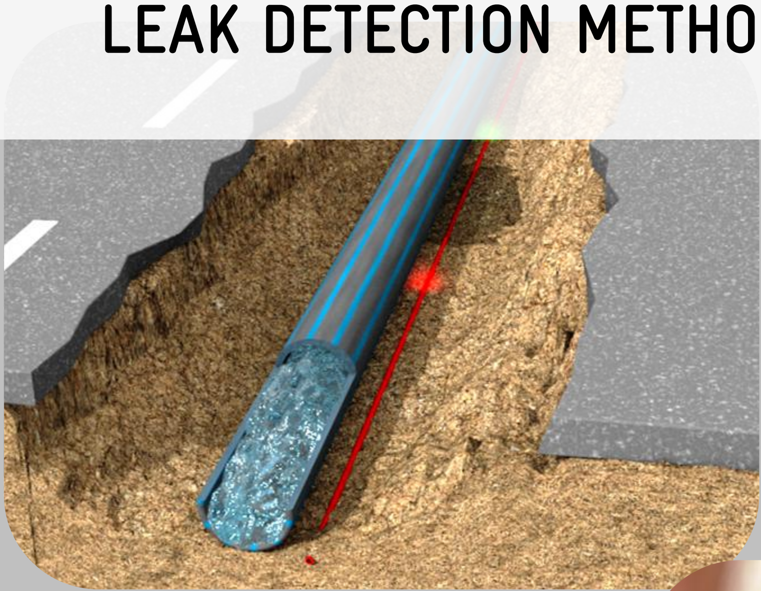
COMPARISON OF SUITABLE LEAK DETECTION METHODS



Selection Guideline with special consideration of the conditions in countries with emerging markets and developing economies

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

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Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

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This study is a product of the GIZ Resource-Efficient Water Management Community of Practice, and was technically and financially supported by the bilateral projects “Energy Efficiency for Sustainable Urban Development” (Brazil), “Sustainable Urban Development - Smart Cities” (India), “Climate Resilience of the Water Sector in Grenada” (Grenada) and the “Competence Center Water, Wastewater and Waste Management” (FMB Germany).

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Photo credits/sources: Front cover: Courtesy of Sensor Group & H. Sewerin GmbH. Back cover: Own work & viZaar industrial imaging AG. The sources of all illustrations and photographs used in the text are indicated below each one. If no source is mentioned, the author of this text is the source.

1st Edition, Eschborn, 2022
DOI: 10.5281/zenodo.6625858

CONTENT

ACRONYMS AND ABBREVIATIONS

DAS	Distributed Acoustic Sensing
DMA	District Metered Area
DTS	Distributed Temperature Sensing
e.g.	exempli gratia (for example)
EMDEs	Emerging Markets and Developing Economies
etc.	Et cetera (and so on)
LED	Light-emitting diode
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (German Corporation for International Cooperation)
GmbH	German acronym for "Gesellschaft mit beschränkter Haftung" (limited liability company)
GPR	Ground-Penetrating Radar
GSM	Global System for Mobile Communications
HDPE	High Density Polyethylene
NRW	Non-Revenue Water
PE	Polyethylene
POI	Point of Interest
PVC	Polyvinyl chloride
UK	United Kingdom
USA	United States of America
W	Watt (unit of power)

1. INTRODUCTION

1.1. Preface

Figure 1. Leak located with acoustic methods in Peru (Cortesy: H. Sewerin GmbH)

Unlike the countless existing publications about leak detection, it is not the intent of this study to address the importance of leak detection and repair in reducing water losses, increasing supply security, or energy efficiency of water utilities, etc. It is assumed that the reader will pick up this document because they are already aware of these aforementioned facts.

Many water utilities use equipment that is not suitable or only applicable to a limited extent under specific local conditions. Lost working time and unused, often expensive equipment in storage are only two of the typical wastes. Other consequences on the one hand, are that methods which can work very well under certain conditions are branded as useless and discourage other utilities from using them. On the other hand, many methods are still relatively unknown and can offer an important and efficient contribution to the pre-location and location of water leaks by reducing the effort, helping to prioritise the actual location work, reducing mislocations or locating smaller leaks with pinpoint accuracy - even under difficult environmental conditions.

None of the methods described below can detect or locate all leaks under all circumstances. Each method has its advantages over the others under certain conditions, even though those may only be cost advantages. In most cases, a combined application of two or more methods is advisable. The factors influencing the selection of suitable leak detection methods are numerous, ranging from purely technical factors such as water pressure, soil conditions, pipe diameter and material to environmental factors (rain, heat, noise) and social factors (crime). The capabilities of the water utility itself are crucial as well - since in most cases qualified and experienced personnel play an important role.

Therefore, this publication is intended to support water utilities, especially in EMDEs, (Emerging Markets and Developing Economies), to broaden their knowledge of the currently available methods, including their advantages, disadvantages, application possibilities and limitations to be able to make an initial pre-evaluation of the methods under the respective local conditions. Depending on the situation, this may lead to certain methods being excluded from the very beginning and others being shortlisted. However, under no circumstances should this publication be used as the sole criterion for purchasing equipment or subcontracting leak detection services. In addition, the utility's existing experience, as well as experiences of other utilities with similar problems and conditions, should be included and at least on-site demonstrations of the methods or pilot projects, if needed, should be carried out in the final decision process.

This publication has been prepared mainly through interviews with experts and providers, in addition to the inclusion of own experiences and the use of cited literature, linked websites, webinars, videos, etc. It certainly contains some errors or inaccuracies that cannot be attributed to the interviewees mentioned in the acknowledgements and that could be corrected in a subsequent edition. Therefore, we ask readers (including leak detection method providers) to contact the author by email, either to correct these errors or to suggest additional contributions such as new methods or other variants of the methods.

1.2. Overview and classification of included methods

A total of 24 methods of leak pre-location and leak location are described and evaluated under different aspects in chapters 3 and 4. The distinction between the individual methods is partly fluent and, in individual cases, methods listed in this publication under "Variants" are listed as independent methods in other publications. The locating principle was used as the most important criterion for differentiation. In addition, the practical application for different leak detection tasks (e.g., for indoor leakage or large pipelines) and the availability of information at the time of publication also played a role - albeit a subordinate one.

The 24 methods can be classified in different ways. The most common form of categorisation is the leak detection principle applied, i.e., following the traces left by a water leakage - either the noise produced by the leaking water (acoustic), the fact that the lost water quantities are missing downstream (flow-rate), the temperature changes in the vicinity of the leak (thermal) or other principles. The methods are described in this order of classification.

Another possibility of classification is the difference in the application of the sensor technology. Here, four different categories can be identified: (1) methods where the leak sensors are guided through the pipe in a mobile way - so-called pigs, (2) methods where the sensor elements are placed near the pipe in the form of a cable, (3) methods where the sensors are attached at a point on or in the pipe and (4) methods where no contact with the pipe and also not with the water column is necessary. The table below shows both ways of classification.

Table 1. Classification of leak location methods by principle and sensor type

N°	Method	Principle	Sensor type
1	Listening rods	Acoustic	Contact sensor
2	Ground microphones	Acoustic	Contactless sensor
3	Leak noise correlation	Acoustic	Contact sensor
4	Noise logging	Acoustic	Contact sensor
5	Pushed hydrophones	Acoustic	Pig
6	Tethered hydrophones	Acoustic	Pig
7	Free-floating hydrophones	Acoustic	Pig
8	Distributed Acoustic Sensing (DAS)	Acoustic	Sensing cable
9	Volume balance	Flow-rate	Contact sensor
10	District Metered Areas (DMAs)	Flow-rate	Contact sensor
11	Flow monitoring	Flow-rate	Contact sensor
12	Step test	Flow-rate	Contact sensor
13	Hydraulic leak localization pig	Flow-rate	Pig
14	Thermal imaging cameras	Thermal	Contactless sensor
15	Thermal imaging drones	Thermal	Contactless sensor
16	Distributed temperature sensing (DTS)	Thermal	Sensing cable
17	Moisture measurement	Moisture	Contactless sensor
18	Moisture sensing smart-cables	Moisture	Sensing cable
19	Ground Penetrating Radar (GPR)	Electromagnetic	Contactless sensor
20	Satellite radar	Electromagnetic	Contactless sensor
21	Tracer-gas	Chemical	Contactless sensor
22	Sniffer dogs	Chemical	Contactless sensor
23	Negative Pressure Wave Method	Pressure	Contact sensor
24	Soil probes	Mixed	Contactless sensor

1.3. Methodology of comparison

The different methods used to detect and locate water leaks will be analysed consecutively according to the following aspects:

Overview of the method: Here, the principle of leak detection is first described in a summary with the help of illustrations. In addition, the respective method is classified according to the locating principle, the type of sensor used and its applicability for various leak detection tasks. This should make it easier for the reader to quickly identify the methods relevant to his local conditions. The most important influencing factors are also presented, and some providers of equipment or services are linked. These links to the providers include, if possible, links to products with the different characteristics described under variants of the method.

STEP-BY-STEP DESCRIPTION

Under this header, a step-by-step description of a typical application of the analysed method is given. However, it should only be taken as an example as the application of every method could vary from case to case depending on local conditions and specific tasks.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: These are those variants that follow the same leak detection principle but differ somewhat in their application. If necessary, these variants are also dealt with selectively in the other aspects evaluated.

Combined application with other methods: All methods are always used in combinations with other methods within the process of leak detection, pre-location, location, pinpointing and confirmation of water leaks. Therefore, it will be discussed here which methods are most frequently combined with the described method.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): For each method, the relative frequency with which leaks are not found and the most important influencing factors that could increase or decrease the likelihood of this are analysed.

Likelihood of false positives (dry holes): For each method, the relative frequency of leaks falsely detected and identified as such occur and the most important factors influencing these false alarms are mentioned.

Margin of error: Analysis of the accuracy with which leaks are located and the main factors influencing this margin.

SCOPE AND LIMITATIONS

When should this method be considered? Technical conditions, local circumstances and areas of application, in which the analysed method can work particularly well, are discussed here.

When not to consider this method? Factors that may negatively affect the ability of the tested method to detect and locate leaks are discussed here.

Considerations for application in characteristic circumstances in EMDEs: In this section it is analysed which framework conditions, typically common in EMDEs, can have a positive or negative impact on the applicability of the method. If the method is particularly suitable, this is indicated by a green thumbs-up.

INSTITUTIONAL ASPECTS

Required qualification: This refers to the training that the utility staff should receive before using the method for the first time. This training should usually be provided by the supplier of the equipment required for the method. The necessary pre-qualification will be addressed on a case-by-case basis.

Required experience: This refers to the necessary experience to successfully apply the method in the long term, to be able to assess how staff instability in combination with a lack of good internal knowledge management can affect the utility. In individual cases, useful experiences with other methods are discussed.

Usefulness of outsourcing the method: This item deals with the question of the extent to which it may be worthwhile, from a technical and economic point of view, to outsource the discussed leak detection method.

Necessary or desirable framework conditions at the utility: Here, the prerequisites are addressed that should be fulfilled at the respective utility to successfully use the discussed leak detection method.

ECONOMIC ASPECTS

The cost-effectiveness of the respective method depends on countless technical and economic factors. Therefore, it is not possible to make general statements about whether a method is particularly costly or cost-effective. Nevertheless, some indications will be given to enable the reader to get a clearer idea of the necessary resources for the application of a method in a particular case. To this end, the **investment costs** and the **additional operating costs** are described and quantified where possible. It should be noted that the costs for equipment refer to the price in the country of manufacture, which can be 50% to 100% higher from country to country due to import and transport costs, as well as intermediary margins. In addition, an estimate of the **required number of staff** is given.

Possible additional advantages or disadvantages of the method for utilities: Under this point, additional possible uses of the method are explained. For example, those that are not directly related to leak detection, but bring additional benefits for the utility. In some cases, negative side effects are also mentioned. Where these do not exist, this item is not listed.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Here, the history and the development of the method up to the time of the study are briefly described to better understand the current state of development of the respective leak detection method.

Market penetration: A brief assessment of the current worldwide spread of the application of the method is given here. Where necessary, a distinction is made between the water sector and other sectors, and differences between the spread of the method in EMDEs and industrialised countries are discussed.

Outlook: Under this heading, an often subjective outlook is given for the coming years, in particular on possible technical developments and economic aspects and how this might influence the dissemination of the method, especially in EMDEs.

FURTHER INFORMATION

Links to further useful information about the method are given and briefly described. Among them are case studies, manuals, technical articles and videos. The short videos should help to illustrate the actual description of the method and to facilitate its understanding.

2. DESCRIPTION OF THE METHODS

2.1. Acoustic Methods

2.1.1. General information on acoustic methods

Some of the acoustic methods presented here are the longest used and most widespread leak detection methods. Nevertheless, acoustic location is still being further developed. All acoustic methods are based on the detection of sounds produced when water escapes from leaks. By their differentiation from other noises, leaks can be pre-located, located or pinpointed. Sound propagates in three possible ways: firstly structure born, i.e., through the pipes and fittings themselves, secondly through the water column and thirdly through the surroundings of the pipes (the ground or walls). Each of the different acoustic methods can make one or more of these propagation forms of noise audible or visible (see table below).

Table 2. Acoustic methods by sound propagation medium used for leak detection (in the case of the yellow marked box the use of the method is still restricted)

N°	Method	Sound propagation		
		Ground or Walls	Pipes and Fittings	Water column
1	Listening rods		☑	
2	Ground microphones	☑		
3	Leak noise correlation		☑	☑
4	Noise logging		☑	☑
5	Pushed hydrophones			☑
6	Tethered hydrophones			☑
7	Free-floating hydrophones			☑
8	Distributed Acoustic Sensing (DAS)	☑		☑

Due to their nature, acoustic methods depend on numerous influencing factors: on the one hand, the strength of the original noise, which depends on the shape and size of the leak, and especially on the water pressure; on the other hand, also on factors that favour or hinder the propagation of sound, such as pipe material, diameter, soil properties, etc. This is discussed in detail in chapter 4.

2.1.2. Listening rods

OVERVIEW	
Type of method: Temporary mobile pre location method	
Location principle: Acoustic	**Sensor type:** Contact sensor

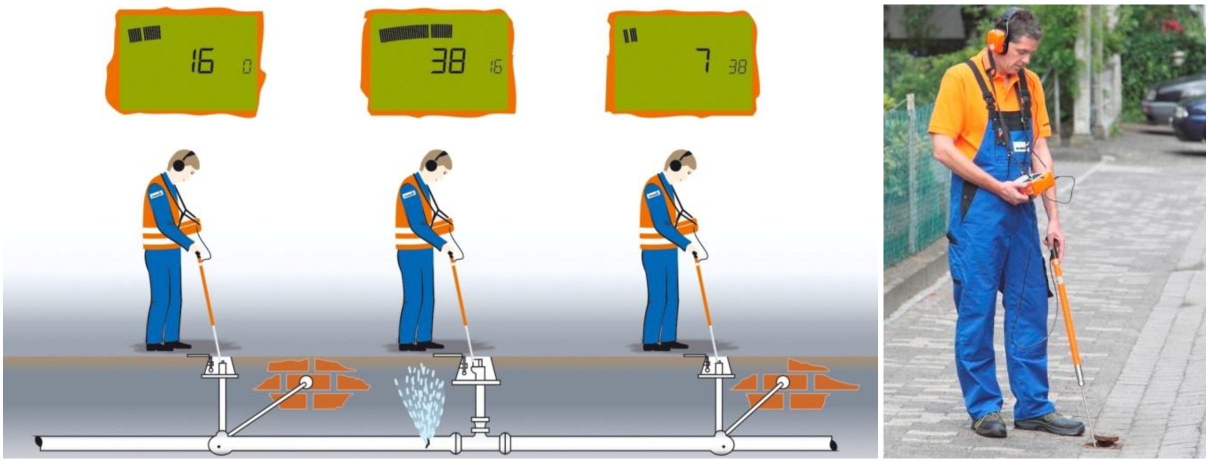


Figure 2. Left: Principle of using the listening rod – walking from fitting to fitting to find if there is a leak noise; Right: Listening rod in outdoor use (Both courtesy of H. Sewerin GmbH)

Leak location principle: With the help of listening rods (also called test rods or, especially the smaller devices for indoor applications listening sticks), the sound vibrations caused by leaks and conducted through pipes and fittings are made audible and sometimes also visible. The noises can also be filtered and amplified. The comparison of the loudness of the leakage noises at the different contact points provides information about the proximity to the leak.

Areas of application	
Applicability for indoor leak location	Yes (one of the most important methods)
Applicability for distribution networks	Yes
Applicability for large diameters pipes	Exceptionally with many access points

Influencing factors			
Water pressure	Important	**Intermittent supply**	Restricts time of use
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary
Pipe material	Important	**Need for access points**	Many (Pipe or fittings)
Soil conditions	No influence	**Method-specific negative factors**	Background noise

Links to providers
SebaKMT GmbH; H. Sewerin GmbH (both Germany); Halma Water Management Ltd. (UK)

STEP-BY-STEP DESCRIPTION

1st Step: Often the first step is to look for hidden fittings, e.g., buried gate valves. Metal detectors are often used to find them.

2nd Step: The listening rod is placed on accessible elements of the water network (gate valves, meter boxes, hydrants, etc.) and noises caused by leaks are identified in this way. In individual cases, the loudness can provide information about the distance of the leak (the louder, the smaller the distance).

3rd Step: To be able to further narrow down the exact location of the leak, it is necessary to listen to other nearby elements of the water network if possible. In individual cases (leakage very close to tested element), it can be located precisely enough to carry out an excavation. In most cases, however, it is only possible to say that there is a leak in the vicinity of a particular fitting or between two of them.

4th Step: After the pre-location with this device, another method is usually used to locate the leak precisely - often a correlator is used afterwards. In the case of leaks in service connections, this can also be a pushed hydrophone or a ground microphone. Other methods are also conceivable, depending on the circumstantial conditions.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the Method: Although listening rods equipped with electronic filters today are most common now, mechanical rods are also used, as they have been for over 100 years. These are extremely robust and very cost-effective. To reach deeper elements (e.g., fittings in manholes), many manufacturers supply magnetic sinking probes or extended rods.

Combined application with other methods: As a classic pre-location method, the combined use with other methods is almost always necessary. In most cases, the ground microphone is used for pinpointing a leak, especially if the listening stick and ground microphone are available as a set. If it is difficult to use the ground microphone (e.g., sound-absorbing ground or deep-lying pipes), tracer gas, or pushed hydrophones, etc. could be used. In the case of overbuilt lines, leak noise correlators are very helpful, and are also very often used as an intermediate step between listening rods and ground microphones.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of not detecting existing leaks is relatively high, but depends on many factors, especially distance between access points, pipe material and pressure. Quiet leaks can be easily overheard, especially if they are not close to the probed fitting.

Likelihood of false positives (dry holes): False alarms are relatively common, especially in systems with a lot of background noise, e.g., due to throttled valves or pressure reducing valves and areas with a lot of ambient noise. However, since it is just a pre-location, this rarely leads to excavations, but to additional leak detection efforts, where the existence of a leak can then often be confirmed or ruled out.

Margin of error: The margin of error depends mainly on the distance between the used fittings but is also very high for nearby fittings, so this is a pre-location method.

SCOPE AND LIMITATIONS

When should this method be considered? The method works technically best the better the sound conduction of the pipes is and the more access points there are. It works especially well in quiet places or at a quiet time of day and with high water pressure. It can also be used very well in utilities with low resources of any kind (investment, personnel, transport, etc.), even if there is limited knowledge of the pipe location. The method allows a quite fast pre-location of leaks.

When not to consider this method? The limitations of this method are a result of the interaction of the following factors:

1. **Plastic pipes:** Sound propagates differently depending on the material. Best in metallic pipes, followed by concrete, asbestos cement and plastic pipes (in that order). The less the material conducts noise, the more difficult (on smaller distance), leakage noises are to track.
2. **Low water pressure:** the lower the pressure, the quieter the leakage sound and the shorter the distance that the sound propagates.
3. **Distance of accessible elements of the water network:** the less accessible elements in an area (the greater the distance between them), the more difficult it is to detect a leak.
4. **Background noise:** the more background noise (e.g., pumping, throttled valves or water consumption) or ambient noise (e.g., traffic), the more difficult it is to detect leakages noises. Noise can be limited by diverting traffic or by limiting leak detection to quiet days/times.
5. **Intermittent supply:** Only works during supply, as without water in the pipes there is no leakage noise.

Considerations for application in characteristic circumstances in EMDEs: Since investment in the equipment is low, the method is very suitable for EMDEs. Added to this is the fact that service connections are often much easier and more frequently accessible than in industrialised countries and there are therefore many more contact points. This makes the method much easier to apply and often more accurate.

INSTITUTIONAL ASPECTS

Required qualification: Not much qualification is needed - the devices are almost self-explanatory. However, the trend is towards somewhat more complicated devices with filter and amplification options, which require additional training.

Required experience: As with ground microphones, a trained hearing is very important - especially in order not to confuse ambient and background noise with leakage noise. Also, in utilities with imprecise and incomplete technical cadastres, a good knowledge of the location of possible contact points (position of buried valves etc.) is helpful. It is a considerable advantage that most utilities already have staff with experience in using such devices.

Usefulness of outsourcing the method: If the utility completely outsources leakage detection, the method will undoubtedly be used by the service provider. Otherwise, the low investment and relatively simple application with fewer staff do not require outsourcing.

Necessary or desirable framework conditions at the utility: Knowledge about the location of the pipes is not as important as with other methods. However, network knowledge can help to save time, e.g., if it is known where valves or other suitable access points are located. In addition, knowledge of the location of the pipes is most of the time necessary for subsequent locating and pinpointing of the leakages.

ECONOMIC ASPECTS

Acquisition cost: Devices for indoor leak detection are usually cheaper (€ 100 -1,000) than those for outdoors, which cost around € 1,000 - 2,000. However, it must be taken into account that devices for outdoor use are almost always offered in combination with ground microphones. This combination costs € 1,500 - 4,000, depending on the features and accessories. There are also mechanical listening rods without any electronic accessories, which cost around € 100 - 200.

Required number of staff: One operator per device.

Additional operational costs: Except for low costs for charging the batteries there are no additional operational costs with this method. Motorised transport of the equipment into the field is not necessary; the operator can walk with the device from one contact point to another. However, as the method is used often in combination with other methods (indoors and outdoors), a car is often still necessary.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: With the help of this method, leaks were already found in the 19th century. Since about the 1950s and 1960s, listening rods have become increasingly user-friendly and are equipped with better filter/ amplification options and also with graphic display and analyses of the results. Nevertheless, traditional listening rods are still widely used. In utilities without any equipment, simply steel rods or pipes with the same objective are used.

Market penetration: Leak pre-location with listening rods has traditionally been the most widely used method worldwide, together with the ground microphone (for locating). Almost all utilities are using them.

Outlook: Despite the numerous new technical developments with more and more methods on the market, this method will continue to maintain a leading position and will not be displaced by other methods. However, combined applications with other methods are already becoming much more common and will continue to do so in the foreseeable future. There is also an increasing integration with other devices in kits.

FURTHER INFORMATION

Playlist of 4 instructive videos about listening sticks for the search of indoor leaks (5 min in total);

Playlist of 5 instructive videos about listening rods for outdoor leak detection (8 min in total);

Video of a typical field mission with the listening rod outdoors (2 min);

Report on leak detection at Wessex Water (UK) with the use of mechanical listening rods (4 min)

2.1.3. Ground microphones

OVERVIEW	
Type of method: Temporary mobile pinpointing method	
Location principle: Acoustic	**Sensor type:** Contactless sensor

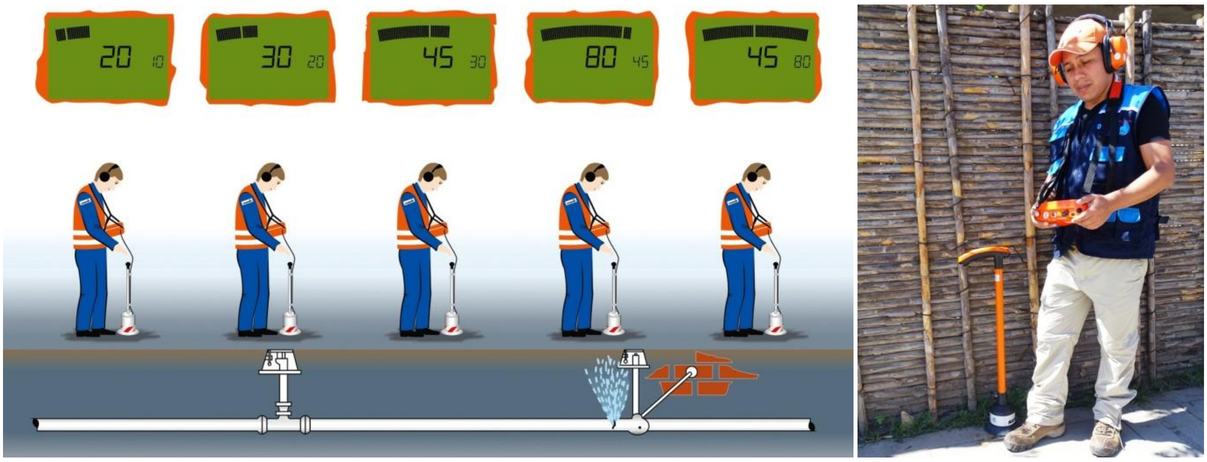


Figure 3. Left: Principle of the ground microphone - the louder the leak noises, the closer to the leak (Courtesy: H. Sewerin GmbH). Right: Modern ground microphone in field use

Leak location principle: With the help of ground microphones, often also called geophones, sound vibrations are made audible and sometimes also visible and then filtered and amplified. For this purpose, the microphone is placed on the ground at short intervals. As leak noises are transmitted through the ground to the surface, the operator of the device can distinguish those noises caused by leaks from others.

Areas of application	
Applicability for indoor leak location	Sometimes
Applicability for distribution networks	Yes (main use)
Applicability for large diameters pipes	To some extent for pinpointing

Influencing factors			
Water pressure	Important	**Intermittent supply**	Restricts time of use
Pipe depth	Important	**Knowledge of pipe location**	Very helpful
Pipe material	Some influence	**Need for access points**	Not needed
Soil conditions	Some influence	**Method-specific negative factors**	Ambient noise

Links to providers
Hermann Sewerin GmbH; Fast GmbH (both Germany); Halma Water Management Ltd. (UK)

STEP-BY-STEP DESCRIPTION

1st Step: In the area identified by a pre-location method, routes above the pipelines are determined based on site plans, external signs or information from the residents, which are to be followed with the ground microphone.

2nd Step: This route is followed by an operator who sets up the ground microphone and listens at certain intervals. The distance between these intervals can vary from 20 cm to one and a half metres and depends mainly on the soil composition, as noise propagates differently. I.e., in loose sandy soils, the output sound can only be heard with the ground microphone near the leak and even at these points, the noise is comparatively quiet. In this case, the intervals at which the ground microphone is placed should be significantly shortened. Furthermore, the distance of the intervals depends to a lesser extent on the depth and material of the pipes.

3rd Step: If characteristic leakage noises can be heard, the point where they are strongest is determined. With modern ground microphones, the noise levels at different points can also be measured, displayed visually and compared with each other. Additionally disturbing noises can be filtered.

4th Step: Starting from the point with the highest noise level perpendicular to the pipeline, more measurements are made. If the noise level decreases with increasing distance from the pipe, as expected if the leakage was pinpointed correctly in the previous step, the leakage can be considered confirmed. This point is then marked with a spray so that the excavation can be carried out here later

5th Step: Especially if there are doubts due to unfavourable environmental conditions (e.g., loud ambient noise combined with not very noisy leakage), the leakage can be confirmed with the help of a soil probe to avoid dry holes. Other ways to silence environmental noise are to check the leakage position again at a quieter time or to close the street from traffic for a certain time.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Differences result from the level of development of the devices - some, very cheap, work mechanically; others have sophisticated filtering, amplifying and analysis mechanisms. Some ground microphones are supplied with long metal rods, which are not used as listening rods in the true sense of the word but are designed to be driven into the ground or inserted through pre-drilled holes. The purpose is to get somewhat closer to the leakage site to hear it better. This is done especially in the case of quiet leakages or a lot of ambient noise to avoid dry holes this way.

An interesting variant, which was distributed in the UK from 2002 to 2008, was the so-called "Magic Carpet". It consisted of eight interconnected microphones, which simultaneously listen for leaks at an already suspicious point at a distance of 30 cm from each other, thus making the location somewhat more precise than is possible with a single ground microphone. However, the device has not caught on, probably because the slightly more accurate location is not worth the extra effort. Following the same principle, a few noise loggers placed close to each other are sometimes used.

Especially for indoor use, some devices work according to the same principle, but are smaller and more mobile to better reach corners and angles.

Another variant, which is used more often in the search for indoor leaks and sometimes in small diameter distribution networks, is the pressure test with air. It consists of injecting compressed air into the pipes with the help of a compressor or compressed air cylinder. The air then escapes with loud hissing noises and can be located with ground microphones or listening rods (Kersting 2015: 45). It is used when the water pressure is not sufficient to produce audible noises or the pipes are empty due to intermittent supply. Although the method is effective in finding leaks and cheap to use, it is always better to use other methods for a very good reason: since air is compressible, high-pressure air bubbles can collect in some places and turn into a real bomb. That can not only cause more damage than the leak looked for but can also injure or even fatally injure the leak locator (see a very illustrative video here). Additionally, it should be considered that the air inserted in the pipes for potable water must meet certain requirements. It must be germ-free and free of oil and dust. Therefore, a special compressor with respective filters is required for this method. Although more laborious, it is much safer to temporarily build up water pressure in the network if hydraulically possible, or to build up water pressure in certain sectors with the help of tankers. Indoors a pressure test with the help of a pressure test pump can be used not only to build up a pressure that makes leaks audible, but also to see if the pressure drops as confirmation of a leak.

Combined application with other methods: Using ground microphones without proper pre-location usually takes far too long. That is why the ground microphone is almost always combined with other methods, whereby it is mostly used to pinpoint leakages precisely only after other methods have previously identified the approximate location. These other methods very often include listening rods and leak noise correlators, but also many other methods. It should be noted that a ground microphone is almost always part of the basic equipment of leak detection teams. Therefore, it is also used to confirm leakages located by other methods, to prevent dry holes. Many leak locators still confirm a leak located with the ground microphone with soil probes.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of overlooking leaks is medium and depends on many factors (ambient noise, pipe depth, water pressure). Under optimal conditions, only a few, insignificant leaks will be missed. Quiet leaks can easily be missed. It should be noted that the noise level is not always proportional to the size of the leak - large leaks can make it easier for the water to escape more quietly and, conversely, small leaks can be much louder, especially at higher water pressure.

Likelihood of false positives (dry holes): The probability of false alarms is low to medium and is higher the higher the ambient noise level is.

Margin of error: The margin of error is very small compared to most other methods (often less than one meter), which is why ground microphones are used especially for pinpointing leaks. The margin of error can be somewhat higher with deeper pipes, non-homogeneous soils, and floor coverings and in soils with very good noise conductivity like rock.

SCOPE AND LIMITATIONS

When should this method be considered? The ground microphone is preferably used when a leakage has already been suspected and narrowed down to a specific, not too large area, to confirm its presence and to pinpoint it.

When not to consider this method? Limitations are a result of an unfavourable combination of the following factors:

1. **Low water pressure:** the higher the pressure, the louder the output noise and the further the sound propagates. Consequently, pipes with low pressure are less suitable for inspection with ground microphones.
2. **Deep pipes:** the deeper the pipe, the more difficult it is to hear a leak.
3. **Unfavourable ground conditions:** the better the soil conducts the sound, the easier it is to hear the characteristic noises at the surface. Conversely, this means that in soils with a high level of sound absorption (loose soils, sand) it is more difficult to locate the leak.
4. **Many ambient noises:** the more noise (traffic, heavy rainfalls), the more difficult it is to distinguish the leakage noise. This influence can be reduced by rerouting traffic or by rescheduling the search for quiet days or certain times of the day. Sometimes disturbing noises can be filtered out by the devices.
5. **Inaccessibility:** Since the method can only locate leaks when the device is directly above the leak, there are sometimes situations where this is not possible (overbuilt pipelines or those under rivers).

Considerations for application in characteristic circumstances in EMDEs: Since the low investment in the method is offset by higher personnel requirements and personnel costs are usually much lower in EMDEs, the method is even more suitable there than in industrialised countries. This is especially the case if other devices such as correlators are not available and therefore longer distances are surveyed with the ground microphone. In addition, damage rates are usually much higher in EMDEs, so the massive use of ground microphones - often inefficient in industrialised countries due to high personnel costs and far fewer leaks - pays off much quicker. On the other hand, this method often cannot give good results in supply areas with low pressure.

INSTITUTIONAL ASPECTS

Required qualification: Very low, the devices are almost self-explanatory and most of the utilities are already working with such devices. However, the technical development is moving towards somewhat more sophisticated devices with additional filter options and different analysis tools, which require some additional training.

Required experience: A well-trained sense of hearing is very important - especially to avoid misidentifying ambient noises as leaks. However, good hearing sense can only be trained to a certain degree with field experience. Especially in utilities with imprecise and incomplete technical cadastres, good local knowledge (location of the pipes or how this can be determined on-site) is also helpful. The user should also have solution competence and the ability to interpret the various influencing factors. It should also be noted that this method is rarely used alone, so the operator should be familiar with the use of other leak detection methods.

Usefulness of outsourcing the method: If the utility generally outsources leak detection, the method will also undoubtedly be used by the service provider. Otherwise, the low investment and relatively simple application with fewer staff do not require outsourcing. It may even make sense to have a ground microphone in stock at the utility for urgent applications despite outsourcing.

Necessary or desirable framework conditions at the utility: Knowing the location of the water mains is desirable to place the ground microphone as accurately as possible above them. If the location of the pipes is not known, the search for leaks takes longer and becomes less accurate. Besides that, the devices do not impose heavy requirements on the utilities.

ECONOMIC ASPECTS

Acquisition cost: The investment in a modern device is about € 1,500 - 4,000 and depends on the sophistication of the device and the accessories supplied (e.g., microphones for different surfaces). Most manufacturers deliver the unit with a listening rod. There are also mechanical ground microphones without electronic accessories, which cost between € 250 and 400.

Required number of staff: One operator per ground microphone. As a leak detection team usually consists of at least two people, some devices offer the option of two people listening at the same time, e.g., if the operator thinks he has located a leak but needs a second opinion. Furthermore, since the ground microphone is mostly used on public roads, another person is usually necessary for safety reasons.

Additional operational costs: Motorised transport is practically always necessary since the ground microphone is usually combined with other methods. Otherwise, only small electricity costs are incurred for charging the batteries.

Possible additional advantages or disadvantages of the method for utilities: Ground microphones can also be used in combination with other devices to search for illegal connections (Ziemendorff & Kersting 2020).

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The first ground microphones were purely mechanical devices similar to stethoscopes and have been used in leak detection for over 100 years. Purely acoustic devices are still in use in many places today. The first electro-acoustic devices appeared around the 1940s and since then have featured increasingly more sophisticated options and higher sensitive microphones. Since the 1950s more devices with graphic display of the results have come onto the market. In addition, the devices are gradually becoming lighter and wireless.

Market penetration: Leak detection with ground microphones, together with the listening rods (for pre-location), is by far the most widely used method worldwide.

Outlook: Despite the numerous new technical developments with more and more methods on the market, this method will continue to maintain a leading position and will not be displaced by other methods. However, combined applications with other methods are already becoming much more common and will continue to do so in the foreseeable future. There is also an increasing integration with other devices in device kits. This is common in the integration of listening rods and ground microphones, and now both are even integrated with tracer gas sniffers in a single device. In addition, some noise loggers are recently being used as ground microphones.

FURTHER INFORMATION

Animated video of combined use of listening stick and ground microphone (3 min)

Video of a typical field mission with listening stick and ground microphone (4 min)

Instructional video about a combined listening rod – ground microphone (28 min)

2.1.4. Leak noise correlation

OVERVIEW			
Type of method: Temporary mobile location method			
Location principle: Acoustic		**Sensor type:** Contact sensor	

Figure 4. Left: One of two microphones with radio connected to a fitting; Right: Screenshot of a located leak indicating distances to each microphone (Both courtesy of H. Sewerin GmbH).

Leak location principle: With leak noise correlators, normally two, sometimes more microphones register leakage noises at different points in the pipe. By calculating the transit times of the sounds, which depend on various factors (like pipe material and the length of the correlated sections), a prediction can be made about the approximate location of the leakage.

Areas of application	
Applicability for indoor leak location	In exceptional cases
Applicability for distribution networks	Yes (main use)
Applicability for large diameters pipes	To some extent with hydrophones

Influencing factors			
Water pressure	Important	**Intermittent supply**	Restricts time of use/ air pockets
Pipe depth	No influence	**Knowledge of pipe location**	Necessary
Pipe material	Important	**Need for access points**	Some-many: pipe, fittings, water column
Soil conditions	No influence	**Method-specific negative factors**	Background noise

Links to providers

SebaKMT GmbH; TROTEC GmbH; H. Sewerin GmbH (all Germany); MWP Inc. (USA)

STEP-BY-STEP DESCRIPTION

1st Step: Exact network maps must be obtained for the pipelines to be correlated, in which in particular the pipe lengths, the diameter and the pipe materials used must be shown.

2nd Step: On-site, one should first try to eliminate all external noise sources (block off traffic, switch off pumps, or possibly choose a better time of day).

3rd Step: Before beginning to correlate, fittings are checked with the help of a listening rod and correlation is then normally carried out only when a leakage has been pre-located with them.

4th Step: In the area where the leakage is to be located, at least 2 (sometimes more; see variants of the method below) microphones or hydrophones are now connected (never both/mixed) to fittings or the water column. The contact points of the microphones are always cleaned first. It must be made sure that the distance between the two microphones is chosen so that both can detect leakage over the entire distance between them. This depends, among other things, on the material, pressure, and diameter.

5th Step: Now the length of the pipe and the sound velocity of the pipe between the microphones are entered into the central unit (the actual correlator). Since the sound velocity is usually not known, it is determined by the correlator with the help of a table. The diameter and the material are used for the determination. If the pipe is segmented and these segments have different materials and/or diameters, this must also be entered into the correlator for the calculation. Whether the diameter influences the sound velocity is at least controversial (see further information). Optionally, the sound velocity can also be determined by an artificial leakage, e.g., by an opened valve. For this purpose, the sound velocity on the measuring section is calculated in 2 consecutive measurements, with and without artificial leakage. This is particularly important if the pipe material is unknown or uncertain. However, this procedure is often difficult to implement in real conditions.

6th Step: Now the actual correlating begins. Both microphones record the sounds, which are sent to the central unit via transmitters and correlated there with software. With the help of the calculated or determined sound velocity, a leakage position is now indicated. It is best to repeat this step once to rule out the possibility that the correlator is sitting on two randomly similar sound profiles and calculates the leak position incorrectly.

7th Step: Optionally, one of the two microphones should be moved, especially in cases where the sound velocity could not be determined and/or there are uncertainties about the pipe material. It should be attempted that the suspected leakage is as close as possible in the middle between the two microphones, which significantly reduces the margin of error.

8th Step: The calculated distance is now walked on the surface, usually with the help of a measuring wheel until the calculated, probable leakage position is reached. In most cases, a confirmation and precise localisation is carried out with a ground microphone and/or soil probes.

9th Step: After the leak has been repaired, the correlation should be carried out again, as larger leaks mask smaller ones acoustically and these can only then be localised.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Particularly when correlating on plastic pipes, especially long pipes with a large diameter, hydrophones are used instead of contact microphones, as water then better conduct the sound over large distances. Often one problem is to create access to the water column - sometimes holes have to be drilled.

Another variant is multipoint correlators. These consist of a system on which more than 2 points are correlated (with some systems up to 8). The advantage, depending on the application, is that a longer line distance can be correlated at once or, if there are enough access points, the results are more accurate from the start without having to reposition the microphones. In areas with high crime rates, however, this leads to such high personnel expenditure that in the end not all the microphones are used. The procedure also takes much more time to find out all the different distances, diameters, and pipe materials for the different correlated sections.

Combined application with other methods: Correlation is almost always combined with other methods. Typically, fittings are first surveyed with a listening rod to see if it is worth correlating and after correlating the leakage is confirmed and pinpointed with a ground microphone. In areas that are very noisy during the day, noise loggers could be used at night instead of listening rods. This triple combination is often used if there is already a well-founded initial suspicion in a supply area, but it is not mandatory. Especially in utilities with high leakage rates it can then make sense to investigate the whole network in this way.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of missing leaks is sometimes relatively high and depends on many factors. The lower the water pressure, the further away the microphones are placed and the poorer the sound conduction due to the material and diameter of the pipes, the more leaks will be missed. It should be noted that to be on the safe side, a pipe section should always be correlated again after repairing a leak to find a possible second leak. It should also be noted that the use of hydrophones, especially in plastic pipes, greatly reduces the likelihood of missing leaks.

Likelihood of false positives (dry holes): The error rate is relatively high compared to other methods, as background and ambient noise (traffic, consumption, pumping) can lead to false positives. Indeed, when correlators provide a result, they do not predict about the trustworthiness of if it is a leak or not. However, this statement is theoretical, since in most cases (Not always! - e.g., due to lack of accessibility or an especially deep installation) the suspected leakage is checked again with a ground microphone or even with soil probes. This significantly reduces the probability of false positives. The likelihood of false positives also decreases with the increasing experience of the user. Another typical source of error is caused by service connections used during the correlation. Thus, if possible, connections on the correlated section should be disconnected for the duration of the correlation.

Margin of error: The margin of error can often be many metres, especially if the condition of the pipes is not or only imprecisely known and it is therefore not possible to estimate the sound velocity. This can theoretically be remedied if it is possible to determine the sound velocity on-site using a test or to reduce the margin with additional correlations by moving one or both microphones. However, since a ground microphone is normally used in addition to the correlator to confirm the leakage and locate it with pinpoint accuracy, this is only a problem if this is not possible (e.g., if the pipe is very deep), otherwise, it will only lead to delays in locating the leak.

