LIFE SWSS

"Smart Water Supply System"

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Author(s):	Pedro Galvão & Adélio Silva
Contributor(s)	

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Executive Summary

Conventional water loss studies focus on the calculation of supply balances for water systems or their subsystems such as district meter zones (DMZ) or Leakage Detection Zones (LDZ). Over the last decade, the concepts and methods developed for system wide water balance calculations (IWA 2000 and AWWA 2003) have been based upon water assets' physical data and the statistics of pipe bursts, service connections and underground conditions.

Performance measures and indicators are used to support the managerial approaches to minimize different components of water losses. These concepts and methods have been adopted by countries around the world (Thornton, 2002; Lambert & McKenzie 2002; Lambert & Fantozzi 2005). More recently, Almandoz et al. (2005) and Walski (2006) developed an alternative approach for assessing leakage through network hydraulic simulation. Nevertheless, none of the previous methods consider how network models can be used to locate the water loss or leakage in a system. On the other hand, a means by which network models can be used to predict leakages quickly within DMZ is important as it assists a water utility to take the correct proactive measures to accurately minimize the leakage.

Water loss reduction targets are a key part of water utilities measured performances, with severe financial penalties being incurred if targets are not met. One of the goals of the implementation of SWSS is to provide a systematic approach that identifies likely leakage hotspots so that detection crews can identify leaky mains more quickly in turn leading to quicker repairs.

1 Leakage detection basics

Different definitions of leakage in distribution systems exist. The most frequently used one defines the leakage as (amount of) water which escapes from the pipe network by means other than through a controlled action. Water leakage is typically classified into background and burst related leakage. Bursts (i.e. main breaks) represent structural pipe failures and background leaks represent the water escaping through inadequate joints, cracks, etc. Leaks can also exist in service reservoirs and tanks (Puust et al, 2010).

Background leakage is the aggregation of losses from all the fittings on the network. Such leaks are typically too small to detect individually. Burst leakage occurs from holes or fractures in the network that can be located using a range of specialist equipment.

While major bursts and gushes on the surface may be reported to water companies by the public, it's vital to keep on top of other, less obvious leaks. While the most visible leaks may be losing water at a high rate, they are usually reported and rectified quickly. Lesser leaks may not result in such spectacular losses per hour, but they can run undetected for far longer and often lead to higher overall losses.

Although the size of a hole may often be tiny – in some cases no larger than a pin – the extent of water losses through leakage can be considerable, particularly where they go undetected for long periods of time. It is these types of losses, rather than the more easily identifiable, large-scale losses, that pose the biggest problem for water operators.

At this point, it is important to emphasise that leakage can never be eliminated. The sheer scale of water distribution networks and the inherent difficulties in accessing pipework, coupled with other factors such as supply pressures, age of pipework and soil characteristics, means zero leakage can never be achieved.

This point is illustrated by the fact that the UK's water distribution networks, even following considerable countrywide investment and modernisation, continue to exhibit an average leakage figure of around 15-25 percent, equating to some 3,300 megalitres of lost water per day.

Rather than striving to achieve zero leakage, therefore, the main concern of water operators should be to manage leakage as closely as possible.

1.1 What causes leakage?

Despite a raft of recent replacement and renewal works using modern plastic piping, much of the country's water mains are still made from iron or lead, with some dating back to the Victorian era. Coupled with this is the high number of joints, fittings, interconnections and relatively short pipe runs that characterise even the most modern water distribution networks, presenting multiple opportunities for leaks to occur. These factors, together with higher supply pressures, mean that some degree of leakage is inevitable. Generally, leaks can be attributed to four main causes, namely:

