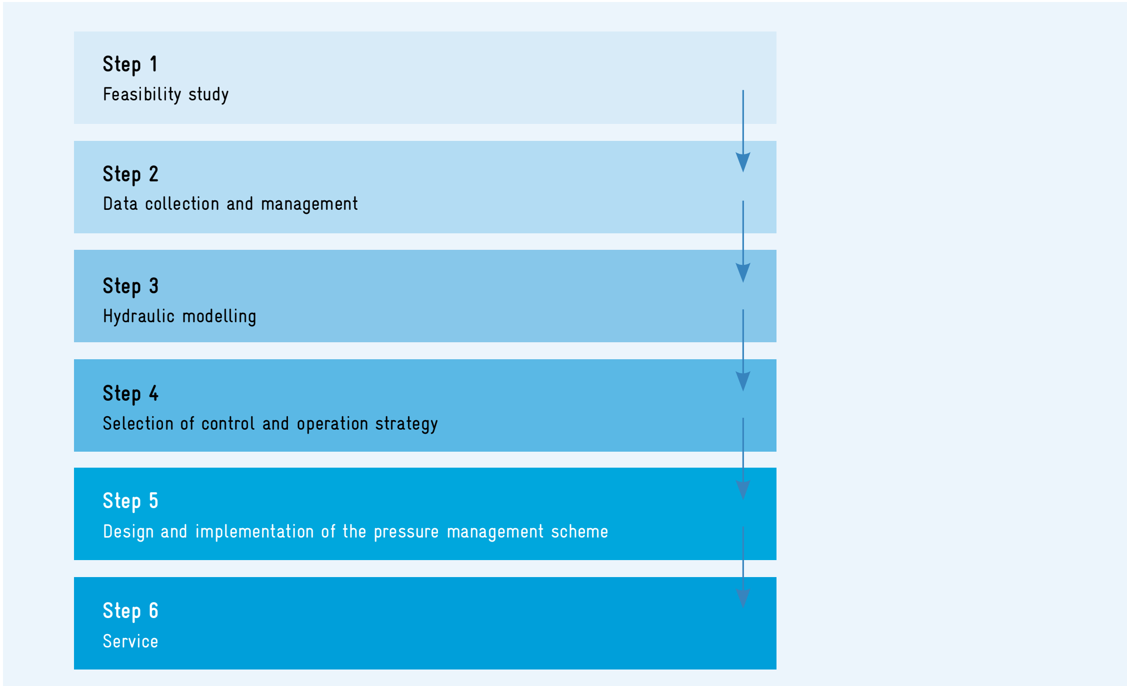
A typical pressure management project is usually composed of the steps shown in *Figure 6.17 on the next page*. However, local conditions can require additional tasks not mentioned here or not every step might be necessary depending on the use case (e.g. hydraulic modelling of the system).

Feasibility study

This step entails an initial assessment that involves a study of the feasibility and financial benefits of implementing a project and comprises the following measures:

- identifying a district metered area (DMA)
- calculating the return on investment (ROI)
- analysing local infrastructure and resources.

Figure 6.17 Typical steps for pressure management implementation



Data collection and management

Data collection and preparation can sometimes be time-consuming depending on local conditions. However, it is necessary in order to determine the most suitable option and to optimise the system further. Data management will be beneficial even if the water utility does not adopt a pressure management programme as it allows the water utility to have better knowledge and understanding of its network.

- → Data collection (e.g. pressure, flow, consumption, pipe and valve data)
- → data structuring and preparation
- → possible purchasing of additional data (GIS data, etc.)
- → verification and plausibility check for available data.

Hydraulic modelling

Hydraulic modelling is necessary to understand the network's existing and future behaviour. This model will help to identify optimal pressure management areas by running simulations. These simulations allow different options to be tested and the best use case for the water utility to be determined.

- Set-up and calibration of the hydraulic model
- execution of simulation runs
- analysis of the results and determination of optimal pressure settings.

Selecting a control and operation strategy
Once the model has been built, different use cases can be tested and the impact of different parameters can be simulated. This allows the best solution to be proposed to the water utility. The hydraulic model can be used to verify the following aspects:

- selecting the best operation strategy for valves and pumps
- simulating a change in the operating mode (from intermittent to continuous water supply).

Designing and implementing a pressure management system
This step involves dimensioning, manufacturing and installing the pressure management scheme and takes account of technical and engineering issues. Training staff and introducing a monitoring system also form part of this step.

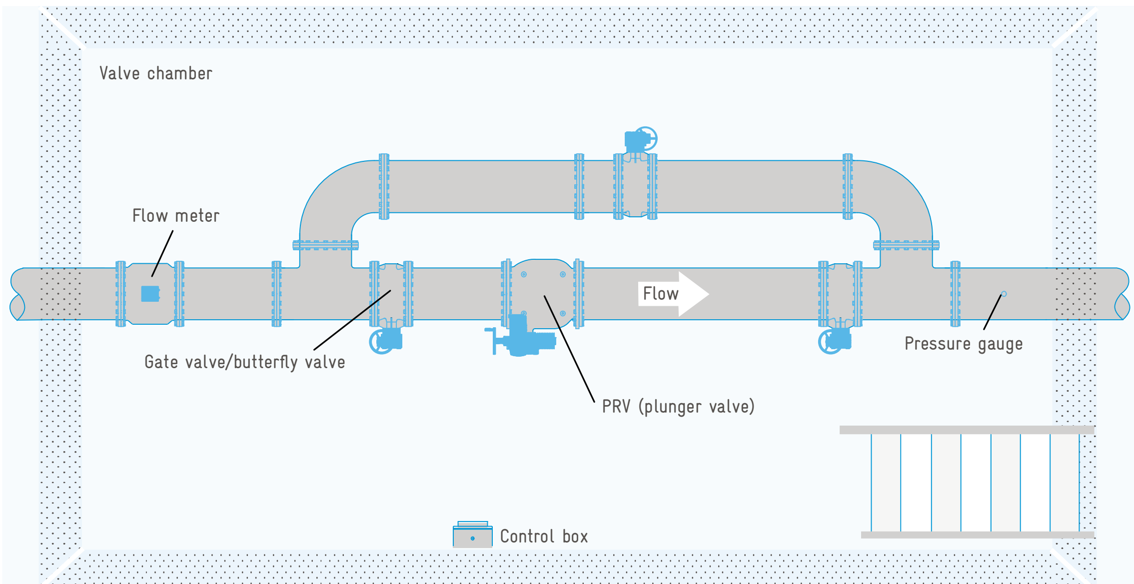
- Dimensioning the system (valves and components)
- manufacturing and constructing the pressure management scheme
- installing valves and programming control units
- setting up the modulation scheme
- performing intensive functional tests of the system
- on-site training for the operator team
- putting in place a monitoring system (SCADA technology).

Service
Service should be provided in the long run and involves technical support as well as further optimising the system. Service measures are generally offered by valve manufacturers in collaboration with water utilities. These measures entail technical support and troubleshooting, online (remote) or on-site system monitoring, system data analysis as well as system recalibration in the case of changes in boundary conditions.

(c) Installing the pressure management system
An underground valve chamber usually has to be installed at the inlet point of the selected distribution zone to install the pressure management system. The chamber should be drainable and has to provide sufficient space for system installation, operation and maintenance.

The whole system usually consists of a PRV (either a plunger or diaphragm valve), a flow meter, pressure sensors, two isolating valves, a dismantling piece and a control cabinet. Diaphragm valves require that a strainer with a dirt trap is installed upstream of the PRV. An air valve should be installed downstream of the PRV if the downstream mains is descending. Installing an air valve upstream of the PRV is recommended for rising or horizontal upstream mains. A bypass with an isolating valve is advisable, too, in order to maintain supply to customers during PRV maintenance works. Butterfly or gate valves should be used as isolating valves. A general layout of the valve chamber and a complete system including bypass is depicted in *Figure 6.18*.

Figure 6.18 General layout of the valve chamber and the pressure management system with a plunger valve and bypass



The flow meter continuously records the actual volume of water that is supplied to the distribution area. The pressure sensor behind the by-pass is used to record the actual pressure as input data for the pressure reduction function of the programmable logic controller (PLC). The PLC records, processes and archives the measured sensor data needed to control the plunger valve. It gathers status information about the measured volumes and pressures and about the actuator. Optionally, all recorded data can be transferred to the water utilities' control room. The plunger valve is powered by a DC, AC, or three-phase actuator depending on the local power supply.

A second PRV can be installed in parallel in the event that the required flow range is higher than the capacity of a single PRV. A larger PRV operating alone captures flows within its minimum and maximum flow range. The smaller valve operates alone in the case of lower flow rates. If both valves are operating simultaneously, the overall capacity is equal to the sum of the maximum flow rate of both valves. [77]

Supplementary materials 6.3

Pressure management implementation

Two PRVs can be installed in series if the required pressure differential causes risk of cavitation. In this case, pressure is reduced in two steps and each valve operates within the cavitation-free area. The pressure modulation controller is installed on the downstream valve. [77] Where the pressure differential is high, a PRV should also be installed on the bypass in order to maintain service during maintenance.

6.4.6 Limitations of pressure management

It should always be kept in mind that pressure management is not a universal remedy, but one method of reducing water loss to be complemented by other measures, such as leak detection and repair, infrastructure management as well as implementing and continuously monitoring DMAs.

Pressure management does not repair a single leak, but it may considerably reduce leakage flow rates. This is an important first step which might alleviate pressure on water utilities and encourage further measures.