SCOPE AND LIMITATIONS

When should this method be considered? Correlators can be used under a wide variety of conditions. The correlator owes its worldwide popularity as one of the most widely used leak detection devices quite clearly to its efficiency in use. Within its application limits, it is very often the device with the highest cost-benefit efficiency due to the speed of leak location. Exceptions are mentioned below. It should also be mentioned that correlators can also locate leaks in inaccessible places, e.g., on overbuilt pipes, as long as it is possible to place the microphones outside the inaccessible area. Finally, until recently, correlation was the best way to investigate very long supply lines. As long as the diameter is not too large (depending on the other factors this could mean something between 10 and 20 inches, in exceptional cases also more), the material is not plastic, the pressure is relatively high and there are enough access points, it can still have cost advantages over other methods in these pipelines. Using hydrophones can push the limits of application even further in long, large-diameter pipelines (even plastic) and it is also often the most cost-effective, although not the most accurate method in this area.

When not to consider this method? This method has some considerable application limits; some of them are quite common:

1. **Low pressure:** As with most acoustic methods, the output noise is lower at low pressure. Below 1 or 1.5 bars correlation is often not possible at all.
2. **Plastic pipes:** Sound propagates worst in plastic conductors, best in metal conductors. In the first case, more access points are required. However, the often claimed inapplicability of correlators on plastic pipes is not true.
3. **Large diameter pipelines:** The larger the diameter of pipes, the less the sound propagates, and it is only possible to correlate smaller distances between the microphones. In this case, hydrophone correlation should be considered.
4. **Maximum correlation distance vs. existing access points:** If there are only a few access points to the pipes, depending on the material, diameter and pressure, a correlation may not be possible.
5. **Intermittent supply/air pockets:** Of course, correlation does not work in empty pipes, but hydrophone correlation fails with air pockets, which are common in intermittent systems, and becomes less accurate with microphones.
6. **Background and ambient noise:** strong ambient noise, or noise propagating strongly in the pipes, such as pumps or pressure reducing valves, impede the correlation or at least make it impossible at certain times of the day.

Considerations for application in characteristic circumstances in EMDEs: One advantage in EMDEs is the often easier access to the supply network and the water column via service connections. This allows smaller correlation distances, the relocation of microphones to increase accuracy and, especially useful with plastic pipes, the use of hydrophones. A disadvantage is the frequent existence of intermittent systems, not only outside the supply times when a correlation is not possible but also because air pockets can remain in the pipes during supply, which can distort the results of the correlation. Similarly, the water pressure is often not satisfactory, which limits the use of correlators (and many other acoustic techniques).

INSTITUTIONAL ASPECTS

Required qualification: To understand the basic principle of correlation, the programming of the devices, the correct application, the determination of the sound velocity, placement of the microphones or hydrophones and the possibilities to reduce the margin of error, a much longer training than required for all other acoustic methods (and maybe all leak location methods) is necessary. In addition, the personnel operating the correlator should also be familiar with the use of ground microphones, as it is usually used in combination with the correlator.

Required experience: Dealing with the inherent inaccuracies, incomplete information, skilful combination with other methods, quick reaction to local conditions, good selection of distances and optimal contact points, etc. requires a lot of experience to get the maximum out of this method and also to achieve higher efficiency. Experienced personnel should therefore not be replaced under any circumstances and new operators should be trained on the job by experienced staff for a longer period (at least three months).

Usefulness of outsourcing the method: Since correlating requires well-trained, experienced, and specialised personnel, outsourcing is quite reasonable, especially in combination with other, mostly also acoustic methods. This should be considered especially if staff stability cannot be guaranteed in the utility. If leak detection is completely outsourced, it can be assumed that the service provider will use correlators. It should be mentioned that outsourcing leak detection is not an easy undertaking, as there are many parameters to consider, which are often not known before outsourcing (especially how many leak can actually be found).

Necessary or desirable framework conditions at the utility: At least the following important framework conditions should be fulfilled at the water utility. On the one hand, it is of great advantage if the condition of the pipes is known very precisely, as this has a decisive influence on the margin of error. The exact location of the pipelines should also be known, as the location refers to the length of the pipeline. A lack of that knowledge would lead to severe delays. Personnel stability is particularly important, as training takes longer than with other methods and experience plays a very important role.

ECONOMIC ASPECTS

Acquisition cost: Correlators currently cost between € 7,000 and - 12,000, depending on whether hydrophones and other accessories are included.

Required number of staff: The correlator can theoretically be handled by only one operator. In practice, however, two operators usually work together, often for safety reasons, but also because both are fully occupied with attaching and moving the microphones, measuring the correlated distances, and confirming leakages with other methods (usually a ground microphone).

Additional operational costs: A car is needed to transport equipment and operators to the field; other operational costs are only incurred for charging the batteries (negligible).

Possible additional advantages or disadvantages of the method for utilities: There are always cases where a supposed leak is located during correlation, but it is an illegal connection. However, this only happens if water is just being consumed via the illegal connection and enough turbulence is generated to cause an identifiable noise. Under no circumstances can correlators be used to systematically search for illegal connections.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Correlators for locating leaks were invented in Germany and the first correlators were also manufactured there. They have been used successfully for locating water leaks since the beginning of the 1980s. Since then, correlation has become the standard method worldwide. Not so new technical developments are correlation with hydrophones and, in the last 10 years noise loggers have also been used for correlation.

Market penetration: The method is one of the most widely used in the world, second only to other acoustic methods such as listening rods and ground microphones. There is a wide range of suppliers of these devices.

Outlook: Correlation will continue to be one of the most important methods of leak detection in the future. Technical improvements, better training and an increasingly better understanding of the underlying principle, as well as falling prices for the equipment, will contribute to this.

FURTHER INFORMATION

Webinar on the use of correlators from Gutermann AG (34 min)

Playlist of instructive videos about the correlator of H. Sewerin GmbH (16 min in total)

Webinar on the use of correlators from Fast GmbH (70 min)

Study of the inherent inaccuracies of correlation (Becker 2014)

Comparison of hydrophone correlators with various other methods for trunk mains (Clark 2011)

2.1.5. Noise logging

OVERVIEW

Type of method: Permanent stationary or temporary mobile pre location method

Location principle: Acoustic	**Sensor type:** Contact sensor

Figure 5. Left: Installation of a noise logger, a readout unit can be seen in the device case; Right: Installed noise logger (Both courtesy of H. Sewerin GmbH).

Leak location principle: Noise loggers are installed at accessible points in the network (valves, etc.) to listen to and record the sound vibrations caused by leaks that are transmitted through pipes and fittings or the water column. The basic idea is that leakage noises are recorded during periods with a low external noise level, i.e., especially at night, and can then be evaluated to identify leaks.

Areas of application

Applicability for indoor leak location	In exceptional cases
Applicability for distribution networks	Yes (main use)
Applicability for large diameters pipes	To some extent with hydrophones

Influencing factors

Water pressure	Important	**Intermittent supply**	Depending on the time, impossible
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary
Pipe material	Important	**Need for access points**	Some-many: pipe, fittings, water column
Soil conditions	No influence	**Method-specific negative factors**	Crime rate

Links to providers

H. Sewerin GmbH (Germany); Halma Water Management Ltd. (UK); Fuji Tecom Inc. (Japan)

STEP-BY-STEP DESCRIPTION

1st Step: Taking into account the availability of access points, pipe lengths, pipe materials and diameters, it is calculated how many loggers are needed for a certain area and at what distance they have to be placed from each other. It should be noted that sound propagates through the pipes with varying intensity depending on the material and diameter - the distance between the loggers must therefore be chosen so that leakages of a certain size can still be heard by one logger.

2nd Step: The noise loggers are installed on suitable points and registered with location and logger number. Since noisy leaks close to the measuring point can also be heard during the day with a listening rod, it is recommended to apply this before installing the logger. Otherwise, the logger software may interpret the already existing leakage noise as a natural noise level. Afterwards, the loggers are usually left in the field for two nights and then collected again (called Lift & Shift method) or permanently placed in a stationary position to identify newly occurring leaks immediately.

3rd Step: The information stored by the loggers is read out either by drive-by patrols or remotely via antennas or the mobile network or, after collecting the loggers, directly with a computer.

4th Step: The information is analysed by software. This determines whether a higher noise level has been recorded in the vicinity of one or more loggers. These are characterised by the fact that they are continuously audible. This is usually a distinctive feature of leaks between around 2 and 4 a.m. Stationary loggers use a different algorithm; they compare the registered noise levels since their installation and can thus determine whether this has increased.

5th Step: The leak or leakages pre-located in this way must then be confirmed on-site by other methods of leak detection, located with pinpoint accuracy and then repaired.

6th Step: After the repair, it makes sense to leave the loggers in the field for at least one more night (unless they are stationary anyway), as louder leaks often mask quieter ones, which can only be detected after the former has been repaired.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: First of all, a distinction must be made between stationary use and the Lift & Shift method. In the former, the loggers are left permanently in the field, so large numbers of loggers are needed, while in the latter, the loggers are usually collected after one or two nights and moved to another area.

Another variant is noise logging with correlating loggers: Here, the loggers are placed in a higher density so that at least two loggers can register a leak and the sounds can be interpreted as with the leak noise correlation method, locating leaks. These loggers can be useful, for example, if environmental noises do not allow correlation during the day and night-time staff deployment is not desired or possible (especially with the Lift & Shift method). For stationary monitoring, these loggers are hardly economically feasible due to their higher price, the higher required installation density and the additional work programming them (they need a lot of data). They also have a shorter lifespan due to the higher battery consumption.

The noise loggers can work with normal structure-borne sound microphones or with hydrophones. The latter are not attached to the fittings but placed directly in the water column. The advantage, particularly in plastic pipes, is that they can listen to larger distances, i.e., fewer loggers are needed. However, it is more difficult to find connection points.

A completely new method uses deep learning algorithms which analyse sounds recorded with noise loggers or other listening devices and examines them with an expanding database for patterns that are typical of water leaks and can thus reduce the number of false positives. This is particularly helpful in noisy places, as the human ear, unlike the software, has difficulty separating sounds from different sources. In addition, taking into account parameters such as pipe pressure and material, the software can estimate the approximate magnitude of a leak by comparing it with leakage sounds of different leak sizes and thus help prioritize repair work. More information can be found here.

Combined application with other methods: The method described is a pre-location technique, i.e., in principle it is only possible to make a statement about which noise logger is in the vicinity of a leak. This must then be confirmed using other suitable methods and the leak located with pinpoint accuracy. Leak noise correlators, ground microphones, the tracer-gas method and others can be used for this. Even in the case of using correlating loggers, the leak must still be confirmed and pinpointed, as with normal leak noise correlation.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of overlooking leaks is relatively high. As with all acoustic methods, the noise level plays a major role, which in turn depends on factors such as pressure, pipe material and diameter and, specifically for the method, the installation density of the loggers. Stationary loggers for monitoring purposes often overlook leaks that already exist when they were installed, which is why they are used often in areas which have been cleared from leaks previously.

Likelihood of false positives (dry holes): The probability of false positives is medium, depending on local conditions. In particular, false alarms can come from: Cooling units, sewage stages, pressure reducers, pumps of all kinds, data stations, petrol stations and nightlife in cities. It makes sense to exclude at least some typical sources of error before use. The Lift& Shift method is more prone to false positives as they do not rely on historical data from the installation site.

Margin of error: Depending on the distance of the loggers from each other, in individual cases, it is often only possible to determine which logger has a leak nearby, sometimes also in which direction, when it is registered by a second logger.

SCOPE AND LIMITATIONS

When should this method be considered? The method is particularly recommended in places where it is very noisy during the day (e.g., due to heavy traffic), but at the same time very quiet at night. If water losses are already low and water costs are high, it can make sense to use stationary loggers to identify leaks as soon as possible after they occur and thus further reduce losses. In addition, the level of personnel costs is also an important factor, as stationary logging requires less personnel. Furthermore, the method is cost-effective to use when few loggers are needed, i.e., for pipes that are not made of plastic, high water pressure and when there are many, closely interconnected pipes in a small area.

When not to consider this method? Under certain conditions, which are particularly common in EMDEs, the use of loggers is not recommended. These include:

1. **High noise levels:** In areas where there is a constant high noise level in the pipes, e.g., due to nearby pumps.
2. **High crime rate:** In areas with a high crime rate, where the loggers cannot be reasonably secured.
3. **Lack of access points:** In areas where the required maximum distance cannot be ensured due to a lack of access points, the benefits of the method are at least severely limited.
4. **High leakage rates:** In areas with high leakage rates, stationary use is often not useful as one of the main advantages of the method is that certain areas will not be surveyed for leaks in vain. The other, more important reason is that they tend to overlook leaks that already exist in the installation area.
5. **Low pressure in plastic pipes:** The combined presence of low pressure and plastic pipes means that the required maximum distance between the loggers is much smaller and many more loggers are needed. Then the method is often no longer economically viable or cannot be used at all if there are not enough access points to the network.
6. **Intermittent supply:** The method only works during supply, as without water in the pipes there is no leakage noise. This is especially a problem if the supply time is outside the optimal logging time, i.e., during the night hours. Additionally, it will also not work when the supply time is too short to fill the network and the house storage facilities like roof tanks so that leaks are masked by flow noise.

Considerations for application in characteristic circumstances in EMDEs: For the suitability of noise loggers in EMDEs it is necessary to distinguish between the Lift & Shift method and the stationary method.

Stationary use for monitoring has little comparative advantage over other methods, especially because of the high proportion of plastic pipes, which requires a very high installation density, the usually much higher cost of imported loggers and the more frequent risk of them being stolen, as well as the lower benefits, because of lower water costs and the high damage rates (which make other methods more efficient).

In contrast, the **Lift & Shift method** which requires less investment and more manpower is more applicable in EMDEs than in industrialised countries. In addition, the use of hydrophone loggers is reasonable, especially in the frequent plastic pipes, which is often easier to realise in EMDEs due to the easier access to the water column (through service connections).

INSTITUTIONAL ASPECTS

Required qualification: Training on the devices and the associated software is relatively uncomplicated. In particular, the user must be able to interpret the data obtained and put it into a meaningful context. It is much more difficult to understand the underlying principles in order to use loggers smartly.

Required experience: Experience is very important to get a feel for how to set up the loggers, where to place them, at what distance and where they are not useful because of external noise sources or other limiting factors.

Usefulness of outsourcing the method: To make statements about outsourcing, it is necessary to distinguish between the Lift & Shift and the stationary method.

> **Lift & Shift method:** When outsourcing the entire leakage detection, it is possible that the service provider, especially under the conditions that make the use of loggers possible and necessary, uses them as one of several methods. Since the loggers are often only used in a limited area of the network (especially in very noisy areas during the day), outsourcing the method itself rarely makes sense, except for very large utilities with many such network areas.
>
> **Stationary installed loggers:** Once installed, the effort is relatively low and the application is not very complex. The most sensible option would be to outsource the installation itself, perhaps with agreements for the subsequent maintenance and reading out of the loggers if there are a lot of loggers.

Necessary or desirable framework conditions at the utility: In areas with a high crime rate, the infrastructure must allow the loggers to be secured (e.g., lockable meter boxes).

ECONOMIC ASPECTS

Acquisition cost: Each noise logger currently costs between € 300 and 850, with costs varying according to readout method, accessories (e.g., adaptors, software) and also quality. Noise loggers with hydrophones are slightly more expensive than the most expensive normal loggers. For the Lift & Shift method it makes sense to use at least 20-40 loggers, for stationary use, the number depends on the factors already mentioned and mainly on the size of the pipeline areas to be logged. In addition, there are usually devices for remote reading of the loggers (€ 1,000 - 2,000).

It should be noted that noise loggers often do not last as long as manufacturers claim, as they are usually placed in poorly ventilated, often damp locations. Rodent damage is also common in some places. Also noise loggers have internal batteries which last about 5-8 years. Only in cases where all battery saving options are used to extend battery life can they last longer (10-12 years). The batteries cannot be changed by the utility but must be returned to the manufacturers for that purpose. Depending on the country this could be more expensive than ordering new loggers.

Required number of staff: With the Lift & Shift method, two staff members are normally employed full-time. With the stationary method, in principle, only one person is needed part-time to read out and analyse the data and carry out maintenance of the noise loggers. The higher the number of loggers, the greater the proportion of time; if there are many loggers in large utilities, more staff is required.

Additional operational costs: A motorised vehicle is always necessary because the loggers are placed and removed at different points, as well as for reading out the loggers. The Lift & Shift method in particular requires a lot of driving around. In case the data is transmitted via the mobile phone network, there are additional telecommunication costs - but it saves long distances for the readout.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The method was conceived in the oil industry in the 1950s, but due to insufficient technical possibilities, it was not used until the mid-1970s. In the water sector, they were first tried out and mass-produced in the 1980s (in Germany) and have been a common leak detection method worldwide since the 1990s. Hydrophone loggers and correlating loggers are more recent developments but are still used much less in relation with noise level loggers.

Market penetration: Noise loggers are used all over the world, but are particularly common in industrialised countries (e.g., especially in France).

Outlook: The method will remain very important. There may be a great potential in EMDEs using the Lift & Shift method, sometimes also with hydrophone loggers.

FURTHER INFORMATION

Webinar on the use of correlating noise loggers from Gutermann AG (36 min)

Webinar on the use of noise loggers from Fast GmbH (78 min)

Animated description of the Lift & Shift method by H. Sewerin GmbH (5 min)

Case study from Luxembourg with successive transition from the Lift & Shift method to permanent monitoring (Pages 20-22; O´Conaill & Riehle 2016)

Detailed case study from New Mexico with permanent monitoring by noise loggers in combination with other leak detection methods (NMOSE 2010)

2.1.6. Pushed hydrophones

OVERVIEW			
Type of method: Temporary mobile location and pinpointing method			
Location principle: Acoustic		**Sensor type:** Pig	

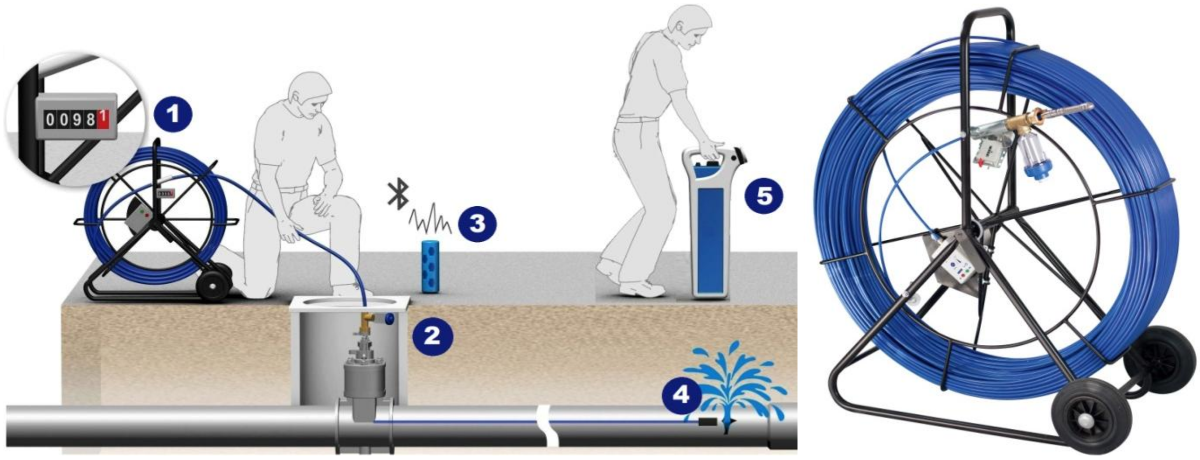


Figure 6. Left: Location of a leak with the pushed hydrophone: 1- Cable reel with length meter, 2: Insertion point with sluice and disinfection container, 3 – Bluetooth speaker, 4 – Device head with hydrophone and transmitter, 5 – Location of the transmitter and the leak from the surface with a locator; Right: Pushed hydrophone (Both courtesy of Fast GmbH)

Leak location principle: Pushed hydrophones, also called hydrophone or acoustic pigs are inserted through sluices into pressurised pipes of different diameters and moved (pushed and pulled) by guide cables. In the pipes, leakage sounds that spread through the water column can then be recorded at close range and transmitted via the cable.

Areas of application	
Applicability for indoor leak location	In exceptional cases
Applicability for distribution networks	Yes (especially for connections)
Applicability for large diameters pipes	Yes, but with different characteristics

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Indirect influence	**Knowledge of pipe location**	Can be used for locating
Pipe material	Some influence	**Need for access points**	Some-many for insertion in the pipe
Soil conditions	Indirect influence	**Method-specific negative factors**	Pipe bends

Links to providers
FAST GmbH; TROTEC GmbH (both Germany); Pipa Ltd. (UK)

STEP-BY-STEP DESCRIPTION

1st Step: In a pipeline area where one or more leaks are already suspected, suitable access points to the water column are first identified.

2nd Step: A sluice is first attached to these, often using different adapters. The sluice is equipped with a disinfection device that moistens the cable to be inserted into the water with disinfection liquid when it is pushed through.

3rd Step: The guide cable is now pushed into the water pipe until it cannot go any further or a leakage noise is identified. The sound is recorded by the hydrophone and transmitted through the cable to a loudspeaker or headphones. Since leaks are often audible at a distance of a few metres, the point where the noise is loudest is now identified by pushing and pulling the guide cable.

4th Step: In the last step, the leak is pinpointed. There are two methods available for this: First, if the location of the pipes is known, the location of the leak can be determined by the inserted length of the guide cable and then found on the surface with the help of a measuring wheel. The second form is if the location of the pipes is not known, the location of the hydrophone can be determined with the help of a locating device (if a transmitter is part of the device).

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: One variant often offered by manufacturers is to insert a small transmitter into the listening head so that it can be located from the surface. In this way, the location of the leak can be determined even if there is no knowledge of the exact location of the pipes. Another additional instrument that can be inserted into the device head consists of an endoscopic camera equipped with LEDs. This allows additional information to be obtained about any existing illegal connections and the general condition of the pipes. A third additional instrument, which can be built into the unit head, has only recently been offered by one supplier: This is the so-called ELECTRO SCAN, a method for non-metallic pipelines, which has so far been used mainly in the sewage sector. Electromagnetic waves are emitted inside the pipe, which, if there is a hole in the wall of the pipe, change in such a way that the leak can not only be located but its size can also be estimated, even if the water pressure is close to zero. Independent of the device head is the application range of the device, which varies from device to device mainly as a function of the diameter of the pipe to be pigged, i.e., the higher the diameter, the more rigid and longer the guide cable must be.

Combined application with other methods: The limited radius of action of the devices on the one hand and the pinpoint location, on the other hand, suggest combining them with pre-location methods - for smaller pipelines, e.g., with the step test, noise loggers, but especially with listening rods, while for large pipelines volume balance and pre-location with satellite radar can come into play.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of not finding existing leaks at the point of use is almost zero, as the hydrophone is guided very close to the leak. Only under conditions where the application limits are fully exploited, namely when the water pressure is very low - which leads to virtually silent leakages, these can be overlooked.

Likelihood of false positives (dry holes): Turbulence occurring in the vicinity of branches and bends can be mistaken for leaks in individual cases. Pressure reducing valves or throttled gate valves can also lead to false positives, although these can often be ruled out if their location is known. Otherwise, leakage noises are clearly differentiable and only if the operator has little experience, the probability of false positives is initially somewhat higher.

Margin of error: Very low, as it can be measured to the centimetre how far the cable has been inserted. Only if the exact position of the pipes is not known can deviations occur. For precisely this reason the devices of many manufacturers are equipped with tracking transmitters and can thus be pinpointed from the surface.

SCOPE AND LIMITATIONS

When should this method be considered? This method has technical and economic advantages under various clearly defined conditions. On the one hand, this is the case when it is relatively easy to insert the hydrophone into the pipes, especially to search for the very frequent leaks in service connections and in pipes that are not very long and have large diameters, where there are good points of insertion. If, on the other hand, it is not so easy to insert the hydrophone and it is necessary to create the access points first, the devices should only be used if other methods fail (due to low pressure, deep pipes, noise level, etc.) or if even very small leaks are to be located because of high water costs or water scarcity. In areas with many illegal connections, a combined search of these and leakages can also be worthwhile, using devices with endoscopic cameras and hydrophones.

When not to consider this method? This method has only a few limitations:

1. **Pipe bends:** The most important application limit is the frequent presence of bends in the pipes, whereby the technology can overcome at least a 90° bend for short sections when more flexible guiding cables are used. As more than one 90° bend are very common in service connections, the technique is not used in these cases.
2. **Pipe roughness:** The range can also be limited in pipes with high roughness (such as cement pipes), especially if occurring in addition to bends.
3. **Lack of access points:** The lack of suitable insertion points in certain line sections can be another important and also frequent problem. Especially in very long lines with large line diameters, there are usually fewer insertion points and since the devices use rigid guide cables, the maximum pigging distance is also greatly reduced by cable bends.
4. **High or low water pressure:** The units can only be used up to a water pressure of 16 bars, although the pressure is rarely higher. Very low pressures are more common. A clear value below which leaks are no longer audible cannot be given, but below 0.5 bar other methods for leak detection should be used in any case and below 1 bar some leaks are missed.

5. **Intermittent supply:** The units only work during supply, as no leakage noise occurs without water in the pipes. This is only a problem if the supply time is very short and the detection is limited to this time.
6. **Very large diameters:** Above diameters of 12", the device must be handled with special care so that it does not puddle up in the pipe. The cable can then break. With some experience, it can be used up to diameters of 24".

Considerations for application in characteristic circumstances in EMDEs: A high proportion of plastic pipes, many of which are operated at low pressure and the tendency for easier access to the water column via service connections in EMDEs make the method seem particularly useful for those. Similarly, this labour-intensive but not very investment-intensive method can often have high-cost advantages in EMDEs in large diameter pipes that are not very long.

INSTITUTIONAL ASPECTS

Required qualification: The operation of the device is quickly explained. However, plumbing knowledge is a basic requirement to correctly connect the device in various situations.

Required experience: Experience with the use of the device only leads to exploring its application limits and to be able to better assess which fittings are best suited for it before insertion. The application itself, on the other hand, is quite easy to learn.

Usefulness of outsourcing the method: Only if the utility generally outsources leakage detection will the method often be used by the service provider (if it makes technical sense). Otherwise, the relatively low investment costs and undemanding applications do not require outsourcing.

Necessary or desirable framework conditions at the utility: Knowing the location of the pipes is less important if the pig head is also equipped with a tracking transmitter. However, it is important to know the hygiene regulations, which vary from country to country, to see whether the equipment for the disinfectant is necessary and then to have disinfectant in stock (more of a problem in industrialised countries).

ECONOMIC ASPECTS

Acquisition cost: The acquisition costs for the actual devices are € 3,000 - 6,000 depending on the size (length of the cables). This price is slightly higher for devices that are additionally equipped with cameras. To locate the device head from the surface, an additional tracking device is necessary, which costs approx. € 1,000 - 3,500.

Required number of staff: One operator is sufficient for smaller devices, which are used e.g., in service connections. For larger and therefore heavier devices with longer cables, two operators are always necessary.

Additional operational costs: Except for the smaller units, which are used especially for service connections, motorised transport to the site is always necessary. Often, only low operational costs are incurred - for the disinfection solution and for charging the batteries. However, higher costs may be incurred whenever it is necessary to intervene pipes to gain access to the water column from the inside, both for excavation work and to repair the pipes.

Possible additional advantages or disadvantages of the method for utilities: When searching for leaks in pipes, air pockets can also often be located acoustically with the help of this system. If the device head is equipped with an endoscopic camera, illegal connections can also be detected and the general condition of the pipes can be determined visually. The tracking device can be used for mapping the location of the inspected pipelines. If there are no suitable access points and the pipe has to be drilled or cut, an improper repair can lead to subsequent leaks. Theoretically, inserting the guiding cable can lead to contamination of the drinking water - but this should be a negligible problem if used properly. In some cases, especially when used on service connections, it is necessary to interrupt the supply.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Pigs have been used in various types of pipelines since the 1950s, e.g., to clean or locate them. Acoustic leak detection with pigs has existed since the 1970s, especially for large pipes. In the current version described here, also for smaller diameters, the in-pipe hydrophone for locating water leaks has only existed for about 15 years.

Market penetration: The method is not yet very widespread and is mainly used in Europe, except for large-diameter pipes.

Outlook: The number of providers has increased in recent years and the respective distribution networks are gradually being expanded worldwide. It can be assumed that the method will occupy an important niche position in the long run.

FURTHER INFORMATION

Short animated video illustrating the principle of the ELECTROSCAN explained under the variants of the method (2 min).

GIZ-webinar about pushed hydrophones in large diameters (Minute 16 to Minute 51)

Video showing the use of a pushed hydrophone in a service connection (7 min)

List of short videos of successful leak detections worldwide

Short case study from the UK finding a leak impossible to locate with other methods

2.1.7. Tethered hydrophones

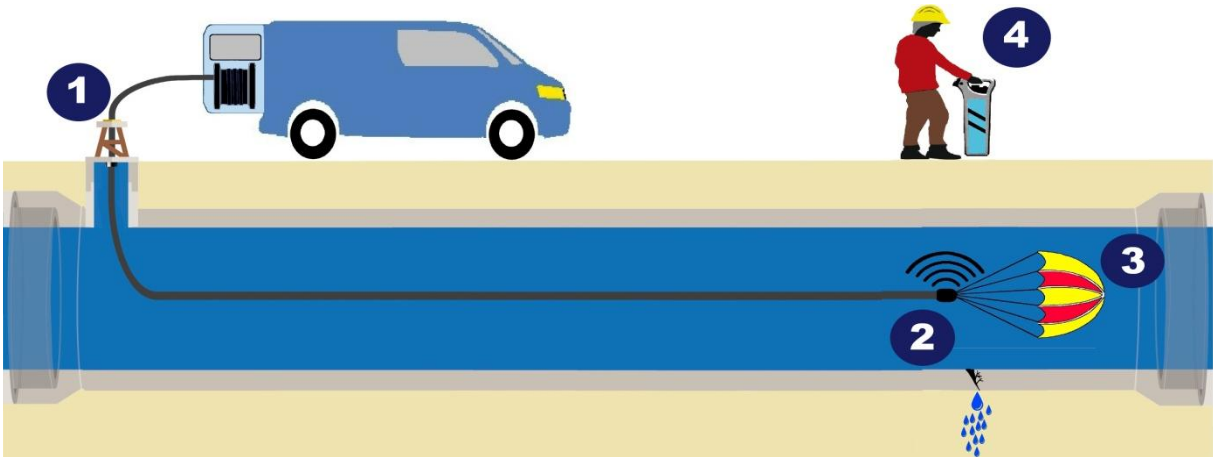
<table>
<tr><th colspan="4">OVERVIEW</th></tr>
<tr><td colspan="4">Type of method: Temporary mobile location and pinpointing method</td></tr>
<tr><td colspan="2">Location principle: Acoustic</td><td colspan="2">Sensor type: Pig</td></tr>
<tr><td colspan="4">

Figure 7. Simplified illustration of the leakage location principle: 1 – Insertion of the device with the aid of a sluice; 2 – Unit head with a hydrophone and locating transmitter; 3 – Parachute that propels the device using the water flow; 4 – Location of the device stopped at a leakage position from the surface</td></tr>
<tr><td colspan="4">Leak location principle: Leakage sounds are recorded and transmitted by a wired hydrophone. This is propelled through the water pipes with a parachute. The actual locating at the surface is done by finding a signal emitted by the device.</td></tr>
<tr><th colspan="4">Areas of application</th></tr>
<tr><td colspan="2">Applicability for indoor leak location</td><td colspan="2">No</td></tr>
<tr><td colspan="2">Applicability for distribution networks</td><td colspan="2">In exceptional cases</td></tr>
<tr><td colspan="2">Applicability for large diameters pipes</td><td colspan="2">Yes (Almost exclusively)</td></tr>
<tr><th colspan="4">Influencing factors</th></tr>
<tr><td>Water pressure</td><td>Some influence</td><td>Intermittent supply</td><td>Restricts time of use</td></tr>
<tr><td>Pipe depth</td><td>Indirect influence</td><td>Knowledge of pipe location</td><td>Can be used for locating</td></tr>
<tr><td>Pipe material</td><td>Some influence</td><td>Need for access points</td><td>Few, big ones for insertion in the pipe</td></tr>
<tr><td>Soil conditions</td><td>No influence</td><td>Method-specific negative factors</td><td>Pipe bends</td></tr>
<tr><th colspan="4">Links to providers</th></tr>
<tr><td colspan="4">Pure Technologies Ltd. (Canada); Pipa Ltd. (UK); Fast GmbH (Germany)</td></tr>
</table>

STEP-BY-STEP DESCRIPTION

1st Step: Before the system is used, information must first be obtained about the pipeline to be examined, such as pressure, flow rate and possible deployment points. In addition, information about which discharge points must be shut off so that the device does not deviate from the planned path or get stuck is required. In some cases, insufficient information may mean that the system cannot be used until this information has been obtained.

2nd Step: Now the device is inserted through a sluice at a suitable point with the help of a special inserting device, which also continuously disinfects the cable.

3rd Step: The parachute opens and the device floats along the pipe at 50-100% of the current speed, recording the sounds and transmitting them simultaneously via the cable. It also sends out a signal that allows it to locate its current position from the surface.

4th Step: At the same time, an operator with a signal receiver on the surface tracks the device and the received sounds are also simultaneously evaluated with the help of a connected computer.

5th Step: As soon as a leakage sound is detected, the device is stopped and possibly retracted to place it as close as possible to the potential leakage point. The operator with the receiver on the surface now locates the signal from the device with pinpoint accuracy and marks the spot. If the exact course of the pipe is known, the length of the uncoiled cable can also provide information about the location of the leak. This means that the receiver on the surface is not necessarily needed; nevertheless, the location is always more accurate this way.

6th Step: The device now continues its way up to a maximum range of 3 km and is then retracted. To do this, the parachute is folded in.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: In addition to the hydrophone, the probe can also be equipped with a camera, which provides additional information about the condition of the pipelines and allows illegal taps to be detected and located. Another variant is to ensure propulsion instead of the parachute with a separate propulsion unit because there can be difficulties with the parachute in strong currents. Another interesting propulsion variant is offered by the British company PIPA. Here, a guide cable of max. 2 km length is already installed in the pipe when the pipeline is laid. This allows a hydrophone to be pulled along the pipeline at any time. One advantage of this method is that no flow is required (more information). Another variation is to use the unit head as one of two microphones for correlation. The other microphone is then attached as in a normal correlation to increase the range beyond the actual cable length. This system was introduced to the market by the German company Fast GmbH shortly before the publication of this document.

Combined application with other methods: As the method is very cost-intensive, it always makes sense to initially examine longer pipe sections for the presence of leaks to see how high the losses are and thus select the areas where leak detection makes economic sense. This can be done, for example, by volume balance.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Unlike with other acoustic methods, the probability of overlooking leaks is very low because there is hardly any acoustic interference from the outside in large-diameter pipes - because the pipe walls are wider, the pipes are usually buried deeper and the device floats close to the leaks. The only possibility is in the case of temporary leaks, i.e., those that occur when the pipe material expands/contracts due to temperature changes and thus the leak only opens up temporarily (which is of course an issue with many methods).

Likelihood of false positives (dry holes): The factors already described for "false negatives" (hardly any interference from the environment, proximity to the leak) also mean that the probability of false positives is very low. Other noises can often be recognised as such because the frequency of the noises is measured precisely.

Margin of error: The device is located precisely from the surface at the point where the leak is loudest. The margin of error is rarely more than one metre.

SCOPE AND LIMITATIONS

When should this method be considered? In large diameter main pipelines of medium length with very few access points, this device is in most cases of application technically superior to all other methods, i.e., on the one hand, it can find more leaks, even those that are otherwise difficult to locate more precisely and has practically no false alarms. Especially if it is really necessary to find all leakages, e.g., because of special water scarcity or water that is particularly expensive to produce (e.g., by desalination of sea water) this is the indicated method. From approx. 6-7 km pipeline length, however, the free-floating device without cable connection is more cost-effective, although it cannot always be used for more complex networks.

When not to consider this method? The limitations of this method are as follows:

1. **Small pipe diameters:** The tool can be inserted in pipelines with a diameter from 200 mm (8") upwards.
2. **Too low or too high pressure:** The method works between 1 to 13 bars.
3. **Lack of access points:** Access of a minimum 50 mm (2") diameter is required.
4. **Too low or too high flow velocity:** A flow velocity of a minimum 0.3 m/s is required for the parachute to open up - the maximum is 3 m/s approx. In addition, the direction of flow should not change during deployment (as in the case of ring mains, for example). The maximum range also strongly depends on flow velocity, as the energy required for propulsion increases with increasing cable length. Below 1 m/s the maximum survey length of 3000 m cannot be reached.
5. **Obstacles:** With each cable bend the maximum range is reduced. Although as mentioned three kilometres are possible under perfect conditions, barely two kilometres are often achieved under real conditions. Bends of more than 130° for cement pipes and 270° for metal pipes cannot be passed through at all.
6. **Incomplete or inaccurate technical cadastres** are, together with the existing obstacles, the most important application limit, although not as severe as with free-floating hydrophones.

Considerations for application in characteristic circumstances in EMDEs: The very high costs of this method combined with mostly low water costs in EMDEs have so far led to the method being used almost exclusively in industrialised countries. This was, even more the case than for the method with free-floating hydrophones. However, more and more providers are entering the market with cheaper systems, which is why this assessment will probably change quickly.

INSTITUTIONAL ASPECTS

Required qualification: A lot of specific knowledge is needed to implement this method of leak detection: for pre-evaluation, to find out if the use of the method is reasonable and possible, to insert the device correctly and identify the points to be blocked off before insertion and also for tracking the device from the surface. These are some of the reasons why the system was only offered as a service until recently.

Required experience: Experience with the application of this system is important to find suitable solutions for ever-varying conditions, e.g., when inserting the device into the pipe. Some of that experience is provided as part of the service, but local knowledge is helpful.

Usefulness of outsourcing the method: Until recently, the system was not offered for sale - only as a service. This also makes a lot of sense because, under normal conditions, the method is only used from time to time, i.e., the relatively expensive equipment would hardly recover its cost quickly. Also, the method requires special qualifications and experience, which is difficult to acquire with only a few applications. The purchase of such a system, which has been possible for a few years through a supplier (PIPA, UK), can only be worthwhile for large water utilities, which, however, often outsource leak location anyway.

Necessary or desirable framework conditions at the utility: Precise information about the network to be inspected is needed since, on the one hand, the feasibility depends on it and on the other hand, billing is based on it. The service provider takes care of everything else.

ECONOMIC ASPECTS

Acquisition cost: As this leak detection method is mainly offered as a service, the investment costs are included in the operational costs (see below).

Required number of staff: In principle, the service provider provides the staff for the leak location. However, the utility often has to provide additional staff for the duration of the work, e.g., to clear access points, close sections of streets or temporarily close gate valves. The actual application of the method is carried out usually by three staff members provided by the service provider.

Additional operational costs: As this method is almost only offered as a service, only operational costs are incurred. At the time of the realisation of this study, the costs for a one-time inspection of a three-kilometre pipeline including the interpretation of the obtained data were about € 20,000 by one service provider in Germany. These are, of course, costs that can only be shouldered by a utility in EMDEs in exceptional cases as an inspection of the pipelines is recommended approximately every two to three years. However, with the emergence of new systems from different providers, costs may drop to € 1000 – 2000 per kilometre in the next few years

Possible additional advantages or disadvantages of the method for utilities: When searching for leaks in pipes, air pockets can be located with the help of this system. With the help of the camera, illegal connections can also be detected and the general condition of the pipes can be determined. If desired, the exact course of the pipelines can be established with the help of the tracking device.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Several parallel developments occurred around the turn of the millennium and thus created this new method. Commercially the Canadian company Pure Technologies has been very successful with a steadily growing distribution network and until recently virtually unrivalled in selling the system exclusively as a service. For some years now, new, very similar systems have been entering the market.

Market penetration: The method is a niche application for medium-length lines with large diameters. Due to the very high costs until now, the system has mainly been used in industrialised countries, especially in North America and Great Britain. In EMDEs, there are only a few projects so far (e.g., in Manila).

Outlook: On the one hand, it is to be expected that other providers will enter the market and contribute to lowering the costs substantially and that the system will become even better known. On the other hand, the market for the free-floating system, which is already more affordable for distances of more than 6-7 km, seem to be more dynamic, which may lead to it taking some market share away from the system with tethered hydrophones.

FURTHER INFORMATION

Animated videos from two providers can be viewed here (3min) and here (1:30 min)

Video with sequences of field work with the method (6 min)

Description of the method with cases in the US and the Philippines (Jo & Boon 2012)

2.1.8. Free-floating hydrophones

OVERVIEW	
Type of method: Temporary mobile location method	
Location principle: Acoustic	**Sensor type:** Pig

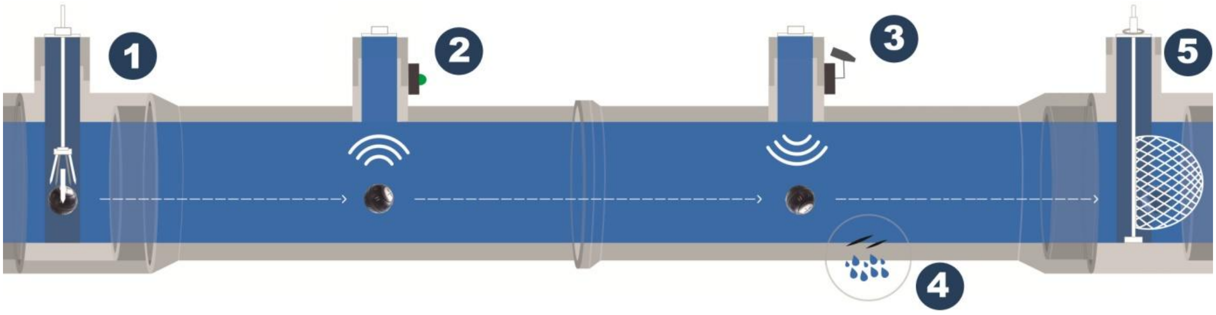


Figure 8. Pipeline inspection with a free-floating hydrophone: 1 – Insertion of the device; 2- Passage detector; 3-Synchronizer for adjustment of the position of detected leaks; 4 – Leak localised while floating by; 5 – Extraction of the device with a net (Courtesy: AGANOVA)

Leak location principle: Leakage sounds are recorded by a free-floating hydrophone that is propelled through the pipes by the water flow. The leak is then located by the subsequent analysis of recorded data – that is the analysis of the precise time when the device recorded that sound.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	No
Applicability for large diameters pipes	Yes (Exclusively)

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	No influence	**Knowledge of pipe location**	Necessary
Pipe material	No influence	**Need for access points**	Very few, big ones for insertion in the pipe
Soil conditions	No influence	**Method-specific negative factors**	Non-closed branches

Links to providers
AGANOVA (Spain); MTA Messtechnik (Austria); Pure Technologies (Canada); JD7 (USA)

STEP-BY-STEP DESCRIPTION

1st Step: Before the system is deployed, information must first be acquired about the pipes to be examined, including pressure, flow rate, possible deployment, extraction and access points for synchronisers and passage detectors; as well as which discharge points need to be shut off so that the device does not deviate from the planned path and get lost.