- Higher supply pressures – supply pressures that exceed the original parameters of installed pipework (particularly older pipework) can cause pipes and/or joints to rupture or burst
- Corrosion – rusting of pipes, fittings and joints steadily reduces their integrity, eventually resulting in failure. Causes of corrosion can arise from both within the pipe, such as acidic waters from upland areas, and outside of the pipe where the external pipe wall is attacked by elements in the soil. In both cases, the resulting corrosion can weaken the pipe wall, reducing its ability to withstand the supply pressure and leading to eventual failure.
- Erosion – this problem often occurs where a leak has already formed. Jets of water from the leak collect sand or stones from the installation environment which then hit the pipe, gradually weakening it and increasing the likelihood of a secondary leak
- Soil characteristics – changes in the soil characteristics at the point of installation can have a material impact on the pipeline. Changes in temperature and moisture can cause the soil to expand and contract, potentially causing the pipeline to bend. Movements in the soil can also

cause movement of the pipeline and its associated fittings, increasing the risk of damage and failure

Reducing the amount of water lost through leakage depends on both the distribution pressure and the amount of time taken to address a leak. Where losses stem from relatively small but steady leaks from a joint or fitting, such leaks can be especially hard to detect, particularly where the installation environment prevents water from rising to the surface.

1.2 Top-down approaches

The objective of top-down leakage assessment approaches is to estimate the leakage in a particular system by evaluating different components of the overall water balance, primarily the water consumed for different purposes. The two main approaches used are the IWA approach (Lambert and Hirner 2000) and the approach used by the OFWAT in the UK. Although quite similar, there are some differences between the two approaches due to slightly different terminology and definitions used for some water balance components (Puust et al, 2010).

Despite the simplicity of a top-down type leak assessment, the leakage estimate obtained via this method is referred to as a crude estimate. Gathering such information helps to decide what the next step in leakage studies should be for a particular network but it does not help to bound potential leak areas.

1.3 Bottom-up approaches

Bottom-up type leakage assessment can be considered the second part of the audit process. **This procedure is implemented when the company has confirmed the data used in the top-down portion**. It includes every area of the company's operation: billing records, distribution system, accounting principles etc. The audit's main purpose is to find out the efficiency of the water distribution system and the measures needed to achieve these. Bottom-up audits require the most accurate and up-to-date data possible.

1.4 Leak detection using SCADA data

The supervisory control and data acquisition (SCADA) system is an ideal platform for performing the advanced analysis that promptly identifies leakage presence.

Leak detection systems based on the data collected from field instruments typically apply one of these leak detection techniques:

- Balancing of pipeline input versus output. This leak detection technique relies on the simple fact that fluid mass flow into the pipeline equals the flow out in a leak-free pipeline. A difference between the input and the output suggests the presence of a leak.
- Hydraulic analysis. Measured values of flows and pressures are compared with simulated values of the same variables, calculated by verified hydraulic models. Significant discrepancies might signal the presence of leaks.
- Monitoring of signals generated by a leak. A burst will cause a sudden pressure drop which will create a pressure wave travelling at sonic velocity both upstream and downstream from the leak. The location of the leak can be calculated using the time difference in detection by the nearest sensors on either side of the leak location.
- Hydraulic parameters trending analysis. Flow (especially minimum night flow) and/or pressure trends can indicate a leak. Typically an increase in the flow and a decrease in the pressure, compared to average conditions, suggest new leaks have appeared.

Methods supporting techniques 1, 2, and 3 above are used primarily to detect and locate bursts in water transmission schemes where metering accuracy is usually high, operations are quite steady, and the presence of non-metered customers is negligible. However, the negative pressure wave technique presents some inconveniences: it only detects the initiation of a leak and not its presence after it has established. Further, false alarms can be triggered by pressure transients generated by noise producing installations such as pumps.

Methods associated with technique 4 above are typically applied to determine the presence of leaks within distribution networks, preferably at a district-metered-area (DMA) level, integrating data from the DMA inlet meter with the SCADA system.

In a typical water supply system, real losses might exist in the distribution networks and in transmission schemes. Therefore, it might be necessary to deploy more than one of the above mentioned leak detection techniques in order to achieve comprehensive leak detection.