Nevertheless, there are some important points to consider when implementing pressure management in a network or district: even if pressure is only reduced to a level which still meets the requirements of domestic and commercial users, some appliances might be affected, like instantaneous hot water systems, fire sprinkler systems or home dialysis systems. Installing booster pumps in multi-storey buildings might be necessary in order to distribute water to the upper floors.

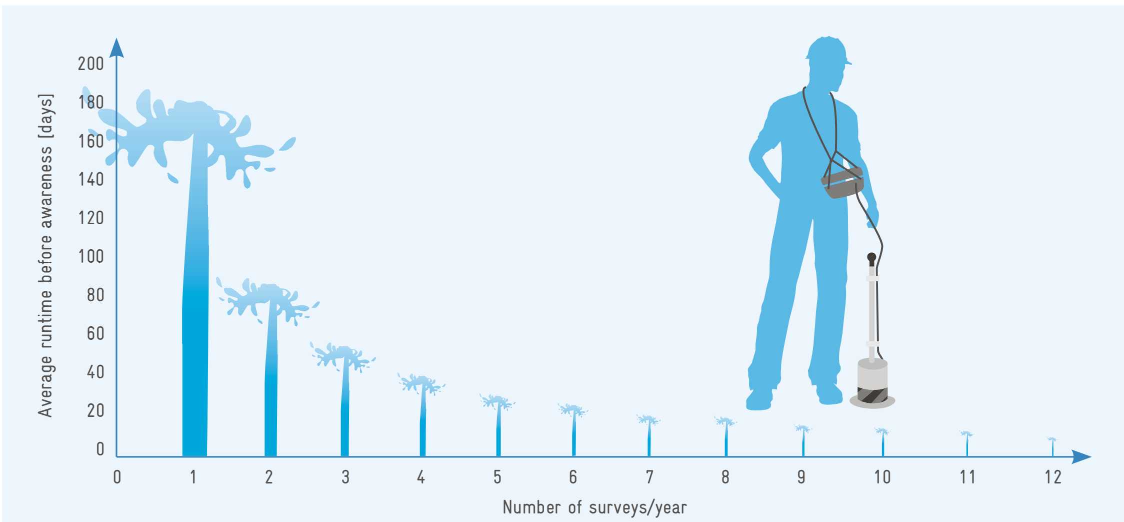
Local fire fighting requirements are an important aspect to be considered when installing a pressure reduction system. Negative impacts on fire fighting capacity have to be avoided by any means, either by an emergency bypass or by using flow modulation. Flow modulation allows pressure to be controlled with a preset profile related to the changing head loss/flow rate relationship within the PMA. In this case, the controller increases pressure with rising flow and thus ensures that the network has adequate pressure for fire fighting. [57]

6.5 Active leakage control (ALC)

6.5.1 Definition and purpose of active leakage control

Active leakage control is an intervention method to counteract real water losses in which a water utility deploys funds, personnel and technical equipment to actively detect and repair leaks that are currently running undetected into the ground. [77] The main purpose of ALC is to reduce the runtime of hidden leaks in order to minimise real water losses. *Figure 6.19* shows how regular surveys influence the awareness time for new leaks in a distribution network or DMA.

Figure 6.19 Effect of the number of surveys on awareness time for new leaks [58]



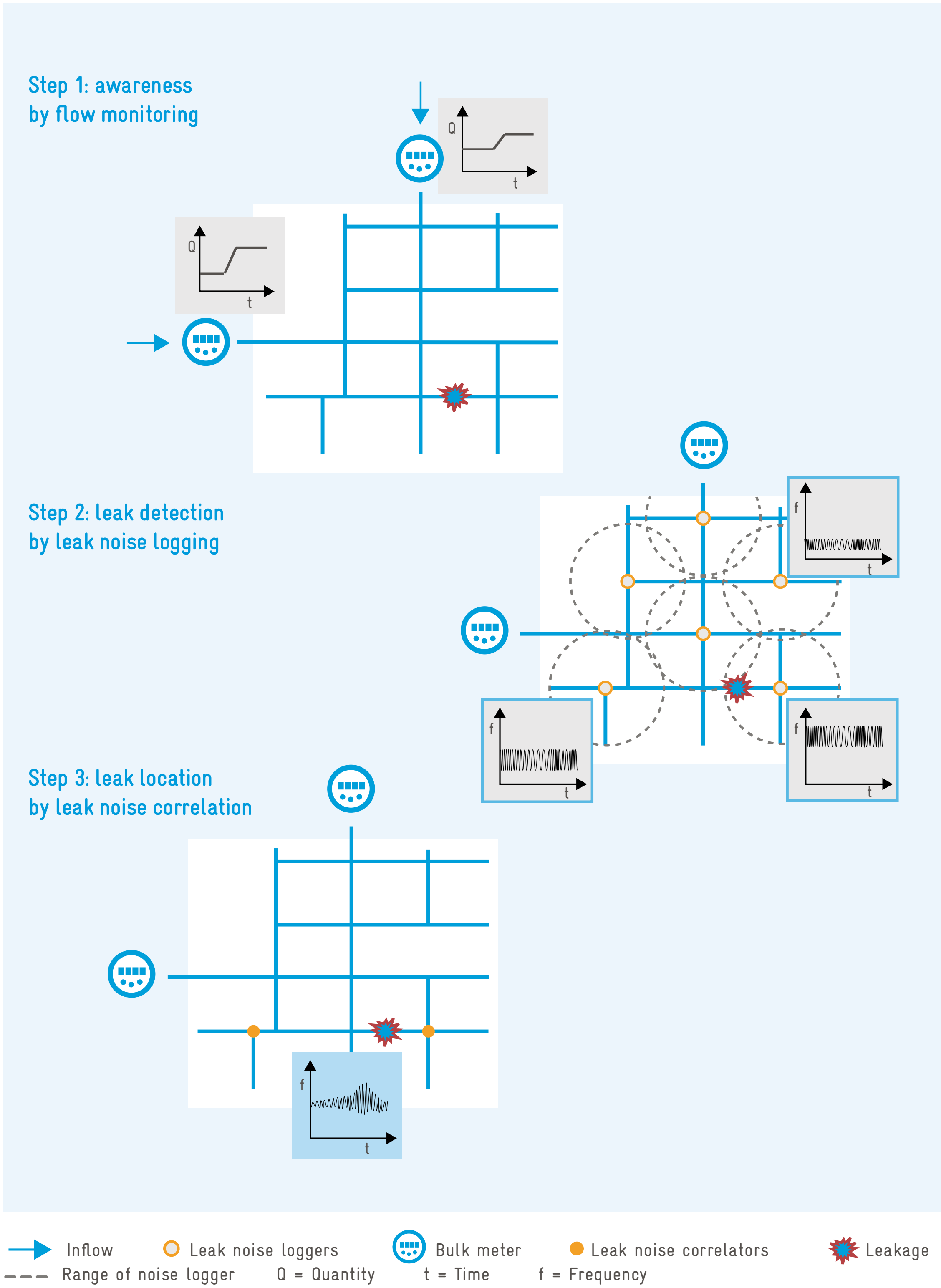
The process of ALC can be divided into three major steps:

1. Awareness: continuous monitoring and analysis of flows is essential to gain awareness of new leaks at an early stage. DMAs and PMAs provide a good opportunity to monitor discrete areas of the water distribution network and facilitate early awareness of even small leaks.

2. Leak detection: this is the process of narrowing down leaks to a certain area of the network or to a certain pipe section. Options include subdividing DMAs by temporarily closing valves (step testing), using leak noise loggers or conducting sounding surveys.

3. Leak location: various acoustic and non-acoustic methods are available for pinpointing leaks: listening sticks, ground microphones, leak noise correlators, ground radar and gas injections, to name a few. Thorough leak detection is a precondition for efficient leak location efforts.

Figure 6.20 Example of three-stage active leak control: awareness, leak detection and leak location



To implement efficient leak detection and location efforts, it is important to ensure that leak detection workers are equipped with accurate and up-to-date maps of the system and its components. Most acoustic leak location technologies depend on the availability of precise information about pipe material, diameter and length. Poor input information leads to incorrect leak location which results in cumbersome and needless excavation works, known as dry holes.

6.5.2 Awareness methods

Three main methods are available to gain early awareness of new leaks and reduce runtimes effectively: flow monitoring, pressure monitoring and noise monitoring.

Flow monitoring

Pipe breaks and bursts cause a more or less abrupt rise in the flow rate, which can be detected by constantly monitoring inflow into an open network or DMA. To this end, inflow should be monitored continuously or for at least one hour during minimum night flow conditions and should be compared to a previously measured reference value. If the increased flow rate remains stable for more than three days, the change is probably caused by a leakage and not by exceptional customer usage. *Kober* and *Gangl* describe a new approach of setting up an early warning system based on ultrasonic flow meters installed at hydraulically relevant positions in an open network. [41] Flows can thus be monitored without having previously implemented a DMA.

Pressure monitoring

Head losses in the network will also be at a minimum during the period of lowest consumption, and the overall pressure may almost reach the hydrostatic level in low leakage systems. High leakage flow rates will cause increased flow velocities and thus reduce pressure. Monitoring pressure in a network can only detect major leaks because small leakage flow rates will not significantly reduce pressure. Information from pressure monitoring may be used to prioritise work: it is advisable to commence leak detection works at the point where the maximum drop in pressure was measured.

Noise monitoring

The discharge of water from a leakage produces acoustic waves or oscillations. These acoustic waves propagate in the water column in either direction of the leakage, and can be detected by leak noise loggers which are usually installed on valves or hydrants. The acoustic waves only travel a limited range, depending on pipe material, diameter, wall thickness, pressure, surrounding ground and other factors. Therefore, a relatively dense grid of noise loggers has to be temporarily or permanently put in place. The advantage of noise monitoring is that it can be implemented and managed with few personnel because installation is simple and data can be read by a vehicle driving past the location. One disadvantage is that the intensity of noise is not directly connected to the leak flow rate, making it impossible to distinguish major breaks from less important minor leaks.