2nd Step: Depending on the manufacturer, the aforementioned devices must be installed at a certain distance on the pipeline that registers the passage of the device or, conversely, allows the device to record when it was at which point. This serves to know its exact position at a given time and thus calibrate its recordings and locate possible leaks more precisely, sometimes also to find the device more easily if it is lost. Ideally, these access points should not be placed too far away, as this makes leak detection more accurate and lost equipment easier to find. Depending on the manufacturer, every 500-1000 metres is recommended, but that is highly dependent on possible access points to the pipe.

3rd Step: Using a custom-made device, the hydrophone is inserted at a valve. Then, propelled by the water flow, the device floats through the pipe, recording all noises.

4th Step: The device is removed at the end of its passage with the help of a net. The net is equipped with a camera that is used to ensure that the net is completely stretched and covers the entire pipe diameter.

5th Step: The data is downloaded and analysed using special software. Up to five types of noise are distinguished: (1) leakage noises, (2) air bubbles, (3) gas inclusions, (4) knocking noises from synchronisers and (5) other background noises. Based on the time elapsed and the flow velocity, the distance from the insertion point or from the synchronisers at which leaks, gas pockets or air bubbles are located is calculated.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: The devices differ somewhat in their application from provider to provider - some are tared and therefore do not get stuck as easily as those which are heavier than water. Another difference is in the location of the device - some can be actively located by emitting signals, while others can be passively located by recording artificially generated sounds at specific points on the pipe. Recently, there are also devices on the market that are not spherical but are elongated. These keep their floating position and can therefore be additionally equipped with cameras, especially for condition assessment or to locate illegal taps.

Combined application with other methods: Since the method is comparatively expensive, it can often be useful to first examine longer pipe sections for the presence of leaks to exclude those pipes in which there are no or only minor leaks. This can be done, for example, by volume balance.

After a leak has been localized by the device, it is useful to check it again with a ground microphone and thus possibly be able to narrow down the leakage point even more precisely (especially if the course of the pipe is not exactly known). However, under certain circumstances (small, quiet leaks, low pressure, very deep pipe), a ground microphone cannot localize the leak. In these cases, soil probes can be used.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Leaks are hardly overlooked and even very small leaks can be found. Only in the case of temporary leaks, i.e., leaks that expand/contract due to temperature changes in the pipe material and only open up temporarily, the leak can be overlooked if it has just closed at the time of inspection. The pipe pressure, on the other hand, plays a much smaller role than with other acoustic methods, since a minimum pressure is already required to move the device. This is usually sufficient to locate all leaks.

Likelihood of false positives (dry holes): Unlike other acoustic methods, the probability of false positives is very low. This is because there is hardly any acoustic interference from the outside in large-diameter pipes because the pipe walls are wider, the pipes are usually buried deeper, and the water in which the device floats can conduct leakage sounds better than synthetic material like PVC or HDPE. In addition, the device passes very close to the leakages.

Margin of error: Under optimal conditions, the margin of error is only one to two meters. However, several factors can cause this to increase significantly. In particular, there is always a higher margin of error if the location of the pipeline is only approximately known or not known at all, i.e., the calculated leakage position in the line can deviate from the position on the surface by many meters. Another source of higher error margins is the distance between the (passive or active) devices or synchronizers for locating the leak detection device, which should be well below one kilometre, but this can be not the case due to a lack of access points.

SCOPE AND LIMITATIONS

When should this method be considered? This method is recommended especially in case of particularly long pipelines with few access possibilities for other methods (correlation, cable-based systems), which can be examined extremely fast. Since leaks in supply networks with small diameters and many access points are usually faster and cheaper to locate and repair, the more complex and expensive location and repair in long pipelines with large diameters should normally only be prioritized when water losses are already somewhat lower, i.e., the effort per leak found in "normal" pipelines becomes increasingly higher. Exceptions to this are cases where major water losses have been identified in large-diameter pipelines and pipelines where accidents can lead to major collateral damage (e.g., because they run through residential areas).

When not to consider this method? The method has quite a few application limits; however, most of them are not very common:

1. **Small diameters:** Depending on the supplier, the devices can be used from 4, 8 or 10 inches (100-250 mm). There is no upper application limit.
2. **Too low or too high water pressure:** 2-25 bars are optimal. The device can also work slightly below and above that pressures (1-30 bars). Large lines rarely operate with water pressures outside this margin.
3. **Too low or too high flow velocity:** Optimal is a minimum velocity of 0.3 m/s. The device can also operate slightly below this (0.2 m/s). At lower speeds, there is a risk that the device will get stuck. Apart from this, the maximum range is also affected by low speeds. On the other hand, a flow velocity that is too high will result in the removal not being secured. In no case should 2.5 m/s be exceeded. Otherwise, the maximum velocity depends on the pipe diameter, i.e., the larger the diameter the lower the

maximum flow velocity should be (e.g., for diameters over 25 inches less than 1.5 m/s is recommended). It is very rare for large lines to operate at flow velocities above this.

4. **Lack of access and removal points:** Valves or gate valves of 4-6 inches (100-150 mm) are best for insertion and removal of equipment. Alternative but laborious options are available if this is not the case.
5. **Open branches:** The greatest risk for loss of equipment comes from line branches that have not been closed before the equipment is used. This is the reason why it shouldn't be used in distribution networks with many branches but rather in long straight pipelines. Some branches are not a problem as long as these are known - however, this is often not the case. Therefore, if there is some uncertainty, device detectors are installed to find out approximately where the device was lost.
6. **Risk for device loss:** A combination of particularly dirty or corroded pipes with bends and low flow velocity can lead to the device getting stuck and lost.
7. **Service not available:** Service providers are not yet established in many countries. However, the distribution network of the different providers is gradually being expanded.

Considerations for application in characteristic circumstances in EMDEs: Technical cadastres are often incomplete, inaccurate, or non-existent in utilities in EMDEs. This can often make the application of the method difficult or even impossible since in such cases the risk of losing the valuable device is much higher. Also, the still very high costs of this method in combination with much lower water costs in EMDEs have so far led to the method being used mainly in industrialized countries. However, both factors (increasing water prices, decreasing costs of the method) are developing in a direction that could gradually make these economic factors less important.

INSTITUTIONAL ASPECTS

Required qualification: For the correct application of the system, a lot of specific knowledge is necessary, such as for the pre-evaluation to find out where the device will be inserted / removed and whether the application is possible or useful at all. In addition, training on the correct insertion of the trapping net and the identification of the points to be blocked off (otherwise the device will be lost) is recommended. The evaluation of the points for the attachment of synchronizers/detectors may require additional qualification as well. Finally, special qualification is necessary for the correct evaluation of the data, with the help of specialized software. All these are reasons why most suppliers offer the system only as a service and do not sell it to utilities.

Required experience: Experience with the application of the system is important to develop alternative solutions on-site (e.g., in case of missing insertion or withdrawal points, unknown line route, quick action in case of loss of a device, etc.).

Usefulness of outsourcing the method: The system is not offered for sale by most providers, but only as a service. This also makes sense since the method is only used from time to time, i.e., the relatively expensive equipment would hardly be used constantly. In addition, a special qualification and experience is needed, which is difficult to acquire with only a few applications.

Necessary or desirable framework conditions at the utility: Exact information about the network must be available for many reasons, such as the limitations of the method, the possibilities of attaching detectors or synchronisers and the exact network length, among others, as they are the basis for billing the service. Everything else is taken care of by the provider.

ECONOMIC ASPECTS

Acquisition cost: As this leak detection method is mainly offered as a service, the investment costs are included in the operational costs (see below).

Required number of staff: In principle, the service provider provides the staff for the locating work. However, the utility often has to provide staff for the duration of the work, e.g., to clear access points or temporarily close gate valves, normally two persons. The actual application of the method is carried out by two staff members provided by the service provider.

Additional operational costs: As this method is almost only offered as a service, only operational costs are incurred. At the time of the realisation of this study, the costs for a one-time inspection of a pipeline were about € 1,000 - 4,000 per inspected kilometre. The costs depend on the one hand on the chosen service provider, but above all on the total length of pipe to be inspected (the shorter the more expensive). An inspection of the pipes is recommended approximately every two to three years.

Possible additional advantages or disadvantages of the method for utilities: When searching for leaks in pipes, air pockets can also be located acoustically with the help of this system. In case of including a camera into the device, like mentioned under variants of the method it can also detect illegal taps or assess pipeline conditions.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The first system of this type was developed in Canada starting in 2004 and has been on the market since around 2008. It is interesting that this system was first developed for the water sector and then adapted for other types of pipelines like oil pipes (often the development tends to be the other way around). The system, which was initially distributed worldwide by only one supplier and therefore expensive, has several new competitors since 2014. That has somewhat reduced the initially very high cost, but it is still an expensive method due to technological factors.

Market penetration: The method is a niche application for very long lines with large diameters. In the first few years since its market launch, it was mainly used in North America, but as a result of the expansion of dealer networks and the market entry of new suppliers, it is also finding increasing acceptance in Europe. The system is also increasingly being used in developing countries, albeit still in isolated cases.

Outlook: This very new method is still under constant improvement. This will probably have an impact in two directions: First, the diameter from which the device can be used could be further reduced. Secondly, the probability that the device will be lost could be lowered, thus reducing costs. Also, the emergence of more competitors will likely lower the very high cost somewhat. Nevertheless, this method will be still one of the more expensive methods in the long run.

FURTHER INFORMATION

Short animated video of the method from different manufacturers: System Nautilus; System Smart Ball; System Pipe Inspector (about 2 min each).

Illustrated product brochures: System Nautilus; System Smart Ball; System Pipe Inspector

Longer presentation about the device combining hydrophone and cameras

Evaluation of the method and comparison with some other methods.

2.1.9. Distributed Acoustic Sensing (DAS)

OVERVIEW	
Type of method: Semi-permanent or permanent stationary location method	
Location principle: Acoustic	**Sensor type:** Sensing cable

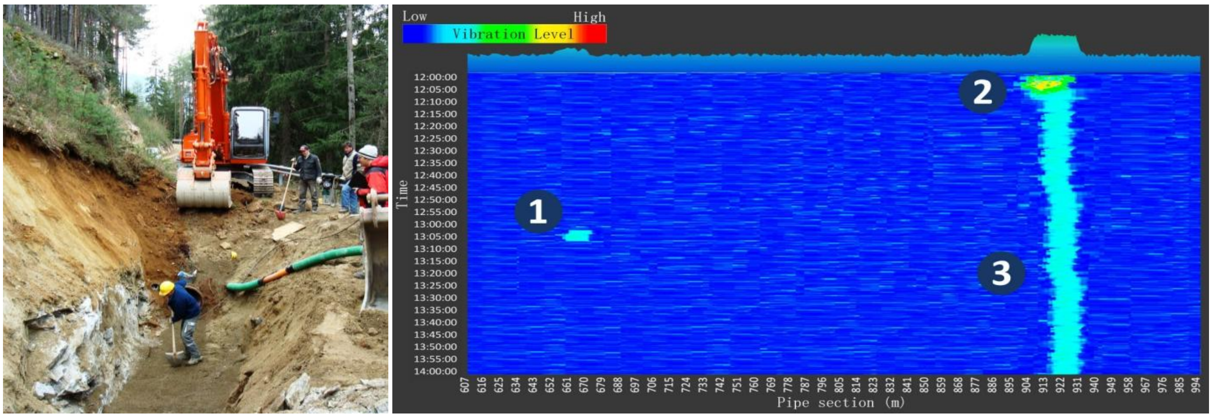


Figure 9. Left: Laying a fibre optic cable with a pipe (Courtesy of Solexperts GmbH); Right: Simplified presentation of DAS results: 1–Temporary acoustic event (e.g., a train passing), 2 – Pipe burst with heavy vibration levels, 3 – Leak with continuous low detectable vibrations.

Leak location principle: Distributed Acoustic Sensing (DAS), sometimes called Distributed Vibration Sensing consists of laying a fibre-optic cable on or (rarely) in pipelines. This can detect acoustic vibrations and assign them to a specific section of the cable. The vibrations can be caused either by the cable break itself or by the noise that the leakage causes permanently. In this case, the system must be able to distinguish the noises caused by leakage from other environmental noises that usually only occur temporarily. In addition, the cables can detect temperature deviations (although not as accurately as DTS – Distributed Temperature Sensing, see respective chapter) and locate them - this information can be crossed with the location of the vibration, if necessary, to confirm the results obtained.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	Possible
Applicability for large diameters pipes	Yes (Preferentially but not exclusively)

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Small influence
Pipe depth	Positive influence	**Knowledge of pipe location**	Can be used for locating
Pipe material	Some influence	**Need for access points**	Not needed
Soil conditions	Some influence	**Method-specific negative factors**	Already-laid pipes

Links to providers
AP Sensing GmbH (Germany); Silixa Ltd. (UK); OptaSense Ltd.

STEP-BY-STEP DESCRIPTION

1st Step: The laying of a fibre optic cable should already be included in the planning of new pipelines. At this point, it is still not absolutely necessary to decide between DAS and DTS, as the corresponding analysis device can be purchased at a later date.

2nd Step: If it has already been decided which method is to be used, a single-mode fibre optic cable should be used for DAS, which should be as close as possible to the pipe (20 cm), while a multimode fibre optic cable is more suitable for DTS and should be buried about 50 cm under the pipe.

3rd Step: It is important to precisely georeference the length of the fibre optic cable in relation to the water pipeline during the laying of pipes and cables. The very precise location from the surface in the event of a leakage alarm can otherwise become very inaccurate.

4th Step: After completion of the installation, a zero measurement is performed. The aim of this is to ensure that the cable is functioning properly, to detect and repair any damage and produce baseline data. These values, which describe a situation without leakage, can then be used as reference values for later measurements. It may also be possible to simulate one or more artificial leakages to prove the functionality.

5th Step: The measurements for leakage location can be taken continuously with a stationary device that can be programmed to trigger an alarm at certain threshold values. The associated software can use machine learning to distinguish temporary and local vibrations from those triggered by leaks and becomes increasingly accurate with prolonged use. Due to the high cost of the measuring device, rotating use at several pipelines is also conceivable.

6th Step: If the interpretation of data anomalies as leakages is not entirely clear, which happens especially with smaller leakages and if the machine learning process is not yet very advanced, it is advisable to confirm the location by another method.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: A variant of the method can be used if the permanent use of expensive equipment is not worthwhile (e.g., if there are many distant but not very long pipelines). This consists of using a device temporarily at different points to share the fixed costs. However, this also has some not insignificant disadvantages: Firstly, the pressure waves that occur during a pipe burst, which are an important indicator of leaks, can only be detected by chance. Secondly, leakages are then often only detected with some delay and thirdly, the function of machine learning is affected, which usually leads to the threshold values for the leakage alarm having to be set somewhat higher so that smaller leakages tend to be overlooked. In addition, the method can be combined with the distributed temperature sensing (DTS) method. Whether this is worthwhile in individual cases can only be determined by carefully studying the local conditions and technical details of the pipes (diameter, material, temperature differences, etc.). Another variant is to lay cables inside the pipes. Since water usually conducts sound better than the surrounding soil, this method (in contrast to DTS) works better in the pipes. Another advantage is that the cables can even be retrofitted with this method. However, this is usually not legally possible, e.g., in the EU due to hygiene regulations.

Combined application with other methods: DAS is used to detect and pre-locate leaks to within a few metres. To keep excavation work low, pinpointing methods such as ground microphones, soil probes or leak sniffer dogs can be used depending on the initial situation, especially if the method has not been in use for very long, i.e., if the machine learning process is not yet very advanced due to insufficient data and there is therefore still an increased possibility of false positives.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Smaller leaks are easily overlooked, especially if the leak is just on the opposite side of the pipeline to the fibre optic cable. For this reason, the installation of two or even more cables is recommended for particularly large pipe diameters (from around 1.5 metres). Under optimal conditions, it is possible to locate leaks with an approximate flow rate of more than 20 L/h. The system has no problems with locating multiple leaks, such as those that can occur after earthquakes.

Likelihood of false positives (dry holes): In principle, the probability of false positives is low. However, this depends on which thresholds are programmed for pressure waves, continuous noise (and possibly temperature changes), i.e., whether one also wants to detect particularly small leakages. Since the system uses machine learning, i.e., it is only gradually able to distinguish all natural diurnal, local and seasonal fluctuations from possible leakages. Therefore, it makes sense to lower the threshold values only gradually to reduce false positives and at the same time to be able to locate many, gradually smaller and smaller leakages.

Margin of error: The margin of error on kilometre-long pipelines is about five metres. The device itself measures to an accuracy of one metre - but this margin of error only refers to the length of the cable, which does not correspond 100% to that of the line due to bends and stretching. In addition, the exact position of the cable must be recorded very precisely during installation and set in relation to the pipelines, otherwise, even greater deviations are possible. An interesting possibility to reduce the margin of error to about two metres is the weight drop method. This involves dropping a weight on the ground at several points near the leakage. These vibrations are in turn recorded so the cable and the leakage location can be located more precisely.

SCOPE AND LIMITATIONS

When should this method be considered? Before installing long pipelines with large diameters, Distributed Acoustic Sensing should be considered for long, large diameter pipelines, especially if the more economic method (DTS) is not suitable due to low temperature differences between the conducted water and the surrounding subsoil. This is even more the case if the pipeline is deep and only a few access points are planned or there are longer pipeline sections which are completely inaccessible (e.g., under rivers), as many other methods of leak detection are either not applicable at all under these circumstances or result in significantly higher costs. In addition, the system should be considered on such pipelines that have already been laid with nearby fibre optic cables (mostly for telecommunication purposes). The investment in the method is of course much lower under these circumstances.

When not to consider this method? The most important application limit is the case where pipes have already been laid without fibre optic cables or pipes with unfavourably-laid fibre optic cables (at long distances, encasings), as the re-laying of the cables is prohibitively expensive. Rare exceptions can be restoration work on lines or above-ground pipelines. The alternative of laying cables inside the pipelines does not exist in most cases due to justified hygienic concerns or lack of authorisation but may be a good alternative in some countries.

Considerations for application in characteristic circumstances in EMDEs: The low-maintenance and easy-to-operate devices have a great sustainability advantage even with high staff turnover and low maintenance capacities, as it is common in many utilities in EMDEs. On the other hand, pipelines are much less likely to be automatically laid with fibre optic cables than in industrialised countries, which must be taken into account in the planning phase.

INSTITUTIONAL ASPECTS

Required qualification: Since installation and commissioning are always carried out by the provider, the training of the water supplier's staff to use the method is not very demanding and takes about 3 days.

Required experience: Since the system's software uses machine learning, empirical values are collected and continuously integrated independently of the responsible personnel. However, the experience values from the staff can play a role in the mentioned non-stationary use of the equipment.

Usefulness of outsourcing the method: From a technical point of view, outsourcing is not necessary because the devices are easy to operate and the data is easy to interpret. However, outsourcing would make sense if a water utility does not want to use the method to constantly monitor the pipelines, but only to check them for leaks from time to time. Since the fixed costs for the devices are relatively high (higher than the devices used for the DTS-method), this can make sense, but the accuracy (machine learning through constant data input) can suffer somewhat.

Necessary or desirable framework conditions at the utility: Just as with the DTS-method the installation of the cables on pipelines must be included in the planning from the very first stages, but the absence of legal regulation in most EMDEs can be a serious obstacle.

ECONOMIC ASPECTS

Acquisition cost: The investment consists mainly of two parts: A variable investment as a function of the length of the fibre optic cable, which costs € 1-3 per metre (the exact cost depends, among other things, on complexity and workmanship, e.g., against breakage resistance, and is usually rather close to the lower price indicated). For the laying itself, unlike the laying of the fibre optic cable for the DTS method, no additional shaft has to be dug, which is why the extra costs for laying the cable are lower and should not exceed € 0.5 per metre. As mentioned in the chapter about DTS, the service life of the cables is probably longer than 50 years. Regardless of the length of the cable(s), fixed costs for the measuring device of currently about € 150,000 are added to this. This value refers to a device suitable for about 50 km of line and includes costs for training and the associated software. As already mentioned, it is possible to divide these fixed costs among several pipelines by rotating the device. Since leaks in newly installed pipelines often occur only after years of use, the payback period of the investment can often be relatively high.

Required number of staff: Only one part-time operator is needed to analyse the data. Additional staff is then required after each leak detection to confirm and pinpoint the leakage.

Additional operational costs: Operational costs of this method are low and consist on the one hand of the energy costs for the laser (approx. 400 W). On the other hand, the laser and the computer for evaluation have to be renewed approx. every 10 years. Rarely, repair costs for damaged cables must be added.

Possible additional advantages or disadvantages of the method for utilities: A possible benefit of this method is that, at least with permanent use, third party intrusion can also be detected, an application that has already proven itself with oil pipelines. The fibre optic cables can also be used for telecommunications purposes.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The underlying principle, Rayleigh scattering, which is also responsible for the sky being blue, has been known for over 100 years. This principle has been used in fibre optic cables for information transmission since the invention of the laser in the early 1960s, and increasingly so since the 1970s. The first patents for the use of DAS also date from this decade - however, DAS systems only became relevant for the water sector in the last 10 years, after it had already been used in the oil and gas sector, mainly due to the sharp and rapid drop in the cost of cables and equipment.

Market penetration: Outside the water sector, the system is already widespread worldwide, but in the water sector in EMDEs there are still only very few projects (e.g., on the Arabian Peninsula). This is because this method is still very new.

Outlook: The still further falling prices, the rapid spread of laid fibre optic cables and the mostly expensive alternatives of temporary leak detection in large diameter pipes, combined with rising water prices worldwide and increasing water stress, suggest a bright future for this method in the water sector.

FURTHER INFORMATION

GIZ-webinar about Distributed Acoustic Sensing (Minute 51 to Minute 104);

Collection of case studies, articles and presentations from different sectors on DTS and DAS;

Technical-physical description of the functional principle of DAS for pipeline monitoring (Zuo et al. 2020)

2.2. Flow-based methods

2.2.1. General information on flow-based methods

The principle of flow-based methods is simple - water that escapes through a leak is missing downstream. Since water has the advantage over other substances that are frequently conducted through pipes, especially gases, but also other liquids from the petrochemical industry, that its volume hardly changes due to pressure and temperature changes, the principle for water is theoretically easier to apply. In practice, however, this is only true for non-complex long pipes or small pipe sections, as water also "disappears" from the network for other reasons - namely through consumption or because it "hides" elsewhere due to a narrow degree of interconnection. Therefore, the application of flow-based methods in supply networks is often very complex and requires either a lot of information about the network to simulate the flow conditions (even artificial intelligence can be used, see Flow Monitoring below) or numerous, often cost-intensive preliminary works (e.g., to set up District Metered Areas - DMAs).

Unlike almost all other methods, the flow-based methods can also estimate the size of the leaks and thus often prioritise field operations. The methods described are used to pre-locate leaks and are hardly capable of detecting small leaks. The only exception is the hydraulic leak localisation pig described last in this subchapter, which is not only used for pinpoint location but also locates very small leaks - an award-winning innovation from England that has only been on the market for a decade.

2.2.2. Volume balance

OVERVIEW	
Type of method: Permanent stationary or temporary mobile pre location method	
Location principle: Flow-rate	**Sensor type:** Contact sensor

Figure 10. Left: Measuring sensors attached to a pipe - in the enlargement at the bottom left, it can be seen that the irregularly applied layer of paint has been removed so as not to distort the measurement results; Right: Central unit that converts the data from the sensors into flow rate and water volume per period of time and stores that information for later uses. (Both photos courtesy: Julian Gonzales)

Leak location principle: The water volume flowing through the pipe is measured at two or more measuring points, then statistically adjusted and compared with each other. If the volume downstream has decreased so much that it exceeds a certain threshold value determined by measurement errors, it can be assumed that there has been a loss of water between the measurement points, usually caused by leakage.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	No (see flow monitoring)
Applicability for large diameters pipes	Yes

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary
Pipe material	No influence	**Need for access points**	Very few (pipe)
Soil conditions	No influence	**Method-specific negative factors**	Crystal-clear water

Links to providers
Flexim GmbH; KROHNE GmbH (both Germany)

STEP-BY-STEP DESCRIPTION

1st Step: Usually two, sometimes more, ultrasonic flow meters with clamp-ons are installed, usually on longer pipelines and at a large distance, and programmed for the measurement, i.e., all data that influence the accuracy of the measurement - diameter, thickness and material of the pipe, water temperature, as well as the possible presence of coatings - are entered. In addition, depending on the device, the frequency and the duration of the measurement can be programmed. When selecting suitable measuring points, it must be ensured that no turbulence is present at the point, which would make the measurement inaccurate. In addition, the installation points must be cleaned beforehand.

2nd Step: Depending on the length and flow velocity, a minimum period of time is required to record enough data to determine the difference between the volumes of water flowing through the individual points. It may be worth waiting a little longer so that minor measurement errors are not noticeable due to the amount of data collected.

3rd Step: The devices are dismantled and the recorded data is downloaded and evaluated with the help of suitable software. This software calculates the volumes in the time period to be taken into account for the individual measuring points based on the measured flow velocities over time, because firstly the water measured at point 1 needs a certain amount of time to get to point two and secondly the flow velocity changes during the measurement so that the time period taken into account at the two measuring points is not only time-shifted but can also be of different durations.

4th Step: The determined volumes are compared with each other and if a certain threshold value (usually at 1-2% percent of the total volume, as 1% is the margin of error of the flow meters) is exceeded, a leakage can be suspected.

5th Step: If leakage is suspected between two flow meters, the distance between the meters can be halved to determine on which half the leak is located, to further isolate the affected section. Depending on the length of the pipe, this can be done several times. However, it should be taken into account that several small leaks distributed over several pipe sections can sometimes no longer be detected if the measuring section is subdivided, namely if they can fall below the threshold value for leaks.

6th Step: Leakages pre-located in this way are then confirmed and pinpointed using other appropriate methods (see under "Combined application with other methods" below).

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: One variant of the method is to use it as a permanent monitoring system, but for long pipelines with mostly large diameters, there are other, usually more accurate monitoring methods that additionally locate the leakages. By using several flow meters and suitable software, the method can also be used for somewhat more complex conditions, whereby the transition to flow monitoring is blurred. Other variants are conceivable by using other measuring principles (such as magnetic-inductive), but although they are partly more accurate, they are usually not considered because they are very difficult to mount and more expensive.

Combined application with other methods: Since this method is used in particular for pre-location on large diameter pipes, it is often used in combination with pinpointing methods. On the one hand, hydrophone correlators and pushed hydrophones can prove suitable, especially if the sections to be examined are somewhat shorter and sufficient access points are available. On the other hand, tethered and free-floating hydrophones are more suitable for medium to long distances.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Only larger leaks can be found with this method. This is because the minimum error margin of flow meters is 1%. This does not sound much at first, but it can amount to many cubic metres per hour for pipes with a large diameter and high flow velocity. To ensure that the margin of error is not significantly higher and thus the probability of missing even more leaks, it is important to set the correct parameters on the flow meter, mount the sensors correctly and choose a longer measuring period. Especially in old pipes, which have corrosion and/or deposits that affect the diameter, additional deviations of the measuring result may occur.

Likelihood of false positives (dry holes): False positives with this method can result from various reasons. On the one hand, measurement errors can occur due to the incorrect installation of the sensors for the flow meter, e.g., at an unsuitable location with turbulence, or the input of inaccurate parameters (diameter, material, wall thickness). However, it is mainly the inherent measuring error of the devices that can be responsible for false alarms. Taking this margin of error into account (usually around or above 1% of the measured volume), the threshold value for a leakage alarm should be chosen. The closer this is to the measurement error, the more likely it is that there will be false positives, but also fewer leaks will be missed.

Margin of error: The margin of error with this method depends exclusively on the distance between the measuring devices and can therefore be reduced, if technically possible and reasonable, by gradually shortening the measuring distance.

SCOPE AND LIMITATIONS

When should this method be considered? This method is particularly suitable for prioritising the use of often complex or more expensive methods for the precise location of leaks in large-diameter pipes, especially in the case of long pipe sections of low complexity.

When not to consider this method? This method has only a few limitations:

1. **Crystal-clear water**: Water without any particles and a very low electrical conductivity cannot be detected by an ultrasonic measuring device. This can occur in individual cases with untreated water.
2. **Complexity:** The method only works for simple, clear, mostly linear flow conditions, because the more complex the meshing of the pipe is, the more devices are needed and the subsequent measurements become less accurate. Other methods, like flow monitoring are then often more advantageous.

3. **Unsuitable access points:** At the points where the devices are attached, there should be very precise information about the properties of the pipe, no turbulence, incrustations or corrosion, otherwise the accuracy of the method suffers so much that it becomes unsuitable. However, the latter often occurs with very old pipelines (i.e., those that leak frequently).

Considerations for application in characteristic circumstances in EMDEs: As this pre-location method can often be carried out in an uncomplicated and cost-effective manner precisely where cost-effective leak detection methods can rarely be applied, it is often used to prioritise leak detection where it is profitable. It is also particularly suitable in EMDEs where water costs are often lower.

INSTITUTIONAL ASPECTS

Required qualification: Since even small mistakes when attaching the sensors to the lines and determining the required data can lead to false-positive or false-negative measurements, training is very important, but does not take very long. Depending on the software used, calculation and interpretation of the data obtained should also be a point in the training, although many utilities already have engineers who can do the necessary calculations even by hand if necessary.

Required experience: When using this method, experience in selecting contact points, installing sensors and determining the required pipe data is a great advantage, but it does not take as long as with many other methods to acquire it. Since flow meters are often already used for other applications, the experience may even already be available at the utility.

Usefulness of outsourcing the method: The method should be seen more as a first step towards outsourcing the actual leak location, i.e., the pipes or pipe sections are pre-identified, upon which a highly specialised leak location activity is then carried out by third parties. Since the method is not very time-consuming, especially if there are not many long pipes with large diameters, the volume of work is usually not worth the outsourcing, whereby very large utilities can be an exception.

Necessary or desirable framework conditions at the utility: Pre-location without subsequent location (and repair) of leaks is of course never meaningful, but in this particular case it is mostly pre-location on pipelines which require particularly technically complex and often expensive methods to locate leaks with pinpoint accuracy once they have been pre-located. This means that before the method is applied, it should already be clear how to proceed in the event of a successful pre-location.

ECONOMIC ASPECTS

Acquisition cost: The cost of the units varies greatly, especially depending on the accessories supplied and the equipment and software of the central unit. Simpler ultrasonic flow meters are available from € 1,500, and more than € 8,000 need not be spent on particularly sophisticated units.

Required number of staff: Although the method can theoretically be carried out by a single operator, the use of one person per device (i.e., usually two) often makes more sense due to the often long distance between the measuring devices and possible safety concerns.

Additional operational costs: Due to the usually large distance between the individual measuring points, motorised mobility is necessary; a motorbike may be enough due to the small size of the equipment. Other costs may be incurred for excavations to create access points to the pipe.

Possible additional advantages or disadvantages of the method for utilities: The same flow meters can also be used for the step test method and to calculate flow rates in water catchment and production. When using the method, illegal tapping can sometimes be detected if it happens during the measurement process.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Although the principle of ultrasonic flow measurement has been known for much longer and measuring devices based on this principle were sold as early as the 1970s, suitable devices for the application described here only came onto the market in the mid-1990s, but were initially still expensive and error-prone, which has changed significantly since the turn of the millennium.

Market penetration: The required flow meters are distributed worldwide. Although many utilities already use them for various applications, they are still very little used for leakage pre-location, mostly because methods for precise location of pre-located leaks are not known, not available or too expensive to use.

Outlook: The increasingly cheaper and easier-to-use devices will probably become established as one of the pre-location methods for other leak detection methods in large diameter pipes described in this document. This may also be because the overall water loss rates are decreasing and thus otherwise difficult to locate and therefore often initially ignored leaks in these pipes are gaining in relative importance.

FURTHER INFORMATION

Video about the installation of a clamp-on ultrasonic flow meter on a pipeline (3 min)

The Ultrasonic Flow Measuring Principle (3 min)

Podcast about the method (37 min)

2.2.3. District Metered Areas (DMAs)

OVERVIEW	
Type of method: Permanent stationary pre location method	
Location principle: Flow-rate	**Sensor type:** Contact sensor

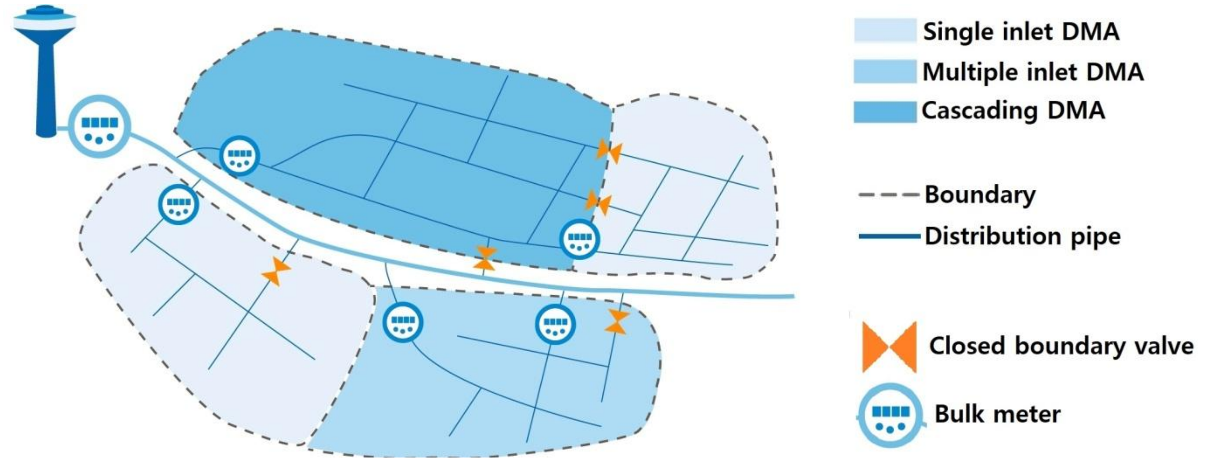


Figure 11. Typical layout of DMAs, based on Farley 2001 (Source: Baader et al. 2011)

Leak location principle: By setting up DMAs-District Metered Areas (sometimes called sectorization or zoning), the supply network is segmented in such a way that it is possible to determine the difference between the amount of water flowing into that segment of the network and the measured (or estimated) consumption, and thus determine the water losses sector by sector. In addition, the water losses can be divided into real and apparent (commercial) losses by night minimum flow measurement.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	Yes
Applicability for large diameters pipes	No

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Depending on the time, impossible
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary (only for setting up)
Pipe material	No influence	**Need for access points**	Very few (pipe or water column)
Soil conditions	No influence	**Method-specific negative factors**	Unfavourable topography

Links to providers
Water Distribution Modelling and Analysis Software WaterCAD - Bentley (USA) and EPANET

STEP-BY-STEP DESCRIPTION

When using this method, a distinction must be made between setting up the DMAs and using existing DMAs for leakage pre-location. The setting up can be very different, e.g., as follows:

1st Step: The first step before setting up a DMA is to update or carry out for the first time the technical cadastre (including the location, length, material and diameter of pipes, location and condition of valves, reservoirs, etc., but also the topography), as well as the customer cadastre to be able to calculate demand.

2nd Step: All the data obtained is fed into software (e.g., Water CAD is very widely used, but also EPANET which is public domain) to create the model with which an initial simulation of pressure, flow rates and consumption, among other things, is carried out.

3rd Step: With the help of field measurements of pressure and flow with mobile devices, the computer model is calibrated. Among other things, errors in the creation of the technical cadastre are found and corrected to keep the deviations between real data and the model as small as possible (guideline: below 5%).

4th Step: With the model created in this way, different possibilities of setting up DMAs can be run through, which activities are necessary for this and the best option, both technically and economically, can be selected. For this, the supplier must also have an idea of how large he wants to design the individual DMAs. A DMA can be of different sizes - 500-3000 service connections are normal, smaller DMAs are rather rare and larger ones are more common. There are many theoretical suggestions on how to determine the economically or hydraulically optimal size (see further information), but often practical considerations play a larger role (geographical and topographical conditions, etc.).

5th Step: This last step consists of the actual implementation of the DMA. This often involves extensive field work such as the installation of flow meters, pressure reducers, the replacement of obsolete gate valves and also the replacement or initial installation of water meters, which can be very costly. Sometimes, however, it is much easier, e.g., with already existing, isolated supply areas that simply need to be equipped with a flow meter at their entrance to turn into a DMA.

The use of already existing DMAs to pre-locate leaks can then proceed as follows:

1st Step: The consumption volume via water meters is measured or (partially) estimated and then compared with the inflowing water volume, with the meters being read as promptly as possible (smart metering can be very helpful), as otherwise additional estimates are necessary. If possible, they can also be measured during an interruption that exists anyway due to intermittent supply or is artificially caused by a shut-off (e.g., see the video by Vitens under further information). The resulting difference is the water loss in this DMA - consisting of apparent and real losses.

2nd Step: The water volume flowing into the DMA is measured during the time with the lowest consumption (usually from 2-4 a.m.) and an assumed minimum night consumption per connection is subtracted (no estimation is necessary with smart meters). Then, to make this real water loss comparable with other DMAs, this volume is divided by the length of the pipes and/or the number of connections. The difference of total losses (calculated in the first step) and real losses (calculated in the second step) are the apparent or also called commercial losses.

3rd Step: In the DMA with the relatively highest real losses, the leak detection teams are deployed, then in the DMA with the second most real losses, etc.

4th **Step:** In addition, in the DMAs with the highest apparent losses, the possible reasons are investigated (meter inaccuracies, illegal connections, etc.).

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: DMAs can have one or more inflows, as well as none, one or more outflows (often to other DMAs, see figure above). On the one hand, this influences the calculation of the water quantities and may make it necessary to shut off inflows and outflows to carry out night minimum flow measurements. Otherwise, complicated calculations may be necessary to make the different flow rates comparable over time. In addition, there are DMAs which are only occasionally used as such for night minimum flow measurements, i.e., where all inlets and outlets are closed except for one (measured) inlet (comparable to the principle of the step test, but on a larger scale).

Further variants result from the principle of data acquisition (remote transmission or on-site reading) and the technical principle of flow measurement (ultrasound, Woltmann, piston meter, etc.). Ultrasonic meters, however, are now more the standard, among other things because they do not need to be recalibrated (very important for stationary monitoring!), do not change the flow characteristics (unlike immersed devices) and the supply does not have to be interrupted for installation.

Combined application with other methods: This method is a classic pre-location technique, i.e., a statement is only made as to which DMA has leaks or often in which DMA the largest amount of water is lost, to prioritise the actual location work. These are then carried out with the help of other methods. Acoustic methods, tracer gas, etc. can be used. It is often a practical option to interpose a step test, as this is usually easier to realise in DMAs, to further narrow down the location(s) of the leakage(s).

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of overlooking leaks is rather higher than with other pre-location methods (e.g., satellite radar and noise level loggers), because if a leak is already assumed with small changes in the flow rate, far too many false positives would have to be accepted. One of the reasons for this is that the margin of error in measuring the flow rate is at least one percent, depending on the chosen flow metering device. It is also important how large the DMA is. Thus, the higher the total water flow, the easier it is for a leak to dissipate. This is the case if the area for the DMA is chosen too large. The smaller the DMA, the easier it is to lower the threshold. Likewise, the threshold value can be reduced if experience values from the same DMA are already available.

Likelihood of false positives (dry holes): The probability of false positives is closely linked to the probability of missing leaks. The smaller the increase in nightly flow (or water losses), the greater the uncertainty as to whether it is a leak, water meter inaccuracies, nightly change in consumption, illegal tapping, new users or indoor leaks. Some of these uncertainties can at least be eliminated or reduced by using a combination of night flow measurement, water loss calculation and water meter reading. Under-registration of the bulk meter at the input of the DMA leads to underestimation of losses and higher false-negative results.

Margin of error: The margin of error depends solely on the size of the DMAs, i.e., the smaller they are, the more accurately the leaks can be narrowed down.

SCOPE AND LIMITATIONS

When should this method be considered? The use of DMAs for leakage pre-location can make sense under very different conditions. On the one hand, for utilities with low water losses, where systematic leakage detection without initial suspicion is no longer economically viable, and for water utilities with high water costs or water shortages to detect leaks promptly. On the other hand, however, also for utilities with low capacities for leakage detection to prioritise these capacities in such a way those losses can be reduced quickly. It is advantageous if there are already high rates of water consumption metering before the DMAs are set up. In addition, it can significantly reduce the investment if the utility plans to set up DMAs from the start in larger projects for renovation or installation of new supply areas.

When not to consider this method? This method has some important limitations, which are particularly common in EMDEs:

1. **Unplanned urban growth:** In areas where cities are growing unplanned, i.e., no reasonable prediction of future water demand can be made; the establishment of DMAs can exacerbate difficulties in meeting the growing demand. Therefore, they should not be established before the consolidation of these critical areas.
2. **Intermittent water supply:** Real losses can be distinguished from apparent losses only when there are virtually consumption-free supply periods. In intermittent supply, there may be no periods of no consumption as consumers use water and fill tanks as long as they are supplied. Additionally, in intermittent supply, air release valves should be installed if the topography is calling for that to avoid meter misregistration which can lead to false negatives.
3. **Low water pressure:** In systems with low water pressures, DMAs can, depending on the topography, lead to even lower water pressures which argue against setting them up at all.
4. **Lack of water consumption measurement:** Leakages on the consumer side also lead to higher nightly flows, but can hardly be distinguished from leaks in the public network, especially in areas with low consumption metering. This is especially true as consumers without meters often tend to ignore their leaks.
5. **High incidence of illegal connections:** Illegal connections by definition do not have a water meter - so the same applies as in the previous point. This leads to the fact that real losses cannot be distinguished from apparent losses.
6. **Inaccurate or incomplete technical cadastres:** To segment the supply network, it is first necessary to know where it is located, how it is interconnected, where the valves are located, and so on. If this is not the case, it is not possible to isolate DMAs. For example, it is often the case that when pipe sections are renewed, not all the old pipes are disconnected, thus rendering the concept of DMA not completely useless, but severely distorting the obtained data.

