Management of NRW at Canal de Isabel II - A Case Study

Abstract

Reducing Non-revenue water (NRW) is a complex issue that requires many coordinated actions. When NRW values are high, and investment and technology are readily available, it is relatively easy to tackle this issue and see immediate results. That said, where technological resource is scant, it becomes harder to determine the best course of action. For this reason, it is imperative that the effectiveness of every action is assessed in order to optimise the best resource, with the aim of reducing NRW further.

Canal de Isabel II SA MP (thereafter, Canal de Isabel II) is a public company that manages the entire water cycle in the Madrid region, serving more than 6.5 million people boasting a distribution network of some 17,800km long. Over the last decade, Canal de Isabel II has been reducing its NRW by applying an integrated approach that deals with every component of NRW at DMA level, which has led to a reduction of 30% during the above period. To achieve this goal, a comprehensive set of performance indicators were required in order to determine actions to be taken at DMA level as well as assessing their performance. Such action, provides for a cycle of continuous improvement.

This paper sets out to showcase this set of indicators and how they have been instrumental in bringing about tangible results.

1. Introduction

Minimising NRW is a fundamental objective that every water distribution company should strive for. Firstly, a precise understanding of what NRW is, its components, and calculating the company's water flow balance is essential (AEAS, 2014). This is an inevitable starting point for establishing a successful strategy (Liemberger et al, 2004; Farley et al, 2005). Secondly, relying on a suitable set of performance indicators, as standardised as possible, and whose calculation is rooted in the company's procedures, constitutes the second fundamental step to address (Alegre et al, 2000).

Once the strategy is established, it must have the strong support of the senior management of the company and the necessary resources for its development. It is important to note that while short-term results are achievable, reducing NRW is a very lengthy, in fact, never-ending endeavour, and therefore, this support must also be sustained over time.

While the approach to addressing the issue, in general terms, has not changed significantly over the past few decades, there have been highly relevant technological advancements that greatly facilitate goal achievement. Among others, the deployment of IoT networks, smart meters, and artificial intelligence are making substantial strides in achieving NRW reductions within much shorter timeframes. However, it should be noted that, as these advancements are not yet accessible to all budgets and all companies, there are ways to improve this issue without resorting to the latest technological breakthroughs, although undoubtedly, the outcomes may be somewhat less impactful.

Canal de Isabel II, S.A. MP (thereafter, Canal de Isabel II) is a public company that manages the entire water cycle for the region of Madrid in Spain. It provides drinking water, wastewater and reclaimed water services to more than 6.7 million people in the above region. It currently manages a drinking water network more than 17,800 km long, split into some 600 DMAs.

Reducing NRW has been one of the company’s top priority for a very long time. Madrid is located in a semi-arid region and, as a consequence, reducing losses is not just an economic or environmetal issue, but a question of its very survival. Predictably, it has always played a major role in the framework both of the past and the current strategic plan.

One of the key factors related to the way that Canal de Isabel II is tackling this problem is its twofold approach. When dealing with such a large network, it seems that the only feasible strategy consists of splitting it into smaller portions (DMAs) and handle them separately. Nevertheless, Canal has managed to design and implement a course of action that combines both the local and the global level.

1.1. *Global level.*

Tackling the issue of real loss calls for a long-term initiative. Based upon a risk-appraisal approach, the condition of every pipe is assessed using historical data and is assigned a probability of failure. Subsequently, a risk index is compiled by aggregating both failure probability and damage values. Damage value equates to the number of property-hours where supply is interrupted as a consequence of a hypothetical burst. Roughly a 1% percent of pipes are replaced every year, following a risk appraisal to prioritise maintenance. It is envisaged that this percentage will reach 2% by 2023 and will be sustained for at least five more years.

1.2. *Local level.*

Notwithstanding the above approach, such a large network requires breaking down into manageable chunks by adopting the usual DMA-approach. For each DMA, a comprehensive set of performance indicators is assigned. Moreover, each individual component that makes up NRW can be estimated respectively. It is precisely this detailed analysis which enables Canal to execute targeted action plans that are subsequently assessed accordingly.

2. Methods

Our particular approach is taken from the Deming's cycle; a paradigm of implementing a continuous-improvement quality system. Once a NWR breakdown is completed and each DMA is assigned a set of KPI values, the dominant component is selected for action. Only one component is dealt with at a time, affectionately known as the "onion principle". From the moment an action is conceived and subsequently rolled out, its performance is scrutinised, thus generating a new cycle. This action concludes when the DMA reaches a NWR-level that cannot be improved upon using reasonable resources. As a result, the DMA moves to a "monitoring status", in which only night flows are observed in order to detect leakage.