6.5.3 Leak detection methods

Three methods are at a water utility's disposal to narrow down leaks to a certain area of the network or to a specific pipe section: step testing, leak noise loggers and sounding surveys.

Step testing

Once a new leak has been identified within a DMA or open network by means of the awareness methods outlined above, the zone can be temporarily subdivided into smaller areas. Flow meters have to be installed at the inlet points of each subdivision to monitor inflow. Each subdivision can now be systematically reduced by closing off valves. A large drop in the flow rate indicates a leak in the section that just has been closed. [22] Night work is required because step testing should be executed during minimum night flow conditions. Furthermore, it usually involves service disruption for customers.

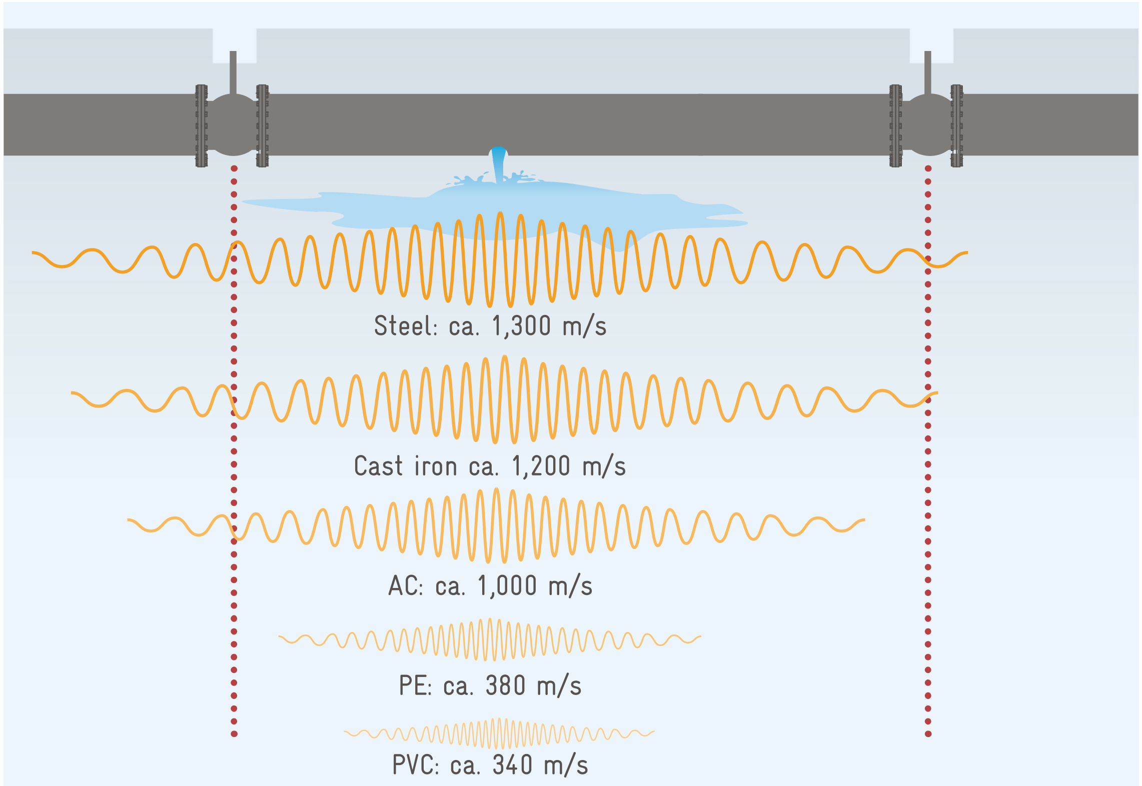
Leak noise loggers

Once a new leak has been identified, the leak detection team may place leak noise loggers at the strategic points of the network to determine the leak's approximate location. Leak noise loggers are compact units consisting of an acoustic sensor (accelerometer) and a programmable data logger. [28] When assigning the loggers, it has to be considered that sound wave propagation is significantly influenced by the predominant pipe materials used in a water distribution network *(see Figure 6.21 on the next page)*. The range between two leak noise loggers may be up to 200 m in predominantly metallic networks, while the range may decrease to 80 m in networks with large amounts of PE and PVC pipes. Internal concrete lining may also weaken the quality and propagation of acoustic waves. [33]

Noise loggers can be broken down into two groups: (1) noise sensors which usually have a magnetic base to facilitate their installation on valves, hydrants or fittings and (2) hydrophones, which are microphones inserted into the pipes in order to have direct contact with the water and to take advantage of better acoustic waves propagation in the water column.

Noise loggers can be programmed to monitor system noise between 2 and 4 am when interfering ambient or consumption sounds are at a minimum. [77] The leak will be closest to the noise logger where the highest intensity of noise has been recorded.

Figure 6.21 Relationship between material and propagation of acoustic waves, based on [33]



Sounding surveys

Sounding surveys involve listening for leak noises directly at valves, hydrants and stop-taps of service connections or at the surface above the pipe alignment. [22] Sounding is usually executed with listening sticks (simple mechanical sticks or electronically amplified sticks with a microphone and a headset) or ground microphones. The sounding survey is an effective, but time-consuming method because practically every valve has to be accessed. Stop-taps, in particular, should be sounded because a good portion of leakage occurs from service connections. The shorter the distance between single soundings, the better the chances of receiving even weak acoustic waves from a leakage. The success of acoustic surveys often depends on the experience and the skilled ears of leak detection workers. [33]

6.5.4 Leak location methods

Once the approximate area of a leak has been determined, leak location methods should be used to find the exact location (± 1 m) in order to reduce excavation efforts. Several acoustic methods can be performed, for example listening sticks, ground microphones, and leak noise correlation. If acoustic methods are unsuccessful, several non-acoustic methods are also available.

Supplementary materials 6.4

Leak detection and location methods

Listening sticks and ground microphones

Water flowing out of a leak under high pressure causes vibrations in the pipe and the surrounding soil. This vibration is transmitted along the pipe as structure-borne noise and in the surrounding underground as ground-borne noise. Making direct contact between a listening stick and the pipe at valves or hydrants allows structure-borne noise to be heard, provided that it is loud enough and distinguishable from background noise. Amplifying the noise with an electro-acoustic microphone allows leak noise to even be detected in PE and PVC networks with unfavourable acoustic propagation characteristics. Having identified the pipe section between two valves where the leak is located, the pipe alignment should be surveyed for ground-borne noise by means of a ground microphone. For this purpose, the microphone, which is protected against traffic noise and wind by an isolated housing, is placed above the pipe on the surface at intervals of one or two meters until the exact position of the leak has been identified. [3]

Leak noise correlation

Correlation is a mathematic method for calculating the time delay between two signals emitted from the same source. In practice, two microphones are attached to a valve or a hydrant at both ends of a pipe section. The microphones are equipped with transmitters to transfer measured results to the correlator. Acoustic waves (signals) emitted from a leakage (source) on this section of the pipe travel along the pipe and reach the microphones after a certain amount of time. The signal will first reach the microphone located closer to the leak. The correlator analyses the structure of the noise and measures the time delay Δt until a noise of the same structure is recorded at the second microphone. The use of correlation is thus impossible if the signal is too weak to reach both microphones.

The correlator is able to calculate the exact position of the leakage by means of *Equation 6.1 on the next page* considering the time delay Δt between the two microphones, the length of the pipe section as well as pipe diameter and material.

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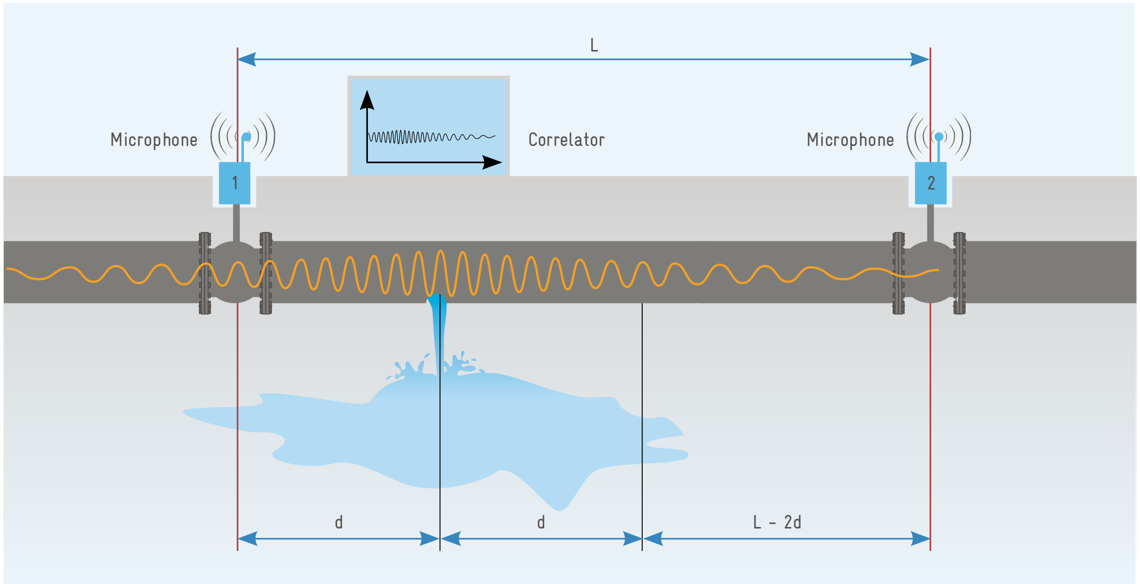
Figure 6.22 Schematic illustration of the functionality of leak noise correlators



Equation 6.1

$$d = \frac{L - v \times \Delta t}{2}$$

Where:

d	[m]	Distance from the leak to microphone 1
L	[m]	Length of pipe section
Δt	[s]	Time delay
v	[m/s]	Acoustic wave propagation velocity

Precise input information about the pipe material, diameter and length, e.g. from the network register, are essential for producing correct results for the leak noise correlator.