Considerations for application in characteristic circumstances in EMDEs: All application limits of this method, which either lead to the fact that DMAs do not work so well for leak pre location or are not possible at all to isolate (or only very cost-intensive), are unfortunately disproportionately frequent in EMDEs.

INSTITUTIONAL ASPECTS

Required qualification: For the preparatory work to set up DMAs, experts are needed who can operate the simulation software, among other things. For common software such as Water CAD, such experts are usually available everywhere. After setting up the DMAs, the actual pre location of leaks is relatively easy. However, especially in cities with changing hydraulic conditions (e.g., growing cities with new demand), experts are still needed to react to the changing conditions and to work through and implement the best options.

Required experience: After the DMAs are installed, the data can be evaluated and interpreted with relative ease. To set a balanced threshold point from which to look for leaks in a DMA, and thus keep false positives low if possible without overlooking many leaks, it is necessary to gain and evaluate experience over a long period of time. For water suppliers with high leakage rates in several DMAs, this is not necessary at first, as the method is initially only used to eliminate the largest leakages.

Usefulness of outsourcing the method: Outsourcing the method only makes sense if the necessary work to set up the DMAs is planned and carried out. The collection and evaluation of the data can be done by the utility itself without problems.

Necessary or desirable framework conditions at the utility: Very good information about the network is necessary before setting up DMAs. A less interconnected distribution network prior to the establishment of DMAs tends to result in significantly lower costs.

ECONOMIC ASPECTS

Acquisition cost: The total cost of setting up a DMA is highly variable. In some cases it may be enough to close a few valves and install a flow meter, in others investments for preliminary studies, pressure valves, several flow meters and even new pipelines are necessary and can significantly exceed € 100,000 per DMA. In general, it can be said that DMAs are more expensive to set up in heavily interconnected networks.

Required number of staff: Only one staff member is needed part-time to collect and analyse the water loss data. Additional staff may be needed from time to time to read all the meters in the DMA.

Additional operational costs: Other costs are only incurred from time to time for maintenance or adapting the DMAs to new conditions and can vary considerably.

Possible additional advantages or disadvantages of the method for utilities: DMAs are often, but not always, set up to minimise water losses, but also, among other things, to better regulate the water pressure within a supply network or to guarantee a continuous supply in certain sectors. With a careful analysis of the data obtained, even apparent (commercial) losses can be quantified and lead to important measures such as the search for illegal connections or the replacement of over-aged water meters. The establishment of DMAs can lead to water quality difficulties if more areas of the network have dead spots where particles can accumulate. In addition, DMAs often increase the possibility of supply disruptions because, unlike interconnected systems, they cannot compensate for peaks in demand or leaks that are not found (see below under further information Farley 2010). For the same reason, pressure management can sometimes be difficult.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: DMAs have been used to monitor water losses since the early 1980s, first in the UK, then in Germany and, at the latest since the late 1990s, also worldwide.

Market penetration: DMAs are widely used around the world and are considered a standard solution for monitoring water losses and prioritising leakage detection. However, the often high initial investment and the complicated planning and implementation have led to slow uptake of DMAs, especially in EMDEs.

Outlook: DMAs could slowly but surely play an increasingly important role, partly due to support from international development cooperation. However, there is also the possibility that DMAs will be at least partially replaced by flow monitoring, which overcomes some of the disadvantages of DMAs.

FURTHER INFORMATION

Tutorial videos about: (1) how to generate DMAs with the WaterCAD District Metered Areas tool (19 min) and (2) how to create Pressure zones and DMAs with the WaterCAD Pressure Zone Manager (24 min);

Short illustrative video introducing the topic of DMA (4 min)

Video documentation of the set-up and evaluation of data from a DMA in Mozambique - Part 1; Part 2 (13 min in total)

IWA Guidance notes for District Metered Areas (Morrison et al. 2007)

Description of typical problems with DMAs (Farley 2010)

Proposal for a calculation method for optimal DMA size (Hunaidi & Brothers 2007)

2.2.4. Flow monitoring

OVERVIEW	
Type of method: Permanent stationary pre location method	
Location principle: Flow-rate	**Sensor type:** Contact sensor

Figure 12. Left: Control box of a flow-measuring station consisting of 1- Controller, 2- Power supply, 3- Converter, 4- GSM-Modem for data transmission, 5- Power connection, 6- Battery Pack for emergency power supply; Right: Software analysis tool indicating a likely leak position and the approximate value of lost water (Both courtesy of RBS Wave GmbH)

Leak location principle: The flow rate is measured at several points in the water supply network. In comparison with historical, calculated flow rates and flow rates measured at other points, a statement can thus be made as to whether there are leaks in a particular section of the pipe network. Particular attention is paid to the flow rates at the low-consumption night-time.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	Yes
Applicability for large diameters pipes	No (see volume balance)

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Depending on the time, impossible
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary (only for setting up)
Pipe material	No influence	**Need for access points**	Very few (pipe)
Soil conditions	No influence	**Method-specific negative factors**	High leakage rates

Links to providers
RBS wave GmbH; SebaKMT GmbH; VAG GmbH (all Germany)

STEP-BY-STEP DESCRIPTION

When using this method, a distinction must be made between the installation of the monitoring units and using them afterwards for leakage pre-location. The installation is normally like follows:

1st Step: The steps for preparation are basically the same as for setting up a DMA (for details see there): 1. Creation or updating of the technical cadastre, 2. Creation of a hydraulic model (software-based, e.g., with WaterCAD), 3. Calibration of the model. This way, the optimal position of the individual flow monitoring stations can be determined by using hydraulic simulations and one or more so-called virtual DMAs can be set up.

2nd Step: Now several stationary flow monitoring stations are installed. To do this, the pipe is uncovered at the point where the measurement is to be made and a measuring device or sensors are attached there. When installing the flow meters, there are many factors to consider, such as wall thickness, diameter and material. This determines which sensors are installed and at what distance. As specified by the manufacturers it is also important to ensure that there are no disturbances to the flow in the installation area (e.g., due to nearby bends), otherwise incorrect measurements will occur. The two sensors of the measuring device are attached to the pipe longitudinally from the outside with special protective devices against damage and deterioration. The sensors can be installed on all types of pipe material.

3rd Step: The fully installed monitoring unit is wired to a nearby control box. This contains the central unit, which calculates the flow velocity and the flow quantity from the received data, the transmitting unit, which sends the data to the central unit via the mobile phone net, an emergency battery and a connection to the power supply of whatever kind.

The actual use of flow monitoring to pre-locate leaks can then proceed as follows:

1st Step: The flow rates are metered and stored, especially the nightly flow at low-consumption times (2-4 o'clock is considered a reference value, but depends on local conditions), and later transmitted to the central unit, so that they can be analysed in the morning when work starts.

2nd Step: The data is analysed. Leakages which are already present when the system is installed can be detected if the actual flow is compared with an expected flow. Therefore, the minimum night flow is considered in particular, as the expected flow can be determined most easily here as there is hardly any domestic consumption during these night-time hours. This night-time flow should be relatively constant and should not change much from day to day. The minimum night consumption occurring at these hours is best determined locally from empirical values (example: in some small European towns 0.4-0.8 M3/h for 1000 inhabitants are estimated). If the values are higher and cannot be explained in any other way (e.g., by industrial night-time consumption), one or more leakages could be expected.

3rd Step: Compared to a temporary installation of flow meters, the stationary flow measurement is more accurate over a longer period of time. The flow rate is repeatedly compared with older values and fluctuations are detected at an early stage. A relatively sudden increase in the night flow, which is also confirmed over several nights, can be interpreted as a leak. A leakage alarm can therefore be triggered even with small increases in flow.

4th Step: It should be noted that other events (e.g., a factory starting production, agricultural irrigation, an additional pipeline section is put into operation, World Cup football results in many people staying up late) also influence the flow rate and lead to permanent or temporary changes. Before the actual leak detection begins, these changes must be identified and taken into account.

5th Step: The leak that has been identified and assigned to a specific area must be confirmed by other methods and located with pinpoint accuracy.

Optional step: The system can be gradually expanded by installing more monitoring stations, thus making the pre-location increasingly accurate. This expansion can be designed in such a way that areas with higher leakage rates, in particular, can be prioritised and examined more precisely.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: A distinction can be made in this method according to the type of flow meter. There are various metering principles, which are not dissimilar to those of water consumption meters. Non-invasive ultrasonic meters have become the standard, among other things because they do not need to be recalibrated, which is particularly important for stationary monitoring. In addition, unlike immersed devices, they do not change the flow characteristics and the supply does not have to be interrupted during installation. In particular, for large diameters, it is also more economical compared to the magnetic-inductive system, which is also very accurate.

Combined application with other methods: The method described is a pre-location technique, i.e., it is only possible to make a statement about the area in which a leak is located. This must then be confirmed using other methods and the leak located with pinpoint accuracy. Depending on the circumstances, listening rods, leak noise correlators, ground microphones, tracer gas, etc. can be used.

ACCURACY AND RELIABILITY

Likelihood of false negatives (Overseen leaks): Small leaks are usually overlooked. The probability for that is slightly higher than with other pre-location methods (satellite radar, noise level loggers) because if a leak were to be assumed even with small increases in flow rate, too many false positive alarms would have to be accepted. The margin of error of the flow meters is 1% of the metered value with a low metering barrier of 0.01 m/s. It is also important how large the measured zone is. For example, if the measured zone is very large, the base flow is higher and a leakage below the possible metering accuracy is easily lost. However, the closer the network of flow meters is, the more likely it is that the threshold can be lowered, also if experience values are already available because the monitoring system has been installed already for a longer period of time.

Likelihood of false positives (dry holes): The probability of false positives is closely linked to the probability of missing leaks. The smaller the increase in flow, the greater the uncertainty as to whether it is a leak or if there is another reason. These can include illegal tapping, new users or changing consumption patterns. Leakages in the public network can also hardly be distinguished from leakages on the consumer side, especially if there is little or no water metering. Mismeasurements by the measuring devices are rather rare, whereas human errors in attaching the sensors can occur somewhat more frequently. The latter, however, can only lead to false positives at the beginning of the measurements and in the absence of historical data. However, since it is a pre-location method, this rarely leads to excavations, but to additional and then fruitless leak detection efforts.

Margin of error: With this method, the margin of error depends exclusively on the distance between the individual measuring points, i.e., the more flow meters, the smaller the margin of error.

SCOPE AND LIMITATIONS

When should this method be considered? This method is particularly suitable for utilities with such low leakage rates that systematic leakage detection without initial suspicion is no longer economically feasible or utilities with very high water costs or water shortages and therefore, it is important to detect leaks very quickly. Among these, the installation of a flow monitoring system is particularly worthwhile if, on the one hand, there are no DMAs yet, they are very expensive to implement or it is technically not advisable to set them up, e.g., for reasons of water pressure. On the other hand, it may be useful to install flow monitoring systems instead of noise loggers if large pipe sections are made of plastic and the loggers are therefore not technically or economically feasible. By using a flow meter, the volume of a leak is known, which is the basis to quickly set up further steps. However, it should always be kept in mind that very small leaks are usually overlooked with this method.

When not to consider this method? The limitations of this method are as follows:

1. **Intermittent water supply:** The method works much better if there are virtually consumption-free supply periods or there is a predictable consumption hydrograph. With intermittent supply, there may be no periods of no consumption as consumers use water and fill tanks as long as they are supplied.
2. **High leakage density:** In areas with a lot of leakages everywhere, the system is not useful as a pre-location tool. However, loss rates in individual areas can be compared to prioritise leakage detection and subsequent pipe repair.
3. **Low levels of consumption metering:** Leaks at the consumer also lead to higher nightly flows, but can hardly be distinguished from leaks in the public network in areas with a low installation density of water meters. In addition, consumers without water meters often tend to ignore their leakages.
4. **Mobile network coverage:** The data transmission via mobile phone network must be ensured.

Considerations for application in typical circumstances in EMDEs: Several of the limitations of this method mentioned under "When not to consider this method?" (e.g., intermittent supply, lack of consumption measurement) are particularly common in EMDEs. In addition, the investment costs of this already capital-intensive method are usually higher than in industrialised countries due to import costs and intermediary margins, high crime rates (which often require additional security measures) and unclear hydraulic conditions (requiring additional preparatory work).

INSTITUTIONAL ASPECTS

Required qualification: One difficulty is to correctly mount the sensors of the flow meters and to correctly gather the necessary data such as material, wall thickness and diameter in the field, otherwise the measurements are erroneous. For this reason, this is often offered as a service. For hydraulic simulations to identify which values are to be interpreted as leakages, as well as reacting to changing hydraulic conditions (e.g., growing cities with new demand), experts are still needed even after the installation of the flow meters.

Required experience: Once the system is installed, all that is left is to evaluate data, which is relatively easy, especially with software support. To set a balanced threshold point from which to look for leaks in a suspicious section, and thus keep false positives low if possible without overlooking many leaks, it is necessary to gain and evaluate experience over a long period of time. This is possibly a point which will be supported by artificial intelligence in the near future.

Usefulness of outsourcing the method: Outsourcing is only recommended for the planning and installation of the stations. The actual flow monitoring can usually be done easily by the utility with relatively little effort. In the case of very large utilities, outsourcing including the maintenance of the stations could make sense.

Necessary or desirable framework conditions at the utility: An updated technical cadastre is important, but not 100% necessary, although it can lead to higher installation costs if it is missing. The utility should have the capacity to react to changing conditions in a metered sector (new consumers, industrial settlements, etc.), record them quickly and include them in the calculations, as otherwise false alarms can quickly occur.

ECONOMIC ASPECTS

Acquisition cost: A measuring station, which consists of the flow meter, the control unit, the transmission unit and an emergency battery, as well as the associated equipment box, costs about € 10,000 - 12,000. In addition, there are the installation costs, as well as possible additional costs (e.g., for a solar panel) depending on the type of power supply. The number of stations depends on the installation density and the size of the network. Normally, the stations are installed at intervals of a few kilometres (~10-15km), but as already mentioned, the installation density can also be higher.

Required number of staff: Except in megacities, one person part-time should be enough to monitor the data. Of course, additional staff is needed for the actual leak location and from time to time for the maintenance of the monitoring stations.

Additional operational costs: The operational costs of the system are limited to negligible electricity costs and a monthly flat rate for the transmission of data from the individual measuring stations. The lowest flat rate should normally be sufficient for the amount of data to be transmitted.

Possible additional advantages or disadvantages of the method for utilities: The monitoring stations can also be equipped to collect additional data; especially water pressure, temperature and more recently even water quality data, at a modest additional cost. One advantage over DMAs is that hardly any changes to the existing supply system are necessary and therefore the possible negative collateral consequences described there do not occur. In certain locations, the equipment boxes are not wanted, among others for aesthetic reasons (e.g., in historic city centres). A change in the flow situation inside of a DMA is often not caused by a leak but by a closed or semi-closed valve. When the monitored flow in an area is compared with a hydraulic model, the area of the changed operating condition can be localized.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Since the early 80s, the method of leak detection with District Metered Areas (DMAs) spread all over the world because of its reliability and accuracy. However, there were often collateral problems with water quality and security of supply by creating dead-end pipes when closing valves. Non-DMA-based flow monitoring is a response to these common problems that attempts to preserve the benefits of DMAs at the same time. Flow monitoring has become a serious alternative since the early 2010s.

Market penetration: As the method is quite new, it is not yet very widespread, but it is now offered by many important companies (Siemens, SebaKMT, RBS-Wave, VAG) and is already being used successfully at many locations, especially in Europe. Similarly, there are initial applications in Latin America.

Outlook: Due to its technical advantages, the method will probably partially replace DMAs - but not where DMAs already exist, where it is very cost-effective to establish them or where they are necessary mainly for other reasons (pressure management). The method can also be used to minimize the number of existing DMAs or to upgrade the monitoring by additional virtual DMAs in an existing large one.

FURTHER INFORMATION

Video about the installation of a complete monitoring unit (4 min)

Video about flow monitoring with a focus on the actual metering (4 min)

Illustrative video about the overall flow monitoring process (5:30 min)

Article, comparing flow monitoring with pressure monitoring, arriving at the conclusion that the latter is not economically feasible (Osmanevic & Gaus 2019, only in German)

Detailed article about the method (Gangl & Navas 2016, behind a paywall)

2.2.5. Step Test

OVERVIEW

Type of method: Temporary mobile pre location method

Location principle: Flow-rate	**Sensor type:** Contact sensor

Figure 13. Left: Closing of a control valve. Right: Simplified representation of the measurement results of a step test between 2 a.m. and 4 a.m. - the two red bars represent the large reduction in flow after closing gates 6 and 18, which indicate leakage in the sections that have been shut off, while the smaller reductions in flow when closing the other gates are due to small amounts of consumption or dripping taps, etc.

Leak location principle: At the entrance to a supply area, the flow rate is measured at the time of lowest consumption (at night) and gradually the supply to parts of this area is shut off, starting with the most distant gate valve. The drop in flow rate after the gradual shut-off provides information about the location and size of possible leaks.

Areas of application

Applicability for indoor leak location	No, but see variants of the method below
Applicability for distribution networks	Yes
Applicability for large diameters pipes	No

Influencing factors

Water pressure	Some influence	**Intermittent supply**	Depending on the time, impossible
Pipe depth	No influence	**Knowledge of pipe location**	Not necessary
Pipe material	No influence	**Need for access points**	Very few (pipe or water column)
Soil conditions	No influence	**Method-specific negative factors**	Defective valves

Links to providers

HWM-Water Ltd (UK); SebaKMT GmbH (Germany); OMEGA Engineering Inc. (USA); Flexim GmbH (Germany)

STEP-BY-STEP DESCRIPTION

1st Step: A mobile flow meter (normally with a data logger) is installed at the entrance of a part of the supply area. The metering device is attached to the exposed pipe. This is mainly done at night when consumption is close to zero, so it is convenient to prepare the connection point for the test already in daylight. The flow is constantly recorded by the device, but also monitored at the same time by a staff member.

2nd Step: Now, starting with the most distant ones, gate valves are gradually closed by a second operator. Depending on the number of valves to be closed and the time available (the low-consumption time could be, for example, the two hours between 2 and 4 a.m.), there should be at least 5-10 min between the closing of the individual gates. The time of the individual closing processes must be noted - the exact time should be synchronised with that of the flow meter. It is also convenient if the two workers can communicate by mobile phone or radio.

3rd Step: As soon as there is a significant drop in the flow rate, a leak can be suspected in the last disconnected pipe section. To rule out an increase in consumption due to short-term consumption, the valve can be opened again to check once more (for a longer time if possible) whether there is an increase in the flow rate again (leak) or not (no leak).

4th Step: After the closest valve to the flow meter has also been closed, the measurement is finished and the flow meter is uninstalled.

5th Step: The data can be graphically evaluated on a computer on the same day. The temporal curve of the flow rate allows, after assigning the times of closure of the individual valves, the pre-location of one or more leakages to specific pipe sections between two valves.

6th Step: The suspected leaks are confirmed using another method and located with pinpoint accuracy.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: To prevent a single running faucet from negatively influencing the measurement results, it may make sense to shut off all service connections during the test. Theoretically, the test could then also be carried out during the day, but the interruption of the supply is much more inconvenient for the users and any illegal connections or connections that cannot be shut off tend to have a negative influence on the result.

If smart meters are available, the measured consumption can also be deducted and the method can then theoretically be applied during the day. In EMDEs, however, this variant is often unsuitable because of the presence of illegal connections and incomplete commercial cadastres.

A simplified version of the step test is often used in searching for indoor leaks and consists of closing off individual sections while tracking whether the meter registers and at what moment it stops, thus quickly narrowing down the section in which the leak is located.

Combined application with other methods: The step test is a pre-location technique, i.e., it is only possible to make a statement about which gate valves have leaks between them. This must then be confirmed and the leak must be pinpointed using other methods. Acoustic methods can be used for this but if acoustic methods do not lead to success in the tested area, the combination of the step test and the tracer-gas method can be optimal, as they do not depend on factors like ambient noise.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Small leakages are easily overlooked, as they only lead to small changes in the flow rate, which could also be interpreted as night consumption - otherwise, if the threshold above which small flow rates are interpreted as leakages is low, the number of false positives increases. If it is possible to prevent consumption by disconnecting the service connections - slightly smaller leakages can also be detected, even without a higher probability of false positives. In this case, the source of false positives is limited to consumption from illegal or otherwise unregistered connections or those that cannot be disconnected for technical reasons. It should be noted, however, that even through these connections rather little is consumed at night time.

Likelihood of false positives (dry holes): The probability is relatively high since even a single water tap that is left on accidentally overnight or intentionally (e.g., swimming pool filling) can lead to false reports - the same applies to indoor leaks. However, as it is a pre-location technique, a false alarm does not lead to dry holes at all, but additional efforts searching for non-existent leaks. This does not apply if it is possible to prevent any consumption by disconnecting the service connections - in this case, the source of false-positive reports is limited to consumption from illegal, unregistered connections or connections that cannot be disconnected for technical reasons.

Margin of error: With this method, the margin of error depends solely on the distance of the valves used, i.e., the more valves are available (and functioning!), the more accurate the pre-location.

SCOPE AND LIMITATIONS

When should this method be considered? The step test is particularly suitable in areas with high noise levels, plastic pipes, low pressure and similar obstacles for acoustic location. It is all the more accurate the more functioning valves are available and if it is possible to shut off all service connections in the tested area for a short time, which makes it less susceptible to errors. It can often be used when no other pre-location options are available to the utility and then save a lot of time in the actual leak location. It works best in branching networks.

When not to consider this method? The method has quite a few application limits; some of them are quite common:

1. **Intermittent supply:** If water is not available at the best time to use the method (i.e., at night) because of intermittent supply, the step test will not work.
2. **Low levels of water metering:** Unless it is possible to disconnect all connections in the surveyed area during the test, a low level of water metering is a real problem, as in such cases leakages at the consumer site are much more frequent and cannot be distinguished with the method from leakages in the public network. However, cases where the utility is also specifically looking for leaks at the consumer site must be distinguished.
3. **Defective gate valves:** Especially, but not only in EMDEs, gate valves are often defective, difficult to access or impossible to find, which makes the method at least less accurate (as the pre-located sections become larger) or even not applicable (if certain sections cannot be closed). The importance of this factor is shown by the fact that, in

Germany, the widespread use of the method and its relative usefulness led to many valves being repaired or replaced.

4. **Interconnected water systems:** The method cannot be used for closely interconnected water systems in which it is not possible to shut off certain areas (also in combination with the previous application limit).
5. **Presence of large customers:** In pipe sections with large customers with variable night-time consumption (factories, nightclubs, etc.), the interpretation of the data is always difficult or impossible if their connections cannot be shut off for the duration of the test.

Considerations for application in characteristic circumstances in EMDEs: The relatively high night-time workload, combined with low investment, speaks more in favour of an application in EMDEs. In addition, it is often less problematic to briefly interrupt the supply there, but above all, service connections can often be disconnected quickly and easily, which increases the accuracy of the method. On the other hand, typical application limits (broken valves, intermittent supply) are rather common in many EMDEs.

INSTITUTIONAL ASPECTS

Required qualification: The training for the correct use of the flow meter takes about one day and is usually included in the delivery. The main difficulty is to learn how to correctly attach the sensors and correctly record data such as material, wall thickness and diameter of the pipe where the meter is attached, otherwise the measurements will be incorrect.

Required experience: The experience needed for this method itself is limited, but some experience is necessary for the complementary field work, such as correct gate valve operation (e.g., to avoid pressure surges or to recognise why a gate valve does not close). In most utilities, however, there are staff members with this experience.

Usefulness of outsourcing the method: Since the work is carried out during the night and it is often difficult to assign permanent employees of the utility for that, outsourcing the method often makes sense. If it is not difficult, outsourcing is not necessary, as the needed qualifications and experience can also be acquired by employees. They often have advantages over third parties in terms of knowledge of their network.

Necessary or desirable framework conditions at the utility: The location and type of gate valves must be known and they must be functional and accessible. The latter is a common obstacle. A detailed cadastre is also necessary, to know which branches are shut off. In addition, the staff must be able to work at night.

ECONOMIC ASPECTS

Acquisition cost: Simple flow loggers for the entrance of a sector can be bought for as little as € 2,000. Advanced step-test specialised instrument sets can cost something between € 7,000 and €10,000.

Required number of staff: Two operators are needed - one is responsible for successively shutting off the valves, the other for operating and monitoring the flow meter. Since the method is mainly used at night, this can tend to lead to higher personnel costs.

Additional operational costs: Motorized transport for the flow measuring device is not needed, as it only weighs two to three kilograms. There are usually no further costs. Sometimes gate valves need to be repaired. When working in dangerous neighbourhoods at night, there may be costs for security measures of some kind.

Possible additional advantages or disadvantages of the method for utilities: Closing valves can cause pressure surges and thus damage, especially in the case of high water pressure and old pipes. Changes in the direction of flow can cause incrustations to detach, which can lead to water quality problems. In addition, the supply must be interrupted for larger pipe sections - since this mostly happens at night, this should not be too much of a problem. However, as already mentioned, night-time use of the method in dangerous neighbourhoods may pose a safety risk to the utility staff.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The step test emerged in the 1960s as a pre-location method and developed from the nightly minimum consumption measurement, which has existed practically since the existence of the water supply, when it was observed that the water reservoirs lose more water than usual during the low-consumption night hours. Until the 1980s, it was one of the most widespread pre-location methods due to a lack of alternatives. Since then, it has been partially replaced by other methods, first mainly by noise level loggers, then also by DMAs, flow monitoring, satellite detection, etc., but without being completely displaced by them. This is especially true in Europe, as interruptions in supply have become less and less acceptable and labour laws have made night work more difficult or at least more expensive.

Market penetration: It is still a widespread method, which is also quite well-known.

Outlook: On the one hand, new methods will probably continue to substitute the step test, but will not replace it in the foreseeable future. On the other hand, new devices are coming into the market – these are simplifying the step test with computer support, making it also more accurate. The installation of DMAs at many water utilities also facilitates the application of this method.

FURTHER INFORMATION

Simple, well-illustrated description of the step test (IHE Delft)

Method to combine field step tests with hydraulic modelling (Boulos et al. 2008)

Description of different ways to perform the step test (Farley 2001; see chapter 9)

2.2.6. Hydraulic leak localization pig

OVERVIEW	
Type of method: Temporary mobile location and pinpointing method	
Location principle: Flow-rate	**Sensor type:** Pig

Figure 14. Left: 1 – Central unit, 2 – Hose containing the guiding cable of the hydraulic pig, 3 - Water extraction hose 4 – Disinfection liquid, 5 – Signal locator; Right: Operation of the device in the pipe: 1 – Entering the pipe deflated, 2- Inflating the bladder, 3 – Advancing through the pipe, 4 – Stopping on the leak position (All courtesy of Ferret Technology)

Leak location principle: A pig head equipped with a hydraulically expandable bladder is inserted into a pipe with a suspected leak and, after expansion, is propelled forward by the water pressure. When it passes a leak, this causes the water pressure built up behind the bladder to drop, causing the bladder to stop.

Areas of application	
Applicability for indoor leak location	Sometimes
Applicability for distribution networks	Yes (especially for connections)
Applicability for large diameters pipes	No

Influencing factors			
Water pressure	Easily adaptable	**Intermittent supply**	Relatively easy to adapt
Pipe depth	Indirect influence	**Knowledge of pipe location**	Can be used for locating
Pipe material	Important	**Need for access points**	Many, small ones for insertion in the pipe
Soil conditions	Indirect influence	**Method-specific negative factors**	Pipe bends

Links to providers
[HWM-Water Ltd.; Ferret Technology Ltd. (both UK)]

STEP-BY-STEP DESCRIPTION

1st Step: Most of the time, the device is only used when a leakage is already suspected or has been pre located. First of all, an insertion point must be found, usually on a service connection (meter box) or on the pipe itself. The device set has various common adapters for this purpose. Often it is necessary to dig an access to the pipe itself, cut it and (after the test) repair it.

2nd Step: The device head, which is first disinfected with a chlorine spray, is inserted into the pipe via an umbilical cord (a hose). Water is fed into the pipe through this umbilical cord to fill this and build up the pressure that pushes the pig. The head is available in different sizes up to 45mm (2 inches) in diameter and consists of a hydraulically expandable bladder and a tracking transmitter. The water with which the umbilical is supplied is taken from the water network or a tank with a second hose. The section to be examined is now pressurised with this water. Initially, the bladder is not yet expanded so that the water can continue to flow. Both hoses are connected to the central unit, through which on the one hand the pressure can be regulated and with which on the other hand the head can be expanded or contracted.

3rd Step: Now the water pressure in the bladder is increased so that it blocks the pipe. Then the pressure of the water behind the bladder is increased. Now, very slowly, water is let out of the bladder until the wired head of the device moves forward hydraulically, but still so little that no water can flow past.

4th Step: If the head hits an obstacle (e.g., a fitting), it can be emptied further for a short time to be pushed further and then immediately brought back to optimum pressure. Thus, driven by the water pressure behind it, it continues on its way.

5th Step: When the head passes a leak, the pressure behind the head suddenly decreases so that it comes to a standstill (larger leak), or at least the speed is throttled (small leak). In the latter case, the leak can be confirmed by expanding the head even further. The water pressure (measured at the central unit of the unit) should drop sharply at this point at the latest - the leak is thus confirmed. To distinguish a leak from an obstruction, it can be read on the central unit whether there is a water flow (leak) or not (obstruction). Leaks occur particularly frequently at fittings. However, since the bubble is emptied at these, the leak is not found immediately. This is not a real problem because as soon as the bubble is free again, it is filled again (expanded) and now the leak is found a few centimetres behind the fitting.

6th Step: The location of the device head and thus the leakage, from the surface, is carried out via a built-in transmitter, which is located a few centimetres behind the bladder. A locating device is used for this purpose, with which the possible course of the pipe can be followed and which can locate the transmitter precisely to within a few centimetres. If the exact location of the pipe is known, this locating method is not necessary, as the inserted cable length is also displayed with centimetre accuracy and the location of the leak can be determined with the help of a measuring wheel. Both locating methods can also be combined to save time in the search and still ensure accuracy. i.e., the approximate location is determined by the length of the cable and the direction of the pipe and then only a small area is walked with the locator. The locator does not work in metallic pipes - which are much easier to locate by other methods.

7th Step (optional): Especially in older pipes flushing of the inspected pipe is recommended because the existence of bacterial microfilm is likely after several years of use. This film, together with other particles will be disturbed by the device head and can affect water quality.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: In its basic setting, the unit works in the direction of the normal water flow. With the help of an additional kit, this can be reversed under certain conditions (see link here).

The company Palmer (HWM Group) offers a similar pig, but it is pneumatic rather than hydraulic, with the disadvantage that small leaks (as air is compressible) can be missed. This pneumatic device does not seem to be very successful commercially, at least it is hardly offered anywhere and possibly the production was stopped recently (information from the manufacturer was requested but remained unanswered).

Combined application with other methods: The limited radius of action of the method on the one hand and the possibility of pinpoint leaks, on the other hand, suggests combining it with methods for pre-location - e.g., with the step test, noise loggers or listening rods. Since it does not work against the water pressure, it should be considered, if all other conditions remain the same, whether a pushed hydrophone should not be used instead.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Very small leaks can also be found - from about 0.01 l/s.

Likelihood of false positives (dry holes): The probability of false positives with this method is almost zero. It is conceivable that in the case of pipes or fittings with incrustations and thus an irregular surface, water flows past the balloon and thus simulates a leakage. In practice, however, such cases have not yet been reported and are very unlikely. In addition, illegal or unregistered connections can be perceived as leaks, but this is not a real problem (in which case these connections are then noticed, which would be more of a positive side effect).

Margin of error: The margin of error is very small because it can be read to the centimetre of how far the cable has been inserted. If the exact position of the pipes is not known, the head of the device, located at the leakage can be found with centimetre accuracy using a locator probe.

SCOPE AND LIMITATIONS

When should this method be considered? This method is particularly suitable for the most precise localisation of pre-located leaks when acoustic methods fail (due to low pressure, deep pipes, noise level, etc.), especially when there are many insertion points, few obstacles and smooth pipe surfaces. It is also very useful when even small leaks need to be detected due to high water prices or water scarcity. In the case of intermittent supply, it is also conceivable to carry a small water tank (not much water is needed) - this way, leaks can also be found in empty pipes.

When not to consider this method? The limitations to be considered before purchasing the devices or using this method are as follows:

1. **Obstacles:** The main application limitation is the frequent presence of pipe bends, where the technique can overcome 90° bent pipes, but not if the bend consists of a fitting on which it can get stuck (especially with small pipe diameters like ½"). It should tend to get around such obstacles a little easier like a pushed hydrophone.

2. **Rough pipe surface:** If the surface in the pipe is very rough, the bladder will easily get stuck, can be damaged or will not seal the pipe completely. This can happen, for example, due to corrosion in iron pipes, lime deposits or in concrete pipes. However, in plastic pipes, these problems usually do not occur.
3. **Large pipe diameters:** The system works in diameters up to 2" (50 mm). It is theoretically possible that this will be extended by manufacturers in the future.
4. **Water pressure too low or too high:** 20 mH_2O (=2 bar) is optimal. According to the manufacturer, it works in a range of 5-50 mH_2O (=0.5-5 bar). However, the water pressure can be regulated down with valves and if it is lower, it can be built up with the help of a pump.
5. **Few access points:** Although it is somewhat easier to gain access via the pipe for the small diameters where this method is used, the cost of the method is significantly higher if there are no insertion points, especially if there is also extensive excavation work or sealed surfaces. Under these circumstances, depending on the other circumstances, other methods, e.g., acoustic, may prove to be faster, easier and more cost-effective.

Considerations for application in characteristic circumstances in EMDEs: The method

has particular comparative advantages in systems with low pressure, as well as in intermittent supply, which are frequent in EMDEs. In addition, the devices are comparatively inexpensive. The comparatively high personnel requirements have less of an economic impact in most EMDEs than in industrialised countries.

INSTITUTIONAL ASPECTS

Required qualification: The device is not particularly complicated to operate. The main functions are quickly explained, but it still requires some practical training to fully understand it. In addition, it is necessary to be able to operate the tracking device. All in all, the training offered by the manufacturer only takes about 3 hours.

Required experience: Some experience is needed to find suitable insertion points, choose the right head size, select the right pressure, distinguish obstacles from leaks and decide whether an obstacle is surmountable or not (to prevent damage to the head). Also, some plumbing experience is often useful, for instance for the repair of created direct access points to the pipes.

Usefulness of outsourcing the method: The rather simple handling, combined with the low price of the device, makes outsourcing unnecessary. In the UK, where the system is mainly used so far, many utilities use it directly as well as through many service providers.

Necessary or desirable framework conditions at the utility: It is important to know the local or national hygiene regulations, to see to what extent devices for disinfectants are necessary and then to have them in stock. From time to time, equipment heads have to be restocked.

ECONOMIC ASPECTS

Acquisition cost: Depending on the accessories, the purchase costs for the devices amount to approx. € 3,500 - 5,000. The most important difference is whether they are supplied with or without a tracking device. In addition, a few hundred Euros should be added for the device heads for different diameters.

Required number of staff: Only one operator is required to handle this device.

Additional operational costs: Since the unit weighs almost 20 kg and often requires additional accessories, motorised transport is always necessary. When used in empty pipes, a larger tank (from 200 to 500 litres or even more, depending on the task) must also be brought into the field. Operational costs also arise from the replacement of the bladders. These can be used 5-10 times and cost € 30 - 50 per piece, depending on size. Further costs can always arise when it is necessary to gain direct access to the water pipes, as they have to be repaired afterwards - suitable repair clamps can cost up to € 20 (depending on the diameter).

Possible additional advantages or disadvantages of the method for utilities: During leak search, illegal connections may be found. If there are no suitable access points and the pipe has to be drilled or cut, an improper repair can lead to subsequent leaks. Theoretically, inserting the cable can lead to contamination of the drinking water - but this should be a negligible problem if used properly. When using the device, it is usually necessary to interrupt the supply; however, this usually only affects smaller line sections.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: In the second half of the 1980s and the beginning of the 1990s, the method gradually developed from the pressure test method used for the acceptance of newly installed pipelines, whereby new methods were first invented and patented which made it possible to check sections of pipelines that had already been laid by dividing them up step by step with shut-off devices. In a further step, a device such as the one described here was developed, which no longer carries out the inspection in sections, but pushes the shut-off devices through the pipes step by step, thus allowing pinpoint location. In Germany, this device has been used by the company of one of the inventors (Gerhard Ritter) ever since but only as a service. A version for sale in the UK has only been offered since 2011 by Ferret Technology - the system is, with smaller variants, the company's only product and received some important awards for innovative products in the water sector in 2012 and 2013. Since then, the system has been improved step by step. Another company (Palmer, now Halma Water Management) is offering a similar device for some years.

Market penetration: The device is used by many leak detection companies and water utilities in the UK, as well as some in Ireland. In addition, it is distributed in a few English-speaking countries (e.g., USA, Australia and South Africa), but is still hardly known there.

Outlook: This method has great potential, especially for low water pressure and intermittent supply and, as the dealer network is still being established, will certainly soon be distributed in other countries, including EMDEs.

FURTHER INFORMATION

Several videos that illustrate the working principle of the method very well can be found here (total duration 15 min).

Guidelines for the individual components of the equipment

Study on non-acoustic methods in the UK, mentioning that several utilities are using the method effectively (Bold et al. 2017: page 8).

Success stories directly from the supplier of the device can be found here and here.

2.3. Thermal methods

2.3.1. General information on thermal methods

Thermal leak location is based on the principle that leaking water changes the temperature of its surroundings - either because it is warmer or because it is colder than the material surrounding the pipes, i.e., usually the ground or, in indoor areas, walls. In addition, the leakage of water on surfaces can lead to temperature decreases through evaporation. These temperature changes can be registered with the help of modern technology and, depending on the conditions, interpreted as being caused by leakages. This already point out the most important and unfortunately frequent application limit that the three thermal methods described have in common: Lack of temperature differences between the water and the surrounding material. In addition, there are further important application limits for each method, which are explained in detail in the following subchapters. However, if the thermal methods described here are applicable, they very often have great advantages over other methods, especially in terms of cost and speed in locating leaks - and are therefore worth considering.

OVERVIEW	
Type of method: Temporary mobile pinpointing method	
Location principle: Thermal	**Sensor type:** Contactless sensor

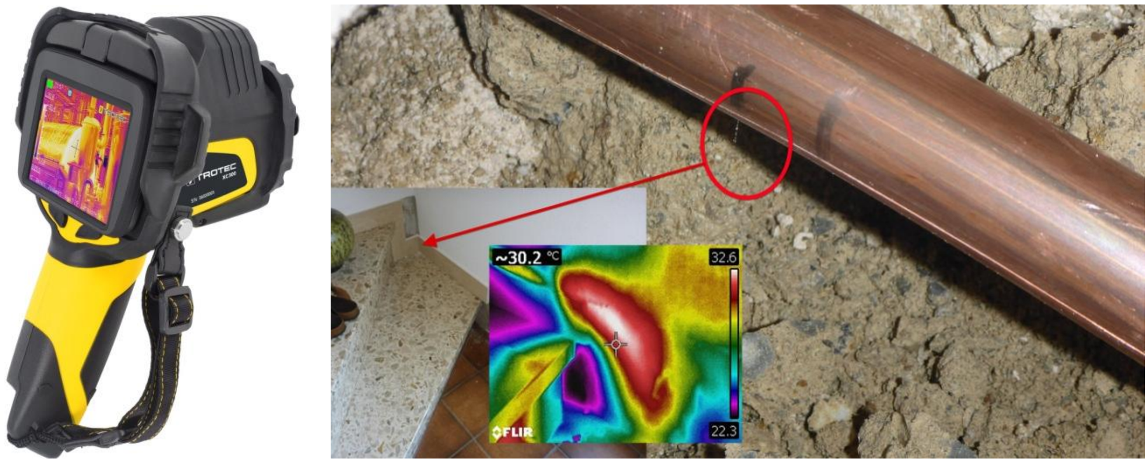


Figure 15. Left: Handheld thermal imaging camera (Courtesy: TROTEC GmbH); Right: Thermal image of a detected leakage indoors (Courtesy: viZaar AG).

Leak location principle: Thermal imaging cameras graphically display the smallest temperature differences on surfaces. Leakage can lead to characteristic changes in the temperature of surfaces on the one hand because the drinking water has a different temperature than the material surrounding it, and on the other hand because of the heat extraction caused by evaporation, thus providing clues to the location of possible leaks. The handheld thermal imaging cameras described here are mainly used to search for leaks indoors.

Areas of application	
Applicability for indoor leak location	Yes (one of the most important methods)
Applicability for distribution networks	No
Applicability for large diameters pipes	No

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Important	**Knowledge of pipe location**	Helpful
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important: building material conditions	**Method-specific negative factors**	Isolation materials

Links to providers
Testo SE & Co. KGaA; Robert Bosch GmbH; TROTEC GmbH (all Germany)

STEP-BY-STEP DESCRIPTION

1st Step: The thermal imaging camera is pointed at walls, ceilings and the floor.

2nd Step: Detected temperature anomalies are interpreted on-site, depending on the context, to find out whether they indicate the presence of leaks.

3rd Step: At suspicious locations, where e.g., temperature changes with the typical amorphous shape of leaks on surfaces appear, other methods are used to confirm and possibly pinpoint the leakage.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: A useful extension is the combination of thermal images with real images, as this greatly simplifies the interpretation of the results. Many providers now offer such cameras.

Combined application with other methods: Except in very obvious cases, this method is always combined with several other methods. Suspicious spots found with the thermal imaging camera are especially often checked with moisture measurement. In addition, listening rods or tracer gas are often used. Fluorescent dyes are also used to find pre-identified sewage leaks.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of not finding existing leaks with this method is relatively low if there are not several wall or floor layers (insulating materials) and if there are, it is medium, i.e., smaller leaks, in particular, are then easily overlooked.