1.4.1 Monitoring pressure transients

One of the commonly used the techniques for pipe burst detection is based on monitoring pressure transients in the distribution system, which occur after a sudden failure (rupture) of a pipe. By measuring pressure at different locations at a very high sampling rate (e.g. 2000 Hz) the propagation of the pressure transient in the network can be measured, and the burst location can be approximated. **The technique is only applicable for actual bursts**. Pipe failure which develops gradually will not induce a pressure transient and will therefore not be detected by this technique.

1.4.2 Monitoring flow or pressure and flow in a LDZ

When flow and pressure measurements are present they can be used for on-line monitoring. Stephen Mounce researched detection techniques and tested those techniques in a real water supply system in North Yorkshire, UK. In a practical application in a six month test period the system was able to detect 7 of 18 reported bursts (11 events missed), where the system generated a total of 46 alerts (39 were not related to actual bursts).

1.4.3 Real time modelling support

Integration of near real-time hydraulic data with hydraulic computer simulation models allows utility engineers to operate and control their large-scale, urban water distribution systems in real time. In conventional practice, hydraulic models are calibrated off line (USEPA, 2005), typically using a one-week sample of flow rate and pressure measurements within the network.

Thereafter, uncertain system parameters (e.g., water demands and pipe roughness) are adjusted until an acceptable match is achieved between the model outputs and physical observations. The main limitation of all off-line calibration procedures is that they approximate the unknown parameters using a short-term sample of hydraulic data. The calibration results may represent the system hydraulics during the short period of the sampling procedure, but they cannot be expected to accurately represent the system conditions for the full range of operational conditions that can occur. In principle, much more realistic predictions can be achieved by updating the hydraulic state estimation using continuous on-line hydraulic measurements provided by a sensor network installed within the distribution system.

Several studies have proposed methods for assimilating on-line measurements into hydraulic state estimation models. Davidson and Bouchart (2006) proposed proportional and target demand methods. These are two techniques for adjusting estimated demands in hydraulic models of water distribution networks to produce solutions that are consistent with available SCADA data. Shang et al (2006) presented a predictor–corrector method, implemented in an extended Kalman filter to estimate water demands within distribution systems in real time. A time-series autoregressive moving average model was used to predict water demands based on the estimated demands at previous steps; the forecasts were corrected using measured nodal water heads or pipe flow rates. Although these studies were not tested against real-world cases of complicated urban water systems monitored with on-line sensors, they provided a modeling framework and the mathematical tools to enable larger applications to be used for more complex systems.

1.5 Limitations of the leakage detection procedures

The efficiency of leakage detection/location depends on the quality and quantity of field data collected (pressure, flow rates, GIS information such as diameter, pipe roughness, etc) and mostly on the head losses (and consequently on the flow velocity) throughout the pipe network system.

The reliability on the leakage detection and location procedure depends highly on the flow changes during a day time. That means that for oversized systems, the detection of leakage points would be more difficult and the reliability offered by the algorithm would be lower. The searching method success is directly related to the total head loss that a leakage is causing along a water main. Therefore, a leakage will only be detected with a high degree of reliability if the water that is being lost is significant and if pressure loggers installed in the system are capable of registering the changes in pressure.

The probability to locate minor leakages tends to be very low with automatic methods. In these cases it is highly recommendable to complement the automatic leakage search method by means of acoustic methods, even though the success of these latter methods is very dependent on the pipe material.

As the leakage search method is not based on a deterministic method but on a heuristic method (evolutionary algorithm), it does not make any assumption about the objective function which only consists of minimizing the difference of the observed and calculated nodal hydraulic heads and pipe flows.

Under high flow velocity conditions (higher head losses), the water loss detection using the model might be affected by errors introduced into the model parameters such as pipe roughness for instance. That is why it is important to build a very good calibrated hydraulic model.

It is not easy to provide figures on the percentage of success or the efficiency of the leakage detection/location method, not even the authors of the algorithm are offering concrete figures about it since it is not an exact technique.

However the consultant experience shows that if data quality and quantity are good enough, the errors obtained in comparison with acoustic methods are much lower (measured as distance to the real leakage), provided the water leakage is originating a head loss several times greater than the error of the pressure meters.