2.1. *NRW breakdown.*

NRW is primarily made up of *four components* (see Figure 1)*:*

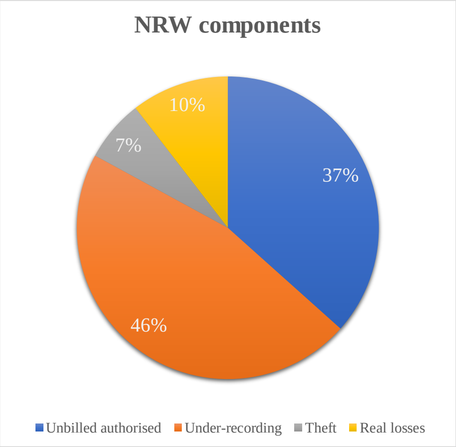

Figure 1. Components of NRW at Canal de Isabel II as of March 2023

- **Unbilled authorised consumption.** It can have various sources. In the case of Canal de Isabel II, the most relevant ones are four: firstly, the consumption by public entities which, due to historical reasons, were not recorded or billed, and are pending legalisation; secondly, the water used to flush the distribution network whenever necessary; thirdly, the water supplied to a large settlement, *Cañada Real*, which is measured but not billed; and finally, the water consumed in internal processes. The current estimate is 37% of NRW volume.
- **Meter under-recording**. Water meters are known to systematically underestimate water consumption. The company has carried out exhaustive studies into this irregularity (Guzmán et al, 2010), which estimates meter inaccuracy at around 46% of total NRW.
- **Theft.** Although this component has a somewhat lower impact, it must however not be overlooked: 7% of NRW is currently attributed to theft.
- **Leakage.** DMAs were initially conceived as a way of tackling leakage. Over the last decade, Canal has managed to reduce this amount to a third of its original value; currently, this noteworthy figure sits below 2 litres per meter per day. Leakage accounts for 10% of total NRW.

2.1.1. Estimation of NRW components

Given that the method is based upon choosing the dominant NRW component, being able to estimate it accurately is of vital importance. The basic principles upon which Canal de Isabel II is carrying this out are as follows.

2.1.2. Unbilled authorised consumption

In this component, two highly distinct parts can be identified: what is measured and what is not measured. Obviously, what is measured does not require estimation. In the case of Canal de Isabel II, this corresponds to the majority of uses in internal processes and the supply to Cañada Real. As for what is not measured, the methodology is specific for each of the cases. Regarding network flushes, all of them are recorded as work orders in the network maintenance information system. By using the duration of the flush, the diameter of the drain, the percentage of opening, and an estimation of the pressure at that point, the volume used in these operations can be easily determined.

As for the usage by public entities without contracts, which is the major component, virtually all of it corresponds to garden irrigation. To estimate this volume, the cadastral data about public gardens and the distribution network are combined in the geographic information system to determine which of them do not have a connection, what their area is, and the nature of the vegetation. Based upon this information, along with the weather during the calculation period, it is possible to estimate how much water has been consumed for the irrigation of these gardens.

2.1.3. Under-recording.

Through granular-detail monitoring of a representative sample of customers, Canal de Isabel II has been able to harness updated, accurate flow histogram for a wide demographic. This process is on-going. In addition, the installed meters are also sampled and tested in our laboratory, and according to their technology and age, error curves can be mapped for every meter type. The aforementioned data and the meters currently being used by Canal (1.6 million) provide a good estimate of under-recording.

2.1.4. Theft.

This component is particularly tricky to estimate. A representative sample of DMAs were rigorously checked for theft a few years ago. The results were subsequently extrapolated and a global figure of 0.8% of total supply was established as the unavoidable average theft rate. This figure is added to the actual volume of the water actually recovered in detected fraud.

2.1.5. Real losses.

Real losses are calculated as the difference between total NRW and the sum of the three above components. Consequently, this formula is overly reliant on the accuracy of the other estimates and, as such, it is affected by the uncertainty of the other components, resulting in it being the least accurate of them all. As a consequence, determining whether leakage is the most important component of NRW in a DMA is usually based on minimum night flow. In order to establish the night flow baseline in a DMA, it is first of all thoroughly scoured for leaks. As soon as it is ascertained that a DMA is as leakage-free as state-of-the-art technology can provide, the resulting night flow is set as the target to be met consistently.