Likelihood of false positives (dry holes): There can often be many reasons for temperature differences on the surface, from rainwater penetration to splash water or because different materials conduct the temperature differently. Therefore, a possible leak should always be confirmed by another method and, especially in the case of a large area with a drop or rise in temperature, the leak should also be pinpointed.

Margin of error: Since thermography only measures temperature differences on surfaces, it only provides indirect information about the location of the leakage. An important factor is always how far the damaged pipe is from the measured surface and which path the escaping water takes. However, especially with walls or floors made of only one material, the margin of error is very small.

SCOPE AND LIMITATIONS

When should this method be considered? Thermal imaging cameras are used in particular to find moisture spots much more quickly than the methods otherwise used. This is mainly done when looking for leaks indoors, especially when there are no insulated surfaces.

When not to consider this method?

1. **Air humidity of close to 100%** results in no water evaporation in humid places and therefore no temperature drop due to evaporation energy (note: lower air temperature=

faster saturation of the air). Therefore, the method cannot be used under humid conditions if at the same time the water has approximately the same temperature as the building materials surrounding it.

2. **Intermittent water supply** leads on the one hand to the fact that the time in which leakages can be located is limited. On the other hand, this can become a problem if the supply time is outside the optimal time for leak detection. The optimal time is usually when the water temperature and the temperature of the floor and walls are as different as possible, e.g., when the water is very cold when everything else has heated up due to sunlight and high air temperature in the early afternoon hours. This is often not a problem, as many consumers in locations with intermittent supply have high tanks. In this case, however, it must be taken into account that the water in elevated tanks can get quite hot.
3. **Isolated surfaces:** If the leak is separated from the surface under investigation by cavities, isolating layers or similar, i.e., there is no or very weak thermal conduction, the method cannot work. This is the most common limitation.
4. **Angled or hidden surfaces** may not be visible with the thermal imaging camera, as in addition, depending on the device, a distance of at least 50 cm is necessary.
5. **Metallic surfaces** reflect infrared radiation very strongly, so it is almost impossible to measure their surface temperature with a thermal imaging camera. However, this is not a very common problem.

Considerations for application in characteristic circumstances in EMDEs: Multiple wall layers, especially for insulation purposes and wide walls, are much more common in developed countries for climatic, building code and economic reasons, among others. As this is the main limitation, the method often works much better in EMDEs.

INSTITUTIONAL ASPECTS

Required qualification: The devices are self-explanatory after reading the accompanying instructions and are usually sold without additional training.

Required experience: Some experience with the device is useful, but can be acquired relatively easily and quickly, especially since in case of initial doubts there is usually the possibility to check the results with the help of other methods.

Usefulness of outsourcing the method: Most utilities do not offer indoor leakage detection, so this form of leakage detection is almost always private. Even if the utility offers leak detection to its clients for a fee or free of charge, it may make sense to subcontract this out, e.g., on a commission basis.

Necessary or desirable framework conditions at the utility: Other methods of confirming leak location should always be available to avoid dry holes.

ECONOMIC ASPECTS

Acquisition cost: Good quality professional indoor units currently cost between € 500 and 2,500. The main differences are in the angle of coverage and the resolution of the temperature.

Required number of staff: Even when used in combination with other methods, often only one leak searcher is needed indoors.

Additional operational costs: Since other devices used to search for leaks indoors (moisture meters, listening sticks) are also small, motorised transport is not necessary. Nevertheless, if equipment for repairing the leaks is also carried, which is often the case, it is necessary. Otherwise, there are no additional costs, except for charging the batteries of the device.

Possible additional advantages or disadvantages of the method for utilities: Handheld thermal imaging cameras can also be useful to improve energy efficiency in utilities, especially on pumps. There, they can detect malfunctions, which are manifested in temperature increases on their surface caused by friction (Ziemendorff 2022). Often this use of the cameras can be more important to the utility than their use for leak detection.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The first thermal images date back to the 19th century. Serious research for their practical application dates back to the 1940s. Until the beginning of the 1980s, the technical possibilities for making low-cost and easy-to-use devices available were still limited. Since then, prices have been falling steadily until the present day, coupled with ever new application possibilities and technical improvements. Through building thermography, initially used to better protect buildings against heat loss, it was soon discovered that water leaks could be located with the same method, and so the use of thermal imaging cameras has been established for indoor leaks since the 1990s.

Market penetration: Thermal imaging cameras are standard equipment for indoor leak detection in industrialised countries and are also increasingly used in EMDEs.

Outlook: The often more favourable conditions and further decreasing prices for the devices, coupled with rising water prices and higher indices of consumption metering, will most likely lead to a strong increase in the use of thermal imaging cameras in EMDEs.

FURTHER INFORMATION

Indoor leak location with a thermal camera combined with other methods (4 min)

Illustrative explanation of the principle of how a thermal imaging camera finds moisture (6 min)

2.3.3. Thermal imaging drones

OVERVIEW	
Type of method: Temporary mobile location method	
Location principle: Thermal	**Sensor type:** Contactless sensor

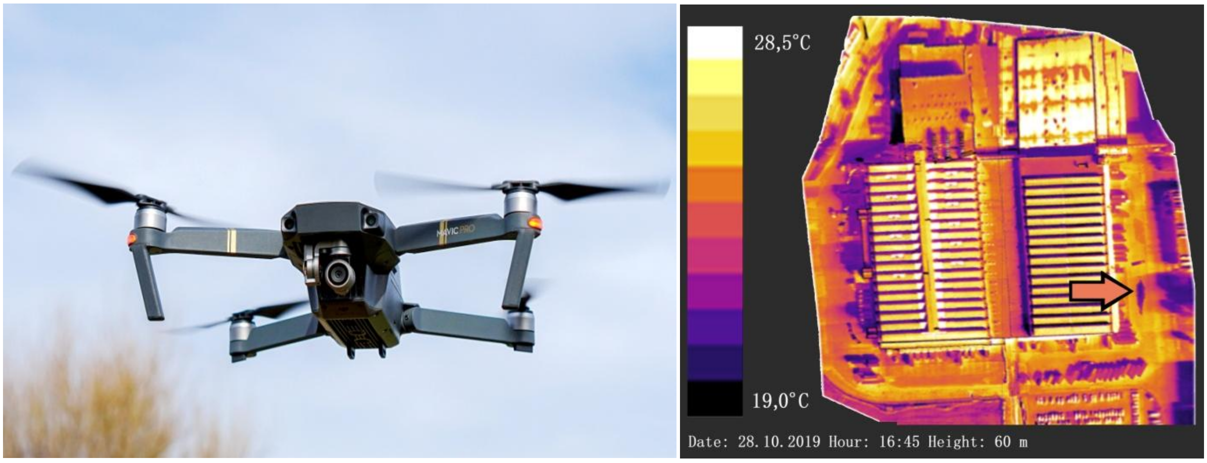


Figure 16. Left: Thermal imaging drone (Creative Commons: Sinky); Right: Thermal image, the red arrow indicates a probable leakage (Based on Creative Commons: Stoermerjp)

Leak location principle: Thermal imaging cameras graphically display small temperature differences on surfaces. Leakage can lead to characteristic changes in the temperature of surfaces on the one hand because the drinking water has a different temperature than the surrounding ground, and on the other hand because of the heat extraction resulting from evaporation, thus providing information about the location of possible leaks. Thermal drones or copters can be used to fly over large areas and measure, record and analyse these temperature differences to conclude the location of possible leaks.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	Yes
Applicability for large diameters pipes	Yes

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Depending on the time, impossible
Pipe depth	Important	**Knowledge of pipe location**	Necessary
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	Rainy or windy conditions

Links to providers
[Flir Systems Inc. (USA)]; [Parrot Drone SAS (France)]; [viZaar AG (Germany)]

STEP-BY-STEP DESCRIPTION

1st Step: The pipelines in a specific area to be investigated are flown over with the help of a drone-mounted thermal imaging camera. The camera images are recorded and not simultaneously evaluated on-site. Drones are equipped with a thermal imaging camera in addition to a normal camera - for the pilot. It is important to inform the public beforehand to avoid irritation or, in certain areas, confusion, which could, for example, lead to the drones being shot down.

2nd Step: Multiple inspections of the same area are recommended, as certain parts of the surface are temporarily not visible (e.g., street stands) and short-term changes in the surface temperature (e.g., due to a poured out bucket of water, a previously parked car) can be detected. In addition, the angle of the image is important, which is why the area under investigation should be surveyed several times from different angles so that, for example, tall houses do not block the view.

3rd Step: The images from the thermal imaging camera are then downloaded and combined with the location plan of the pipelines to facilitate the interpretation of the thermal images.

4th Step: The evaluation itself should, if possible, be carried out by the drone pilot personally and in cooperation with people familiar with the supply area, as this makes it easier to interpret the information with the help of what is seen. During the evaluation, points of interest are determined - these are points where there is a certain probability of leakage, i.e., they are points which show characteristic amorphous temperature differences near the pipeline during multiple overflights or inspections.

5th Step: These points of interest are then checked using other suitable methods to locate the possible leak with pinpoint accuracy.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: For outdoor leak detection, the thermal imaging camera can be used in the following ways: a) on vehicles driving around the area to be inspected, b) with high tripods, c) on helicopters or aeroplanes, and d) on drones. The latter variant has practically displaced the others for reasons of cost and efficiency.

A useful extension is the combination of thermal images with real images, as this greatly simplifies the interpretation of the results. Sometimes the real images can give more information about leakage than the thermal images, e.g., due to increased vegetation caused by higher soil moisture in arid or stationary arid areas. However, drones always have a real-image camera installed anyway so that the drone pilot can orient himself.

Combined application with other methods: Because of the possibility to fly over large areas quickly, but the uncertainty of whether a thermographic anomaly is a leak, the method is always combined with other methods for confirmation and to pinpoint the location of leaks. The exact method chosen depends on the local conditions, but conventional acoustic methods are often the best choice.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The likelihood of missing leaks is relatively high - trees, canopies, roadside stands, cars, etc. can completely mask certain areas. Small leaks also cause very little temperature change on the surface. Material and thickness of the pavement also play a very important role - asphalt in particular is a very poor conductor of temperature (e.g., much poorer than concrete).

Likelihood of false positives (dry holes): There can be many different reasons for temperature differences on the surface, depending on the local conditions. Irregular surfaces absorb solar radiation differently. Also, surfaces that are only partially overshadowed produce different results. However, multiple examinations with a certain time interval (one day) can reduce the number of false alarms. Nevertheless, a possible leak should always be treated only as a point of interest and confirmed again by another method and pinpointed.

Margin of error: Since thermography only measures temperature differences on the surfaces, it only provides indirect information about the location of the leakage. This is another reason why further pinpointing methods are always necessary. However, an important role is always played by how deep the damaged pipe is, which path the escaping water takes and the surface condition. Nevertheless, the margin of error can be within one meter in individual cases (very good capillarity of the soil, no ground cover).

SCOPE AND LIMITATIONS

When should this method be considered? When applicable, this method is extraordinarily efficient because it is very fast. However, this is not very common. Thus, it can be applied when a sum of factors complements each other. These are:

- a good capillarity of the soil
- high-temperature differences between water and soil (especially in the upper layers), which is why the method works particularly well with hot water pipes
- low humidity, especially in warm areas (evaporative cooling!)
- as few as possible false alarms due to other use of drinking water in public areas. Therefore, the method is often suitable for long pipes in otherwise difficult to access or remote, sparsely populated areas.

When not to consider this method? This method has numerous and very frequent application limits:

1. **High humidity:** Humidity close to 100% leads to the fact that in humid places water does not evaporate and therefore no temperature drop due to evaporation energy can be measured (note: lower air temperature= faster saturation of the air). Therefore, the method cannot be used when, in addition to high humidity, the temperature of the drinking water is approximately that of the soil surrounding it.
2. **Intermittent supply:** The time in which leaks can be detected is much shorter. Since the method is very fast in the application, it is only a big problem if the supply time is not the optimal time for the search.

3. **Low pressure:** results in a smaller amount of water escaping and therefore a smaller measurable temperature difference at the surface. Thus, depending on the pressure, only larger leaks can be found and/or it only works when temperature differences between water and subsoil are even higher.
4. **Unfavourable weather conditions:** Drones cannot be flown in wind and rain. In strong sunlight, the surface temperature is usually (e.g., on asphalt), so strongly influenced that the temperature changes through the leak can no longer be detected. Therefore, the best conditions to detect temperature drops are usually in the late afternoon hours (when it is cloudy) or in the early evening hours. Conversely, the time of dawn is best to detect temperature increases caused by leaks (e.g., in cold places in winter).
5. **Low capillarity:** At the surface, temperature changes caused by leaks can only be measured if the drinking water from the leak rises to the surface by capillarity. When the water infiltrates completely, the surface temperature is not affected.
6. **Overgrown or covered surfaces:** Plant growth on the surface severely limits the ability to measure the surface temperature. The same occurs when the surface is covered for other reasons (traffic, street markets, etc.).

Considerations for application in characteristic circumstances in EMDEs: An advantage in EMDEs is that pipes are often located at shallower depths than in industrialized countries (due to the lack of threat of freezing and the lower cost). On the other hand, a common disadvantage is that drinking water is used more frequently in public spaces, e.g., for car washing, to wet dusty streets or even for sewage disposal on public roads, which makes false alarms more common. Likewise, much more common in EMDEs, very narrow alleys can lead to problems with clear views of the ground.

INSTITUTIONAL ASPECTS

Required qualification: Training on the thermography camera itself is very simple, for the operation of the drone, a little more difficult, but also not complicated. The software for the interpretation of the data is also not difficult to use.

Required experience: On-site experience under very different conditions is extremely important. The numerous influencing factors which determine, among other things, the best time of day, optimum weather, etc., can only be gained in local circumstances through practical application in a specific area and can only be transferred to a very limited extent. Therefore, initial failures must be accepted to wait for the learning curve for the interpretation of the images under local conditions.

Usefulness of outsourcing the method: Since experience plays a very important role and especially small and medium-sized utilities hardly ever need a drone all the time, outsourcing often makes sense.

Necessary or desirable framework conditions at the utility: Rights are often necessary to fly drones, but in any case the residents should be informed, otherwise there may be adverse reactions. Good knowledge of the location of pipelines is also necessary, as is the capacity to analyse the images, as this takes much longer than the actual flying. In addition, other equipment for precise leak detection should be available to confirm and refine the results.

ECONOMIC ASPECTS

Acquisition cost: The investment in a thermal imaging drone varies greatly depending on the equipment; the flight characteristics of the drone itself influence the price more than those of the thermal imaging camera. At the moment, these drones cost € 5,000 - 20,000, but prices are dropping quickly. Although such drones are equipped with anti-collision sensors, a total loss can never be completely ruled out.

Required number of staff: During the drone flight, two employees are needed; one of them has to concentrate on the screen to fly the drone, while the other one is responsible for the safety of the pilot. This step usually does not take very long; much more time is needed for the actual analysis of the thermal images obtained, for which one person (ideally the drone pilot) is sufficient.

Additional operational costs: Unless the surveyed area is close to the utility, motorised transport of the drone is recommended. Other operational costs consist only of charging the batteries.

Possible additional advantages or disadvantages of the method for utilities: Some thermal imaging drones can not only provide data on temperature fluctuations at the surface, but also topographical data, which is necessary for the technical cadastre.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Thermal imaging cameras for remote leak detection were already used sporadically in the 1990s on district heating pipes (from aeroplanes), but it was not until the development of modern and, above all, much less expensive drones in the last decade that the method gained momentum, initially again only for hot water pipes. In the drinking water sector, the method has only been applied in the last 5 years, e.g., in Great Britain and the Netherlands.

Market penetration: Although the application for leak detection on drinking water pipes is still in its beginnings, drones are already offered and sold by numerous suppliers worldwide, usually without pointing out the numerous application limitations.

Outlook: Since experience has only been available for a few years, the method is still relatively unknown, but due to constantly falling prices (both of the drones themselves and the thermal imaging cameras) it has great growth potential, albeit within relatively narrow application limits.

FURTHER INFORMATION

Video showing the use of a thermal imaging drone by Anglian Water/UK (2:30 min)

Video showing the detection of a water leak by a thermal imaging drone (2 min)

Successful experimental field study in Montreal (water much warmer than surface) (Fahmy & Moselhi 2009)

Successful experimental study in Lybia (water much colder than surface) (Shakmak & Al-Habaibeh 2015)

2.3.4. Distributed temperature sensing (DTS)

OVERVIEW	
Type of method: Semi permanent or permanent stationary location method	
Location principle: Thermal	**Sensor type:** Sensing cable

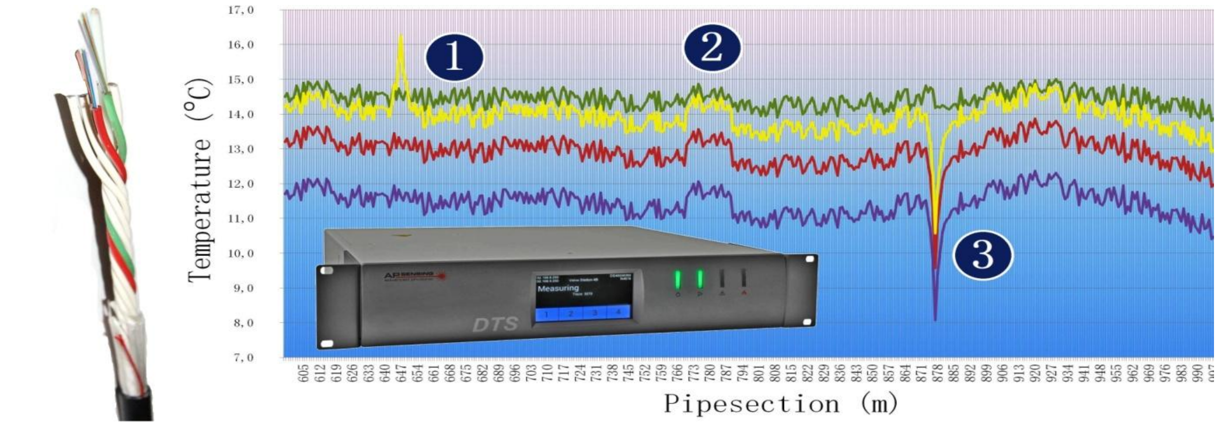


Figure 17. Left: Fibre optic cable (Creative Commons: Asurnipal); Right: Green- temperature curve of zero measurement. Yellow, red and blue - the measurements on three consecutive days at the same time. The general differences between the curves are weather-related, 1 - Temporary temperature increase at 650 metres line length (which can be caused by a parked car). 2- Pipe section about 35 metres long with a permanently higher temperature (e.g., because this section is under a bridge). 3 - Local temperature drop caused by leakage on all days, but not at the zero measurement (Source: photo of the device: AP Sensing GmbH).

Leak location principle: A laser beam is constantly directed through a fibre optic cable buried under the water pipe. Since even small fluctuations in the temperature of the optical fibres made of quartz glass lead to changes in the intensity of the backscattering of the light due to the oscillation of the glass fibre molecules, measurements can be taken at the end of the cable with the help of a device and evaluated. Temperature changes can be assigned to a cable section. Depending on the strength and duration of the temperature changes, these can be interpreted as being caused by leaks or other events.

Areas of application	
Applicability for indoor leak location:	No
Applicability for distribution networks:	Possible
Applicability for large diameters pipes:	Yes (Preferentially but not exclusively)

Influencing factors			
Water pressure:	Some influence	**Intermittent supply:**	Small influence
Pipe depth:	Positive influence	**Knowledge of pipe location:**	Can be used for locating
Pipe material:	No influence	**Need for access points:**	Not needed
Soil conditions:	Important	**Method-specific negative factors:**	Already-laid pipes

Links to providers
AP Sensing GmbH; Solexperts GmbH (both Germany); Silixa Ltd. (UK)

STEP-BY-STEP DESCRIPTION

1st Step: Before planning to lay a fibre optic cable together with a water pipe to apply this method, it should be ensured that this leads to the desired results. For this purpose, the temperature of the conducted water should be known or at least accurately calculated or estimated. This temperature can change only slightly in the course of the route of the pipelines, but much more with seasonal fluctuations. This also applies to the temperature in the trench below the pipe, again depending on the section and the season. If the temperature difference between subsoil and water is at least temporarily above more than 3°C along the entire route, the installation may be advisable (the higher the difference, the better).

2nd Step: Toto lay the fibre optic cable, it is necessary to make another, albeit very small, trench under the actual trench for the pipe. It cannot be laid directly next to the pipe, as the temperature of the soil near the pipeline takes on almost the same temperature due to the constant flow in the pipe. Particularly with metallic pipes, due to their good thermal conductivity, a somewhat longer distance should be chosen.

3rd Step: It is important to precisely georeference the length of the fibre optic cable in relation to the water pipeline during the laying of pipes and cables. The exact location from the surface in the event of a leakage alarm can otherwise become very inaccurate.

4th Step: After completion of the installation, a zero measurement is performed. The aim of this is to ensure that the cable is functioning properly, to detect and repair any damage and produce baseline data. These values, which describe a situation without leakage, can then be used as reference values for later measurements. It may also be possible to simulate one or more artificial leakages to prove the functionality.

5th Step: The measurements can be taken continuously with a stationary device that can be programmed to trigger an alarm at a certain threshold (e.g., at 3°C deviation within 10 m). However, since the measuring devices are the most expensive part of the equipment, it is also possible to take measurements at certain intervals so that the device can rotate between different locations.

6th Step: The interpretation of the data is relatively simple - a temperature is assigned to each point of the cable at each measurement time, thus creating a simple two-axis diagram. Newly occurring temperature anomalies at certain points can be interpreted as leaks, provided other explanations (such as melt water or heavy rainfall) can be ruled out. If there is any doubt, it is possible to wait and see whether the results are permanently confirmed, e.g., by taking new measurements after several days without rain.

7th Step: If the interpretation is not entirely clear, which happens especially with the combination of small temperature differences and small leaks, it is worthwhile to confirm the leak detection with another leak detection method.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: One variant is that a fibre optic cable also contains a heatable copper cable (a so-called hybrid cable). The temperature rise in the cable during heating is determined by the heat transport mechanisms around the cable. The measured temperature differences between the output measurement and the heating measurement are evaluated for leak detection. Areas with small temperature differences indicate a flow around the cable and thus leakage. This method was developed by the German company GTC Kappelmeyer/Solexperts GmbH. It has the advantage that if there are very small temperature differences between water and soil, these are first created and thus, regardless of the initial conditions, leaks can be located. However, it must be clarified in advance whether this variant is necessary at all since hybrid cables with copper are significantly more expensive (by approx. 250-300%) and require several heating points (from one heating point, 1 km can be heated in both directions). Therefore, a connection is needed every 2 km, which must first be installed. The copper cable is then only heated during the measurement and not continuously. Unlike normal fibre optic cables, hybrid cables do not have to be laid at a certain minimum distance from the pipeline, which saves a small part of the additional costs.

Combined application with other methods: The location with this method should be confirmed and pinpointed with the help of a ground microphone or soil probes. This is particularly necessary if the course of the pipeline has not been recorded with precision - as the cable length usually does not correspond exactly to the pipeline length or there are doubts about possible external temperature changes (heavy rainfall, floods).

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): With large temperature differences between water and the ground surrounding the pipeline, only very small leakages do not lead to significant, detectable temperature changes. Loss rates greater than 0.1 liters per second can often be detected (this already corresponds to the definition of otherwise hardly detectable background leakages). In addition, leakages cannot be detected in the case of seasonal fluctuations for the time in which the water has approximately the same temperature as the ground (less than 3°C deviation). However, as soon as a change occurs, it will be detected. It may therefore make sense to wait for more favourable measuring conditions. The system has no problems with locating multiple leaks at the same time.

Likelihood of false positives (dry holes): The probability of false positives is low when used correctly under acceptable environmental conditions. However, it is higher the smaller the temperature difference between water and soil, since in this case one must also react to smaller changes in temperature, so the threshold value for possible leak detection is set lower. In addition, false alarms can occur, at least for a short time, at points where, e.g., heavy precipitation, high water, groundwater inflow or condensation cause temperature differences similar to those that would be expected if a leak were to occur. Since these are almost always temporary occurrences often known to the utility, it is advisable to wait and see whether the result changes over a certain period of time, and if not, the leak is confirmed.

Margin of error: The margin of error on kilometre-long pipelines is about five metres. The device itself measures to an accuracy of one metre - but this margin of error only refers to the length of the cable, which does not correspond 100% to that of the line due to bends and stretching. In addition, the exact position of the cable must be recorded very precisely during installation and set in relation to the pipelines, otherwise, even greater deviations are unavoidable. However, there are several methods to significantly reduce the margin of error. One possibility is to look for special points such as a manhole, a bridge or a street crossing. All these locations have usually different day / night temperature cycles. By looking at temperature changes over distance and time, it is possible to identify these points and map them accordingly, which, if these points are close to an identified leak position, can help to reduce the margin of error. Another method of reducing the margin of error even further is by using any form of induced temperature change, e.g., using a heat gun or ice spray if the pipeline is accessible or, if the pipeline is buried, putting a good volume of hot or cold water on top of the ground. With these, the margin of error can be reduced to two metres, which is sufficient for excavations on large diameter pipes.

SCOPE AND LIMITATIONS

When should this method be considered? Before installing long pipelines with large diameters, this method should be considered whenever the water, at least seasonally, has a clear temperature difference to the ground. The possibility should be considered all the more if the pipeline is deep and only a few access points are planned or if there are longer pipeline sections which are completely inaccessible (e.g., overbuilt areas), as many methods of leak detection are either not applicable at all under these circumstances or result in significantly higher costs. If the temperature difference mentioned does not exist, two other methods can be evaluated: heatable hybrid cables (see under variants of the method), or DAS - Distributed Acoustic Sensing. Both require significantly higher investments but are thus often still more cost-effective than other methods for leak detection in the aforementioned conditions. Another application for DTS is to monitor sewage pipes, as sewage is usually warmer than the environment, so leaks can often be easily detected there. Other leak detection methods encounter their application limits there even more frequently than is the case with water pipelines.

When not to consider this method? The most important limitation is with pipelines that have already been laid, as re-laying the cables (under the line) is prohibitively expensive. Rare exceptions can be restoration work on lines. The second most important application limit is the temperature difference between water and the surrounding ground. If this difference is permanently below 3°C, the application of the method is not useful. Due to seasonal fluctuations, this is not so frequent; nevertheless, temporary "blindness" of the cable can occur due to these fluctuations - then the observation period must be changed.

Considerations for application in characteristic circumstances in EMDEs: This leak detection and location method is quite cost-effective relative to other methods for large pipelines (e.g., tethered and free-floating hydrophones) - this is true in industrialized countries and EMDEs alike.

INSTITUTIONAL ASPECTS

Required qualification: For engineers, training on how to operate the equipment and interpret the measurement should be easy and take one to two days at most.

Required experience: Data interpretation is relatively simple. Initial experience is already gained from the zero measurement. At locations where the threshold is set very low due to not very high-temperature differences between water and soil, the experience can play a more important role in the interpretation of the data.

Usefulness of outsourcing the method: The fixed costs for the metering devices are relatively high, which makes it desirable to distribute them among as many utilities as possible by renting or outsourcing metering or pooling. This will not be possible, at least not initially (one utility has to start), and will remain therefore a cost driver. From a technical point of view, however, outsourcing is not necessary because the devices are easy to operate and the data are easy to interpret.

Necessary or desirable framework conditions at the utility: The installation of the cables on pipelines must be included in the planning from the very first stages. Since the technology is not yet very well known and therefore hardly legally regulated in most EMDEs, this is probably the most important factor that could still strongly hinder the further spread of the technology in the next few years.

ECONOMIC ASPECTS

Acquisition cost: The investment consists mainly of two parts: A variable investment according to the length of the fibre optic cable, which costs € 1-3 per metre (the exact cost depends, among other things, on complexity and processing, e.g., against breakage resistance, and is usually rather close to the lower price indicated). For the laying itself, a small additional trench must be dug half a metre below the pipe, which, with the laying of the cable, can cost between € 0.5 to € 1.0 per metre, depending on labour costs and local circumstances. Regardless of the length of the pipe(s), there are also fixed costs for the measuring device of currently about € 50,000. This value refers to a device suitable for about 24 km of the line (12 km in both directions) and includes the costs for training and software. As already mentioned, it is possible to divide these fixed costs among several pipelines by rotating the device. The service life of the system is very long - at least 30 years have been confirmed for the fibre optic cables, but more than 50 years are probable. Damage is rare, mostly caused by rodents, and can be quickly detected, located and repaired by replacing the affected part of the cable. Since leaks in newly installed pipelines often occur only after years of use, the payback period of the investment can often be relatively high.

Required number of staff: Only one part-time operator is needed to analyse the data. Additional staff is then required after each leak detection to confirm and pinpoint the leakage.

Additional operational costs: The operational costs of this method are low and consist on the one hand of the energy costs for the laser (up to 300 W). On the other hand, the laser and the computer for evaluation have to be renewed every 10 years approximately. Rarely, repair costs for damaged cables can be added.

Possible additional advantages or disadvantages of the method for utilities: Just as with the DAS method, the fibre optic cables can additionally be used for telecommunication purposes, although at least in industrialised countries it is mostly the other way round, i.e., cables already laid for telecommunication purposes are additionally used for DTS.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The underlying principle, the so-called Raman scattering, was discovered in 1928 by the Indian physicist Chandrasekhara Venkata Raman, for which he was awarded the Nobel Prize in 1930. This principle has been used in fibre optic cables for information transmission since the invention of the laser in the early 1960s, and increasingly so since the 1970s. The actual fibre optic temperature measurement was developed at the University of Southampton in the early 1980s and has since been used for early detection of fires, damage to dams, dykes or oil pipelines and much more. Applications in the water sector, initially on hot water pipes, have only existed since the turn of the millennium. The market for the systems has been growing very rapidly in recent years and prices are falling.

Market penetration: For leakage detection in the water sector, the system is still very new and is only gradually spreading. In many countries, there are still some entry barriers to overcome - lack of knowledge about the system, legal obstacles and, above all, the high fixed costs for the measuring devices, which cannot yet be shared during the initial installation.

Outlook: Market projections for fibre optic temperature measurement continue to expect high growth rates. This and the rapidly growing number of providers will lead to a further decrease in costs (per km and for the measuring devices), which will make the already comparatively inexpensive method even more competitive. If the barriers to entry are overcome, a rapid increase in use is expected.

FURTHER INFORMATION

Webinar on the different applications of DTS and DAS (58 min)

Case studies, articles and presentations from different sectors on DTS and DAS

Overview of the different variants of DTS and their respective operating principles (Dornstädter 2016)

2.4. Moisture detection methods

2.4.1. General information on moisture detection methods

Some of the methods do not look for changes indirectly caused by the leakage but detect the actual water. The environment of the leakage site becomes wet and thus changes the electrical conductivity and permittivity of the surrounding materials, which can be detected by various methods of moisture measurement on the one hand and by ground-penetrating radar on the other. Finally, satellite radar leak location detects the particular spectral signature of treated drinking water.

2.4.2. Moisture measurement

OVERVIEW			
Type of method: Temporary mobile pinpointing method			
Location principle: Moisture		**Sensor type:** Contactless sensor	

Figure 18. Left: Capacitive moisture measurement device (Courtesy: TROTEC GmbH); Right: Combination of a moisture map with a real image, showing the likely spot of a leak beneath the darkest blue part with the highest moisture content.

Leak location principle: With the help of this method, the relative humidity of different materials is measured at several points on a surface to determine the distribution of the moisture that occurs when water escapes from a leak. This allows statements to be made about the presence and exact location of the leakage. This method is mainly used to find leaks in the interior, but can also be used to find small leaks in elevated tanks.

Areas of application	
Applicability for indoor leak location	Yes (one of the most important methods)
Applicability for distribution networks	No
Applicability for large diameters pipes	No

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Important	**Knowledge of pipe location**	Helpful
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important: building material conditions	**Method-specific negative factors**	Isolation materials

Links to providers

TROTEC GmbH; GANN Mess- und Regeltechnik GmbH (both Germany)

STEP-BY-STEP DESCRIPTION

1st Step: The first measurement is taken at a point that has a high probability of having a certain moisture content that is not affected by leakage and is considered normal for the material under investigation (e.g., wood, cement or clay). At this point, the same material should prevail in the section to be tested.

2nd Step: The measuring device is placed on the surface of the area to be examined and the moisture is read. This can be done in a matter of seconds.

3rd Step: The readings are repeated at other points around the perimeter until the humidity increases and the maximum value (or values) is found. This is either the leak or the point where the water escapes and collects most easily.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: This method has numerous technical variants. Those that are suitable for leakage detection are divided into:

1. **Capacitive moisture measurement:** In this case, the dielectric constant is measured with electromagnetic waves through a sphere placed on the surface. The method measures the moisture close to the surface (approx. 0-5 cm).
2. **Resistance moisture measurement:** Here, the electrical resistance between two points is measured. Since this decreases with increasing moisture, the relative moisture content in the same materials can be compared. The moisture is measured between the two measuring points, which are usually very close to each other (depending on the material from one to a few centimetres). Many devices use both this and the capacitive method.
3. **Microwave method:** This is based on measuring the energy loss that occurs when water is excited to resonance by microwaves, causing it to absorb most of the waves. The advantage of this method is that the microwaves penetrate somewhat deeper (approx. 20-30 cm depending on the material). This advantage is particularly important if the surface coating (e.g., of a wall) does not absorb the moisture. The devices are somewhat more expensive than those for the above-mentioned variants.
4. **Neutron (or Troxler) gauges:** These determine the moisture content by emitting neutrons from radioactive isotopes, which allow an accurate analysis of the concentration of hydrogen atoms from water. It is independent of the material and has a penetration depth of just fewer than 30 cm. Although it is used in some industrialised countries in certain situations for leak detection, its use does not seem to be justified in most cases due to the high safety requirements, regulatory restrictions and high investment and operational costs.

Further variants result from the software used by the devices. For example, some devices offer the option of programming an alarm when a certain humidity level is reached. This has the advantage of being able to examine larger areas more quickly. Some devices also allow the results to be displayed two-dimensionally as a so-called moisture matrix or moisture map to gain a better overview of the moisture distribution over the entire examined area. If necessary, the matrix can be combined with real images, also to find the leaks more quickly.

Combined application with other methods: Before using moisture measurement, a thermal imaging camera is often used, which is not quite as accurate, but much faster. In addition, the method is often combined with other methods, especially with listening sticks, sometimes also with the tracer-gas method.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of overlooking leaks is low to medium, depending on the materials used and the different construction layers. Where uniform building materials with few layers dominate and the pipe depth is only shallow, leaks will hardly be overlooked with this method. If, in addition, there is a well-founded initial suspicion when looking for leaks indoors (this is usually the case), it is even less likely.

Likelihood of false positives (dry holes): Since the method does not specify whether the moisture is due to drinking water, all other reasons for the presence of moisture (wastewater/splash water/rainwater) can lead to false positives. However, the correct interpretation of the results when assessing the respective situation can significantly reduce the probability of false alarms and is usually low.

Margin of error: The moisture often spreads less homogeneously due to different types of soil or building materials, and within areas that are already completely wet (in the case of long leakage runtimes), differences can hardly be measured. Also, the water may first accumulate and spread in a place that is relatively far from the leak.

SCOPE AND LIMITATIONS

When should this method be considered? Moisture measurement for indoor leak detection is a standard method - perhaps the most commonly used. It is most suitable when the building material is homogeneous and does not consist of several layers. It can be used especially when acoustic methods fail due to various factors such as very noisy ambient and/or low pressure.

When not to consider this method? This method has some application limits, which are common:

1. **No moisture absorption:** Moisture measurement is only applicable to a very limited extent or not at all on surfaces that cannot absorb moisture, either because they are separated from other building layers by cavities or because they consist of materials that do not absorb moisture per se.
2. **Presence of non-leakage-related moisture:** Especially where leakages are frequent - in bathrooms, non-leakage-related moisture is also frequently encountered (splash water), which at least limits the applicability of the method.
3. **Very large areas:** The examination of very large areas can be very time-consuming.

Considerations for application in characteristic circumstances in EMDEs: Since uniform building materials with few layers and rather thin walls predominate in EMDEs, among other things for climatic reasons, the method can be used there more frequently and is often more accurate. The very low investment in the equipment is certainly an additional advantage, which is particularly important in EMDEs.

INSTITUTIONAL ASPECTS

Required qualification: The devices are exceptionally easy to operate. The interpretation of the results, as this is dependent on the material, requires some learning. More advanced methods, especially those that facilitate interpretation by graphing the results, require some additional qualifications. In addition, some aspects have to be taken into account (edges, material jumps, proximity of metal, etc.) in order not to misinterpret the results.

Required experience: Some experience with the device can be useful, mainly to increase the pace of the application. Otherwise, experience is mainly necessary for the leak locator to be able to decide which leak detection method to choose and when, and how to combine the different methods.

Usefulness of outsourcing the method: Most utilities do not offer indoor leakage detection, so this form of leakage detection is almost always private. Even if the utility offers leak detection to its clients for a fee or free of charge, it may make sense to subcontract this out, e.g., on a commission basis.

Necessary or desirable framework conditions at the utility: Further equipment for pre-location and confirmation of location should be available.

ECONOMIC ASPECTS

Acquisition cost: The acquisition costs vary from device to device depending on the method described under the variants and the accessories (€ 20 and 600).

Required number of staff: Even when used in combination with other methods, often only one leak searcher is needed indoors.

Additional operational costs: Since other devices used to search for leaks indoors (thermal imaging cameras, listening sticks) are also small, motorised transport is not necessary. Nevertheless, if equipment for repairing the leaks is also carried, which is often the case, it is necessary. Otherwise, there are no additional costs, except for charging the batteries of the device.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The foundations for the resistance measurement method were laid as early as 1826 with the discovery of Ohm's law, and the method was still used in the 19th century, especially in laboratory experiments to determine moisture. Since the 1930s, the first devices for the building industry and thus also for leak detection came onto the market. The capacitive method was invented at the beginning of the 1960s and was initially only used in the timber industry, but since the 1980s it has also been used for leak detection, where it quickly became one of the most important methods for leak detection indoors. The microwave method, on the other hand, has only been used for leak detection since the mid-90s.

Market penetration: The very low price of the devices coupled with the ease of use has led to almost all private leak detection companies owning one or more devices and using them frequently. However, in many places in EMDEs (mostly due to lack of water metering and/or low water prices) there are no such companies yet.

Outlook: Rising water prices and the increasing share of connections with water meters, will lead to a further spread of private leakage detectors and thus to the spread of the method in EMDEs.

FURTHER INFORMATION

Video with a capacitive moisture measurement device for indoor leak search (7 min); Example of a microwave moisture measurement device with moisture mapping

2.4.3. Moisture sensing smart-cables

OVERVIEW			
Type of method: Semi permanent or permanent stationary location method			
Location principle: Moisture		**Sensor type:** Sensing cable	
 Figure 19. Left: Laying of moisture sensing smart cable near the water pipe in the sand bed of the trench; Right: Measuring device connected to an inspection chamber (Both photos courtesy of Sensor).			
Leak location principle: For the application of this method, sensing smart-cables are laid near the water pipes. These measure changes in the dielectric constant (relative permittivity) of the soil around them and, since the presence of water usually increases it by a multiple, can detect leaks and associate them with a specific sector on the smart-cable and thus localise them.			
Areas of application			
Applicability for indoor leak location		No, but see variants of the method below	
Applicability for distribution networks		Yes	
Applicability for large diameters pipes		Yes	
Influencing factors			
Water pressure	Small influence	**Intermittent supply**	Small influence
Pipe depth	Positive influence	**Knowledge of pipe location**	Can be used for locating
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	Already-laid pipes
Links to providers			
This brand-new method is currently only offered by the company that developed it: [Sensor (Slovakia)].			

STEP-BY-STEP DESCRIPTION

1st Step: For this method, the installation of the sensing smart-cables must be already taken into account in the planning phase of the laying of new pipelines or even in time of the pipeline installation process, as the retrofitting of the smart-cables is not possible or at least prohibitively expensive.

2nd Step: When laying the pipelines, the sensing smart-cable is simply laid in close proximity to the pipelines. In addition, the smart-cable ends are laid to the surface in small inspection chambers for later measurements. Since the maximum cable length is 300 metres and measurements can be made in both directions, the installation of these chambers is only necessary every 600 metres, but depending on local conditions, the distance can be less. Each smart-cable is also equipped with a chip that stores the ID and the position of the cable for easier later identification at the construction and post-construction maps and also to avoid confusion between the two smart-cable ends in the inspection chamber.

3rd Step: After laying the smart-cables, a zero-point measurement must first be carried out with the pipes still empty. This can identify areas that may have been damaged during laying or those with increased natural soil moisture, which can later lead to false alarms. The first leaks can then already be localised during the initial pressurisation of the pipes, which is why the method can also (depending on the local legal requirements) be used for commissioning. Utility staff training in the later use of the method usually takes place in parallel with these two initial measurements.

4th Step: The leakage detection then consists of connecting the measuring device using Wi-Fi or interface connectors to a laptop with proprietary software, to the smart-cables located within the individual inspection chambers. When increased soil moisture occurs, this is detected and assigned to a point on the smart-cable and thus located precisely or in the worst case within a few metres in difficult soil moisture conditions. In principle, the frequency of these measurements can be chosen by the utility. However, since the measurement is not particularly complex, it could take place once a year, or when other monitoring devices (e.g., DMAs or Flow monitoring) indicate that there is localised water loss taking place.

5th Step: The exact leakage point can be located from the surface with the help of a measuring wheel along the known path of the pipe (which can also be identified using the electromagnetic measurement from above). Once located it can then be determined whether it is possibly a non-leakage-related temporary entry of water or whether it is a leak. Since the measurement is based on soil moisture conditions up to an accuracy within a few metres, this can be confirmed quite quickly with the help of other methods and located with pinpoint accuracy. When repairing the leakage, special care must be taken not to accidentally damage the sensing smart-cable.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: One variant of the method is used for pipes with a particularly large diameter. On these, two or more smart-cables are laid on both opposite sides of the pipe, as the distance between the cable and the leak can otherwise be too great to ensure 100% reliable detection of all leaks. The number of additional cables can be computed using a simple equation based on pipe diameter.