2 SWSS leakage detection approaches

The methodology being used in SWSS to support leakage detection includes 3 basic procedures: mass balance analysis, flow and pressure data analysis and model simulations.

The leakage detection alarms will be activated when some abnormality is detected in the mass balance analysis (including night flows analysis), and/or in the pattern analysis and/or in the model/data pressure patterns analysis.

Regarding the mass balances it is common to observe not fully closed mass balances. This may mean that consumptions non-considered in the mass balance are taking place or that there still remains some minor issues of signals calibration in the SCADA system. In any case it is necessary to take this fact in consideration in the mass balance.

The proposed solution is to apply a data pattern analysis to the mass balance and to trigger an alarm when the mass balance residual deviates from the expected patterns. However, this method will only indicate if there is a possible leakage in the specified leakage detection zone (LDZ).

In the cases where the signals (e.g. pressure and flow) are not properly filtered by the SCADA system SWSS provides a set of automatic procedures to "clean" these data sets:

- Mapping gap periods: the absence of values within a period larger than a predefined time length (ex. 30 min) it is assumed to be a gap;
- Filter values below a minimum and a maximum values;
- Filter values that have a time variation larger than a threshold. The main goal of this is to filter spikes;
- Filter consecutive values that have exactly the same value. It is common to observe periods where consecutive values with exactly the same value are recorded;

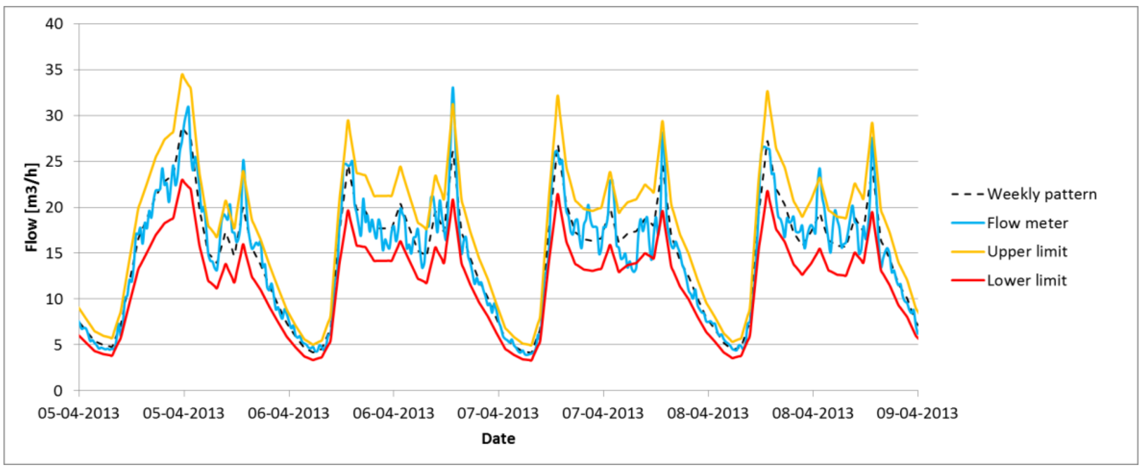
- Filter noisy periods. In this case a time window is specified, for example a day. In this case for each day is compute the standard deviation and the average. If the ratio standard deviation: if average is above a specify threshold the period is considered "noisy" and the values of the entire period are filter out.

2.1 Patterns estimation

For the patterns estimation the user only needs to specify the type of pattern to compute: daily pattern or weekly patterns or weekend / week day pattern. The methodology used computes for each hour of the pattern cycle chosen the median (or percentile 50) of the entire signal data after being filter.