Non-acoustic methods

The methods described above can detect leaks which produce a certain amount of noise. Other methods have to be applied if the emitting water does not generate an audible sound, or if acoustic waves are absorbed by the pipe material.

→ **Tracer gas:** the pipe section to be surveyed has to be taken out of service and isolated by closing off valves. Helium or hydrogen gas is then injected into the isolated pipe section. Gas escaping through the leaks permeates to the surface and can be detected by using gas detectors. [77]

- **Ground penetrating radar (GPR):** GPR is a reflection technique which uses high frequency electromagnetic waves to acquire subsurface information. The radar waves are reflected by changes in the subsurface material or conditions. Leakage can thus be identified by either finding underground voids created by the emission of water or by detecting anomalous changes in the properties of the surrounding material due to water saturation. [19]

Non-acoustic leak location methods like tracer gas usually require especially skilled personnel and also involve great effort. Nevertheless, they may be a viable alternative to acoustic methods in networks with very low pressure, intermittent supply or for locating hard-to-find background leakage.

6.6 Leak repair

6.6.1 Purpose

As described in *Chapter 3*, the overall runtime of leaks consists of awareness, location and repair times *(ALR – see Figure 3.2 on page 51).* Long leakage runtimes will generate large amounts of water losses, even from relatively small leaks. Therefore, water utilities should always aim to reduce ALR times to the economic minimum. *Chapter 6.5* described different methods of minimising awareness and location times for new leaks. This chapter shall highlight the importance of performing fast and sound leak repairs to reduce water losses.

6.6.2 Organisational issues and operating procedures

Several departments within a water utility are normally involved in the process of repairing leaks, for example the customer service team (receives customer complaints and issues work orders), the control room (observes increased consumption in a zone and requests the leak detection and repair crew), the warehousing department (keeps repair materials in stock and orders supplies) and the leak repair crew itself. It is important that operational procedures are organised efficiently among all involved departments and are well documented. [16] Leak repairs should be prioritised according to the size of the leaks and considering the security of supply throughout the whole system.

It is important that the leak repair personnel are well trained, motivated and equipped with all necessary equipment, vehicles, communication devices and safety gear. The number of repair crews should be appropriate for the number of leaks and bursts needing to be repaired in specified target times.

The warehousing department should make sure that frequently used parts are always in stock as long delivery times for required spare parts are not tolerable. Analysing the failure database and failure rates might help to identify damage-prone types of pipes and valves *(see Chapter 5.7).*

The water utility's policy also has a strong influence on the speed and quality of repairs. Repair times can be reduced by setting performance targets for how fast a main break, a service connection leak or a defective valve have to be repaired. With regard to service connections, it is usually highly inefficient and causes high water losses to oblige customers to repair or replace any privately owned part of the service connection up to the customer meter. In many cases it will be more efficient for a water utility to offer free or subsidised repair or replacement, without liability, which can be covered by a small additional fee on the customer's water tariff. [77]

6.6.3 Execution of repair works

The quality of leak repairs plays a significant role in the overall leakage management process. [77] Poor materials, the need for improvisation and bad workmanship make it probable that new leaks will occur at the same place. Therefore, leak repairs should be executed by well-trained and skilled labourers. Repairs often have to be carried out under time pressure. Nevertheless, a frantic pace must be avoided and safety rules have to be complied with on all accounts:

- → adequate safety gear for all personnel
- → structural safety of the excavation pit
- → signposting and traffic detours
- → illumination for night works
- → sump pump to allow for dry working space
- → informing affected customers. [74]

Generally speaking, optimal repair methods vary depending on the type of leakage. Circumferential cracks can be fixed with leak repair clamps. Flexible clamps are available if pipe ends are out of alignment. Longitudinal cracks are usually too big for repair clamps. In this case, entire pipe sections have to be exchanged. Pinhole leaks caused by corrosion or perforation also can be repaired by means of repair clamps. If there are many pinholes on a pipe section, exchanging the pipe should be considered. Leakage from pipe joints can usually be stopped by dismantling and replacing the rubber gasket. Defective valves and fittings should be replaced and possibly be overhauled in the utility's workshop. [3] In the case of service connections, it is usually more reasonable to replace than to repair defective connections.

Each repair should be measured, documented and its exact position should be defined, e.g. by means of handheld GPS receivers. The data should be transferred into the failure database for statistical analysis and graphic visualisation in the GIS, which may help to improve the water utility's maintenance and repair processes.

6

6.7 Infrastructure management

6.7.1 General overview

Infrastructure and asset management is indispensable from a water loss reduction perspective. The goal is to meet the required level of service in the most cost-effective manner by creating, acquiring, maintaining, operating, rehabilitating and disposing of assets to provide for present and future water utilities opting for water loss reduction solutions.

Infrastructure management is also a systematic integration of advanced and sustainable management techniques into a management paradigm or way of thinking, with the primary focus on the long-term life cycle of the asset and its sustained performance, rather than on short-term, day-to-day aspects. Water supply systems need infrastructure management to:

- address ageing water infrastructure assets before they fail
- keep assets productive, and not allow them to become disruptive liabilities
- treat all decisions as investment decisions to maximise limited financial resources
- make costs transparent to support financial decisions. [87]

The *Figure 6.23* sketches a flow chart for asset management at the management, strategic and execution levels. It is a continuous process aiming to improve performance in the short, middle and long run.

The lifetime of the infrastructure is prolonged by implementing pressure management. Reducing the pipeline pressure not only saves water by reducing real losses; it also decreases new pipe breaks, increases asset life and defers pipe replacements.

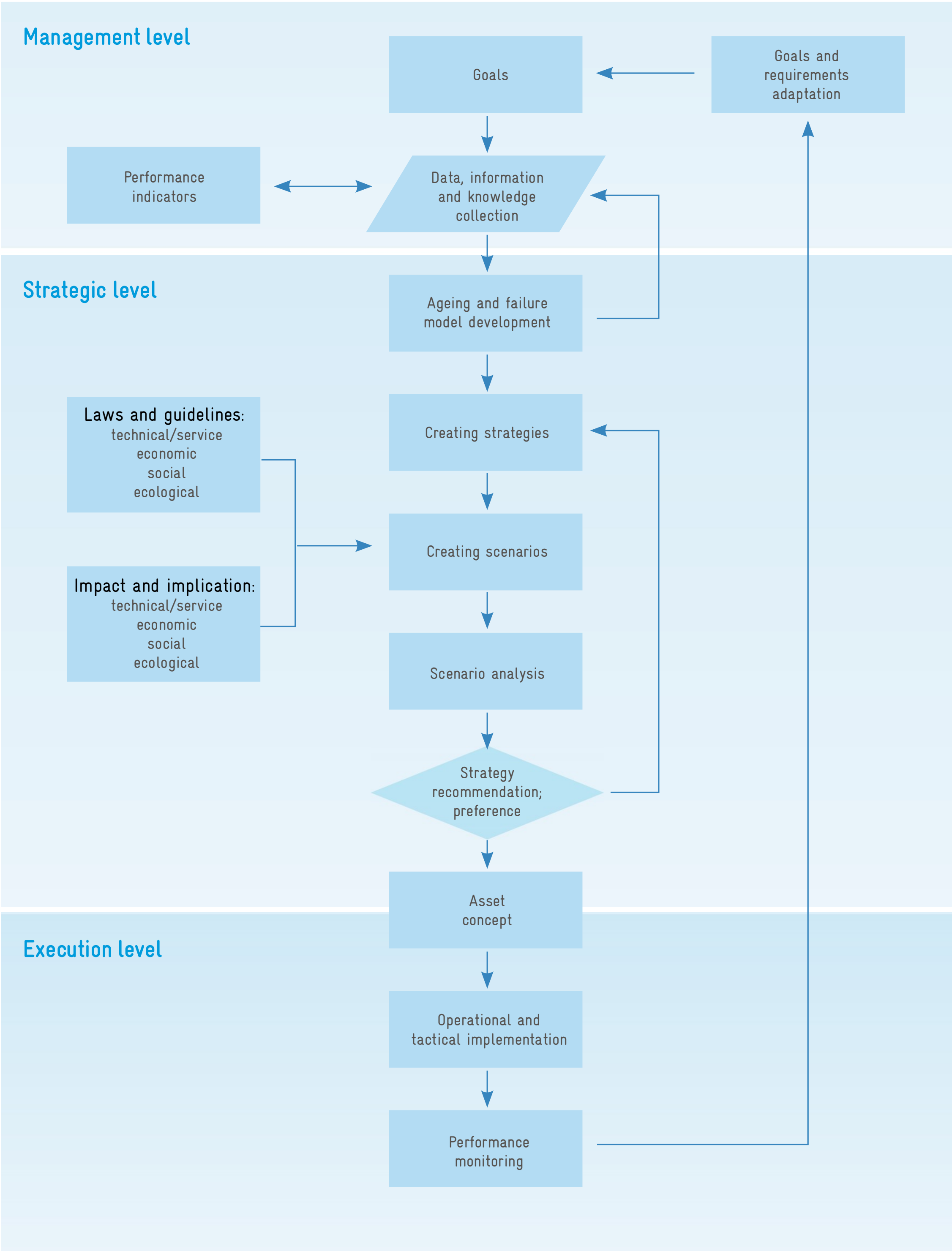
6.7.2 Factors contributing to the deterioration of utility infrastructure

It is expected that a type of pipe that initially works will fail after a certain operating period. Three factors basically contribute towards reduced infrastructure performance:

- deterioration
- material ageing
- functional deterioration.