In the near future, this system is planned to be offered for permanent monitoring. A similar method is sometimes used indoors to monitor particularly vulnerable infrastructure, such as computer servers or storehouses. However, the focus is not on the early detection of leaks to reduce water loss, which is why this method will not be discussed further here.

Combined application with other methods: Once a leak has been found and located using this method, it is pinpointed to keep the excavation work to a minimum. For this purpose, ground microphones are particularly suitable in the case of low ambient noise levels and pipes with moderate to high pressure. Otherwise, soil probes are in particular suitable because the leakage has already been narrowed down precisely or to a few metres.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Leaks from a size of 100 l/hour can be detected and located without any problems. Depending on the position of the leak relative to the smart-cable, much smaller leaks can also be located. Since leaks tend to become larger over time, leaks that are so small that they are not detected during measurement will become incrementally more observable within the measured data with each measurement over time. It is of course possible to miss those leaks that only occur temporarily coinciding with changes in the temperature of the pipe material (due to expansion and contraction) if measurements are taken at unfavourable moments. However, such leaks are rare. In the case of intermittent supply, care should be taken to take the measurements only well after the start of the supply period - otherwise, leakages could be overlooked.

Likelihood of false positives (dry holes): In principle, false alarms can always occur if the sensing smart-cable has become damp at the time of measurement for reasons that cannot be attributed to a leak. To avoid false alarms, measurements should therefore not be taken after heavy rainfall. Otherwise, depending on local conditions (cable depth, capillarity/permeability of the soil, floor covering, etc.), other reasons can either be ruled out from the very start, brought to light by inspection (washed cars, sprinkling of public garden areas) or, in case of doubt, confirmed or rejected by a second measurement, e.g., at intervals of one day. All in all, false alarms can therefore be reduced to a minimum if the method is used properly and if situation-related conditions are interpreted correctly. Since another method is usually used to pinpoint the leaks, dry holes can often be avoided even in these rare cases.

Margin of error: The highest possible margin of error (at maximum cable length) is five to six metres with this method, but normally it is much less than two to three metres in unfavourable soil moisture conditions. Therefore, it may often be advisable to narrow down the leakage further using appropriate complementary methods.

SCOPE AND LIMITATIONS

When should this method be considered? This method can be quite economical, especially in large-diameter transmission pipelines, where the search for leaks is much more expensive than in distribution networks. It is also economical especially in pipelines that are not very long, since DTS and DAS can have cost advantages beyond a certain length. In distribution networks with smaller diameters, the advantage can often be on the technical side, namely whenever other methods, especially acoustic methods, have difficulties locating leaks due to the frequent combination of plastic pipes with low pressure and short supply times or streets with high traffic levels. In addition, the system can be interesting for water suppliers who either have high personnel costs for leak detection (often more of a problem in industrialised countries) or have difficulties in keeping qualified personnel for this in the utility in the long term. Finally, as the system can also detect small leaks and, with a high inspection frequency, quite quickly, it can be interesting in places with very expensive water supply or extreme water shortages. On the other hand, the system can usually be used in places with heavy rainfall because, apart from a few spectacular exceptions, there are almost always dry periods and an annual inspection of the pipeline networks is more than sufficient for most utilities.

When not to consider this method? This method has a frequent and a less common application limit:

1. **Already installed pipelines:** The most important limitation is undoubtedly the presence of already installed pipelines, as the cost of retrofitting is prohibitive.
2. **High water table:** Since the system measures soil moisture, it cannot be used in places where the soil is always saturated, which mainly occurs with a permanently high water table. Intermittently high water tables can be tolerated so long as vertical smart-cables are installed to verify the level of the water table at the time of measurement. Water table and rain cannot give false positives because they affect the whole smart-cable, not just a point as is the case with a leak. Their effect is the reduction in the ability to detect rather than the introduction of a false positive.

Considerations for application in characteristic circumstances in EMDEs: The easy handling of this low-maintenance system is certainly often an advantage in EMDEs, given the more widespread instability of staff in many utilities. Since the smart-cables have to be installed when the lines are laid and the distribution systems in EMDEs are often still in the process of expansion (due to fast-growing cities, among other things), there is also a more frequent opportunity to use the method here than in industrialised countries. On the other hand, the (still) quite high investment costs can be an obstacle and often reduce the application to long pipelines with large diameters that are otherwise uneconomic to inspect.

INSTITUTIONAL ASPECTS

Required qualification: The required training takes place in parallel with the laying of the smart-cables and the zero measurements with empty and pressurised pipes. This involves explaining the simple proprietary software, how to interpret the displayed data and may involve locating the smart-cables from the surface. In total, the training takes a maximum of one week.

Required experience: Experience is not necessary for the actual measurements, which are very easy to obtain, but can sometimes be very useful in interpreting local conditions to avoid false positives.

Usefulness of outsourcing the method: The simple and quick handling of the method with low staff requirements makes outsourcing sensible at most for very large utilities with many laid smart-cables.

Necessary or desirable framework conditions at the utility: The fact that the technology is not yet very well known and therefore not regulated by law is probably the most important factor that could prevent state-owned utilities in particular from using the technology. As with other innovations, international cooperation could play an important role.

ECONOMIC ASPECTS

Acquisition cost: The sensing smart-cable has a cost of approximately € 5 per metre, plus minor installation costs (depending on the country, about € 0.5/m). It should be noted that, unlike fibre optic cables for DTS, the smart-cables do not require a minimum distance from the line, so they can simply be laid parallel to the line in the trench. Additional, albeit simple, inspection chambers with the smart-cable ends to which the measuring device is later connected must be installed at a maximum distance of 600 metres. The smart-cables have a guaranteed service life of 30 years, but from other sectors where similar cables have been used for much longer, it is known that they usually exceed a service life of 50 years (and thus that of most water pipes). In addition to these costs, which vary according to the length of the cable, there is the investment in the mobile measuring device (currently € 5,500); software (currently € 800) and a laptop, which can of course also be used for other purposes. Since leaks in newly installed pipelines often occur only after years of use, the payback period of the investment can often be relatively high.

Required number of staff: In principle, only one operator is needed part-time, the time required depending on the number and distance between the measuring points. Usually, additional staff is needed to pinpoint the detected leaks, but they only spend a little time on this, as the location has already been narrowed down relatively precisely. Since ground microphones are usually used for this purpose, which also requires only one operator, this work can also be carried out by the same person.

Additional operational costs: Apart from charging the laptop and the batteries of the measuring device, there are no other electricity costs. Maintenance of the system mainly consists of cleaning the contact points now and then, which is done before the individual measurements. Maintenance costs for the system are very low, especially because damage to the cable can be located precisely during the first measurement and it is not necessary to replace the entire cable but only to repair the affected area (much easier than with fibre optic cables!). Due to the distance to the individual contact points and the frequent need to pinpoint located leaks, motorised transportation for the leak locator is useful.

Possible additional advantages or disadvantages of the method for utilities: An added value can be the initial use of the smart-cable directly after installation for commissioning - at least as an additional method to the use of more complex procedures such as pressure test or tracer gas. The smart-cable can also be used afterwards to locate the pipelines with pinpoint accuracy using electromagnetic signals, especially for plastic pipes that can often not be detected by other means.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: This method was only invented after the turn of the millennium and was first used in practice in Italy in 2012 (for agricultural irrigation systems). Since 2017 this patented system has also been offered for water leakage localization.

Market penetration: Since the system is still very new, especially for use in the drinking water sector, only ten projects (in Italy, Korea and Slovakia) have been carried out worldwide. The dealer network is still being built up, but is already present on all continents so that the method can be acquired and applied wherever it is required. However, the same method is already used much more frequently in other sectors such as mining, agriculture and the waste industry.

Outlook: It is expected that with a larger scale of its application, the investment costs will decrease significantly due to economies of scale and thus become interesting for more and more utilities, also in EMDEs. In addition, it is planned to offer the system as a continuous leak monitoring system in the near future.

FURTHER INFORMATION

Animated video about the method (4 min); Detailed, illustrated product brochure

2.4.4. Ground Penetrating Radar (GPR)

OVERVIEW	
Type of method: Temporary mobile pinpointing method	
Location principle: Electromagnetic	**Sensor type:** Contactless sensor

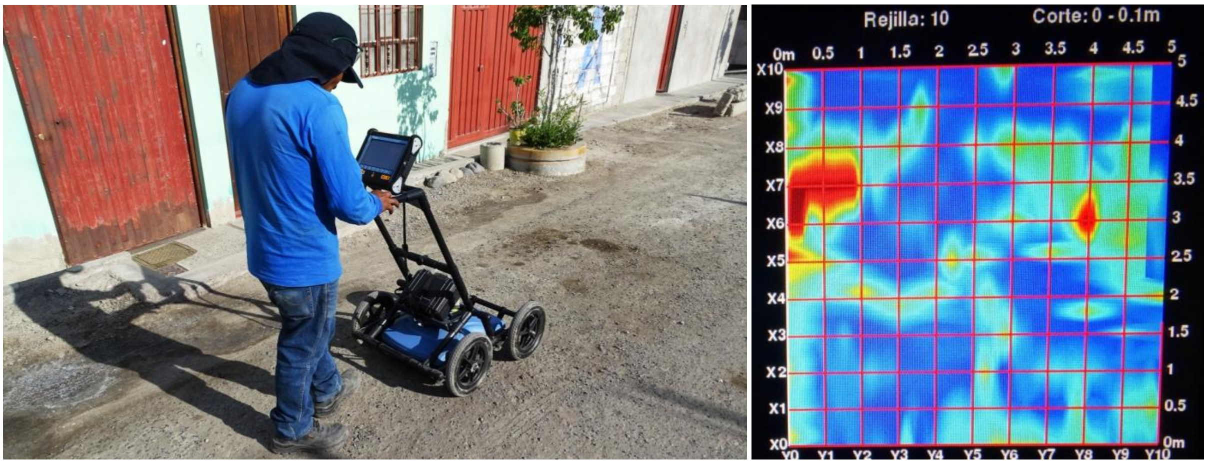


Figure 20. Left: GPR-cart used in the field; Right: Radargram created with the grid method

Leak location principle: The GPR (Ground Penetrating Radar) emits ultra-wideband electromagnetic waves into the earth and records the reflections produced by different layers, which vary according to the material's conductivity and permittivity. The depth at which the reflection is created is calculated by measuring the time between the initial transmission of the signal and the receipt of its reflection, thus allowing the creation of a radargram that graphically represents different soil conditions (including buried objects such as pipes or stones) in different ways. Since the permittivity and conductivity of the soil is altered by the presence of drinking water and thus the propagation speed of the radar wave, as well as the fact that parts of the radar pulse are reflected by abrupt changes in these parameters, leaks can be located under certain conditions.

Areas of application	
Applicability for indoor leak location	In exceptional cases
Applicability for distribution networks	Yes
Applicability for large diameters pipes	Yes (for pinpointing)

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Some influence	**Knowledge of pipe location**	Can be used for locating
Pipe material	Some influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	Many objects in the ground

Links to providers
Sensors & Software Inc. (Canada); Radiodetection Ltd. (UK); Malå (Sweden)

STEP-BY-STEP DESCRIPTION

1st Step: On-site, the GPR is first assembled. Usually, it consists of 3 parts: a cart, the transmitter/receiver unit and the computer with screen. Then various parameters are set, such as frequency used, filter options, the assumed moisture content or the dielectric constant of the soil. To ensure that the data is optimally displayed at the searched depth (around the water pipe), one often makes a test on-site, e.g., by crossing the water pipe several times and changing one of the parameters at each crossing until the result is optimal, i.e., the pipe is perfectly recognisable.

2nd Step: Since the leakage can best be located if the course of the pipe is known exactly, the pipe is first walked across at several points until its exact course is known and marked.

3rd Step: Now, in contrast to locating the pipeline with the GPR, the pipeline is not walked across but along its course at walking speed. At the same time, the radargram is displayed and recorded. Especially in the case of larger pipe diameters, additional radargrams should be recorded to the left and right of the pipeline.

4th Step: Now the radargram is interpreted. To simplify the interpretation of the radargram, various filter options are used, which make the differences in the ground conditions easier to see.

5th Step: One possibility, which can be used especially in cases of suspected leaks and doubts, is not to walk a line but an area. This method is called the grid method and consists of walking along and across a complete area in strips with the GPR. The computer processes the information into a three-dimensional radargram, which can be viewed according to depth layers, for example, to recognise the typical amorphous shape of a leak.

6th Step: Particularly in the case of difficult interpretations, which are common when using GPR, the data is simply recorded in the field and then evaluated and interpreted in the office using appropriate software.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Depending on the necessary penetration depth, antennas with different frequencies are used. For use in leak detection on normal water pipes, which are usually at a depth of less than 2 meters, the 400 MHz frequency is usually best suited, while 200 MHz is more suitable for greater depths (up to 7 meters, but depending on conditions), although vertical resolution suffers at lower frequencies. The use of multiple frequencies simultaneously always has at least the same resolution of the higher frequency and only decreases with increasing detection depth.

In addition, there is also vehicle-based GPR, which is not in direct contact with the surface. The advantage in leak detection is not the higher speed (which is good for other applications such as measuring asphalt thickness) since the number of data points is lower at a higher speed and thus leaks could be overlooked. The main advantage is the width of the device (approx. 1.30 m instead of 50 cm) which, especially if the position of the pipes is only approximately known will help to better detect the typical amorphous shape of leaks.

Combined application with other methods: Because of the relative slowness of the method, a pre-location should always be made, e.g., with satellites, thermography drones or others. Because of the high probability of false positives, suspicions should be confirmed by other methods, e.g., soil probes.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Since there must always be a balancing process due to the likelihood of false positives, leaks, while rarely missed on the radargram (taking into account the application limits), can often be misinterpreted and thus not correctly located.

Likelihood of false positives (dry holes): Since the GPR only provides information about anomalies in the subsurface, but not about whether a certain location has water and whether this comes from a leakage, misinterpretations can easily occur especially - but not only so - if the operator lacks experience.

Margin of error: If a leak has been correctly identified with the GPR, then the margin of error is extremely small and depends exclusively on the spread of the water in the ground, i.e., since it is not the actual leakage point that is indicated, but the moist ground, small deviations can occur. In addition, the depth of the leakage is also indicated to within a few centimetres.

SCOPE AND LIMITATIONS

When should this method be considered? It is especially conceivable to use it in desert areas, with a low water table and low presence of other limitations of this method, especially when other methods fail (high noise level, low pressure, plastic pipes and hardly any access to pipes). There, the method will work well especially if the drinking water has high electrical conductivity (e.g., because it comes from wells, which is common in desert areas) and the subsurface has low conductivity.

When not to consider this method? This method has numerous application limits, some of them are common:

1. **Unfavourable surface condition:** For the GPR to achieve comparable results, the surface should be homogeneous. On curbs or stairs, for example, this is not the case.
2. **Unfavourable ground conditions:** sodic, saline soils, as well as those with high clay content, i.e., all those which have a particularly high electrical conductivity, are unsuitable for the application of the GPR since the electromagnetic waves disappear in the ground with hardly measurable reflections.
3. **Heterogeneous soils:** the presence of cables, pipes, shafts, roots, stones, waste, different rock layers, ruins, etc. makes the interpretation of the radargram much more difficult or even impossible, especially when there is no information about what to expect in the subsurface.
4. **High groundwater level:** the groundwater level should be below the pipes, otherwise leaking water cannot be detected, especially if the electrical conductivity of the drinking water is similar to that of the groundwater.
5. **Unfavourable weather conditions:** Soils soaked by precipitation have the same effect as a high groundwater table.
6. **Electrical conductivity of soil and water:** since the GPR represents contrasts of conductivities, the greatest possible differences in the conductivity of the soil and the water leaking through a leak are desired (in most cases, water should have a higher conductivity than the soil). If this is not the case, the location will be very difficult or even impossible.

7. **Inaccessibility:** Since the method can only locate leaks when the GPR is directly above the leak, there are situations where it isn't possible (overbuilt pipes).

Considerations for application in characteristic circumstances in EMDEs: Desert areas are quite common in EMDEs. Since the use of fossil water with high electrical conductivity and soils with low electrical conductivity especially in desert areas are associated with water scarcity and therefore often with low supply pressure and intermittent supply, GPR could be a good niche application there with real advantages over other systems. In addition, many utilities in EMDEs already have GPRs for finding illegal connections and creating technical cadastres.

INSTITUTIONAL ASPECTS

Required qualification: The training should not be limited to the simple functioning of the GPR, but also the correct calibration of the device in the field, the filter options, the subsequent evaluation with the help of software and, above all, practical application examples and the correct interpretation of the data.

Required experience: Very much. Since the respective local conditions can be very different, especially for this method, only the application on-site can gradually lead to a better calibration of the GPR, but above all to a better interpretation of the data. Initial false positives can hardly be avoided as part of the learning process. For those reasons, rotation of trained and experienced staff is not desirable and should, if necessary, be accompanied by good knowledge management (training on the job of new staff).

Usefulness of outsourcing the method: As described, the operation of the GPR is something that is best done by highly qualified personnel on a full-time basis. Therefore, outsourcing the method can be often advisable. In this case, it should be considered to what extent the detection of illegal connections and leakage detection (and possibly technical cadastre) can be combined in a single contract since the GPR (if the conditions are given) is suitable for all this.

Necessary or desirable framework conditions at the utility: Knowledge of the location of the pipelines is not necessary, especially in the optimal conditions under which the GPR should only be used, as pipeline courses are usually easier to recognise than leakages - an advantage over many other methods. However, the knowledge of location can speed up the location work. Furthermore, it is desirable that the capacities of experienced radar users are available on-site for training. Due to the limited experience with the equipment worldwide, this is often not the case, but this can soon change for the better. Because of the required qualifications and experience, personnel should not be replaced if possible, so that they can gradually specialise.

ECONOMIC ASPECTS

Acquisition cost: The acquisition costs for a GPR cart are about € 15,000 - 35,000. The amount of investment depends in particular on the number of frequencies used, the software supplied and the size of the scanning unit. The car-mounted GPR mentioned under variants of the method can cost up to € 250,000.

Required number of staff: In principle, only one operator is needed, but for safety reasons, another staff member is usually added who, among other things, also ensures traffic security and clears obstacles out of the way of the GPR.

Additional operational costs: The GPR is always brought to the field by motorised transport and only then is it assembled. Except for charging the batteries, there are no additional operational costs.

Possible additional advantages or disadvantages of the method for utilities: In most cases, GPRs are used by utilities not for leakage detection but for mapping underground infrastructure, including technical cadastres of pipeline networks and searching for illegal connections. The use of these expensive devices for multiple purposes is likely to make a lot of sense for many utilities.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Although the idea of using GPRs to locate buried objects is more than 100 years old, the first ground penetrating radars for locating pipelines, among other things, did not appear on the market until the mid-1970s. The devices, which were falsely described as easy to use, experienced a first boom in the 1990s, but it quickly became apparent that advanced knowledge of application limits, setting up the devices and interpreting the data was necessary to use them correctly. GPRs and their software support have steadily improved since then and have also become significantly less expensive. The equipment is now sold worldwide by many manufacturers for a wide variety of applications. Most vendors offer equipment specifically for utilities, which is tailored to their specific needs (low penetration, at high resolution). Many misconceptions persist: on the one hand, that they are easy to use and deliver fast results, and on the other hand, that they never actually deliver what they promise.

Market penetration (for leakage location): The myth of the GPR as an all-purpose device for locating lines, illegal connections and leaks (in some cases) quickly and without complications has led to a very wide distribution of the devices. However, they are often not used at all due to the numerous application limitations. Where they are used by well-trained and experienced personnel under good conditions, they have also been successful in locating pipes and illegal connections. Leak detection with GPR, on the other hand, is still in its infancy, especially since there has been no focus on its use under the ideal conditions described above for GPR, which has led to many failures so far under suboptimal conditions.

Outlook: GPRs are still undergoing further technological development, which could still push the application limits somewhat. The trend towards even cheaper devices will likely continue. Above all, however, it is likely that in the leak detection application field, the practical and successful experience will confirm the niche application described here and assign the GPR an important place in the leak detection portfolio.

FURTHER INFORMATION

Playlist of instructive videos about the GPR of Radiodetection (14 min in total)

Some successful examples in leak location with GPR in Romania with the respective radargrams (Pages 6-10; Alexandru 2016)

There are numerous publications on the subject of leak detection with GPR, but it is revealing that almost all of them describe tests under laboratory conditions (Google Scholar search).

2.4.5. Satellite radar

OVERVIEW	
Type of method: Temporary mobile pre location method	
Location principle: Electromagnetic	**Sensor type:** Contactless sensor

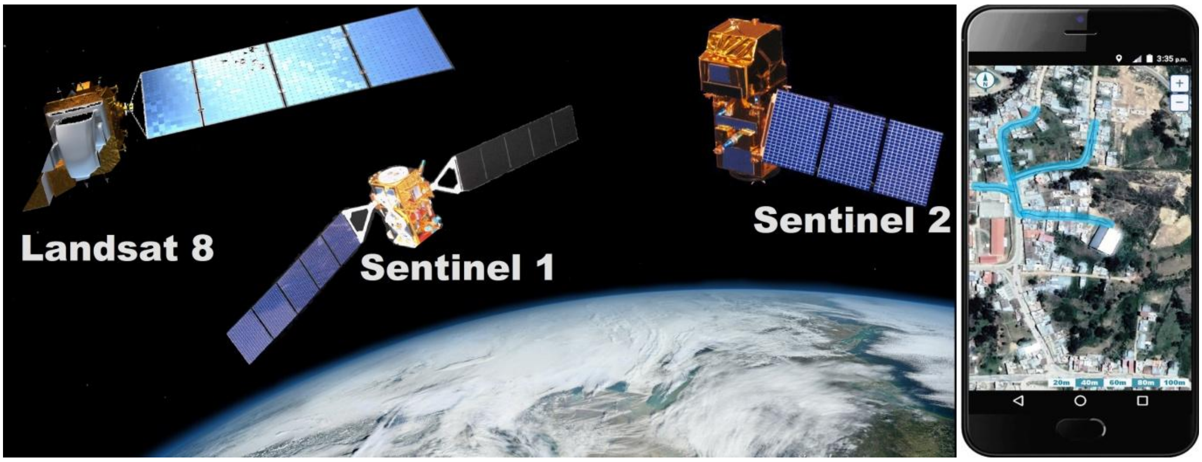


Figure 21. Left: Several satellites that provide geospatial data for the possible use for leak detection (Source Landsat: NASA/Goddard Space Flight Center Conceptual Image Lab; Sentinel 1&2: Rama); Right: The probable location of leaks can be displayed on tablets or cell phone for confirmation and pinpointing them.

Leak location principle: Satellite images taken with a Synthetic Aperture Radar (SAR), which can penetrate up to two metres deep into the ground, are analysed for traces of drinking water using spectral analysis and the location of these points is compared with the pipeline network to conclude the existence of possible leaks. The identified possible leakage points are called points of interest (POI), which are then checked with leak detection teams to confirm the leakage and its exact location. Unlike optical methods, SAR can also be used at night or in cloudy conditions.

Areas of application	
Applicability for indoor leak location	Can find indoor leaks incidentally
Applicability for distribution networks	Yes
Applicability for large diameters pipes	Yes

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Depending on the time, impossible
Pipe depth	Some influence	**Knowledge of pipe location**	Helpful
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	High leakage rates

Links to providers
Utilis Ltd. (Israel & USA), Rezatec Ltd. (UK)

STEP-BY-STEP DESCRIPTION

1st Step: First of all, it must be clarified between the water utility and the service provider to what extent the method makes sense and is applicable. If available, a digital pipe network plan is provided. If there is uncertainty as to whether the method works under local conditions, a proof of concept can be carried out by the service provider. This is a kind of free test run to check whether meaningful images can be provided under local conditions.

2nd Step: Satellite images of the defined observation area (up to 70x70 km) are taken. The radar signal of the satellite can penetrate up to 2m into the ground. This signal is reflected and the reflections are registered by the satellite.

3rd Step: The radar image is transmitted to the service provider and analysed there with software support. Here, the soil moisture and the conductivity of the water are considered as indicators to distinguish rainwater and other water sources from drinking water. The exact parameters and algorithms used are trade secrets.

4th Step: The results of the analysis are transmitted after two or three weeks in the form of a digital map of the study area within a simple digital app. Points of interest (POI) are marked on this map, representing possible leakage points.

5th Step: The identified POIs must be checked with the help of further leak detection methods to identify them as leaks and pinpoint them.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: One variant is to use older satellite images. The advantage is that these are cheaper than current images, but this has the corresponding disadvantage that leaks that occurred after the image was taken cannot be identified.

Another variant is to rent the service for a longer period of time. This has the advantage that it is significantly cheaper per analysis and the detection becomes much more accurate due to images taken from different angles. This is particularly advisable in cities with numerous tall buildings. For this purpose, certain locations that are temporarily not visible can be detected from a different angle during a new analysis.

A method that analyses additional optical images is used by the British company REZATEC. Among other things, it also looks for ground displacements or unusually heavy vegetation.

Combined application with other methods: As this is a pre-location method, other methods must be used to check POIs and pinpoint leaks. These can be acoustic methods (leak noise correlation, ground microphones, and hydrophone pigs), tracer gas or others, depending on the local conditions.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): In a single flyover, about 30-50% of the leaks can be found. This rate can be gradually increased by further flyovers at a different angle. Influencing factors that can lead to a lower rate include:

1. Occultation of areas, e.g., by buildings, parked cars, market stalls, pipes under rivers, etc. (Vegetation is not a problem as the radar penetrates it).

2. In the case of intermittent supply, several hours of empty pipes at the time of the flyover will automatically lead to leaks no being detectable. This is especially a problem because in many utilities never all areas are supplied at the same time.

3. Deep lines can be a problem as the radar penetrates the highest three metres, but often only two metres, depending on conditions. However, this is not a problem if the soil has a high capillarity, i.e., the leaking drinking water can still be detected in the upper soil layers.

4. High groundwater levels lead to fewer localisations, as the electrical conductivity of the drinking water decreases rapidly due to mixing with groundwater.

Likelihood of false positives (dry holes): False alarms occur in about half of the cases. The reasons for this are manifold, but particularly frequent is that drinking water has been correctly located in the soil, but this is not due to leakage, e.g., construction sites where water is used or the irrigation of areas with drinking water, especially gardens. Indoor leakages in open areas such as front gardens often cannot be distinguished from leakages in public areas because of the margin of error. Depending on the task, this can also be interpreted as a false positive.

Margin of error: Leaks are located within a radius of a maximum of 150 m distance around a Point of Interest; in most cases the deviation is significantly smaller. Therefore it is a pre-location method, where the actual locating and pinpointing is carried out using conventional methods.

SCOPE AND LIMITATIONS

When should this method be considered? Depending on other factors, the application can be worthwhile from a minimum of 250 - 800 km network length and here in particular for long pipelines in areas that are difficult to access or remote, but which should not be too deep. Because of the large area investigated, the method also has great economics of scale, i.e., the larger the service area, the more cost-effective the method. Pre-location with satellites can also have a real cost advantage in well-maintained networks with low leakage rates and where leakages are difficult to find and not visible, as the costs of locating without pre-location are particularly high here. It can also be used in networks where other methods have difficulties, e.g., due to a high proportion of plastic pipes or in areas with high noise levels.

When not to consider this method? The limitations to be considered before purchasing the service of pre location of leaks with satellites are:

1. **High leakage rates:** In areas with many leaks where the POI is located up to 150 metres from the actual leak, the method will not provide added value, i.e., leaks are to be expected anyway.
2. **Small service areas:** In supply areas of small utilities, the high fixed costs are then distributed over only a few kilometres of pipe.
3. **Drinking water similar to natural water:** If the drinking water has a low electrical conductivity and thus resembles naturally occurring water in spectral analysis, the false positives can become more frequent. In arid or semi-arid areas, however, this does not have to be a real restriction.
4. **Unfavourable soil conditions:** The method also does not work as well in soils that do not retain much moisture, i.e., where water runs off immediately or seeps away.
5. **Intermittent water supply:** Because the satellite flies over the area at a specific time, intermittent water supply can be a big problem, namely when the supply has been suspended long before the fly-by so the leakage water has evaporated or seeped away in the meantime.

6. **High water table:** A high water table means that the drinking water is easily diluted in the groundwater and then more difficult to detect.

Considerations for application in characteristic circumstances in EMDEs: Although several conditions for the application of the method are more frequent in EMDEs than in industrialised countries (megacities, high proportion of plastic pipes, shallow pipes), mainly one factor leads to the fact that this system is rather rarely applicable: the high leakage rates, which strongly limit the usefulness of the application of the satellite method in its present form in the majority of cases. Other limiting factors (lack of technical registers, intermittent supply) must also be taken into account. This assessment could change if it were possible to reduce the damage rates, at least locally, and/or if the method will gain in accuracy through technical progress.

INSTITUTIONAL ASPECTS

Required qualification: No special qualifications are needed to understand the digital maps with POIs transmitted by the service provider.

Required experience: Experience with checking the Points of Interest may help to assess whether there is leakage or some other reason for reporting the POI.

Usefulness of outsourcing the method: The method is only available as a service. It should be noted, however, that the service consists of two parts, which currently come from one source: (1) The actual satellite radargram and (2) its analysis using patented and partly unpublished software-supported methods. It is quite conceivable that this will be split into two parts in the future.

Necessary or desirable framework conditions at the utility: For the interpretation of the data obtained by the satellite, a digital plan of the pipeline locations should be available so that both pieces of information can be superimposed and thus interpreted more easily. If no maps of the water mains are available, the road course is used instead. Since the method serves as a pre-location, this also works quite well within the supply area, but not for large pipelines that run outside the urban area. In addition, capacities must be available to investigate the often numerous POIs promptly using other leak location methods.

ECONOMIC ASPECTS

Acquisition cost: As this leak detection method is only offered as a service, the investment costs are included in the operational costs (see below).

Required number of staff: For the application of the satellite pre-location itself, no staff member is required on the part of the utility, but for the subsequent localisation and confirmation of leakages.

Additional operational costs: As this method is only offered as a service, only operational costs are incurred. At the time of the realisation of this study, the costs for a one-time flyby and the evaluation of the radargram of a 70 x 70 km area were about € 30,000 - 35,000. Both the use of older satellite images and longer-term contracts for several flybys at certain intervals can significantly reduce this one-off fixed cost.

Possible additional advantages or disadvantages of the method for utilities: In contrast to leak detection with conventional technologies, there has often been a great media response to the use of this method, at least so far. This can be exploited by utilities to project a modern image and to draw the public's attention to the importance of using water responsibly.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The method originates from space flight and was previously used to detect water on Mars and later used to discover water sources in the desert. It is only since 2016 that the same method has been sold worldwide as a service by the Israeli company UTILIS, and since then it has been discussed extraordinarily widely in the specialised press and mass media and is therefore now very well known, although usually without many details. Since about 2018, the British company REZATEC has also been offering similar services but is hardly known for it, among other things probably because it sells numerous other satellite-based applications.

Market penetration: The system has now been applied in many countries, especially, but not only, in industrialised countries. There is a constantly growing network of local representatives, mainly in industrialised and emerging countries (including 8 Latin American countries, as of the end of 2020).

Outlook: The skilful marketing of the system in a sector that is always hungry for technological innovations will probably lead to the method continuing to receive a strong following - certainly also in places where it is not so well-suited for. It is difficult to assess whether the technical limits have already been reached or whether the accuracy of the method, both in terms of false positives and margin of error (resolution of radargrams), will be improved in the foreseeable future. If so, application limits will be shifted significantly, increasing the method's applicability in developing countries in particular. It is also likely that other providers will enter the market, which usually leads to falling prices and greater pressure to innovate. As mentioned above, it seems that this process has already begun, since recently there has been at least a second company providing satellite detection of leaks with asset risk assessment.

FURTHER INFORMATION

Numerous, short case studies, consisting mainly of the results, including from EMDEs and white papers

Article on the possible efficiency gains with the method (Gagliardo 2019)

Several recorded webinars can be accessed (after registration). These are the best source so far for in-depth information on the method.

2.5. Other methods

2.5.1. General information on other leak location methods

In addition to noises, missing water, temperature changes and the actual water in the ground, leaks in water pipelines leave numerous other traces that can be detected by other methods:

1. The leak hole itself can be located by the tracer gas method.
2. Chlorine, which is often used to treat water, can be sniffed out by sniffer dogs.
3. At the moment of occurrence, there is a pressure wave triggered by the pipe break. This can be located by the Negative Pressure Wave Method.
4. Finally, a series of parameters can be analysed by soil probes.

2.5.2. Tracer-gas

OVERVIEW	
Type of method: Temporary mobile location and pinpointing method	
Location principle: Chemical	**Sensor type:** Contactless sensor

Figure 22. From left to right: Injection of forming gas via a meter box; Carpet probe; Borehole probe; Bell probe (All courtesy of H. Sewerin GmbH)

Leak location principle: With the tracer gas or gas injection method, an ultra-light gas (helium or hydrogen mixed with nitrogen) is injected into the pipeline, which diffuses to the surface even through very small holes in the pipe. At the surface, the gas is traced and its concentration is measured using suitable gas detection sensors. This way existence and the position of the leak can be determined.

Areas of application	
Applicability for indoor leak location	Yes (one of the most important methods)
Applicability for distribution networks	Yes
Applicability for large diameters pipes	To some extent with bubble creators

Influencing factors			
Water pressure	No influence	**Intermittent supply**	May facilitate use
Pipe depth	Some influence	**Knowledge of pipe location**	Very helpful
Pipe material	No influence	**Need for access points**	Few (for gas injection)
Soil conditions	Important	**Method-specific negative factors**	Windy conditions

Links to providers
H. Sewerin GmbH; TROTEC GmbH; Fast GmbH (All Germany)

STEP-BY-STEP DESCRIPTION

1st Step: Identification of a supply area in which first all connections, gate valves and access points are closed. The section is then drained as completely as possible.

2nd Step: Selection of a suitable access through which the lines are filled with forming gas (95% nitrogen, 5% hydrogen) to 3-4 bars (for indoor use 1-2 bars could prove to be sufficient). If the normal pressure in the line is significantly higher, slightly higher pressure is also possible.

3rd Step: Then it is waited until the gas can diffuse through the leaks to the surface. Depending on the soil conditions and the depth of the pipes, this can take a few minutes up to half an hour, while in exceptional cases it may be much longer. But even if the first molecules can be measured very quickly on the surface, it is usually worth waiting a little longer to ensure the reliability of the results. The time is counted from the moment the gas pressure is reached, which, depending on the volume of the pipes, can take some minutes or much more. A pressure drop in the meantime can be interpreted as the confirmation of a leak or an indicator that not all accesses are closed.

4th Step: Now the surface above the pipes is scanned with a gas measuring device - usually a carpet probe (see figure above) - until the hydrogen is detected. Since the gas does not automatically escape vertically at the point where the leak is, but rather the easiest way to the surface, this step should be regarded as pre-location.

5th Step: Depending on the surface condition, further probes are used (see figure above). Usually, small holes are drilled in the ground (e.g., in the asphalt) near the pipeline to see where the gas diffuses more easily. The leak is suspected and dug at the point with the highest measured gas concentration.

6th Step: It must always be kept in mind that there can be more than one leak in the area, i.e., the search does not automatically end with the first leakage discovery. If there are several leaks, they are often found during the first pass. If not, then the leaks are very close together and are usually easily found during excavation. Nevertheless, a second look can often be worthwhile.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: As already mentioned, it is possible to use helium instead of forming gas. This is detected with the help of mass spectrometers. However, this method has numerous disadvantages, especially in economic terms, since both the investment in the detection equipment and the cost of the helium are considerably higher. In addition, spectrometers are not very versatile in the field.

Another variant is the use of bubble generators. With these, the tracer gas can be introduced into the water while the network is in operation. Besides the advantage that the supply does not have to be interrupted, only a fraction of tracer gas is needed. For this very reason, however, the method using more gas in drained lines is more accurate. When using the method with filled lines, there is also a risk that the bubbles will accumulate at the top of the pipe, especially if there is no strong turbulence in the line (low flow velocity) - then only leaks that occurred in this part of the pipe can be detected. In addition, sometimes the bubbles can escape through automatic air valves and lead to false positives.

Combined application with other methods: Since this method is very time-consuming, it should only be used if other methods (especially acoustic methods) fail. However, since this is usually never the case in 100% of the network within a utility, this method should be understood as a complementary method. For the same reason, the method should only be used when there is already a reasonable suspicion of leakage and it has been narrowed down to a sector that can be shut off, i.e., methods for identification and pre-location (such as night-time noise loggers or satellite radar) should be used beforehand. Since the step test method locates a leakage between 2 shut-off gate valves - and this is a perfect application section for a tracer-gas test - the combination of these methods is often logical, especially if acoustic methods fail.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): The probability of missing leaks is very low. This can occur if the gas is not waited for to diffuse or the gas diffuses in a completely different, possibly inaccessible or unexpected location due to unpredictable subsurface conditions. Also, sometimes, certain areas of the section under investigation cannot be completely drained and part of the pipe continues to hold water. In this section and the parts it blocks, leaks can be missed because the tracer gas simply does not reach there. Relatively close, multiple leaks can usually be located without difficulty.

Likelihood of false positives (dry holes): The probability of false positives is close to zero. Exceptions can occur due to poorly calibrated gas measuring devices or strong emissions from old cars.

Margin of error: The margin of error is small, in favourable conditions smaller than with acoustic methods. However, this can become larger due to unfavourable conditions in the subsoil - since the gas takes the easiest path to the surface, it does not always escape vertically.

SCOPE AND LIMITATIONS

When should this method be considered? This method is used particularly when acoustic methods fail. This is in a noisy environment and when the noise level of the leaks is very low, due to low water pressure and also while the pipes are empty due to intermittent supply. It is also recommended for finding even the smallest leaks - those that are difficult to identify by other methods. This is worthwhile, for example, when water is particularly expensive or very scarce. Last but not least it is a good method to use if the pressure test on newly laid pipes fails, i.e., the existence of leaks has been proven. Tracer gas is then often used to find the leaks, which are usually very small at the beginning.

When not to consider this method? The tracer gas method has the following limitations:

1. **Unfavourable soil condition:** In compact soils, the gas may not escape at all or may diffuse at a very great distance. This sealing of the soil can be temporary due to rainfall or permanent, e.g., in shale soils.
2. **Windy conditions:** With strong winds, the tracer gas diffused to the surface is quickly blown away and can either not be detected at all or at the wrong location. In many places this is only a temporary problem; in others, it can make the method mostly inapplicable.

However, the influence of wind can be reduced by the right choice of probes, e.g., bell probes that suck the gas from the ground can mitigate the influence somewhat.

3. **Volume to be filled with tracer gas:** Filling large transport pipelines with tracer gas at a sufficient pressure quickly reaches its limits because the amount of gas required is very large and the method then becomes too expensive. In addition, it is often not desirable to empty these lines. However, an exact application limit cannot be given here. In the case of medium diameter pipes with high flow velocity, the mentioned variant with bubble generators can also be used, whereby the quantity of the required gas is much smaller and it is also not necessary to empty the pipes. In this case, however, it must be ensured that the probed section is not too long, as the gas bubbles will then rise to the surface and leakages in the lower section of the pipe can no longer be found.
4. **Unfavourable network conditions:** In pipeline systems, which cannot be safely disconnected (sectorized), or in which it is not guaranteed that the service connections are closed (e.g., in the case of many illegal connections), so that no gas escapes, the use of the method is not reasonable. This is also true if it would theoretically be possible to disconnect a sector, but the location of the gate valves is not known, are difficult to access, or do not close properly. This factor is likely to be by far the most important in EMDEs.
5. **Unfavourable topography:** In very flat areas it can be sometimes difficult to drain a whole sector so that water pockets will stop the advance of the tracer gas.
6. **Supply difficulties:** In some countries, the necessary calibration of the sniffer may not be offered. Locally, there may be bottlenecks in acquiring forming gas.
7. **Inaccessibility:** The method can only locate leaks when the device is more or less above the leak.

Considerations for application in characteristic circumstances in EMDEs: The relatively high costs do not have such an impact in EMDEs, as these consist to a large extent of personnel costs (which are lower there). Most importantly, many utilities in EMDEs have limited supply for only a few hours (often only 1 - 2 hours) or the water pressure is not sufficient to locate leaks acoustically. Here, the tracer gas method can often be one of the few ways to locate leaks. On the other hand, it can become a real problem that there is often a lack of maintenance of the control valves. This may cause them to no longer be able to be closed completely, allowing tracer gas to escape from the surveyed sector.

INSTITUTIONAL ASPECTS

Required qualification: The training on the devices is relatively short compared to acoustic methods. It is necessary to create an understanding of tracer gas and its diffusion. The trained staff should ideally have previous experience in leak location, as this simplifies the interpretation of the results and the proper maintenance of the equipment.

Required experience: Since local conditions can vary greatly from utility to utility and even within a supply area, there is a learning curve with the application of the method, e.g., how long the tracer gas takes to escape, how often boreholes are needed and at what distance, when it is not advisable to use it at all, etc.

Usefulness of outsourcing the method: In many water utilities, the tracer gas method is used sporadically when other methods fail (e.g., in supply areas with low water pressure or a lot of ambient and background noise). In this case, outsourcing only makes sense if the entire leak location is outsourced. Also conceivable, but not mandatory because of the only moderate qualification and experience required, is to contract specifically this location method as a service in intermittent systems with few hours of service and/or low water pressure.

Necessary or desirable framework conditions at the utility: If the approximate location of the pipes is known, the application of the method takes less time. It is important to periodically provide funds for the purchase of forming gas and calibration of the sniffers. Because of the required experience, the staff should not be rotated frequently or if necessary, the new operators should be trained on the job for at least one to two months.

ECONOMIC ASPECTS

Acquisition cost: The price of the devices varies greatly from € 3,000 to € 10,000 and depends mainly on the scope of supply - there are different carpet, bell and suction probes. For indoor use, there are much cheaper sniffers (about € 500). This refers to devices that use forming gas as tracer gas. Spectrometers that use helium are much more expensive.

Required number of staff: For the use of the method outdoors, two operators are practically always needed - one to operate the various sniffer probes and one to keep an eye on the gas pressure and carry out other supporting work. For leak detection with tracer gas indoors, one person is sufficient even if several methods are used in combination (mainly for reasons of space and cost).