This method is complemented by calculating the theoretical minimum night flow by means of adding a fixed night demand value for each customer, according to type. Should these two methods differ significantly, a thorough inspection is carried out in order to account for the disparity. There are usually two likely outcomes: an error in DMA data (either customer number or type, or in flow accuracy); secondly, there are customers who consume a huge amount of water during the night, such as industries and hospitals. In either case, a purposeful baseline is set.

Even though this method looks relatively straightforward, things are somewhat trickier in Madrid. Given that demand in Madrid is mainly seasonal, night flows in summer, in a leak-free DMA, can be many times higher in summer than winter, owing to the fact that many gardens, both private and public, are irrigated at night during spring and summer (see Figure 2). Therefore, the baseline must always be set during the winter. This poses a significant problem, given that it can lead to leaks going undetected during hot spells. AI-based methods have proven useful in tackling this problem, though it has been nigh on impossible to scale them up due to a lack of historical data in many DMAs, particularly where the number of bursts and leaks is very low. This issue will be resolved when the current deployment of smart meters concludes. When customer consumption data is available, not only will there be a baseline night, fundamental in the analysis of NRW, but also, it will provide accurate measurement of real leakage for each DMA (see Figure 10).

Figure 2. Sample of a DMA with highly seasonal night flow.

2.2. *Tackling NRW*

2.2.1. Unbilled consumption

The causes for the existence of unbilled consumption are highly specific to each water utility, making it difficult to provide general guidelines for dealing with this issue. Therefore, in this section, only the methods employed by Canal de Isabel II will be presented. In general, if consumptions are metered, it is easier to reduce them as the amount, timing, location, and user responsible for consuming the water are known. Additionally, these consumptions are usually hard to eliminate without modifying the regulations that support them. That is the reason why another significant PI is Unaccounted-for Water (UfW), which is NRW minus unbilled metered consumption. Therefore, the focus must be on unmetered consumptions, in our particular case, those related to park irrigation.

At Canal de Isabel II, the issue is addressed in the following manner: first, DMAs with a seasonal pattern of NRW are selected, where NRW is significantly higher in summer than in winter, and there are public gardens without connections within them. In collaboration with the respective city council, the water supply to these green areas is investigated on-site. Once unmetered connections are identified, contracts are formalised, including the installation of corresponding meters. The effectiveness of the measures taken is verified as detailed later on in this paper.

2.2.2. Under-recording

Dealing with under-recording basically comes down to replacing those customers meters which are significantly underperforming. Broadly speaking, it can be as simple as choosing the oldest ones for replacement. Even though that might look like a good strategy, it may prove not to be so, due to a couple of strong reasons. Firstly, given that we are trying to reduce NRW, some criteria about meter size and the amount they should be metering ought to lead to a higher reduction in NRW volume with the minimum number of meter replacements. Secondly, replacement operations can be very expensive and slow in an area as large as Canal de Isabel II's. As a result, carrying out a selection of candidates that are concentrated in smaller areas must lead to a quicker and cheaper performance than using meter age as the only driver.

That said, having the network split into DMAs turns out to be extremely helpful when talking this issue. As it turns out, using solely three performance indicators at a DMA level leads to outstanding results:

1. NRW percentage at DMA level. Even though NRW should not be measured in terms of percentage, it is the simplest to calculate and it turns out to be good enough for this purpose. As a rule of thumb, DMAs whose NRW is 50% over global average should be addressed. In our case, given that average NRW is currently 15,7%, only DMAs over 23,2% should be explored.
2. Having a high NRW level is not enough, given that it can have many root causes. It must be taken into account that under-recording is usually higher at smaller flowrates. Therefore, DMAs with higher NRW when demand is smaller are the ideal candidates for meter replacing. He typical shape of monthly NRW in a good candidate is one with higher percentages in winter, such as the one shown in Figure 3. As a rule of thumb, we would replace meters in those DMAs that meet the criteria exposed in the previous paragraph, and whose winter/summer NRW percentage ratio is over 10%. For this purpose, winter spans from October to March, and summer from April to September.