In addition to the natural process of deterioration, material ageing can be accelerated by the absence of network maintenance *(shown in the Figure 6.24 on page 185)*. Maintenance also

Figure 6.23 Flow chart for infrastructure asset management



involves material characteristics, the laying and bedding conditions in the ground and the quality inspection and assurance cycle.

The physical environment also needs to be specified in connection with material ageing (substantial ageing). On the one hand, the pipe undergoes internal stresses based on the type of operation, the maximum and transient pressure and possible ground movements. On the other hand there are fewer swayed points, such as the frost load, traffic load and third-party influences due to civil works.

The third point of material ageing relates to the supply network's characteristics. These have a natural background, such as a bio film and contaminant intrusion and/or permeation.

Functional deterioration can also be expressed by non-substantial immaterial ageing. This includes changes in the network's hydraulic capacity due to demographic changes or rising standards. Legal changes are also to be considered and might influence functional deterioration.

6.7.3 Collecting and organising asset information

It is essential to collect and organise descriptive information about the assets in order to gain insight into the infrastructure. These include:

- age, size, construction materials, location, and installation date
- an assessment of the assets' condition
- key information on operating, maintenance, and repair history
- the assets' expected and remaining useful life
- operating pressure
- assets' value, including historical cost, depreciated value, and replacement cost.

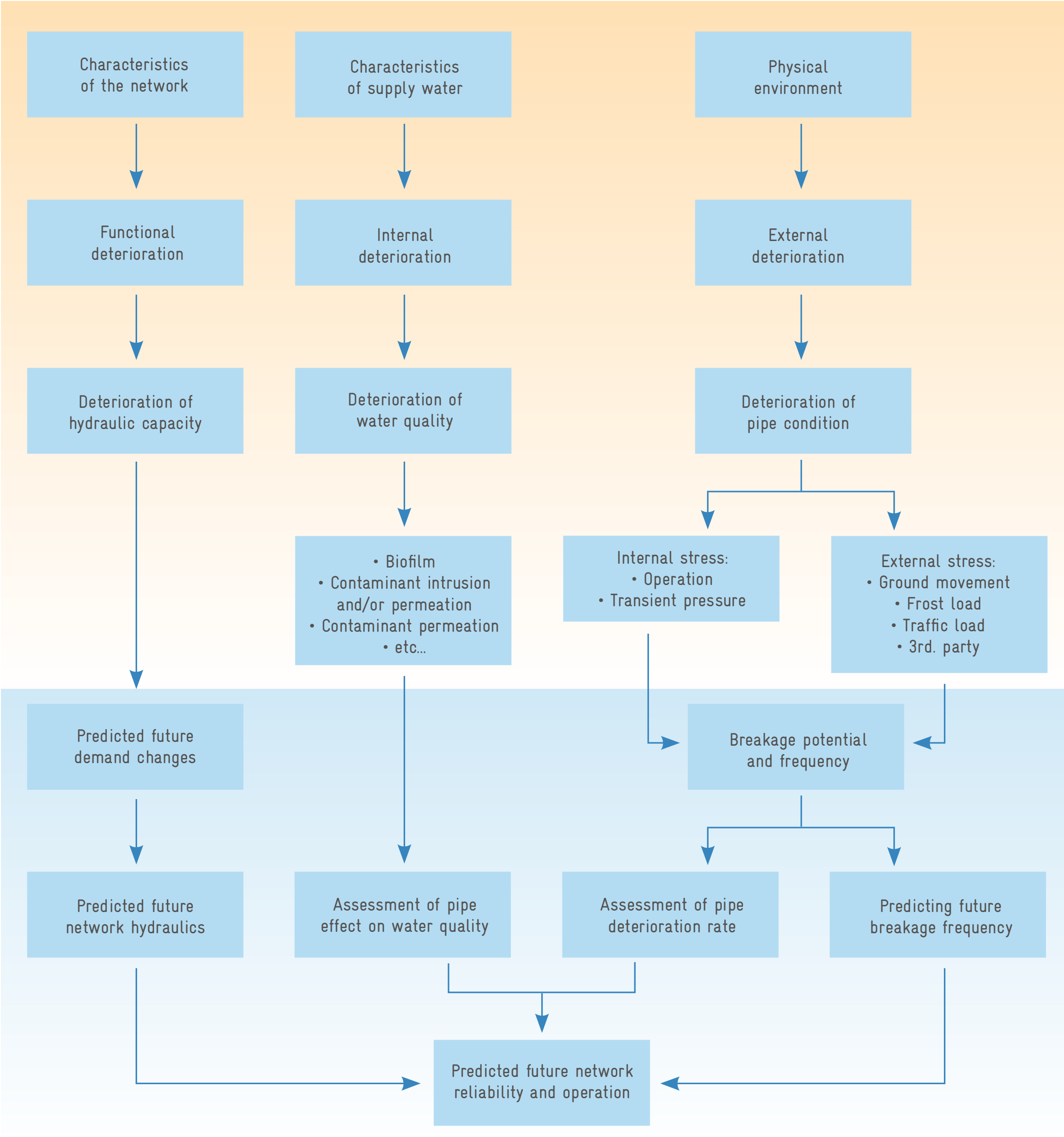
The collected data needs to be checked for plausibility with regards to their formal, logical and temporal consistency. The next step is to pinpoint unique identifiers that describe a clustering process.

6.7.4 Analysing data

This step follows the data collection and organisation process and entails an analysis based on specific indicators. These indicators are the service life and the risk of failure, and support the risk assessment process and life cycle cost analysis.

The service life can be defined as the time between installation of the pipe and its replacement, and is classified by the following characteristics:

Figure 6.24 Factors and mechanisms feeding into the decision-making process



- **Technical/service:** the period of time over which a property is held for a particular purpose or level of service.
- **Usual operation:** service life to be expected under normal local operation and maintenance conditions.
- **Economic:** the period of time when the equivalent net annual worth is at a minimum.

6

- **Depreciation:** the period of time when the investment is depreciated on the accounting books.
- **Residual:** remaining service life of pipes in operation with respect to its material condition and defined maintenance efforts. [31]

As mentioned above, the second indicator is the failure risk which can be subdivided in the following way:

- **Exogenous risks:** The risk of failure originating from factors totally outside the utility management's control.
- **Operating risks:** A kind of failure that exists under normal operating conditions when utility systems are not externally or abnormally stressed.
- **Supply risks:** A failure in the form of shortages resulting from inadequate supplies of raw water relative to the demand. [10]

The risk assessment process analyses the water suppliers' readiness to assume risk and may change due to local and cultural aspects.

A lifecycle cost analysis should be run as the final data analysis step. The goal is to determine actual cost allocation per km by taking into account centralisation and decentralisation aspects of the installed supply network.

6.7.5 Data integration and decision-making

The data integration process is classified into different categories:

1. Maintainability

Maintainability is the probability that a failed system or component will be restored or repaired to a specified condition within a period of time. It can be separated into:

- Reactive maintenance, which is performed in response to unplanned or unscheduled downtime of a unit, usually as a result of a failure.
- Preventive maintenance, which is a scheduled downtime, usually periodical, with a well-defined set of tasks, such as inspection and repair, replacement, cleaning, etc.
- Predictive maintenance, which estimates when a part is near failure and should be repaired or replaced through diagnostic tools and measurements, and thereby eliminates presumably more costly unscheduled maintenance.

→ Proactive maintenance should only be performed when required and to the extent that it is cost-effective. Proactive maintenance is generally assumed to be less costly than reactive maintenance. [84]

2. Performance indicators

Performance indicators (based on IWA specifications) facilitate continuous analysis and benchmarking. The objective is to describe the resources spent (e.g. repair cost/km) or conditions (e.g. number of failures/km), to compare sub areas or entire networks and to estimate the benefits of a rehabilitation or pressure management program. It is important to distinguish between calculating repairs to the mains (per 100 km/year) and services (per 1,000 connections/year). In addition, the numbers of repairs should be categorised according to their type and location.

3. Water supply reliability

The integration of water supply reliability helps to identify the most vulnerable points in a water supply system and its pipes. It also assesses the relative importance of each pipe in terms of hydraulic reliability and is based on the hydraulic simulation model's input data file.

4. General reliability

The reliability analysis itself incorporates the survival data, the survival curve, a failure model, a long-term rehabilitation planning and an annual rehabilitation planning.

The failure model, for example, predicts the probability of pipe failures and groups pipes in clusters showing similar behaviour.

Long-term rehabilitation planning explores the investment needs and consequences for future rehabilitation, and defines the optimal rehabilitation strategy. It also allows long-term network behaviour to be predicted in order to pre-define rehabilitation scenarios. It is based on the expected service life distribution for each group of materials and provides a global budget in support of a strategic rehabilitation plan.

Supplementary materials 6.5

Clustering

Annual rehabilitation planning selects the most cost-efficient rehabilitation projects for an annual rehabilitation programme taking into account various criteria.

5. Assets

As mentioned above the integration of the information regarding assets is classified in current and critical state of assets. This can be determined by asking the right questions about the network and is essential for the further decision-making.