Additional operational costs: Especially for the transport of the gas, motorised transport is always necessary for field use. The most important additional cost is the purchase of the forming gas. From under € 100, up to € 200 is charged for filling a 50 L cylinder with 200 bars. Further costs are incurred annually for the calibration of the gas measuring device (about € 200 - 500, depending on the country). It has to be taken into account that the calibration with shipping can take a week, so the device cannot be used for that long.

Possible additional advantages or disadvantages of the method for utilities: Tracer gas can be used to detect unauthorized consumption of water by clients who have a legal connection to the wastewater network, but whose water supposedly comes from a different source, e.g., from a well. In these cases, the tracer gas is injected under pressure into the drinking water in the network. This gas can then be traced afterwards in wastewater, which can be used to prove that water is being stolen from the utility. If the unauthorized water use is confirmed, it still has to be pinpointed with a suitable method. In the most frequently-used variant of the method - with empty pipes - prolonged service interruptions in the surveyed sectors can hardly be avoided.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The tracer gas method has developed from the passive detection of gas leaks in gas pipe networks, which has been in use since the early 1930s. Since the 1940s and 1950s, various tracer gases have been used to detect leaks in cables, containers, piping systems, etc., and since the late 1960s/early 1970s, various, mostly very expensive tracer gases have also been used in the water sector. In the meantime, the more favourable mixture of hydrogen/nitrogen has prevailed as tracer gas. Helium, which was the first actively used tracer gas, continues to play a subordinate role.

Market penetration: In the last 10-20 years, the detection of water leaks using tracer gas has increased dramatically. This is mainly due to two factors: traditional acoustic methods have great difficulties in finding leaks in plastic pipes, which, however, represent an ever-increasing proportion of water pipes worldwide. In addition, with rising water prices and water shortages, the location of smaller leaks is also becoming increasingly important. In both cases, the tracer gas method is particularly suitable.

Outlook: Since the trends that have led to an increase in the use of tracer gas detection in recent years will continue (increasing proportion of plastic pipes, increasing water scarcity and rising water prices), it can be expected that this method will continue to spread quickly.

FURTHER INFORMATION

Webinar from IWA water loss specialist group about tracer gas leak location (75 min)

Video of a combined listening rod/ground microphone & tracer gas device (4 min)

Short description of a device that uses helium as a tracer gas with small case studies

Example of a bubble generator for the use of tracer gas in pressurised pipes

2.5.3. Sniffer dogs

OVERVIEW	
Type of method: Temporary mobile location and pinpointing method	
Location principle: Chemical	**Sensor type:** Contactless sensor

Figure 23. Left: Weimaraner during sniffer dog training, learning to react to specific scents (Courtesy: Luis Bonifaz); Right: English Springer Spaniel, the dog most common used for water leak detection (Creative Commons: Heinz Höfling).

Leak location principle: Specially trained sniffer dogs are led on a leash, either following the course of the pipes or (indoors) without a leash from room to room and sniff out the characteristic scent of chlorine caused by a drinking water leak and indicate their find.

Areas of application

Applicability for indoor leak location	Yes, but more mould-sniffing dogs
Applicability for distribution networks	Yes
Applicability for large diameters pipes	Yes

Influencing factors

Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Some influence	**Knowledge of pipe location**	Helpful
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	Non-chlorinated water

Links to providers

CAPE SPC (UK); AMS Plumbing (Australia); The Sniffers (Belgium)

STEP-BY-STEP DESCRIPTION

1st Step: The dog and its handler are brought to the area of operation and the pipelines are walked. Often double teams are used, then one dog can rest while the other continues searching - besides, the dogs stimulate each other. Such a double team can inspect a length of 15-17 kilometres per day. Leashes are used so that the dogs do not stray too far from the course of the pipeline.

2nd Step: As soon as the dog has sniffed the scent it has been trained for, it indicates by barking and/or wagging its tail. The form of the indication varies from dog to dog.

3rd Step: The sniffer dog receives a standardised reward, e.g., it is allowed to play with its favourite toy. Interestingly, food is not one of the typical rewards. After a short break, the search for leaks can be continued.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Different variants exist due to the breed of dog used. In general, German Shepherds, Labrador Retrievers and Weimaraners are used as sniffer dogs. However, so far experiences in leak detection are mostly with smaller dogs such as spaniels and mongrels. A brief survey conducted in the course of the present study revealed that by far the most widely used breed for water leakage detection is the English Springer Spaniel (see figure above). This dog combines an excellent sense of smell with great endurance over long distances and the ambition to find his target - all qualities that serve him well during long hours of outdoor work. The English Springer Spaniel is also somewhat easy to train and maintain.

A variant that can be used if the water is not chlorinated is to add harmless odorous substances to the water. Another variant that has spread in Germany recently is dogs that sniff for mould and thus detect indoor leaks indirectly. These mould-sniffing dogs are certified by the German Technical Inspection Agency (TÜV).

Combined application with other methods: When searching for leaks indoors, a combination with other methods is not necessary. In outdoor areas, methods for pre-location (satellite radar, or flow-based pre location methods) can be useful, especially on particularly long pipes, i.e., the sniffer dog is used in areas where there is a well-founded suspicion of leakage. Often, as with many methods, the use of a ground microphone can be useful to confirm the existence of the leak.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Under certain conditions, e.g., other dogs or particularly interesting smells, the dog can be distracted. However, part of the training is that this should not occur. On unsuitable (sealed) floors, sniffing out leaks is not possible. Likewise, a leak can be masked by other, very strong odours (faeces, petrol), but this is rather rare in practice. Otherwise, the sniffing performance of dogs is not even close to being surpassed by the most sophisticated instruments. To illustrate the tremendous olfactory sensitivity of dogs: They can detect the equivalent of one drop of a liquid in 20 Olympic-size swimming pools (Angle et al. 2016). That is why the concentration of chlorine and the size of the leak do not matter. In order not to run alongside a leak, it is only necessary to know the approximate location of the pipes, as the dog will move within a radius of some meters anyway.

Likelihood of false positives (dry holes): The likelihood of a sniffer dog misidentifying a leak is very low with good training, as the scent of chlorine is very different from other odours. A real problem, however, can be that the presence of drinking water does not always indicate a leak (e.g., because someone has washed their car). Here, the correct interpretation of the given situation by the dog handler is necessary to avoid false alarms, which is possible in most cases. "Animal failure", on the other hand, seems to occur only in about 10% of the cases.

Margin of error: The margin of error is very small and similar to that of the tracer gas method, as the smell of chlorine similarly diffuses to the surface. However, the smell of chlorine rises to the surface along the course of the leakage water, i.e., if it continues to flow for several metres; it will also be sniffed by the dog everywhere along with the water presence.

SCOPE AND LIMITATIONS

When should this method be considered? Indoors, dogs are usually used when no other method works but the existence of a leak has already been confirmed. Outdoors, the use of sniffer dogs is particularly useful where surfaces are not sealed with asphalt or similar materials, especially on long pipes that cannot be pigged or correlated due to a lack of access points. Use in areas with low water pressure or in unsafe neighbourhoods can also be advantageous. There are also positive experiences with leak detection dogs for sewage leaks - an otherwise very difficult field for many leak detection methods.

When not to consider this method? Sniffer dogs have some important limitations for leak location:

1. **Inaccessibility:** The most important limit when searching for leaks indoors is that the dog cannot sniff the ceiling and high walls. Also outdoors (similar to tracer gas), sniffer dogs cannot locate leaks when the site of the actual leakage is inaccessible.
2. **Compact or sealed soils:** Also similar to the use of tracer gas, in very compact or sealed soils, the chlorine odour may not come out at all or at a very great distance. This effect can also occur temporarily due to rainfall.
3. **Non chlorinated water:** The use of sniffer dogs is not possible if the drinking water is not chlorinated and it is not possible or economically not reasonable to add odorants.
4. **Other limitations:** Within urban areas, there are probably further application limits due to numerous olfactory influences, but these have not yet been explored. Another limitation could be availability as in some countries it’s difficult to find suitable sniffer dog trainers. Locally and temporally, there can be problems when it is very hot because, just like humans, dogs do not like to work in very hot conditions.

Considerations for application in characteristic circumstances in EMDEs: The very extensive training of sniffer dogs is much cheaper in most EMDEs than in industrialised countries. Thus, this is probably the only method where the investment costs are not significantly higher due to import costs and intermediary margins. In addition, drinking water is more frequently chlorinated in EMDEs, which is why the method can be used more often. Another advantage could be that, unlike the often expensive leak detection devices, sniffer dogs can hardly be stolen - an important advantage in areas with high crime rates.

INSTITUTIONAL ASPECTS

Required qualification: Sniffer dogs require highly specialised training, which can take three to six months. However, it is much easier to train an already trained sniffer dog for a new scent, in this case, chlorine - this only takes about two weeks.

Required experience: Experience is especially required from the dog handler who forms a team with his sniffer dog - he should ideally have experience in leak detection and cannot be replaced easily.

Usefulness of outsourcing the method: Outsourcing the method has great advantages, as it ensures that handler and dog are not separated due to personnel changes in the utility. The fact that, as already mentioned, sniffer dogs can be retrained relatively quickly for new scents is another aspect that makes outsourcing reasonable.

Necessary or desirable framework conditions at the utility: In the case of a utility-owned sniffer dog, all the conditions for appropriately keeping a dog must be in place (exercise, food, accommodation, veterinarian, etc.) and must be in place all the time. In addition, the dog must be used frequently for leak detection; otherwise, it will quickly forget how to sniff chlorine.

ECONOMIC ASPECTS

Acquisition cost: The costs for sniffer dogs and their training vary widely worldwide and tend to be significantly cheaper in EMDEs. In Germany, the training of a Sniffer Dog costs about € 20,000. In contrast, the purchase of the dog itself is hardly significant, since, as already mentioned, no special dog breeds are needed. Additional, but also not very high costs have to be considered for the dog's equipment (transport cage, leashes, doghouse, etc.). Sniffer dogs can be used for 7- 8 years after completing their training and then retire - this is somewhat but not much less than the lifespan of most of the devices described here.

Required number of staff: When locating leaks, one staff member is needed per dog, this is also the case when, as already mentioned, working in double teams. Furthermore, it must be taken into account that dogs also need care and attention outside of their working hours.

Additional operational costs: Sniffer dogs are brought to the place of leak search in a cage in a car with a loading area. Even when not in action, which is not advisable as described, it also incurs costs for food, veterinary, refresher training, equipment and accommodation, which can be between € 1,500 and € 4,000 per year depending on the country.

Possible additional advantages or disadvantages of the method for utilities: An interesting side effect that has been observed with the use of sniffer dogs in leak detection is that it often draws public attention to the important activity of leak detection, as the local press likes to focus on this; for them, it is a curious topic. Since almost everyone likes dogs, this can also be a benefit for the image of the utility.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: Sniffer dogs have been used for hunting for thousands of years. In the course of history, more and more uses for sniffer dogs were added - whether to search for drugs, explosives or truffles and also in the search for leaks in oil, gas or water pipes. The use of sniffer dogs was relatively popular in Germany and other countries until the 1970s, before the introduction of modern leak detection methods. Since then it has declined sharply, only to become somewhat more popular again around 2015, especially where modern methods have reached their limits.

Market penetration: Currently, sniffer dogs are used in many areas, but only very sporadically in leak detection. They are used outdoors especially in Great Britain and the USA, and indoors mainly in Germany.

Outlook: The successes in the use of leak detection dogs in recent years have been "celebrated" by the press (including the specialised press) with enthusiasm and out of all proportion to their relative importance. This could fuel the comeback of leak sniffing dogs, which can often make sense from a technical point of view.

FURTHER INFORMATION

Documentary on the combined use of pre-location by satellites and the Sniffer Dogs Snipe and Denzel West Cumbria Water/UK (10 min)

Fan page of the Central Arkansas Water leak detection dog (USA)

Detailed newspaper article about the leak detection activities of the spaniels Danny and Halo in Queensland (Australia)

Article on Sniffer Dogs and their efficiency on different pipes (Penspen Integrity 2010)

2.5.4. Negative Pressure Wave Method

OVERVIEW			
Type of method: Permanent stationary pre location method			
Location principle: Pressure		**Sensor type:** Contact sensor	

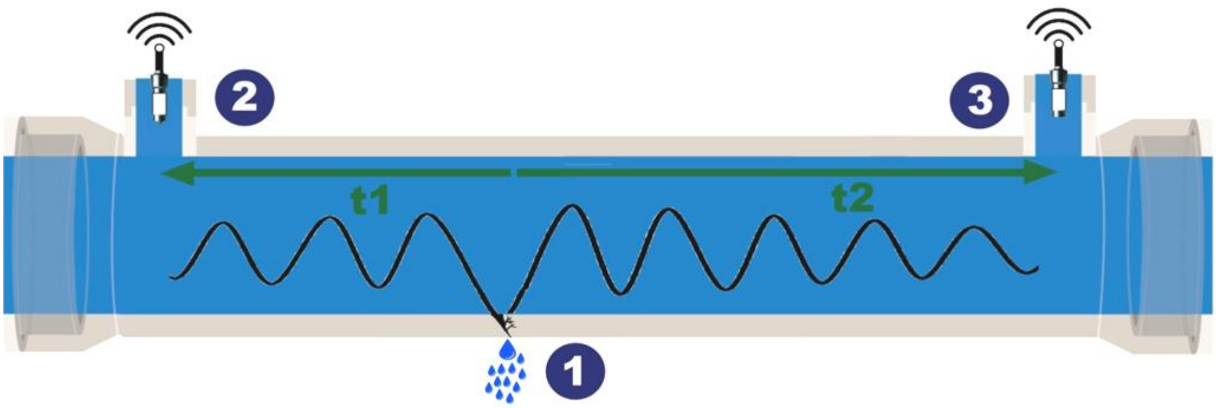


Figure 24. Illustration of the location principle: 1 - A pipe burst triggers a pressure wave which propagates in both directions; 2 and 3 - The pressure wave is registered at different instants by transient pressure loggers upstream and downstream and transmitted to a central unit which calculates the location of the pipe burst based on the time difference.

Leak location principle: Sudden occurrences of leaks lead to pressure waves that propagate through the pipes at a predictable speed. In this method, transient water pressures are therefore measured continuously at different points in the pipes (upstream and downstream) and the occurrence and position of leaks can thus be calculated.

Areas of application	
Applicability for indoor leak location	No
Applicability for distribution networks	Only in combination with other methods
Applicability for large diameters pipes	Yes (Almost exclusively)

Influencing factors			
Water pressure	Important	**Intermittent supply**	May overlook some leaks
Pipe depth	No influence	**Knowledge of pipe location**	Helpful
Pipe material	Some influence	**Need for access points**	Very few (access to water column)
Soil conditions	No influence	**Method-specific negative factors**	Slack lines

Links to providers
Syrinix Ltd. (UK); Atmos International Ltd. (UK); ENREGRO GmbH (Austria)

STEP-BY-STEP DESCRIPTION

1st Step: At least two pressure sensors are placed in contact with the water column, usually at a very large distance (up to several kilometres) on long pipelines with a large diameter.

2nd Step: Suddenly occurring negative pressure waves indicate a leak if they cannot be explained otherwise and are not measured successively by the sensors but both upstream and downstream.

3rd Step: From the travel time to two measuring devices (upstream and downstream), the location of the pipe break can be approximately calculated.

4th Step: The exact location of the leakage is then determined using other suitable methods.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Many suppliers increasingly offer this method together with complex hydraulic simulation models to extend the applicability to somewhat more complex water pipe systems. However, these computer-based models do not only use pressure sensors but often combine them with other methods, especially flow monitoring, sometimes also noise loggers.

Combined application with other methods: As a pre-location method, further methods are used after the discovery of leakage and the delimitation to a certain area. Since the location of the leakage has already been narrowed down by the method, depending on the location, hydrophone correlation (if there are several access points near the leak), pushed hydrophones (if there is one access point near the leak) or ground microphones (if the pipe is shallow but there are no access points) can be used.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Leaks that develop gradually or very small leaks cannot be detected with this method, especially at low water pressure. In the case of intermittent supply, leakages that occur outside of the supply times can also be overlooked. However, these are not frequent and are usually due to external effects on the pipeline (seismic events, landslides, etc.). Even more seldom, but varying from place to place, is the case where a pipe burst is coincidentally superimposed by another transient pressure event - e.g., by the start-up of a pump or the closing of a valve. Leaks that already exist when the sensors are installed cannot be detected with this method.

Likelihood of false positives (dry holes): False positives mainly depend on the given framework conditions - in linear lines without branches, these are practically excluded, since any pressure surges that occur tend to occur only at the ends of the pipelines and, since they are detected by all sensors one after the other, cannot be misinterpreted as leakage. Since the number of possible pressure surges increases with the higher complexity of the system, the possibility of false positives also increases, which can be reduced but not excluded by software support and intelligent analysis. In addition, it depends on which threshold value a leakage alarm is programmed, i.e., the lower it is set to detect smaller leaks, the higher the possibility of false positives, especially in more complex systems (as with many leak detection methods). Of course, as with other pre-location methods, this rarely leads to excavations, rather to additional leak detection efforts, where the existence of a leak can then often be confirmed or ruled out.

Margin of error: Since the pressure waves propagate extraordinarily fast (approx. 1480 m/s), the smallest deviations in the time recordings at the different measuring stations (upstream/downstream) already lead to a very large deviation, which can be up to +/-200 metres depending on the distance between the sensors. Smaller additional deviations can also be caused by water temperature and dissolved substances. Therefore, this is a system for the timely detection of leaks, which also enables a rough pre-location.

SCOPE AND LIMITATIONS

When should this method be considered? The method is particularly suitable for monitoring long sections with large diameters and low complexity, preferably in pipes that are constantly under pressure. If such pipelines run through areas (such as residential ones) where leaks must be detected particularly quickly to react immediately and avoid collateral damage, this system is particularly recommended. It is a comparatively inexpensive method for monitoring long lines with large diameters and has the advantage over cable sensing methods of being retrofittable.

When not to consider this method? The main limitations of this method are:

1. **Non-leak related pressure surges:** The main problem of the method is to distinguish leakage-related pressure surges from other pressure surges. This is practically impossible in the supply area itself, for example, with many supply connections and complex networks, except, as mentioned under variants of the method, in combination with other methods. Therefore, the method is mainly used on long lines with no or few branches.
2. **Slack-lines:** In long pipelines with few branches, problems may also arise, namely on lines that do not run continuously downhill, so-called slack lines, where pressure surges do not continue at certain points, where the method cannot be used, at least in the affected sections.
3. **Intermittent supply:** If the lines are used intermittently, leakages that occur outside the supply time cannot be detected.
4. **Low water pressure:** The lower the water pressure, the weaker the pressure wave and the shorter the locatable distance, i.e., a higher installation density of the measuring devices must be selected. This can lead to the method not being the most effective from an economic point of view.

Considerations for application in characteristic circumstances in EMDEs: Compared to other methods of pipeline monitoring, this system is relatively inexpensive, but it must be borne in mind that it is only a pre-location method, i.e., additional expenses are incurred for the location itself. It remains to be seen whether technical development will soon lead to easy-to-use ready-made solutions, which could make the system less susceptible to staff changes.

INSTITUTIONAL ASPECTS

Required qualification: The qualification required to use the method is low, especially because the software that comes with the device usually greatly facilitates the interpretation work. However, qualified advice should be contracted for the selection of the points of installation and the correct installation of the sensors.

Required experience: The experience required depends on the complexity of the system on which the method is used, i.e., if it is used mainly for long noncomplex pipelines (and this is by far the most common application of the method), much less experience is required to interpret the data than for more complex applications with many different pressure surges.

Usefulness of outsourcing the method: Outsourcing this method is usually not practical, because often no leaks occur on the monitored pipes for months. With the applications in more complex water systems, which are still in their infancy, this assessment may change.

Necessary or desirable framework conditions at the utility: The data obtained must be interpreted continuously, as leaks are only recognisable at the moment of the pipe burst. If there are problems due to staff instability and data is negligently not analysed at times, leaks will be overlooked. After the pre-location by the method, capacities must also be available to pinpoint the leakage - this is not always an issue of course.

ECONOMIC ASPECTS

Acquisition cost: The transient pressure meter itself costs about € 2,000, a measuring station including transmission unit and installation, however, can cost up to € 10,000, but is significantly cheaper if it is already installed when pipes are laid.

Required number of staff: one person part-time is enough to monitor the data. Of course, additional staff is needed for the actual leak location and from time to time for the maintenance of the monitoring stations.

Additional operational costs: The operational costs of the system are limited to negligible electricity costs and a monthly flat rate for the transmission of data from the individual measuring stations. The lowest flat rate should normally be sufficient for the amount of data to be transmitted.

Possible additional advantages or disadvantages of the method for utilities: Pressure surges caused by third party intrusion when tapping the pipeline and also when using the illegal connection can in the vast majority of cases not only be detected and pre-located, but also distinguished from leaks. Although these are not as frequent on large pipelines as in the distribution network, they can cause great damage and high losses if, for example, pipelines are tapped for agricultural purposes.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: The pressure wave method has been used in pipelines for early detection of leaks since at least the early 1970s, initially for oil and gas pipelines. More recent developments are the increasing accuracy of pre-location through the higher precision of digital time stamps and the applicability in increasingly complex systems through the use of software with learning algorithms and the integration of different sensors (flow measurement, acoustics) to better distinguish between leakage-caused and other pressure surges.

Market penetration: The pressure wave method is more commonly used for oil and gas pipelines, where it is the most common monitoring method, while it is moderately common in the water sector, mainly in industrialised countries.

Outlook: Although the technical innovations are making this system more and more interesting and the sensors are also gradually becoming somewhat cheaper, it is precisely in its market niche (long lines with large diameters) that many other methods have recently been gaining ground. Therefore, different future scenarios are conceivable.

FURTHER INFORMATION

Short case study on a pilot project conducted by Anglian Water (UK)

Podcast about the different applications of the method (28 min)

Short case study with a combined transient pressure & acoustic monitoring system in Park City (Utah, USA)

Collection of numerous papers and case studies on the topic of the Atmos company.

2.5.5. Soil probes

OVERVIEW	
Type of method: Temporary mobile pinpointing method	
Location principle: Mixed	**Sensor type:** Contactless sensor

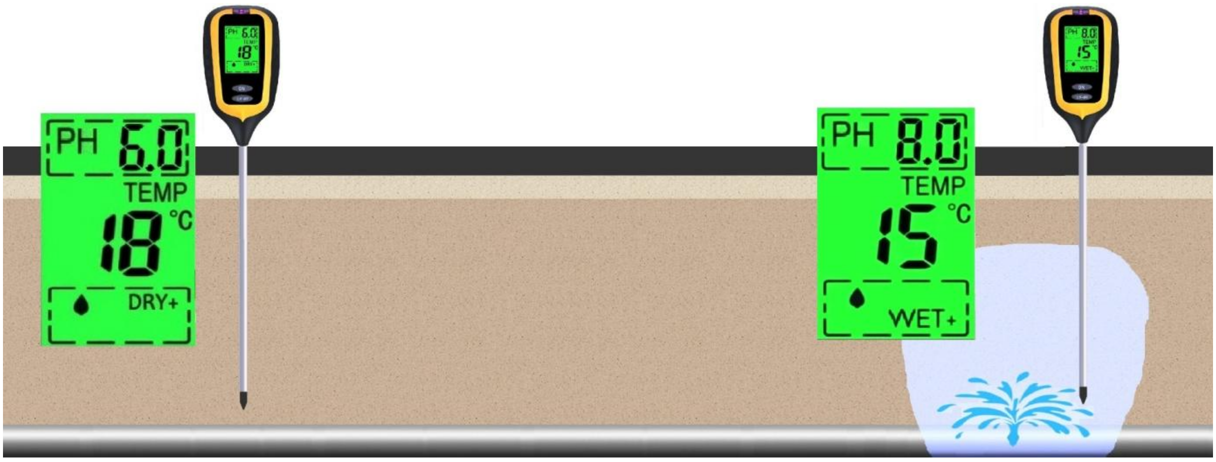


Figure 25. Idealised representation of the functional principle: Left - Soil probe without the presence of leakage; Right - Soil probe with the nearby presence of leakage, indicating lower temperature, higher pH-value and higher moisture content.

Leak location principle: With this method, a probe, usually consisting of a metallic rod, is inserted into the soil at one or more points to draw conclusions about the presence or proximity of a leakage based on the characteristics of the soil at the points investigated. The most common indicator is soil moisture, but other indicators (such as pH or temperature) can also be used. The method is mainly used to confirm leaks that have already been identified and thus avoid dry holes, but can also be used to pinpoint leaks under certain conditions.

Areas of application	
Applicability for indoor leak location	In exceptional cases
Applicability for distribution networks	Yes (main use)
Applicability for large diameters pipes	To some extent for pinpointing

Influencing factors			
Water pressure	Some influence	**Intermittent supply**	Restricts time of use
Pipe depth	Important	**Knowledge of pipe location**	Necessary
Pipe material	No influence	**Need for access points**	Not needed
Soil conditions	Important	**Method-specific negative factors**	Characteristics of drinking water

Links to providers
Step Systems GmbH – Combined Moisture/Temperature probe; Pronova GmbH & Co. KG – moisture probe (both Germany); AGRIS GmbH - temperature probe (Austria); Eijkelkamp – Combined Ph/Electrical conductivity probe (Netherlands)

STEP-BY-STEP DESCRIPTION

Before this method is applied by a utility, it is necessary to clarify how the characteristics of the soil will be most affected by drinking water leakage on-site, i.e., which parameters are best measured and then the appropriate soil probes selected. For example, in arid areas with a low water table, this can be the soil moisture, and in areas that are very hot during the day, where deep groundwater is pumped, it can often be the temperature.

1st Step: The method is used when there is already a justified initial suspicion of leakage and this must be limited to as small an area as possible, otherwise the application does not make sense because of its relatively high effort.

2nd Step: The point where the probe is to be inserted must be exposed - e.g., by drilling a hole in the asphalt or, depending on the nature of the soil, deeper. Care must be taken not to accidentally drill into the water pipes. If the capillarity of the soil is good, it is often not necessary to probe near the depth of the pipe.

3rd Step: The first measurement is taken at a point where the characteristics of the soil are most likely not influenced by leakage to get reference values. At this point, the soil characteristics should be approximately the same as in the actual section to be investigated. This step is not necessary if the reference values are already known.

4th Step: Further measurements are then taken directly at the already pre-identified leakage point or different points to confirm the leakage or to locate it precisely. As mentioned, (at least so far) the most common factor measured and compared to the reference value is soil moisture, but depending on local conditions, other parameters such as temperature, pH, residual chlorine content or electrical conductivity may also provide a much better confirmation of leakage.

5th Step: The measurements can be repeated at further points in the perimeter until the moisture increases and the maximum value is found. This is either the leak or the point where the water escapes and collects most easily.

VARIANTS AND COMBINED APPLICATION WITH OTHER METHODS

Variants of the method: Probes that measure one or two of the mentioned parameters are usually sufficient to confirm the presence of leakage. The parameters are as follows:

1. By far the most commonly used parameter is **soil moisture**, as this can also be confirmed without special sensors using a rod. However, digital devices can not only detect the simple presence of moisture but also measure the degree of moisture and thus, depending on the nature of the soil, also allow an indication of the relative proximity to the leak.
2. If there is a significant **temperature difference** between the drinking water and the surrounding soil, a temperature sensor can be used.
3. If the drinking water has a high **electrical conductivity**, the probe can measure this and thus distinguish it from natural water, usually of very low conductivity (but not in soils with high conductivity such as saline soils or those with high clay content).
4. If the **pH** of the drinking water differs significantly from that of the naturally occurring water (rainwater or groundwater), an additional pH sensor could be useful.
5. Especially if there is high **residual chlorine** content in the drinking water, this can also be measured. Since chlorine does not occur naturally, this can be an option (albeit a

somewhat more complex one) if the other parameters do not provide an accurate indication of the presence of a leak.

There are hardly any probes that measure all five of the mentioned parameters, but as mentioned that is seldom necessary to measure them all.

In places with soils of good capillarity, i.e., where leakage water rises relatively well to the surface, shorter probes are sufficient to measure, e.g., under the asphalt surface, while longer probes are otherwise recommended.

Combined application with other methods: As already mentioned, this method is usually used to confirm the presence of leaks that have already been found by other methods, since inserting a probe is in any case much cheaper than risking a dry hole. It can also be used if the leakage has already been confirmed, but it is worthwhile to determine the leakage location more precisely, e.g., due to asphalting, to reduce the size of the excavation area. This can be the case, for example, when using the tracer-gas method, where simply the already existing boreholes (so that the tracer gas can escape, see description of the method) can be used for probing. Finally, the method can also be used for leak detection itself by systematic probing in places where no other methods are available due to the lack of suitable other equipment or because the existing equipment reaches its operational limits due to the environmental conditions. In this case, too, a well-founded initial suspicion and a reasonably accurate pre-location are necessary, otherwise, the effort for using probes is simply too high.

ACCURACY AND RELIABILITY

Likelihood of false negatives (overlooked leaks): Since this method is almost always only used when there is already a well-founded initial suspicion of leakage, it is rather unlikely to miss leaks if it is applied systematically and suitable parameters are used. Again, however, the probability depends on various factors - small leaks with a short runtime (especially in the case of intermittent supply) are more likely to be overlooked, especially if the exact course and depth of the pipe are not known. Soil conditions again play an important role.

Likelihood of false positives (dry holes): With the correct selection of the measured parameters and the combination of several parameters, the probability of false positives is very low and is often limited to the presence of drinking water that has entered the soil shortly beforehand for other reasons (e.g., car washing or garden sprinkling). Otherwise, depending on the parameters measured, a wide variety of false alarms, albeit rare, can occur, e.g., due to rainwater or soil anomalies. Moreover, by correctly interpreting the results when assessing the respective situation, false alarms can often be ruled out.

Margin of error: The margin of error using this method is in principle very small, which is why it is sometimes used to narrow down the area to be excavated. However, several factors can cause the margin to become larger. A particularly large role is played by the ground conditions, size and duration of the leakage. The combination of these factors can lead to a large area being saturated with drinking water and at least reduce a more precise localisation depending on the parameters used. In addition, moisture sometimes does not spread homogeneously, so the water may first accumulate and spread in a place that is relatively far from the leak.

SCOPE AND LIMITATIONS

When should this method be considered? The method is particularly suitable for confirming leaks that have already been localised using other methods and whenever there is doubt as to whether there really is a leak. This is useful because a small borehole is always cheaper than the risk of digging in vain, especially on asphalted or otherwise covered surfaces. Such doubts are not uncommon, especially when using acoustic methods in supply areas with low pressure. Since hardly any utility publishes the number of dry holes dug, it is difficult to estimate how often this happens, but the minimum percentage seems to be around 10 to 15% and can be significantly higher depending on the experience of the leak detection teams and the local conditions. In addition, as already mentioned, the method can sometimes be used to pinpoint a leak more precisely by taking several probes close to the suspected leakage point to reduce the excavation costs somewhat. The method cannot be recommended for the actual leakage location, as the time required for many tests is usually much too high. A few exceptions are in cases when other methods fail or are not available, the area to be investigated is not too large and there is a well-founded initial suspicion of a leak.

When not to consider this method? Each parameter has different application limits, but if the respective utility selects the parameters that work best for its conditions, the method is only in rare cases not applicable. These can happen in the following cases:

1. **Combination of unfavourable factors:** Due to a combination of unfavourable factors, no parameter gives good results - i.e., at a high water table where the temperature of the drinking water is close to that of the groundwater, which also has a similar pH value and electrical conductivity, and the water has hardly any residual chlorine.
2. **Unfavourable soil conditions:** When the leakage water, e.g., in porous soils, simply drains away and thus does not moisten the surrounding soil.
3. **Difficulties to drill:** In case of difficulties to drill the necessary holes, e.g., due to the combination of deep pipes with inaccurate knowledge of the location of the pipes and low capillarity of the soil and, of course, if the actual leakage position is inaccessible.

Considerations for application in characteristic circumstances in EMDEs: The usually shallower laying depth of the pipelines, the frequent absence of more expensive equipment, the lower labour costs for this rather labour-intensive method and the more frequent occurrence of arid and semi-arid soils, often make this method more suitable in EMDEs than in industrialised countries.

INSTITUTIONAL ASPECTS

Required qualification: The soil probes, depending on the type and number of used parameters, are simple to very simple to operate, so a thorough reading of the manual and a few tests is sufficient without additional training.

Required experience: Local experience with the quality of drinking water and soil as well as about other buried infrastructure (rainwater drains, sewage and cables in order not to damage them), among other things, is very helpful to be able to correctly interpret the values obtained as leakage. In addition, experience can help to apply this method (which is very slow in itself) much faster, e.g., because reference values no longer have to be obtained or the distance between two boreholes can be better selected. On the other hand, experience is not a prerequisite for this method and can often be acquired quickly.

Usefulness of outsourcing the method: Hardly makes sense, except as an additional device when completely outsourcing leak detection. In this case, however, other devices are often available, which are making the use rather rare, except for the confirmation of uncertain leaks.

Necessary or desirable framework conditions at the utility: Knowing the exact location and depth of the buried infrastructure is very important to avoid overlooking leaks and accidentally damaging the pipelines. In addition, permits may be required for drilling on public roads.

ECONOMIC ASPECTS

Acquisition cost: Depending on the type and number of parameters to be measured and the accuracy of the measurements, the devices can cost between € 10 and € 1,500. In most cases, drills of various types are also required, depending on the surface covering and ground conditions.

Required number of staff: Only one operator is needed. Normally, however, the probe is carried as an additional device by a leak detection team consisting of two to three leak searchers and is only used if considered necessary.

Additional operational costs: Operational costs are limited to drilling and plugging the holes needed for probing, which are usually very low, even when asphalt surfaces are involved.

HISTORY, MARKET PENETRATION AND OUTLOOK

History: In its analogue variant - using a rod in the ground near the depth of the pipes to see if the tip is wet - this method, together with mechanical listening rods, is probably the oldest of all leak detection methods. Although inexpensive digital devices for more accurate measurement of parameters other than soil moisture have been used in many sectors (including agriculture) since the turn of the millennium, this now improved method is little used in the water sector and is hardly mentioned in technical publications.

Market penetration: The measurement of soil moisture with analogue or digital probes is still very commonly used to confirm leaks to this day. Although its use for actual detection has declined considerably, it is still used by poorly equipped utilities in the absence of other methods, especially in EMDEs. In contrast, the (multi-parameter) method described here is used rather rarely, despite the low equipment costs, either because of ignorance of the method or because other methods are already being used successfully.

Outlook: As this method offers real advantages under certain commonly encountered conditions, it has the potential to occupy an important niche in the leak detection portfolio, especially if increasingly cost-effective multi-parameter probes enter the market.

FURTHER INFORMATION

Short instruction video for a device that can measure temperature, humidity, pH-value and electrical conductivity of the soil (3 min).

3. AREAS OF APPLICATION OF THE METHODS

3.1. Temporary leak location vs. permanent pipe monitoring

The methods can be divided into those for temporary leak detection and those for stationary permanent monitoring, although the distinction is not clear-cut in individual cases. Of the eight methods which can be used for monitoring (see table below), i.e., which can detect leaks immediately after they occur and in some cases also locate them, two methods (volume balance and noise logging) are also suitable for temporary mobile leak detection, as the sensor technology used is easy to transport and install. The three methods which use cables as a sensor element are a special case. Since the analysis devices, unlike the cables, can be moved easily and their use at several locations is often worthwhile due to their high cost, they are suitable for semi-permanent monitoring, i.e., the line sections equipped with cables can be periodically examined for leaks.

Table 3. Applicability of methods for temporary-mobile and stationary-permanent leak location

N°	Method	Temporary mobile	Semi-permanent	Permanent stationary
1	Listening rods			
2	Ground microphones	☑		
3	Leak noise correlation	☑		
4	Noise logging	☑		☑
5	Pushed hydrophones	☑		
6	Tethered hydrophones	☑		
7	Free-floating hydrophones	☑		
8	Distributed Acoustic Sensing (DAS)		☑	☑
9	Volume balance	☑		☑
10	District Metered Areas (DMAs)			☑
11	Flow monitoring			☑
12	Step test	☑		
13	Hydraulic leak localization pig	☑		
14	Thermal imaging cameras	☑		
15	Thermal imaging drones	☑		
16	Distributed temperature sensing (DTS)		☑	☑
17	Moisture measurement	☑		
18	Moisture sensing smart-cables		☑	☑
19	Ground Penetrating Radar (GPR)	☑		
20	Satellite radar	☑		
21	Tracer-gas	☑		
22	Sniffer dogs	☑		
23	Negative Pressure Wave Method			☑
24	Soil probes	☑		

3.2. Pre location vs. location and pinpointing of leakages

A strict distinction between pre-localisation, localisation and pinpointing is not possible, as many of the methods can also be used far outside their optimal area of application, yet very inefficiently. For example, it is conceivable to reduce the distance between two flow meters to such an extent that they are also able to pinpoint leaks - it is just not possible or economically sensible in the vast majority of cases. Other methods, on the other hand, are pre location and location in one, since they cover large lines or areas at once and are relatively precise at the same time. For some methods, e.g., the correlation and the negative pressure wave method, the margin of error depends on the length of the examined pipe section. Therefore an approximate margin is given here within which the use of the individual methods is reasonable and possible. The maximum of pre location capability is given when leaks can be detected in the longest possible pipe sections/area and the maximum pinpointing capability when leaks are located with an accuracy of one meter or less.

Table 4. Classification of the methods in a Pre-location-Location-Pinpointing-Continuum

N°	Method	Pre-location			←		→			Pinpointing	
1	Listening rods										
2	Ground microphones										
3	Correlation and correlating noise loggers										
4	Noise logging (non-correlating)										
5	Pushed hydrophones										
6	Tethered hydrophones										
7	Free-floating hydrophones										
8	Distributed Acoustic Sensing (DAS)										
9	Volume balance										
10	District Metered Areas (DMAs)										
11	Flow monitoring										
12	Step test										
13	Hydraulic leak localization pig										
14	Thermal imaging cameras										
15	Thermal imaging drones										
16	Distributed temperature sensing (DTS)										
17	Moisture measurement										
18	Moisture sensing smart-cables										
19	Ground Penetrating Radar (GPR)										
20	Satellite radar										
21	Tracer-gas										
22	Sniffer dogs										
23	Negative Pressure Wave Method										
24	Soil probes										

Note: Both in the technical literature and by the manufacturers, different definitions are used for the terms used here. For example, pinpointing a leakage to a small space of about the width of a spade is referred to as "precise location" in older publications. However, it should be clear from the table what is meant in each case as well as the fact that a clear separation is often not possible.

3.3. Indoor leak location methods

Most utilities do not carry out indoor leakage detection as this is the responsibility of consumers. Some offer it as a paid service, some for free as part of campaigns; many others at least advertise the repair of these leaks. This is rational if most of the consumers are billed according to metered consumption - as then there is a great incentive for them to repair leaks quickly (unless the water tariff is extremely low). The case is different for consumers when there is no water metering - leaks are then much more frequent because they are not detected as quickly and because consumers then often have no incentive to repair leaks. It is easy to say that the solution is to install water meters. However, this passe-partout solution often fails in reality. In many areas, there are technical difficulties with the meters, e.g., because they quickly fall apart due to intermittent supply and high lime content, because meters are rejected by the population or because there are simply no funds to buy meters. In these cases, indoor leaks have the same effect on the water losses of the utilities as those on the public mains. In contrast to these, however, they are usually easier to find and, above all, much cheaper to repair. A utility with many unmetered consumers can often reduce its water losses more quickly and cost-effectively by proactively finding and repairing indoor leaks. This is the reason why methods, which are exclusively used indoors, have been included in this document.

Figure 26. Big-4 of indoor leak location from left to right: Moisture meter, Thermal imaging (Both courtesy of TROTEC GmbH), Listening stick, Tracer gas (Both courtesy of H. Sewerin GmbH)

The methods, which are exclusively used indoors, are **moisture measurement** and **thermography** with light hand-held devices. In addition, several methods are used also very frequently, but not exclusively indoors namely **listening rods** and **tracer gas.** The main difference in the indoor application is the use of smaller devices. In addition to this Big-4 of indoor leak detection, ground microphones could eventually be aggregated as a number 5. Already less frequently used are sniffer dogs (which search indoors for mould rather than chlorine). Also sometimes used is a variant of the step test - i.e., where it is possible to isolate parts of the pipe, leak detection can be narrowed down to one section. In exceptional cases, the use of hydraulic leak localization pigs and small pushed hydrophones may be justified. Other methods are only used in large properties, i.e., where the conditions are similar to those for leak location outdoors.

3.4. Methods for leak location in distribution networks

Finding and repairing leaks in distribution networks is the most important task in the topic of leak detection for all water utilities. This is also the reason why most leak detection methods, including the most widely used ones, are designed for this task and are therefore often applied either only or mainly in distribution networks. Leakages at consumer connections play a special role here, as these often account for far more than half of all leakages. Although in principle all methods used in distribution networks are also suitable for pre-locating, locating or pinpointing these leaks, it is worth highlighting two methods that are especially suitable for service connections: the hydraulic leak localization pig and pushed hydrophones, the latter in its smaller, more flexible version. An overview of the applicability of the different leak location methods in distribution networks can be found in the table below.

Table 5. Applicability of the methods for leak location in distribution networks

N°	Method	Applicability in distribution networks
1	Listening rods	Yes
2	Ground microphones	Yes (main use)
3	Correlation	Yes (main use)
4	Noise logging	Yes (main use)
5	Pushed hydrophones	Yes (especially for connections)
6	Tethered hydrophones	In exceptional cases
7	Free-floating hydrophones	No
8	Distributed Acoustic Sensing	Possible
9	Volume balance	No (see flow monitoring)
10	District Metered Areas (DMAs)	Yes (exclusively)
11	Flow monitoring	Yes (exclusively)
12	Step test	Yes (exclusively)
13	Hydraulic leak localization pig	Yes (especially for connections)
14	Thermal imaging cameras	No
15	Thermal imaging drones	Yes
16	Distributed temperature sensing	Possible
17	Moisture measurement	No
18	Moisture sensing smart-cables	Yes
19	Ground Penetrating Radar (GPR)	Yes
20	Satellite radar	Yes
21	Tracer-gas	Yes
22	Sniffer dogs	Yes
23	Negative Pressure Wave Method	Only in combination with other methods
24	Soil probes	Yes (main use)

3.5. Methods for leak location in large diameter pipelines

Large-diameter pipelines are mainly used to transport large volumes of treated or untreated water, usually over long distances. The search for leaks in these pipes is much more difficult than in distribution networks. There are many reasons for this, but usually several of the following factors come into play:

1. The larger diameter causes that leakage sounds cannot be located over large distances - the larger the diameter, the smaller the distance required to identify the sounds/leaks.
2. Many of these pipelines are very long and the distance between access points to the pipeline is normally much longer than in distribution networks where there are many service connections, hydrants, valves, etc.
3. The pipes are often deeper.
4. Because of the large volumes of water they carry, interruption of the supply of these lines is not desirable.