The computed patterns can be uploaded to SWSS to configure alarms that are triggered when a specific signal (flow, pressure or mass balance) is outside of specified limits in persistent way. The limits are defined by the user. The figure below shows a case where the flow (blue line) is compare with the follow limits:

- Upper limit (orange line) = pattern + 20%
- Pattern (black dot line)
- Lower limit (red line)= pattern – 20%

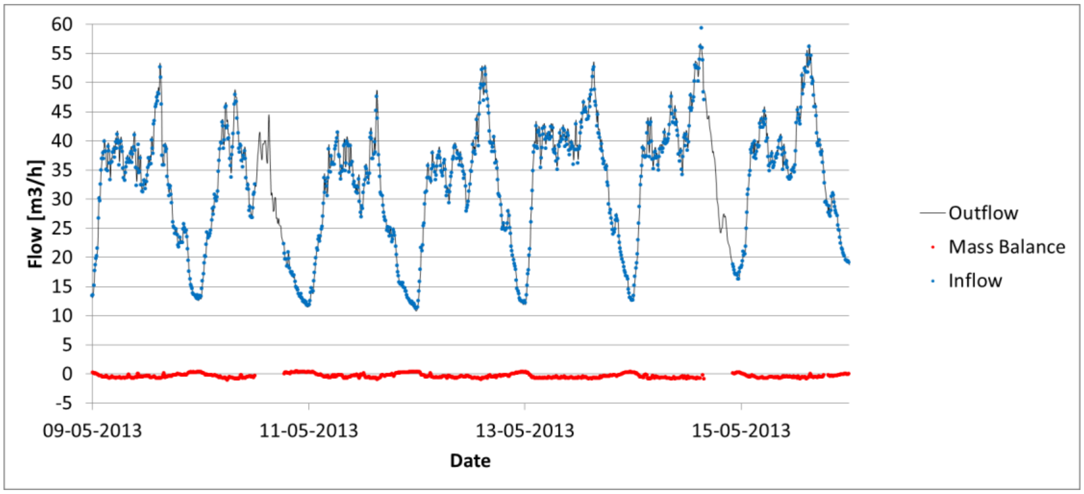


This kind of approach implies that, at least, the "noise" introduced by the leak be more relevant that the uncertainty associated to the sensor itself. It is necessary to take in consideration that no matter the analysis is made its accuracy depends of the quantity and quality of the data available. For instance with short length records it is not possible to identify seasonal patterns and we may be using a "wrong" pattern in a specific month case we don't have enough information to know that the consumptions in that specific month are different from the previous one.

2.2 Mass balance

A mass balance tool is running for each Leakage Detection Zone (LDZ). For each LDZ the inflows and the outflows time series are mapped. The mass balance is computed only for the instants where are valid values available in all inflow and outflows time series. For instants that are inside a time series gap the mass balance in not compute and this is instant is considered to belong to the mass balance time series gaps.

In the figure below it is presented the mass balance computed along one week for one LDZ. In the figure the black line represents the LDZ outflow, the blue dots represent the LDZ inflow and the red dots the mass balance.



The above described approaches, when used together, have the capability to map the probability of a leak on an area controlled by a pressure meter but they are not able to precisely pinpoint the leak location.

The combined use of the model results may help to get a more precise location of the leak. In this procedure the calibrated model is keep running in short periods intervals (let's say 30 minutes) and the model results are continuously being compared with the measured data. In case of a relevant modification of the usual level of agreement between the model and the data pressure values an alarm is triggered pointing which sensor is closer of the location of the identified anomaly. This implies a fully and trusty calibrated model.

In the case of the existence of some advanced leakage detection algorithm, such as the one included in the Bentley Darwin Calibrator, it may be possible (depending of the network characteristics, the accuracy of the available data and the leakage dimension) to get a close location. This tool consists of an automatic calibration and leak detection system for water distribution networks. It allows the speeding up of the lengthy calibration process and detection through automatic simulation of millions of solutions, as well as identifying those that adjust to their field data.