6. Social cost of failure

The social cost of failure has a great impact and has to be considered at this stage of data integration and decision-making. The costs directly incurred by the utility are:

- administrative and legal costs of damage
- public safety costs
- repair and return to service costs
- service outage mitigation costs
- utility emergency response costs. [10]

Effects on routine patterns, such as access impairment and travel delay costs and customer outage and substitution costs, have to be considered. The following points generally have low levels of incidence, but a high impact:

- health damage
- direct damage at the point of failure
- water-borne diseases introduced as a result of failure
- property damages.

The points mentioned (1 to 6) make a contribution towards the decision-making process.

6.8 Summary and next steps

The contents of *Chapter 6* of this technical manual shall enable the reader to:

- ☑ Understand how different maintenance strategies (passive, reactive or pro-active) influence the condition of the distribution network and the level of leakage.
- ☑ Design, implement and operate DMAs in order to monitor flows and to reduce leak runtimes.
- ☑ Know the principles of pressure management and its impacts on leak flows.
- ☑ Understand the various modulation concepts and the characteristics of different types of PRVs and their respective advantages and disadvantages.
- ☑ Select the optimal use case for a specific pressure management application.
- ☑ Execute the typical project stages for designing, implementing and operating pressure management systems.
- ☑ Employ methods for awareness, detection and location of leaks in a water distribution network.
- ☑ Understand the benefits of long-term infrastructure management for ensuring the functionality of networks and reducing water losses.

The case studies presented in the following chapter shall demonstrate how the sum of the presented techniques and methodologies can be realised in practice in order to successfully reduce water losses.


GTH
ANNABA

Case studies 7

Photo: © J. Baader, 2008

Actuator control for PRV

Presentation at the SEDAPAL training center in Lima, Peru

Photo: © E. Oertlé, 2010

Valve chamber with flowmeter

Photo: © J. Baader, 2010

7.1 PM training modules – the example of Lima, Peru

Project title	Water loss reduction in marginalized areas of Lima
Name of areas	Comas (Sector S86) and Breña (Sector S25), Lima, Peru
Non-revenue water (NRW)	37.5% (SEDAPAL, 2008)
Project period/ status	2008 - 2010

7.1.1 Background

Drinking water is a scarce resource in Peru, particularly in its capital Lima, which is situated in a desert region on the Peruvian coast. Environmental pollution and insufficient water resources aggravate the provision of adequate drinking water. Furthermore, the water supply system records real water losses of up to 50% of the water fed into the network caused by leaking pipes and insufficient maintenance.

SEDAPAL, a state-owned enterprise, is in charge of providing the districts of Lima and Callao with municipal services, such as drinking water supply and wastewater services, and is a key stakeholder in the Peruvian water and sanitation sector.

7.1.2 Process development – The training centre approach

Pressure management (PM) has been identified as an efficient solution to reduce water losses in Lima and Callao. Besides the technical installation of PM technology, the aim of this project is to enhance the managerial and operative capacity of the utilities in question.

Generally, it is important to train local practitioners on how to operate PM systems so that they can learn how to maintain technical components and how to measure the benefits of such an investment by themselves. Technical and educational materials have been made available for staff. Furthermore, local trainers at the SEDAPAL training centre have received instruction. Moreover, a memorandum of understanding has been drafted between SEDAPAL, the national association of water and sanitation sector utilities (ANEPSSA) as well as the network to enhance the capacities in the water and sanitation sector (SFCS) in order to ensure a sustainable transfer of PM knowledge on a national level. Under this agreement, the SEDAPAL training centre will be integrated into the SFCS network and utility staff throughout Peru will be trained in the management and technical operation of PM.

The installation of the technology and training SEDAPAL's staff in two pilot areas of Lima serve as best practice example. Ideally, future trainings will be tailor-made for different target groups:

1. Management and planning division:

- → long-term planning and design
- → financing of PM installation
- → economic, environmental and social benefits.

2. Operational staff:

- → technical instructions on PM
- → maintenance and operation of PM technology
- → electronic management
- → PM as part of the water and sanitation supply system.

7.1.3 Achievements and impacts

The following achievements and impacts have been made:

- → experience and knowledge gained in the course of the project has been accurately documented and made available to local and national training centres and networks
- → development of PM training modules (in Spanish)

- capacity development for utility staff through training sessions and workshops
- train the trainer approach at SEDAPAL training centre
- PM training modules integrated into the national SFCS network
- project results and experiences are available for water utilities throughout Peru
- potential for replicating the project
- the project contributes towards the development of the Peruvian water and sanitation sector
- development of a financing model in order to guarantee the future dissemination and implementation of PM within the country.

7.1.4 Lessons learned

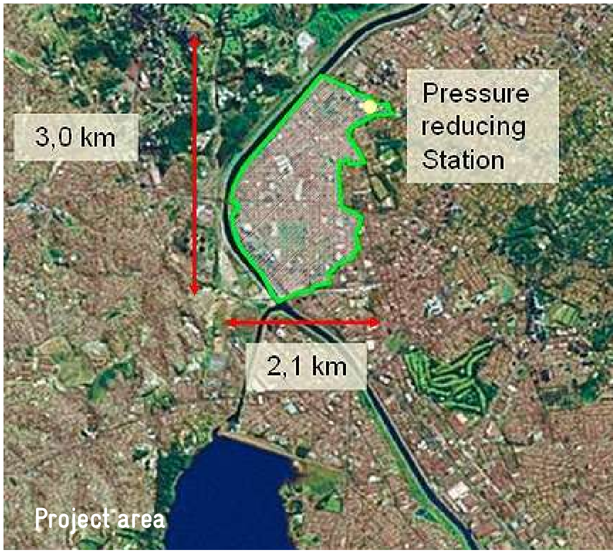
Within the framework of this project, it was important to build upon both national and local structures and networks in order to reach out to water utilities and staff nationwide. The establishment of understanding for PM solutions in local water supply systems will be stimulated by training sessions on PM technology as an integral part of water and sanitation utility training modules. However, this allows water utilities to learn about PM technology and consider if there is potential for replicating PM measures within their own system.

7.1.5 References

- SFC website: *www.vivienda.gob.pe*, visited July 2010.
- SEDAPAL website: *www.sedapal.com.pe*, visited July 2010.

7

Installation of a pressure reducing valve (PRV)



Project area

Installation of a pressure reducing valve (PRV)

7.2 Reducing water losses by pressure management – the example of Santo Amaro, Brazil

Project title	Sustainable water and natural resources management in São Paulo
Name of areas	Santo Amaro, São Paulo, Brazil
Inhabitants	36,000
Service connections	8,895
Length of distribution pipes	83 km
Water losses **01/2005 – 09/2005** **10/2005 – 01/2006** **02/2006 – 06/2006**	 301,702 m^3/month 203,947 m^3/month 178,039 m^3/month
Project period/ status	March 2004 – June 2006

7.2.1 Background

Water consumption is continuously increasing in the metropolitan area of São Paulo. Today, the state-owned water utility Companhia de Saneamento Básico do Estado de São Paulo (SABESP) faces the challenge of meeting the demand of over 17 million inhabitants and ensuring a constant and sufficient supply of potable water in sufficient quantities. Despite the high quality of service provided by SABESP, periods of rotational supply sometimes occur due to a lack of resources during a dry period.

One reason for a lack of water supply is the high volume of water losses that occur during operation due to leakage at critical points, such as the mains and fittings.

7.2.2 Process development

A pilot site was installed in the district of Santo Amaro, consisting of a state-of-the-art water loss reduction system that included pressure regulating valves, control panels, telemetry installations and the supporting software. *(Oppinger, 2009)*

Two technologies were implemented: firstly, time-based modulation and secondly, remote node-based modulation (critical point flow modulation). Flow modulation is expected to yield better results as the PRV is continuously adjusting pressure so that the pressure stays as close as possible to the set value at the critical point.

7.2.3 Results and good practice

The results obtained with both installed technologies are summarised *in the Table below*, showing water savings of up to 41%. Furthermore, new pipe breaks were reduced by approximately 50%. The project had a payback time of approximately four to five months.

F. Paracampos (SABESP) reported his observations from the central business unit of SABESP in 2007: break frequencies at mains and services were around 10 per km/year in the 180 zones with pressure management. However, according to *Thornton*, break frequencies were almost double in areas without pressure management (approximately 19 per km/year).

7.2.4 Lessons learned

This pilot site has demonstrated that modulated pressure management significantly reduces both the volume of water loss and the frequency of new pipe breaks. For the

Technology	Period	Water losses [m^3/month]	Water savings [%]
Without PM	01/2005 – 09/2005	301,702	
Time-based modulation	10/2005 – 01/2006	203,947	-33%
Remote node-based modulation	02/2006 – 06/2006	178,039	-41%

Results obtained in the district of Santo Amaro between January 2005 and June 2006 district of Santo Amaro, this means a reduction of up to 50% in new pipe breaks and 30% more available volume of water, which is sufficient to supply an additional 800 people with potable water. This is of particular significance in a fast-growing metropolis like São Paulo.