Therefore, in the following, large diameter pipelines with the above-described characteristic are referred to. For those with many access points or which only cover very short distances the methods for distribution networks are also suitable.

Four of the methods described (tethered hydrophones, Free-floating hydrophones, Volume balance and the Negative Pressure Wave Method) are used almost exclusively in pipelines with the above-mentioned characteristics, while two others (Distributed Acoustic Sensing and Distributed temperature sensing) are preferred for use in such pipelines.

Thermal imaging drones, moisture sensing cables, satellite radar and sniffer dogs are also suitable but not only for larger diameters within their characteristic application limits. Pushed hydrophones can be used on long distances but are equipped with more rigid and, of course, much longer guiding cables

In addition to the all methods mentioned above, ground microphones, soil probes and GPR are also used under certain conditions on large pipelines to pinpoint leaks that have already been located by other methods, whereby ground microphones and soil probes can only be used to a limited extent, especially in the case of large pipeline depths. The overview of the applicability of the different leak location methods in large diameter pipelines can be found in the table below.

Six monitoring methods used in large-diameter pipelines are shown in the table in italics. Continuous monitoring is used for larger pipes more frequently than in distribution networks because pipe bursts can be potentially very dangerous due to the large volumes of water transported if they are not detected immediately.

An excellent overview of the applicability of some of these methods in different combinations of pipe material, diameter and water pressure can be found in Hamilton & Charalambous 2020, pages 4 to 6. This overview also explains why it is very difficult to make general statements about the applicability of the methods in different pipeline sizes.

Table 6. Applicability of the methods for leak location in large diameters pipelines (monitoring methods are shown in italics)

N°	Method	Applicability in large diameters
1	Listening rods	Exceptionally with many access points
2	Ground microphones	To some extent for pinpointing
3	Correlation	To some extent with hydrophones
4	*Noise logging*	To some extent with hydrophones
5	Pushed hydrophones	Yes, but with different characteristics
6	Tethered hydrophones	Yes (almost exclusively)
7	Free-floating hydrophones	Yes (exclusively)
8	*Distributed Acoustic Sensing (DAS)*	Yes (preferentially but not exclusively)
9	*Volume balance*	Yes (exclusively)
10	District Metered Areas (DMAs)	No
11	Flow monitoring	No
12	Step test	No
13	Hydraulic leak localization pig	No
14	Thermal imaging cameras	No
15	Thermal imaging drones	Yes
16	*Distributed temperature sensing (DTS)*	Yes (preferentially but not exclusively)
17	Moisture measurement	No
18	*Moisture sensing smart-cables*	Yes
19	Ground Penetrating Radar (GPR)	Yes (for pinpointing)
20	Satellite radar	Yes
21	Tracer-gas	To some extent with bubble creators
22	Sniffer dogs	Yes
23	*Negative Pressure Wave Method*	Yes (exclusively)
24	Soil probes	To some extent for pinpointing

3.6. Overview of the areas of application

To get a complete overview of the fields of application of the methods, a tabular summary will be given on the next page.

Table 7. Overview of the areas of application of the different methods

N°	Method	Temporary mobile	Semi permanent	Permanent stationary	Applicability indoors	Applicability in distribution networks	Applicability in large diameters	Pre location	Location	Pinpointing
1	Listening rods	☑			Yes (one of the most important methods)	Yes	Exceptionally with many access points	☑		
2	Ground microphones	☑			Sometimes	Yes (main use)	To some extend for pinpointing			☑
3	Leak noise correlation	☑			In exceptional cases	Yes (main use)	To some extend with hydrophones		☑	
4	Noise logging	☑		☑	In exceptional cases	Yes (main use)	To some extend with hydrophones	☑		
5	Pushed hydrophones	☑			In exceptional cases	Yes (especially for connections)	Yes, but with different characteristics		☑	☑
6	Tethered hydrophones	☑			No	In exceptional cases	Yes (almost exclusively)		☑	☑
7	Free-floating hydrophones	☑			No	No	Yes (exclusively)		☑	
8	Distributed Acoustic Sensing		☑	☑	No	Possible	Yes (preferentially but not exclusively)		☑	
9	Volume balance	☑		☑	No	No (see flow monitoring)	Yes (exclusively)	☑		
10	District Metered Areas (DMAs)			☑	No	Yes (exclusively)	No	☑		
11	Flow monitoring			☑	No	Yes (exclusively)	No	☑		
12	Step test	☑			No, but see variants of the method	Yes (exclusively)	No	☑		
13	Hydraulic leak localization pig	☑			Sometimes	Yes (especially for connections)	No		☑	☑
14	Thermal imaging cameras	☑			Yes (one of the most important methods)	No	No			☑
15	Thermal imaging drones	☑			No	Yes	Yes		☑	
16	Distributed temperature sensing		☑	☑	No	Possible	Yes (preferentially but not exclusively)		☑	
17	Moisture sensing smart-cables	☑			Yes (one of the most important methods)	No	No			☑
18	Moisture sensing cables		☑	☑	No, but see variants of the method	Yes	Yes		☑	
19	Ground Penetrating Radar (GPR)	☑			In exceptional cases	Yes	Yes (for pinpointing)			☑
20	Satellite radar	☑			Can find indoor leaks incidentally	Yes	Yes	☑		
21	Tracer-gas	☑			Yes (one of the most important methods)	Yes	To some extend with bubble creators		☑	☑
22	Sniffer dogs	☑			Yes, but more mould sniffing dogs	Yes	Yes		☑	☑
23	Negative Pressure Wave Method			☑	No	Only in combination with other methods	Yes (exclusively)	☑		
24	Soil probes	☑			In exceptional cases	Yes (main use)	To some extend for pinpointing			☑

4. FACTORS INFLUENCING THE APPLICABILITY OF THE METHODS

4.1. Water pressure

A low water pressure results in less water leaking than with high water pressure for the same duration. This means that the leak leaves fewer traces of any kind and is thus in principle more difficult to detect by all methods, because it produces less noise, less moisture, smaller temperature deviations, less lost water, etc. Only two methods are exempt from this:

1. The tracer gas method, because it does not locate the actual water leak, but the leak hole through escaping tracer gas.
2. The hydraulic leak localisation pig, since this device works even at very low pressure, but above all, the pressure can easily be artificially built up with the help of a small water pump.

A second group are the methods in which a low water pressure usually has no great effect, but a) in individual cases can lead to smaller leaks that can be located with higher pressure being overlooked and b) under extremely low pressures (e.g., around 0.3 bar) can also lead to larger leaks being overlooked. This applies e.g., to hydrophone pigs (pushed, tethered or free-floating), which, because they are very close to the leak, are usually still able to detect leaks. In the case of many other methods, e.g., the flow-based methods, low pressure causes some leakages not to reach thresholds that are interpreted as leakage.

The third group are the methods whose effectiveness suffers most from low pressure. These are all acoustic methods that detect leaks from a certain distance and the Negative Pressure Wave Method. This does not necessarily lead to the inability to locate the leakage in every individual case, as other factors (pipe material) also play a role, but at least increases the effort in the application, often to the extreme that it reaches technical or economic limits.

In the table below, the influence of pressure on the possibility of locating leaks is roughly summarised, whereby it should be noted that the boundaries between the second and third groups are fluid, e.g., Distributed Acoustic Sensing could also be assigned to the third group depending on the distance of the sensor cables from the pipe.

Table 8. Influence of water pressure on the applicability of the methods

N°	Method	Influence of pressure
1	Listening rods	Important
2	Ground microphones	Important
3	Leak noise correlation	Important
4	Noise logging	Important
5	Pushed hydrophones	Some influence
6	Tethered hydrophones	Some influence
7	Free-floating hydrophones	Some influence
8	Distributed Acoustic Sensing (DAS)	Some influence
9	Volume balance	Some influence
10	District Metered Areas (DMAs)	Some influence
11	Flow monitoring	Some influence
12	Step test	Some influence
13	Hydraulic leak localization pig	Easily adaptable
14	Thermal imaging cameras	Some influence
15	Thermal imaging drones	Some influence
16	Distributed temperature sensing (DTS)	Some influence
17	Moisture measurement	Some influence
18	Moisture sensing smart-cables	Small influence
19	Ground Penetrating Radar (GPR)	Some influence
20	Satellite radar	Some influence
21	Tracer-gas	No influence
22	Sniffer dogs	Some influence
23	Negative Pressure Wave Method	Important
24	Soil probes	Some influence

4.2. Intermittent supply

An intermittent water supply is very common in EMDEs and has very different, mostly negative effects on the applicability of the different leak detection methods. The biggest exception is the use of the tracer gas method, as this can be applied even faster and more efficiently in empty pipes. Also relatively easy to apply in empty pipes is the hydraulic leak localisation pig, which can also find leaks in empty pipes using a small water tank and a small water pump.

The second group of leak location methods is only affected by intermittent supply in that leak location can only be carried out during the time of supply. This can lead to problems for two reasons: on the one hand, if the supply time is so short that the leak location teams do not have enough time to locate any leaks and, on the other hand, if the supply times do not coincide with the working hours of the leak locators. The latter can be a problem, especially for permanently employed leak locators. Furthermore, during the filling time of the network, the flow noises can easily mask leakage noises. In water-scarce situations and densely populated areas, the distribution cycles are often so short that the network will only be saturated for a very short time, if at all. One of the methods, the correlation, can also have additional problems during supply times in the case of intermittent supply, as air pockets then often accumulate and negatively influence the accuracy and range of the method.

The third group of methods cannot find leaks in empty pipes either but is hardly affected by the problems just mentioned. These are the methods that use sensor cables and, if used as a continuous monitoring method, can locate the leaks without any problems during supply times. If these methods are only used as semi-permanent monitoring, it is only necessary to make sure that the quick, uncomplicated measurements are carried out during the supply time.

Another group of leakage location methods may not be applicable or only to a limited extent in the case of intermittent supply. On the one hand, there are methods that depend on the existence of an almost consumption-free supply period. These are the flow-based methods, which interpret nocturnal flows as leakages (DMAs, flow monitoring, and step test). The case is similar for noise logging, where leakages are preferably listened for at quiet night times when the pressure is also usually higher due to very low consumption. However, if there is no supply at these times, the method often loses its meaning. That is somewhat different for thermal drones, which are best used at times when the difference between ground and water temperature is highest. However, if there is no supply close to these times, the use of drones can often be ruled out. Similar problems can occur with satellite location, as the time at which the satellite passes over a given area is fixed. If this does not happen to overlap with the supply times, leak detection will at least be severely compromised. This is particularly severe in the case of utilities that deliver the water in a tacked manner to different parts of their supply area, i.e., many satellite fly-bys at different times would have to be waited for and many satellite images analysed to get a useful result at all. A special case is the Negative Pressure Wave Method, which can only detect pipe bursts that occur during supply and misses all others.

A summary of the influence of intermittent supply on the applicability of the different methods is given in the table below.

Table 9. Influence of intermittent water supply on the applicability of the methods

N°	Method	Influence of intermittent supply
1	Listening rods	Restricts time of use
2	Ground microphones	Restricts time of use
3	Leak noise correlation	Restricts time of use/ air pockets
4	Noise logging	Depending on the time, impossible
5	Pushed hydrophones	Restricts time of use
6	Tethered hydrophones	Restricts time of use
7	Free-floating hydrophones	Restricts time of use
8	Distributed Acoustic Sensing (DAS)	Small influence
9	Volume balance	Restricts time of use
10	District Metered Areas (DMAs)	Depending on the time, impossible
11	Flow monitoring	Depending on the time, impossible
12	Step test	Depending on the time, impossible
13	Hydraulic leak localization pig	Relatively easy to adapt
14	Thermal imaging cameras	Restricts time of use
15	Thermal imaging drones	Depending on the time, impossible
16	Distributed temperature sensing (DTS)	Small influence
17	Moisture measurement	Restricts time of use
18	Moisture sensing smart-cables	Small influence
19	Ground Penetrating Radar (GPR)	Restricts time of use
20	Satellite radar	Depending on the time, impossible
21	Tracer-gas	May facilitate use
22	Sniffer dogs	Restricts time of use
23	Negative Pressure Wave Method	May overlook some leaks
24	Soil probes	Restricts time of use

It should be noted that intermittent supply and low water pressure often occur together. Therefore a closer look at the tracer gas method and the hydraulic leak localization pig, as well as the sensor cable methods, may prove worthwhile in such conditions, although of course the other limitations of these methods should always be considered.

4.3. Knowledge of pipe location

Because utilities are often not involved during commissioning and handover, new networks are often put into operation without documentation of their characteristics. Often only older field staff know the actual locations, materials and diameters of the network infrastructure, and these details are not formally recorded anywhere. The lack of knowledge about the location of the pipes especially has a negative impact on the usefulness of many leak location methods and often the knowledge of older staff plays an important part here.

The knowledge of the pipeline location is only not necessary for some methods, namely for acoustic pre-location by listening rods and noise loggers, as well as for most flow-based methods. For some other methods, however, the knowledge of the line course is especially important:

1. Leak noise correlation is particularly affected for two reasons: Firstly, because the length of the correlated sections must be known to calculate the leakage position and secondly the result of the correlation only gives a distance to the leakage, which is difficult to locate from the surface if the pipe location is not known. Additional information on the pipe diameter and material including repaired sections is required.
2. Thermal drones normally find numerous thermal anomalies, which can only be interpreted as a possible leak if they are in the immediate vicinity of the pipelines; otherwise, there are easily numerous false positives.
3. Free-floating hydrophones indicate with some accuracy the position of a leak on the distance travelled. However, if the course and length of the examined sections are unknown, the margin of error multiplies. Since these devices are often used with large pipelines that are buried deep, this can lead to major difficulties such as expensive excavation work over a large area. In addition, it is always a problem with this device that it can get lost. With an unknown course of the lines and possibly existing but unknown obstacles and branches, this problem becomes, of course, more serious.
4. Soil probes are normally not able to locate leaks if the pipe location is not at least approximately known because a few metres away from the leak, there can be already no detectable sign of them. In some cases, the necessary drilling can even damage the pipelines, e.g., because the depth of the pipeline is overestimated.

The importance of knowing the location of the pipelines for these methods should not lead to the wrong conclusion to exclude these methods in case of non-existent, incomplete or inaccurate technical cadastres. Instead, this should be another reason to create and constantly update them, as technical cadastres are also essential for many other activities such as pressure, repair and asset management and so forth. A pipe location should take place even if the cadastre is available to rule out inaccurate cadastres and improve leak location. With most methods, an exact pipe location is an important part of successful leak detection.

With all other methods, knowledge of pipe location is at least helpful. Interestingly, several methods can be used to locate the pipes with pinpoint accuracy, namely:

1. Through a tracking transmitter attached to the device - this is the case with pushed and tethered hydrophones as with the hydraulic leak localisation pig.
2. The sensing cables (moisture sensing, DAS and DTS) can usually be easily found from the surface using a suitable locating device.
3. The GPR can usually locate pipes even better than leakages.

However, even with these pipe location methods, at least an approximate knowledge of the pipe location is helpful, as it greatly speeds up the fieldwork. A summary of the findings of this influencing factor can be found in the table below.

Table 10. Influence of the knowledge of the pipe location on the applicability of the methods

N°	Method	Knowledge of the pipe location
1	Listening rods	Not necessary
2	Ground microphones	Very helpful
3	Leak noise correlation	Necessary
4	Noise logging	Not necessary
5	Pushed hydrophones	Can be used for locating
6	Tethered hydrophones	Can be used for locating
7	Free-floating hydrophones	Necessary
8	Distributed Acoustic Sensing (DAS)	Can be used for location
9	Volume balance	Not necessary
10	District Metered Areas (DMAs)	Not necessary (Only for setting up)
11	Flow monitoring	Not necessary (Only for setting up)
12	Step test	Not necessary
13	Hydraulic leak localization pig	Can be used for locating
14	Thermal imaging cameras	Helpful
15	Thermal imaging drones	Necessary
16	Distributed temperature sensing	Can be used for locating
17	Moisture measurement	Helpful
18	Moisture sensing smart-cables	Can be used for locating
19	Ground Penetrating Radar (GPR)	Can be used for locating
20	Satellite radar	Helpful
21	Tracer-gas	Very Helpful
22	Sniffer dogs	Helpful
23	Negative Pressure Wave Method	Helpful
24	Soil probes	Necessary

4.4. Pipe depth

Deep pipes have a very uneven impact on the applicability of the different methods. The following methods are most negatively affected:

1. The deeper the pipeline, the greater the proportion of leaks that can be missed by **ground microphones**, although it should be noted that this depends on the interaction of several factors such as size of the leak, water pressure and soil conditions. This means that the depth of the pipe can be prohibitive under certain conditions and that, under other conditions; the ground microphone can still be used even on deep pipes.
2. As **thermal imaging** cameras (handheld or drone mounted) can only detect temperature differences on the surface, the ability to detect leaks decreases significantly with increasing pipe depth (exceptions are possible with soil or building materials of excellent capillarity). The same applies to the **moisture measurement** method.
3. **Soil probes** can only be inserted into deeper soil layers with significantly greater effort. Moreover, those with a range of more than one metre are usually not available.

Equally affected by deeper pipes, but to a lesser extent, are the following methods:

1. **Tracer gas method** and **sniffer dogs:** For both methods in the case of deep-buried pipes, the probability of tracer gas or chlorine odour reaching the surface is somewhat lower and the margin of error can be higher but that depends much more on the soil conditions (see next subsection). Tracer gas additionally takes longer to diffuse to the surface.
2. With **satellite radar,** it should be noted that it can detect leaks at depths of two to three metres, depending on the ground conditions. This is sufficient in the vast majority of cases. With **Ground Penetrating Radar**, significantly greater detection depths are possible, but the resolution decreases with increasing depth. This should also only have a practical effect in exceptional cases.

In the case of the methods which use a tracking device to be located from the surface (pushed and tethered hydrophones and the hydraulic leak localisation pig), very deep lines can make it very difficult or impossible to locate that device. However, this is not very common and - in the case of the hydraulic leak localisation pig - almost an absent problem as only small-diameter pipes are investigated with this device and these are usually located at a short distance from the surface.

In the case of the three sensing cable methods (DAS, DTS and moisture sensing) the depths of the pipe may have a positive effect on the respective methods, as influences from the surface (e.g., due to weather or noise) decrease with increasing depth and can thus lead to fewer false positive alarms.

For all other methods, including acoustic and flow-based ones in particular, pipe depth is irrelevant. A summary of the influence of the pipe depth can be found in the table below.

Table 11. Influence of the pipe depth on the applicability of the methods

N°	Method	Influence of the pipe depth
1	Listening rods	No influence
2	Ground microphones	Important
3	Leak noise correlation	No influence
4	Noise logging	No influence
5	Pushed hydrophones	Indirect influence
6	Tethered hydrophones	Indirect influence
7	Free-floating hydrophones	No influence
8	Distributed Acoustic Sensing (DAS)	Positive influence
9	Volume balance	No influence
10	District Metered Areas (DMAs)	No influence
11	Flow monitoring	No influence
12	Step test	No influence
13	Hydraulic leak localization pig	Indirect influence
14	Thermal imaging cameras	Important
15	Thermal imaging drones	Important
16	Distributed temperature sensing (DTS)	Positive influence
17	Moisture measurement	Important
18	Moisture sensing smart-cables	Positive influence
19	Ground Penetrating Radar (GPR)	Some influence
20	Satellite radar	Some influence
21	Tracer-gas	Some influence
22	Sniffer dogs	Some influence
23	Negative Pressure Wave Method	No influence
24	Soil probes	Important

4.5. Pipe material

Pipe material is very often mentioned as one of the most important influencing factors in leak detection. Although the applicability of most leak detection methods is not or only slightly dependent on the pipe material, this can nevertheless be agreed with, because among the methods that are strongly dependent on the pipe material are listening rods, leak noise correlators and noise loggers - some of the most widely-used methods. These are strongly dependent on the pipe material because leakage noise propagates so differently in different materials - worst in plastic pipes, better in cement pipes and best in metallic pipes. This means that leaks in pipes made of the most commonly-used materials in the world today (PE and PVC) can only be located at a much shorter distance than in pipes made of other materials using these acoustic methods. However, this does not mean, as is often claimed, that these methods are completely unsuitable in plastic pipes. If there are enough access points to the pipes, it usually just takes more time and experience to locate the leaks. Another classic acoustic method, the ground microphone, is less affected by pipe material. With better sound-conducting pipe materials, however, leaks can be located from a somewhat greater distance from the ground.

The pipe material also plays a role in the pigging methods, namely the pushed and tethered hydrophones and the hydraulic leak localisation pig. Although it does not influence the actual leak detection, the range of the individual methods is influenced by the different roughness of the pipe surfaces, i.e., the range is higher with smooth surfaces such as plastic than in cement pipes, for example, because the cable is slowed down by friction. Corrosion in iron pipes or lime deposits may affect the range even more, especially the hydraulic leak localisation pig or pushed hydrophones in smaller diameter pipelines.

Pipes made of certain materials can only be located with great difficulty or not at all with the GPR in certain soils, e.g., concrete pipes in some stony grounds. Since the interpretation of anomalies as possible leaks on the radargrams depends strongly on their position in relation to the pipelines, such a condition may limit the usefulness of the method.

Since the Negative Pressure Wave Method has difficulties in detecting leaks that develop gradually, the pipe material is quite important, since such leaks are more frequent in some materials (e.g., plastic) than in others (e.g., asbestos cement). This also applies partly to the Distributed Acoustic Sensing method, which, with constant monitoring, detects the vibrations triggered by the pipe rupture as well as the subsequent leakage sounds, i.e., the slowly enlarging leak is not detected at the moment of occurrence, but soon afterwards.

For all other methods - more than half of those analysed here - the pipe material plays very little to no role. In the case of DTS, when laying the fibre optic cable below metallic pipes, the distance between cable and pipe should be somewhat larger – then the pipe material will also have no influence. A summary of the findings of this influencing factor can be found in the table below.

Table 12. Influence of the pipe material on the applicability of the methods

N°	Method	Influence of the pipe material
1	Listening rods	Important
2	Ground microphones	Some influence
3	Leak noise correlation	Important
4	Noise logging	Important
5	Pushed hydrophones	Some influence
6	Tethered hydrophones	Some influence
7	Free-floating hydrophones	No influence
8	Distributed Acoustic Sensing (DAS)	Some influence
9	Volume balance	No influence
10	District Metered Areas (DMAs)	No influence
11	Flow monitoring	No influence
12	Step test	No influence
13	Hydraulic leak localization pig	Important
14	Thermal imaging cameras	No influence
15	Thermal imaging drones	No influence
16	Distributed temperature sensing (DTS)	No influence
17	Moisture measurement	No influence
18	Moisture sensing smart-cables	No influence
19	Ground Penetrating Radar (GPR)	Some influence
20	Satellite radar	No influence
21	Tracer-gas	No influence
22	Sniffer dogs	No influence
23	Negative Pressure Wave Method	Some influence
24	Soil probes	No influence

4.6. Soil conditions

Soil conditions influence many of the methods investigated here, with by far the most important factor being whether the soil is wet, e.g., due to a high groundwater level - in this case, many methods have difficulty recognising a leak as such. This is evident with moisture sensing methods – but also the GPR cannot be used for leak detection in wet areas (but also not in saline, sodic, or soils with high clay content). With satellite radar, on the other hand, drinking water can in many cases be distinguished from naturally-occurring water by spectral analysis; nevertheless, this can lead to problems in locating raw water leaks and even distinction problems in areas with high groundwater levels (due to mixing of natural with drinking water).

With the three thermal methods, several other soil-related factors are decisive for the applicability of the methods. Firstly, the temperature difference between soil and piped water is important. Secondly, the permeability and capillarity of the soil (or, in the case of handheld thermal imaging cameras for indoor use, that of the building materials) play an important role, although this is less important for distributed thermal sensing (DTS). Thirdly, the surface coating (e.g., insulation materials or asphalting) is also important, but of course not for DTS.

Whether soil probes can detect a leak or not also depends largely on the differences between soil with or without drinking water, i.e., a wet soil with similar conductivity, pH value and temperature does not allow leak detection. This is rare, but soil conditions should at least be known to determine the best parameters to probe.

Sealed soils, i.e., those that do not allow tracer gas and chlorine odours to diffuse to the surface, are the most important application limit for tracer gas and sniffing dogs.

The soil conditions have a somewhat less negative influence on the use of ground microphones - good sound-conducting soils lead to the fact that hardly any leakages are overlooked, but can increase the margin of error somewhat. Conversely, sound-absorbing soils can lead to leakages being overlooked, but the margin of error is then smaller. As already mentioned in the previous subchapter, other factors also play a role here. With Distributed Acoustic Sensing this influence is even smaller because the sensing cable is often located in the sand bed surrounding the line. If this is not the case, different types of soil between the pipe and the cable can conduct the sound differently.

Soil conditions have an indirect effect on the hydraulic leak localisation pig, as it is often necessary to dig up the ground to the pipe to insert the device head into the pipes. In the case of pushed hydrophones, this also happens but less frequently. The soil conditions and the surface may make the necessary excavation work more difficult or more expensive in some cases than in others, but the actual leakage location is not affected by the soil conditions in either method.

For all other methods, including acoustic and flow-based ones in particular, soil conditions are irrelevant. A summary of findings of this influencing factor can be found in the table below.

Table 13. Influence of the soil conditions on the applicability of the methods

N°	Method	Influence of the soil conditions
1	Listening rods	No influence
2	Ground microphones	Some influence
3	Leak noise correlation	No influence
4	Noise logging	No influence
5	Pushed hydrophones	Indirect influence
6	Tethered hydrophones	No influence
7	Free-floating hydrophones	No influence
8	Distributed Acoustic Sensing (DAS)	Some influence
9	Volume balance	No influence
10	District Metered Areas (DMAs)	No influence
11	Flow monitoring	No influence
12	Step test	No influence
13	Hydraulic leak localization pig	Indirect influence
14	Thermal imaging cameras	Important
15	Thermal imaging drones	Important
16	Distributed temperature sensing (DTS)	Important
17	Moisture measurement	Important
18	Moisture sensing smart-cables	Important
19	Ground Penetrating Radar (GPR)	Important
20	Satellite radar	Important
21	Tracer-gas	Important
22	Sniffer dogs	Important
23	Negative Pressure Wave Method	No influence
24	Soil probes	Important

4.7. Need for access points

Another important influencing factor, which often proves to be a real application limit under certain conditions, is the need to gain access to the pipes. Access may be required only to the pipe itself or fittings such as hydrants or valves, to the water column or, in the case of pigging methods, it may even be necessary to insert the leak detection devices into the pipe.

Listening rods and hydraulic leak localisation pigs require a particularly large number of access points. In the case of leak noise correlation and noise logging, depending on pipe diameter and material, water pressure and the method used (hydrophones or microphones), a lot or only a few access points may be necessary. In the case of pushed hydrophones, this depends on the type of hydrophone used - as these are used in different sizes from service connections to long pipes with large diameters.

Only a few, but rather large and often rarely available access points to large-diameter pipes are needed for tethered hydrophones. Also a few, but normally always-available access points are needed for the tracer gas method - for injecting the gas. For each use, the free-floating hydrophone requires two access points - one for insertion and one for removal of the device. Since the deployment distances can reach up to 40 kilometres, this is a great advantage of this method, which is only used in large-diameter pipelines, i.e., those where access points are rare. However, it should be noted that for efficient use, additional simple access points to the pipe for synchronisers and passage detectors are necessary.

Even fewer access points are usually required by the flow-based methods and the Negative Pressure Wave Method.

All other methods do not require access to the pipelines at all. A summary of the need for access points and the type of access points can be found in the table below.

Table 14. Need of access points and type of access points for the different methods

N°	Method	Access points	Type of access
1	Listening rods	Many	Pipe or fittings
2	Ground microphones	Not needed	Not needed
3	Leak noise correlation	Some-Many	Pipe, fittings or water column
4	Noise logging	Some-Many	Pipe, fittings or water column
5	Pushed hydrophones	Some-Many	Insertion in the pipe (small – big)
6	Tethered hydrophones	Few	Insertion in the pipe (big)
7	Free-floating hydrophones	Very few	Insertion in the pipe (big)
8	Distributed Acoustic Sensing	Not needed	Not needed
9	Volume balance	Very few	Pipe
10	District Metered Areas (DMAs)	Very few	Pipe or water column
11	Flow monitoring	Very few	Pipe
12	Step test	Very few	Pipe or water column
13	Hydraulic leak localization pig	Many	Insertion in the pipe (small)
14	Thermal imaging cameras	Not needed	Not needed
15	Thermal imaging drones	Not needed	Not needed
16	Distributed temperature sensing	Not needed	Not needed
17	Moisture measurement	Not needed	Not needed
18	Moisture sensing smart-cables	Not needed	Not needed
19	Ground Penetrating Radar	Not needed	Not needed
20	Satellite radar	Not needed	Not needed
21	Tracer-gas	Few	For gas injection
22	Sniffer dogs	Not needed	Not needed
23	Negative Pressure Wave Method	Very few	Water column
24	Soil probes	Not needed	Not needed

4.8. Method-specific influencing factors

In addition to the common influencing factors already mentioned, numerous others only affect the applicability of one method or another - almost every method has an "Achilles' heel". For the exact application limits and the details of the table below, the respective chapter on the individual methods should be consulted.

Table 15. Other important influencing factors for the different methods

N°	Method	Important influencing factors
1	Listening rods	Background noise
2	Ground microphones	Ambient noise
3	Leak noise correlation	Background noise
4	Noise logging	Crime rate
5	Pushed hydrophones	Pipe bends
6	Tethered hydrophones	Pipe bends
7	Free-floating hydrophones	Non closed branches
8	Distributed Acoustic Sensing (DAS)	Already-laid pipes
9	Volume balance	Crystal -clear water
10	District Metered Areas (DMAs)	Unfavourable topography
11	Flow monitoring	High leakage rates
12	Step test	Defective valves
13	Hydraulic leak localization pig	Pipe bends
14	Thermal imaging cameras	Isolation materials
15	Thermal imaging drones	Rainy & windy conditions
16	Distributed temperature sensing (DTS)	Already-laid pipes
17	Moisture measurement	Isolation materials
18	Moisture sensing smart-cables	Already-laid pipes
19	Ground Penetrating Radar (GPR)	Many objects in the ground
20	Satellite radar	High leakage rates
21	Tracer-gas	Windy conditions
22	Sniffer dogs	Non-chlorinated water
23	Negative Pressure Wave Method	Slack lines
24	Soil probes	Characteristics of drinking water

4.9. Overview of influencing factors

Toto give a better overview of the influencing factors and thus facilitate the preselection of methods for leak detection, an overview is given on the following page.

Table 16. Overview of influencing factors

N°	Method	Influence of pressure	Influence of intermittent supply	Knowledge of the pipe location	Influence of the pipe depth	Influence of the pipe material	Influence of the soil conditions	Access points	Method-specific influencing factors
1	**Listening rods**	Important	Restricts time of use	Not necessary	No influence	Important	No influence	Many	Background noise
2	**Ground microphones**	Important	Restricts time of use	Very helpful	Important	Some influence	Some influence	Not needed	Ambient noise
3	**Leak noise correlation**	Important	Restricts time of use/ air pockets	Necessary	No influence	Important	No influence	Some-Many	Background noise
4	**Noise logging**	Important	Depending on the time, impossible	Not necessary	No influence	Important	No influence	Some-Many	Crime rate
5	**Pushed hydrophones**	Some influence	Restricts time of use	Can be used for locating	Indirect influence	Some influence	Indirect influence	Some-Many	Pipe bends
6	**Tethered hydrophones**	Some influence	Restricts time of use	Can be used for locating	Indirect influence	Some influence	No influence	Few	Pipe bends
7	**Free-floating hydrophones**	Some influence	Restricts time of use	Necessary	No influence	No influence	No influence	Very few	Non closed branches
8	**Distributed Acoustic Sensing**	Some influence	Small influence	Can be used for location	Positive influence	Some influence	Some influence	Not needed	Already-laid pipes
9	**Volume balance**	Some influence	Restricts time of use	Not necessary	No influence	No influence	No influence	Very few	Crystal clear water
10	**District Metered Areas (DMAs)**	Some influence	Depending on the time, impossible	Not necessary (Only for setting up)	No influence	No influence	No influence	Very few	Unfavourable topography
11	**Flow monitoring**	Some influence	Depending on the time, impossible	Not necessary (Only for setting up)	No influence	No influence	No influence	Very few	High leakage rates
12	**Step test**	Some influence	Depending on the time, impossible	Not necessary	No influence	No influence	No influence	Very few	Defective valves
13	**Hydraulic leak localization pig**	Easily adaptable	Relatively easy to adapt	Can be used for locating	Indirect influence	Important	Indirect influence	Many	Pipe bends
14	**Thermal imaging cameras**	Some influence	Restricts time of use	Helpful	Important	No influence	Important	Not needed	Isolation materials
15	**Thermal imaging drones**	Some influence	Depending on the time, impossible	Necessary	Important	No influence	Important	Not needed	Rainy & windy conditions
16	**Distributed temperature sensing**	Some influence	Small influence	Can be used for locating	Positive influence	No influence	Important	Not needed	Already-laid pipes
17	**Moisture measurement**	Some influence	Restricts time of use	Helpful	Important	No influence	Important	Not needed	Isolation materials
18	**Moisture sensing smart-cables**	Small influence	Small influence	Can be used for locating	Positive influence	No influence	Important	Not needed	Already-laid pipes
19	**Ground Penetrating Radar**	Some influence	Restricts time of use	Can be used for locating	Some influence	Some influence	Important	Not needed	Many objects in the ground
20	**Satellite radar**	Some influence	Depending on the time, impossible	Helpful	Some influence	No influence	Important	Not needed	High leakage rates
21	**Tracer-gas**	No influence	May facilitate use	Very Helpful	Some influence	No influence	Important	Few	Windy conditions
22	**Sniffer dogs**	Some influence	Restricts time of use	Helpful	Some influence	No influence	Important	Not needed	Non-chlorinated water
23	**Negative Pressure Wave Method**	Important	May overlook some leaks	Helpful	No influence	Some influence	No influence	Very few	Slack lines
24	**Soil probes**	Some influence	Restricts time of use	Necessary	Important	No influence	Important	Not needed	Characteristics of drinking water

5. METHODS NOT INCLUDED IN THIS STUDY

Apart from the analysed methods for leak location and detection, there are others which are or were applied or mentioned as feasible, but which have not been included in the analysis due to several reasons: they are no longer present on the market, still in development or were dismissed due to their very limited applicability, total inapplicability or inefficiency. A short description is given for each:

Endoscopic inspections: Involves introducing video cameras with LEDs at the end of cables into any point of the drinking water network to look for leaks. Since the difficulties of inserting these cameras in water, and pipes are the same as with hydrophones, but the latter locate leaks with significantly greater certainty, leak detection with cameras only can no longer be recommended. Nevertheless, endoscopic cameras can be a good (and very economic) complementary device to pushed, pulled or free-swimming hydrophone pigs and are used in this combination by some manufacturers. In these cases, this was taken into account when describing the individual methods. The main advantage of this is not that additional leaks are found, for which hydrophones are sufficient, but that additional illegal taps can be detected and further information about the condition of the pipelines can be obtained.

Hydraulic free-floating sphere: It consists of a transmitter enclosed in a buoyant sphere which flows through pipelines and is drawn by the force of water escaping through the leak, plugs the hole and is held in that place. An operator follows the device above ground with a handheld receiver, locating the leak precisely (WWT 2018). This interesting new system, called AquaNav was only announced in 2018 but had not yet been distributed at the time of the present study. However, a leak repair device based on the same principle is already in use.

ULTRAC-Method: This is an acoustic method invented in Sweden shortly after the turn of the millennium. It exploits the fact that low and high-frequency sounds propagate differently through pipes and the water column. Very low frequencies, which propagate through longer distances through the pipes, make noises audible to the human ear (Lange 2002). The device is able to locate leaks from a single listening point by comparing the high and low-frequency components of the noise, taking into account that the latter suffers less attenuation. The so-called "Ultrac Leak Finder" was only commercialised for a short time and is no longer available.

Water dowsing: This method of locating water (also known as *water witching*) has existed for hundreds of years and – even though it has been repeatedly dismissed as pseudoscientific – its use by utilities is widespread across the world. In 2017, it was reported that 10 out of 12 utilities in the UK are still relying from time to time on dowsing rods (Le Page 2017). It involves the supposed detection of magnetic, electromagnetic or other types of waves or radiation which are produced or changed by water and which can be sensed by the human body through wooden or metal rods held in the dowser's hands. An experiment (known widely as the "Scheunen experiments") carried out in 1995 with a group of 500 self-declared expert dowsers has shown that the technique does not produce results any better than random chance in detecting water pipes (Enright, 1995).

Analysis of induced pressure transients: With this method, pressure waves are generated in the water column by opening and closing valves. These waves are reflected differently in pipe sections with leaks than in those without. These pressure fluctuations are recorded and analysed with sensors and in principle allow the position of a leak to be inferred. The main challenge is the correct interpretation of the data, especially in somewhat complex systems and with insufficient information (Shucksmith 2012). Despite encouraging results under both experimental and field conditions, the method has not yet made the breakthrough for leak location but can already be used for the much simpler task of detection of illegal installations (Ziemendorff et al. 2020).

Tracer dyes: Sometimes the use of tracer dyes is also mentioned as a leak location method. These dyes are used when a leakage has already been found but the source is unclear, i.e., due to the presence of several different possibilities, like independent water, sewer and / or drain circuits. In these cases, the colour can indicate in which of the circuits the source of the leakage is. This method is preferably used indoors, but also for sewage leaks. However, it is not an actual leak detection or location method, but rather an additional tool that is used in very special situations.

Systematic digging: A present method for pinpointing leaks is to systematically dig. The disadvantages of this method are obvious: extensive digging is extremely expensive and can take up to several days. This method also involves blocking the road to traffic in the area under investigation for a long time and there is a danger that the urban infrastructure may be affected by the work. Although an effective method in itself (if there is a leak, it will be located), due to the disadvantages mentioned, there should always be a better way to locate leaks.

6. ACKNOWLEDGMENTS

I would like to thank the following professionals for taking the time to be interviewed in detail and for sending helpful information: Ana Cozár (Aganova, Spain), Edmund Riehle (Fast GmbH), Clemens Pohl and Dr. Alex de Joode (AP Sensing GmbH); Axel Fabritius and Jürgen Dornstädter (Solexperts GmbH), Jürgen Loos (GIZ), Jörg Hammann (Hammann+Theurer Wassertechnik GmbH), Tim Krüger (8 SEAS Consulting Engineers), Robert Bargolini (GISS), Dr. Vladimir Nosko (Sensor Group, Slovakia), Mike Ingham (Ferret Technology Ltd.), Enrico Dokter (Aktiv-Trocknungsservice GmbH), Pascal Gruner (SebaKMT GmbH), Hannah Mues (Ingenieurbüro D. Bardenz Georadar GPR), Dr. Gerald Gangl (RBS Wave GmbH) and Robert Skerjanz (GFA Consulting Group). My special thanks go to Michael Kersting (Hermann Sewerin GmbH) for information on several of the discussed methods and to Astrid Regler (GIZ) for reviewing the complete document, and to Johannes Martin, who supported the initial stages of the study as GIZ-Intern. Special thanks also go to Ziad Arbad (Nile Delta Water Management; GIZ Egypt), Rahul Sharma (Climate Smart Cities, GIZ India) and Anesu Takaendesa (Strengthening Service Delivery Program, GIZ Zimbabwe) for the proofreading of the whole document. Finally I would like to thank Julian Gonzales (AKUT PERÚ), Luis Bonifaz and the companies TROTEC GmbH and viZaar industrial imaging AG for their contributions with some of the graphic material.

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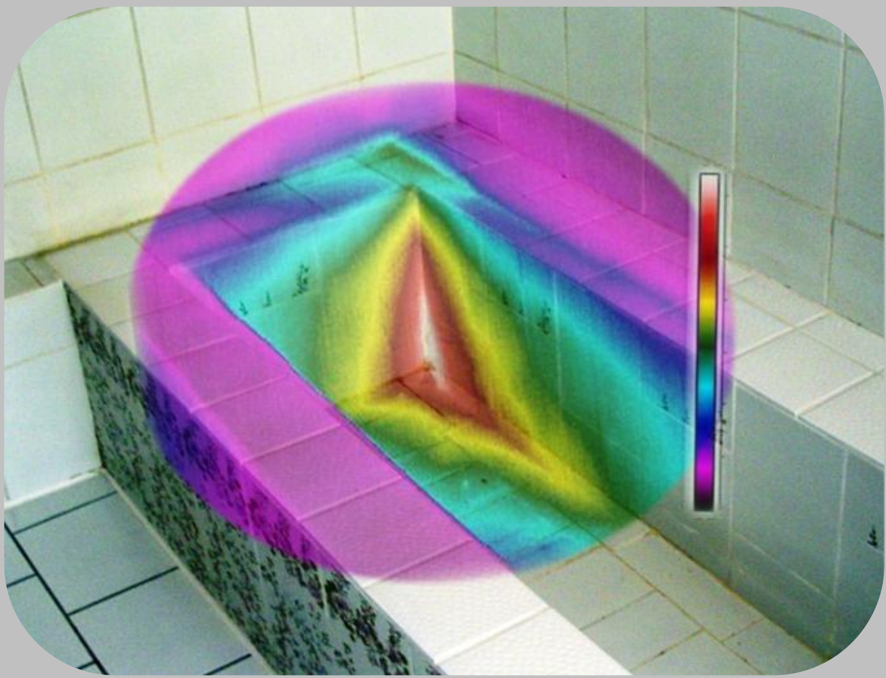

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