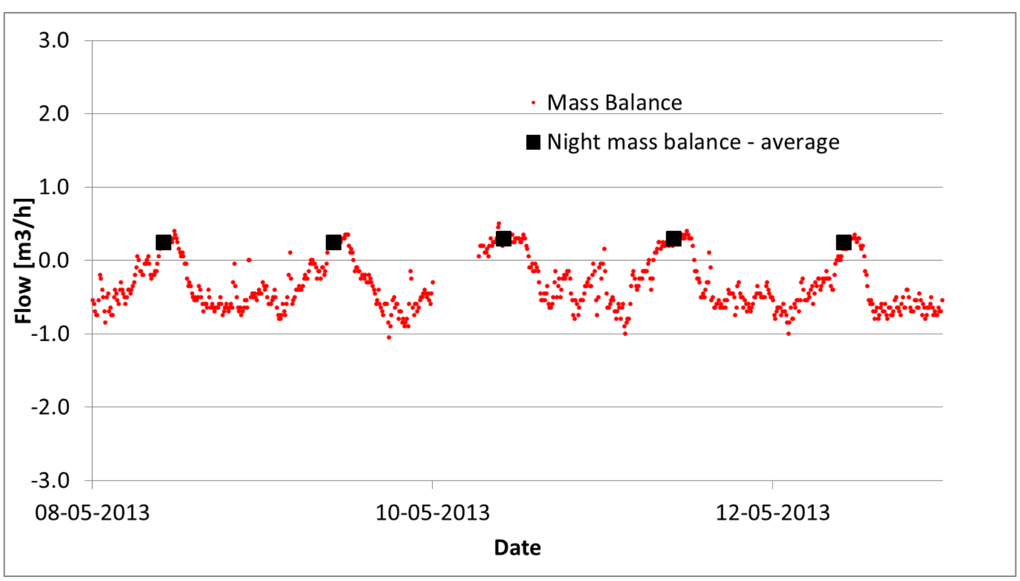
Leak detection functionality allows the minimisation of the effort associated with field work to identify points with more probability, allowing work teams to concentrate on limited areas on the field.

One of the strong aspects of this technology is to allow the user, in an easy and efficient way, to identify the network sectors with the greatest leak probability. The process is based on the dynamic module, real information (pressure and flow) in some points of the network and a genetic optimisation algorithm which automatically develops the leak search process. This technology is already quite consolidated, having been applied in several complex real cases with success, confirming their robustness in face of several types of situations (http://www.bentley.com/en-US/Promo/New+Oil/)

2.3 Night flows analysis

Flow and pressure values in water distribution networks tend to be highly variable. This variability is mainly due to water consumption variability in time. Additionally there is also some high frequency variability associated with the level of accuracy of the sensor itself. In the night period the signals time variability tends to be lower and becomes easier to detect persistent anomalies like leaks. SWSS for every signal time series is able to compute the average value for the night period.

For example in the case of the mass balance of a LDZ the final result tend to have a pattern type evolution like the one present in the figure below (red dots) due to sensors errors or uncontrolled inflow/outflows. In this case the SWSS user has two ways of configure a mass balance alarm: one way (mentioned above) is to configure the alarm considering the deviations in relation a defined pattern; an alternative way is to configure an alarm for the average value of the mass balance for the night period. This mass balance parameter tends to have a constant value in time and a more simple alarm can be configured (see figure below black dots). In this case the alarm threshold can be considered constant.