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Location of valve chamber on plan

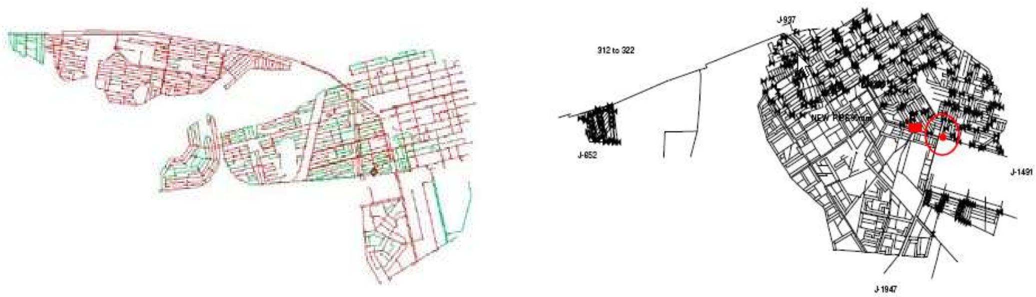
7.3 Hydraulic modelling – the example of Ouagadougou, Burkina Faso

Project title	Hydraulic modelling Burkina Faso
Name of areas	Ouagadougou, water supply areas R7 and RE
Water losses **Supply area RE** **Supply area R7**	 306m³/day 120m³/day
Project period/ status	February to November 2009

7.3.1 Background

Drinking water is a scarce resource in Burkina Faso, and large parts of the city of Ouagadougou are spreading into the surrounding areas without organised water supply each year. Supply areas R7 and RE *(see Figure on next page)* have had continuous water supply without interruptions since completion of the Ziga Project in 2006. Despite the benefits of this project, real water losses have been seen to increase since the system is operated continuously. This is due to the fact that the distribution pipes are constantly producing higher leak flow rates under increased pressure. The objective of implementing pilot projects in the supply areas R7 and RE is to reduce real water losses to 20%.

The Office National de l'Eau et de l'Assainissement (ONEA) is the national water and sewage authority and the biggest national water company. Institutional restructuring has separated rural and urban water supply. This reform aimed to make the company financially viable, and to make access to water and sanitation affordable for low-income areas. The introduction of hydraulic modelling improved maintenance cost efficiency and decision-making in medium to long term. Today, ONEA is considered to be one of the best-managed companies in the region.



GIS representation of supply area R7 (left) and EPANET critical point identification in supply area RE (right)

7.3.2 Process development – hydraulic modelling

One goal of hydraulic modelling is to identify the best technical and economical solution for a water supply network. The system has to be understood to propose alternatives and to be optimised. In the present case, hydraulic modelling was an important step to investigate the possibility of installing a pressure management system and consisted of the following steps:

Step 1: data collection and model set-up

- ONEA supplied their existing hydraulic model to the solution provider.
- Updating the hydraulic model in EPANET (software tool for modelling from US EPA) for the water distribution network with regards to DMAs R7 and RE (small diameters, internal loops, disconnected pipelines, etc.).

Step 2: model corrections

- Verification of input data and plausibility check – formal, logical and temporally consistence of data.
- Inaccuracies with major impacts on the modelling quality have been corrected in coordination with ONEA.

Step 3: model calibration

- → The calibration process was performed on the corrected models, using the consumption patterns observed during days when simultaneous flow and pressure measurements were performed.
- → Pipe roughness has been considered depending on the pipe material and age.
- → Verification of the reservoir level and its impacts on modelling.
- → Minor losses were introduced into the model.

Step 4: valve selection

- → The calibrated model has been used for simulation runs of the DMAs. The analysis of the simulation results has been used to select and dimension the proper pressure reducing valves.

7.3.3 Results and strategy

The recommended solution for an efficient PM system in both DMAs (R7 & RE) provides for the use of several inlets equipped with pressure reduction valves. In both cases, best results are obtained with dynamically controlled pressure reduction valves in order to lower unnecessary excess pressure during night hours. The *following Table* shows simulation results for several model variants:

Reduction of water losses [m^3/day]		
Alternative	PRV – fixed outlet control	PRV – critical point control
PRV at the outlet of the reservoir (variant R7-1)	116	120
Creating three independent sectors, each with one PRV at the inlet (variant R7-2)	51	79
PRV at the outlet of the reservoir (variant RE-1)	65	231
One PRV at each of the two main supply points (variant RE-2)	289	305

Comparison of simulated water loss reduction with two variants

Alternative R7-2 is recommended for area R7 as it offers more flexibility in operating the system. Three valves are installed at the main supply points for each newly created sub area, helping to reduce the subsequent water losses per day. The set point of each valve can be adjusted according to the requirements of each area.

RE-2 is the recommended option for area RE. In this option, two DN 300 valves are installed at the main supply points.

7.3.4 Best practice

In this case study, hydraulic network models were used to design the DMA and select and dimension the PRV. This process requires that reliable input data is available about the existing network and predictions regarding population development, water consumption trends and planned rehabilitation and extension measures in the analysed water supply network.

7.3.5 Lessons learned

- → The results of the model are only reliable if the input data is accurate.
- → Hydraulic modelling allows time and financial savings, as several options can be simulated and compared, without needing real implementation.
- → Cooperation and constant communication with local partners is necessary to gain a clear picture of the actual condition of a water distribution system.
- → Model calibration based on data from measurement campaigns is essential to produce reliable results.

7.3.6 Further development/future outlook

The next step will be to install the pressure management system in area R7 and optimise sector RE.

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Photo: © CUDRC

Installation of a diaphragm valve with bypass

Photo: © T. Baier, 2008


Installation of PM components

7.4 Water losses reduced by up to 40% – the example of Ain Al Basha, Jordan

Project title	Water loss reduction in Ain Al Basha through effective pressure management (PM)
Name of area	Ain Al Basha, Amman Jordan
Service connections	4,098
NRW	47.1% (2005)
Project period / status	January 2007 – July 2008 (completed)

7.4.1 Background

Jordan was estimated to have a non-revenue water (NRW) level of more than 50% in 2004. This is quite alarming given that Jordan is considered to be one of the ten most arid countries in the world.

The condition of the Ain Al Basha water distribution system poses a great number of problems: a very high percentage of real water losses consumes considerable financial and natural resources and leads to a limited supply of water for service customers. Furthermore, strong pressure variations within the system lead to frequent new pipe breaks.

7.4.2 Process development

The objective of the project was to reduce real water losses by means of effective pressure management methods and increasing the capacity of staff dealing with

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network operation. The project was undertaken in close cooperation with the Water Authority of Jordan (WAJ) and generally envisaged in two phases.

Phase I: technical installation of a pressure management system

A feasibility study, comprehensive data collection, documentation and evaluation had to be undertaken at the beginning of the project. The various equipment parts were then fabricated, delivered and installed according to the detailed project plan.

A SCADA system was installed and connected to the WAJ's office in order to operate the PM system at its full potential and to monitor its performance continually. This step enables technicians and engineers to monitor and control the system precisely based on live data and to react quickly to changing demands.

Phase II: embedding PM knowledge

Once the technology was installed, extensive training courses and on-the-job instructions were undertaken to enable the local partner to continue operating the new system. The WAJ's managers and trainers attended an intensive training course in Germany at the outset.

At the same time, VAG experts helped to improve a local training centre for water engineers in Amman. The facility was equipped with training valves and wall charts, and will be used to teach 400 to 600 technicians and engineers per year on how to use valves and pressure reducing valves in the appropriate way. Additionally, Jordanian trainers have been trained in order to sustainably incorporate PM knowledge within the WAJ. Considerable time was spent on practical and theoretical training on the valves. At the end, the trainers had the opportunity to practice what they learned.

7.4.3 Good practice

The projects' advantages for the WAJ include:

- → increased efficiency and lower water supply costs
- → fewer pipe bursts through controlled and reduced pressure
- → increased lifetime of pipe system
- → water losses reduced (down to 30% NRW), saved water used to increase/ improve water supply
- → controlling the valves via the SCADA system
- → evaluation reports (day/week/month/year)
- → capacity development for Jordanian staff.

Reduction of minimum night flow (Flow 2 am)					
Date	No control (m³/h)	Date	With control (m³/h)	Minimum night flow reduction	
03.02.2008	55,01	02.03.2008	37,20	-17.81 m³/h	32%
04.02.2008	55,01	03.03.2008	37,92	-17.09 m³/h	31%
05.02.2008	62,86	04.03.2008	35,28	-27.58 m³/h	44%
06.02.2008	49,46	05.03.2008	34,08	-15.38 m³/h	31%
07.02.2008	51,30	06.03.2008	32,37	-18.93 m³/h	37%
08.02.2008	56,65	07.03.2008	41,05	-15.59 m³/h	28%
09.02.2008	47,16	08.03.2008	36,90	-10.27 m³/h	22%

Results obtained in the district of Santo Amaro between January 2005 and June 2006

7.4.4 Lessons learned

The project's approach of not only implementing PM systems, but also embedding knowledge on PM within the local partner's structures was successful. The WAJ monitors the PM system through the SCADA technology. Additionally, support from VAG can be requested at any time via the internet. Extending the WAJ training centre for water engineers by offering PM courses in Amman caters to sustainable capacity development which is further underlined by the *train-the-trainer* concept.

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Photo: © P. Klingel, 2006

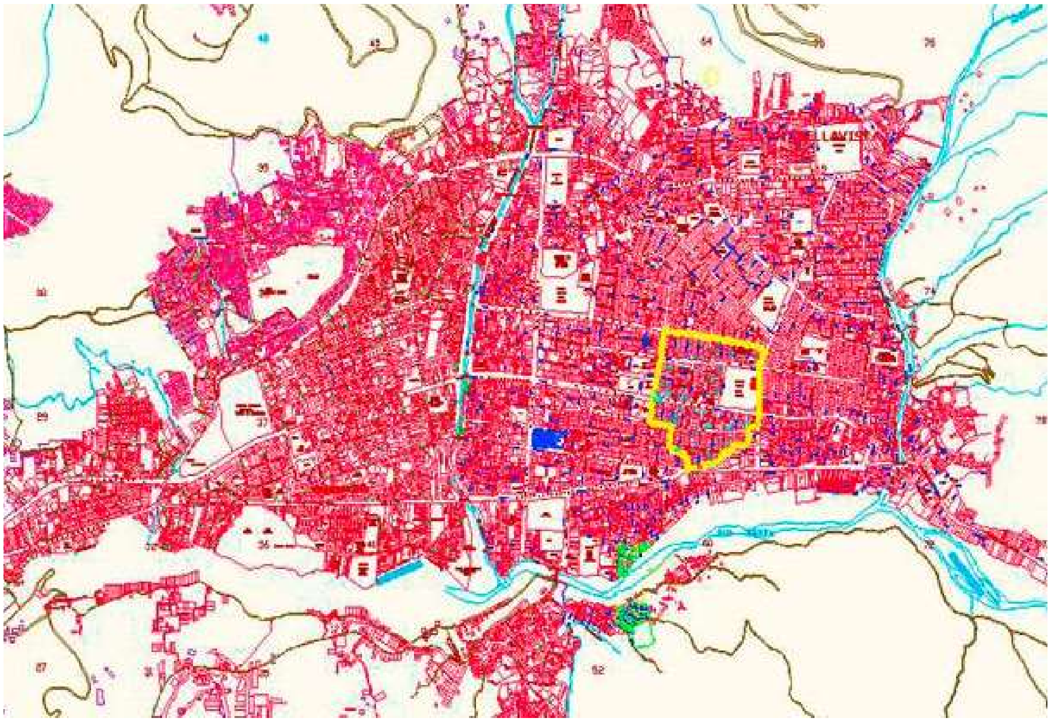
7.5 Reduction of apparent water losses – the example of Huaraz, Peru

Project title	Investigation of water losses and improvement of hydraulic efficiency in a pilot sector of the town of Huaraz.
Name of area	Huaraz District, province of Huaraz, Peru
Inhabitants **service connections**	101,430 22,483
Non-revenue water	51.4%
Project period/status	2008-2010
Reference	Program of measures with fast impact (PMRI)

7.5.1 Background

The city of Huaraz with 100,000 inhabitants is located in northeastern Peru at an altitude of 3,030 metres. Huaraz is a tourist city in the Alley of Huaylas surrounded by the country's largest mountain range. Its water is generated by melting water from the Cordillera Blanca. The water utility Chavin EPS SA is responsible for managing water distribution in the provinces of Huaraz, Huaylas, Chiquián and Aija.

The water utility's overall non-revenue water stands at 51.4% and is higher than the national average of 42.1%. Furthermore, the city has one of the highest consumption rates in the country with a daily per capita water consumption of 388 litres.



Municipality of Huaraz and the pilot area (yellow)

These high losses are generated by a large number of problems including: poor water metering, a large amount of unreported leaks, old pipes, inadequate maintenance techniques and an organisation which is poorly prepared to address these problems. Alternative methodologies were tested within cooperation carried out by GIZ and the water utility in a program of measures with fast impact (PMRI). These included tools, such as water balance, inventory of losses and hydraulic network modelling in order to improve the networks' hydraulic performance and establish a systematic methodology for detecting and controlling water losses.

Water utilities	Volume produced (m³)	Volume billed (m³)	Percentage of NRW (%)				
			2009	2008	2007	2006	2005
TOTAL	1,285,370	740,861	42.10	42.30	42.40	43.30	43.90
SEDAPAL	658,748	411,835	38.50	37.50	37.50	39.10	41.10
Large-sized	393,050	215,481	43.30	45.20	46.00	46.60	46.40
Medium-sized	194,124	99,449	49.70	48.80	49.40	49.60	48.20
Small-sized	39,446	14,094	53.00	62.00	54.00	53.60	50.50

Non-revenue water in Peru between 2005 and 2009. (SUNASS, 2010)

7.5.2 Process development

The work consisted of testing a methodology, using sectorisation and metering as tools to determine and control the condition of the supply system:

- → It started with the selection of a pilot area taking into account several criteria, including simplicity of closure, high continuity, high pressure level as well as diverse categories of consumption patterns.
- → The technical and commercial cadastral parameters has been updated in order to be used to conduct network modelling and estimate water demand.
- → Sectorisation was performed by isolating the pilot area from the rest of the system. The pilot area is composed of 263 service connections.
- → Every installed meter was read in order to find out the extent of under-reporting, which was further analysed by brand and age.
- → After isolation of the pilot area with single inlet, a bulk meter has been installed, allowing the hourly gross consumption of the sector to be recorded in periods of 24 hours and the water balance to be determined at minimum night flows. In addition, monitoring the tank's water level allowed pressure regulation methods to be adopted.
- → An inventory of losses has been carried out allowing the factors causing them to be identified. Commercial and operational corrective measures were taken. Under the new conditions, hydraulic modelling was performed and pressures were regulated within the sector.
- → Finally, a new water balance allowed the results of the adopted measures to be measured.

7.5.3 Results and good practice

The initial water balance showed a non-revenue water level of 69% in an area where 91% of asbestos cement pipes were more than 40 years old and 68% of connections were last metered an average of six years prior.

The loss inventory revealed that 80% of losses were apparent losses and the remaining 20% were real losses.

Corrective measures included installing meters in 121 households, renewing sub-meters and completing the sector metering to 100%. Furthermore, 3.1 km of the water network were inspected with acoustic geophones, ten unreported leaks were detected and repaired, eight of which were found in household connections. The pressure has also been regulated by reducing the peak pressure from 45 to 25 m.

In addition, an overflow in the Batán reservoir that supplies the area was detected where a daily volume of 405 m^3 had been wasted. This overflow was corrected by changing the control system. The final water balance showed a non-revenue water level of 29%, which demonstrates the effectiveness of the actions taken.

7.5.4 Lessons learned

The initial investigation into water loss reduction and operational improvements in a pilot area enabled visible short-term results with reduced investment levels and costs. These results led to general conclusions that can be converted into strategies applicable for the whole system.

The combination of measures, such as sectorisation, determining a water balance and an inventory of losses, allow long-term corrective measures to be identified. Corrective operational measures (installation of meters and leak detection) must be dealt with first. However, the results will not be sustainable without significant investments in rehabilitating old networks.

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Abbreviations

Abbreviations

AC	Asbestos cement
ALC	Active leakage control
AM	Area monitor
AMR	Automatic meter reading
ANEPSSA	Asociación Nacional de Entidades Prestadoras de Servicio de Saneamiento del Péru
ASCII	American standard code for information interchange
AWWA	American Water Works Association
AZP	Average zone point
CAD	Computer-aided design
CAPEX	Capital expenditure
CARL	Current annual real losses
CCTV	Closed Circuit Television
CIS	Customer information systems
DEM	Digital elevation model
DMA	District metered area
DN	Diameter nominal
DSS	Decision support system
DVGW	German Technical Association for Gas and Water
ELL	Economic level of leakage
EPANET	Hydraulic modelling software of the United States Environmental Protection Agency
FHNW	University of Applied Sciences Northwestern Switzerland
GAWANIS	Gas and water network information system
GIS	Geographic information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GPR	Ground penetrating radar
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global system for mobile communications
H	Head
IBNET	International Benchmarking Network for Water and Sanitation Utilities
ID	Identification
IEC	Institute for Ecopreneurship
IHM	Individual household monitor
ILI	Infrastructure leakage index

IWA	International Water Association
IWA WLTF	IWA Water Loss Task Force (since 2010: Water Loss Specialist Group)
IWG	Institute for Water and River Basin Management
KfW	Kreditanstalt für Wiederaufbau
KIT	Karlsruhe Institute of Technology
MNF	Minimum night flow
NDF	Night to day factor
NRW	Non-revenue water
ONEA	Office National de l'Eau et de l'Assainissement (Burkina Faso)
OPEX	Operational expenditure
P	Pressure
PE	Polyethylene
PI	Performance indicator
PLC	Programmable logic controller
PM	Pressure management
PMA	Pressure management area
PMI	Pressure management index
PPP	Public private partnerships
PRV	Pressure reduction valve
PVC	Polyvinyl chloride
Q	Flow
ROI	Return on investment
SABESP	Companhia de Saneamento Básico do Estado de São Paulo
SCADA	Supervisory control and data acquisition
SEDAPAL	Servicio de Agua Potable y Alcantarillado de Lima
TARL	Target annual real losses
TIN	Triangulated irregular networks
UARL	Unavoidable annual real losses
UFW	Unaccounted-for water
UNW-DPC	UN-Water Decade Programme on Capacity Development
VAG	VAG-Armaturen GmbH
w.s.p.	Number of days when system is pressurised
WAJ	Water Authority of Jordan
WDN	Water distribution network
WHO	World Health Organization
WLR	Water loss reduction

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"I am pleased to recommend this Guideline to all who wish to commit themselves to dealing with the problems of water loss management in distribution systems around the world. GIZ and VAG are to be congratulated on their initiative to promote IWA Water Loss Specialist Group principles, together with advanced European technology and know-how, to assist in achieving this important objective."

Allan Lambert, Water Loss Research & Analysis Ltd
Chair of 1st IWA Water Loss Task Force, 1996–1999

"The guidelines give a comprehensive overview of the full range of water loss management and are very valuable for planners in regards to the strategically sound handling of water losses. Especially the application of modern pressure management in conjunction with virtual DMA structures add to efficient water loss management in supply networks with high loss rates and failure frequencies."

Dipl.-Ing. Erwin Kober, Managing Director, RBS Wave

"These guidelines can be useful in serving the wider water community in reducing water loss in distribution systems. UNW-DPC can make sure these are disseminated among interested collaborators as well as encourage their use during our worldwide capacity development events."

Dr. Reza Ardakanian, Director UN-Water Decade Programme
on Capacity Development (UNW-DPC), United Nations University

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