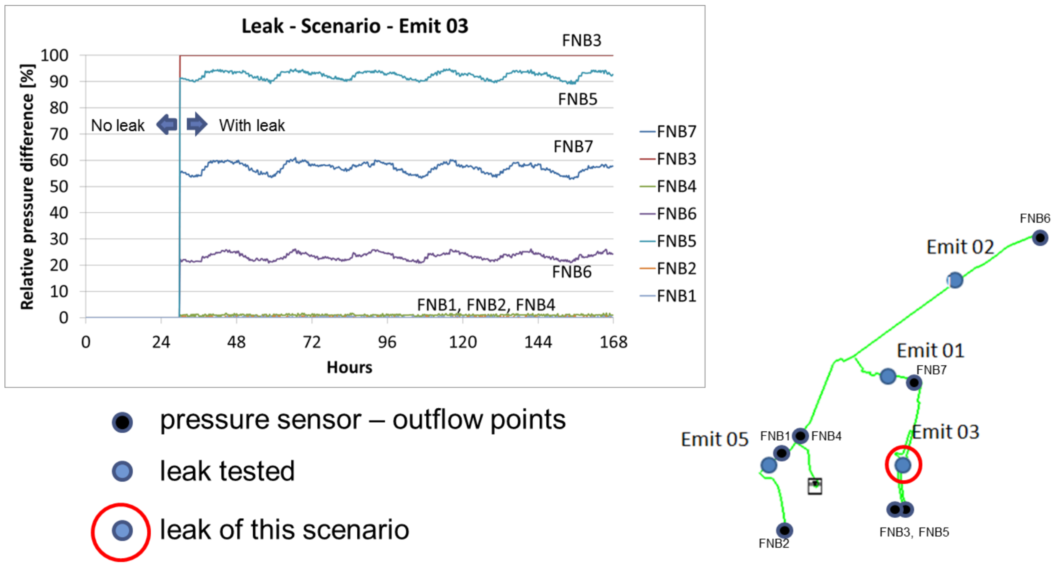


2.4 Model results analysis

SWSS can complement the sensors analysis with model results forced with real time data run in operational way. The main boundary condition of the water distribution model is the LDZ's outflows. In the case of a leak the model forced with real time data give an "approximate image" of the water distribution network with no leaks. A way of detecting the area of the leak in the LDZ is comparing the model pressure results with the sensors pressure data. This is quite effective in LDZ's where the pressure gradient is strong.

To help SWSS operator to identify more easily the areas where model results diverge more from the measure data the pressure differences are normalized. For each LDZ the difference between the measured and model results is computed in all pressure sensors. This parameter is normalized using the minimum and maximum differences occurring in the LDZ. The final parameter is a percentage where 100% corresponds to higher pressure difference occurring in an instant and 0% the minimum.

The figure below exemplifies the method for a virtual case to simulate a leak in point Emit 03 and compare these results with a situation without a leak. Both model solutions where compared and the parameter described above was compute in 7 points (FNB1 to FNB7 – LDZ outflow points). The figures shows the bigger pressure differences are located in the monitoring points downstream of the leak as expected from the hydraulic point of view.



2.5 Critical segment analysis and operation modelling

Besides the evaluation of the occurrence of a leak in the network, SWSS leakage detection system may include complementary analysis tools that may help to maintain a continuous awareness of the more critical areas. Some hydraulic models include analysis tools that allow the identification of crucial elements in the water distribution infrastructure and the evaluation of the associated failure risk. These analysis tools include the consideration of the network pressure distribution (higher pressure areas have more probability of failure), the age and material of the pipes and the history of leaks in each area.

This information may also be used to adopt improved operational controls based on rules, variable velocity (VSP) pumping and the dependent pressure consumption (PDD), that minimise energy consumption and improve system performance.

2.6 Overall LDS analysis

The above referred approaches are integrated in an easy to use graphical client where the probability of a leakage is displayed for each LDZ as a function of the previous analysis. Although the definition of the alarms may be set up by the user, presently the default approach is:

- Mass balance: once a mass balance anomaly is detected (either in the instant flows or in the night flows) an alarm is activated indicating that in that specific LDZ there is a probability of a leak.
- Signal analysis and model results analysis: the second step is to try to pinpoint as close as possible the origin of the anomaly. In order to do that it is performed an evaluation of the major differences between the observed pressure values and the computed pressure values in each network monitoring point. Those with higher differences are the ones that have a higher probability to be closer of the anomaly. Note that this kind of analysis only leads to good results in the cases where the pressure gradients exist.
- Use of critical segment analysis: in the cases where the previous method is not useful because of the existence of negligible pressure gradients the crossing of information about the mapping of critical segments with the areas where there was detected a possible anomaly may be used to start to look first for the leak in the most critical areas.

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