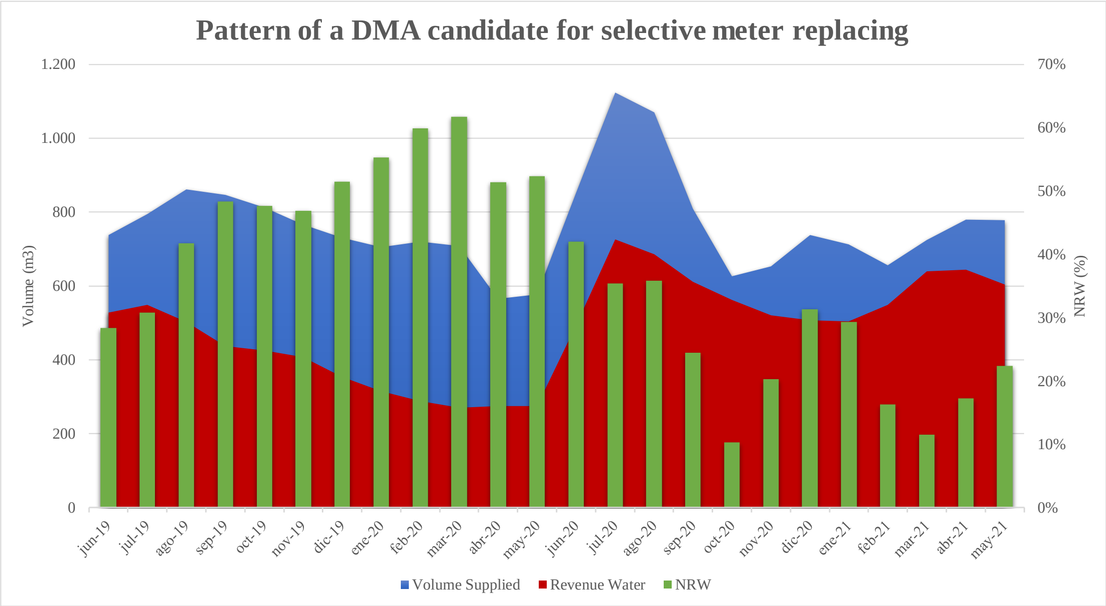

Figure 3. NRW pattern of a DMA candidate for meter replacing. In this case, replacement took place in summer 2020, resulting in a reduction of NRW to a half its previous value.

3. Unless there has been some quality-control issue, only very old meters should be replaced. Therefore, a third performance indicator, related to meter age, should be used. Canal de Isabel II has determined that meters newer than 14 years old should not be replaced, unless there is some other reason to do so. Therefore, only DMAs with a significant number of meters over that age (let us say, more than 20%) are selected for meter replacement.

Having chosen the most appropriate DMAs using the above procedures, meters over 14 years of age are targeted for replacement, starting with DMAs with the higher winter/summer NRW ratio.

This procedure has been used over several years in Canal de Isabel II. However, a new law which states that there should be no meters over 12 years of age came into effect in 2020 in Spain. Combined with our smart metering programme, the above procedure turned out to be useless in 2021. Nevertheless, it led to very good results over the previous years. That is the reason why it is exposed in this paper, given that it can be used elsewhere, provided that law does not set any maximum age for meters.

2.2.3. Theft

Theft can be addressed in multiple ways, most of which can be highly dependent on the particularities and customs of the region. First of all, it must be noted that those who steal water, and who are worth looking for, are large users, mainly business which use large amounts of water in their core processes or large properties with a swimming pool or a large garden. There are, of course, small thefts that can be also detected. Nevertheless, unless there is a large concentration of them in a particular area, it is better to focus on the former before trying to deal with the latter.

Searching for water robbers is worth a twofold approach:

- Firstly, build a catalogue of businesses which should be using large amounts of water, classifying them into different categories, such as:
    - Large sporting facilities, especially those with a swimming pool.
    - Car wash facilities
    - Laundries, particularly the largest
    - Theme parks
    - Large shopping centres
    - Cemeteries

Such a catalogue can be built by using most of the map applications available on the Internet.

The same procedure can be applied to parks and public recreational areas. Even though it might not be thought as water theft, it is worth mentioning that public facilities, such as city council or governmental buildings, or ornamental fountains may not have a recorded service connection with a meter and a contract. Due to historical reasons, it may happen that having these contracts and paying for water may have not been compulsory in the past and many could continue to use water non-metered. Nevertheless, it is a potential source of loss, given that there might be substantial internal losses in those customers' networks, that go unseen for the lack of a meter, not to mention the loss of revenue that it represents (see 2.2.1).

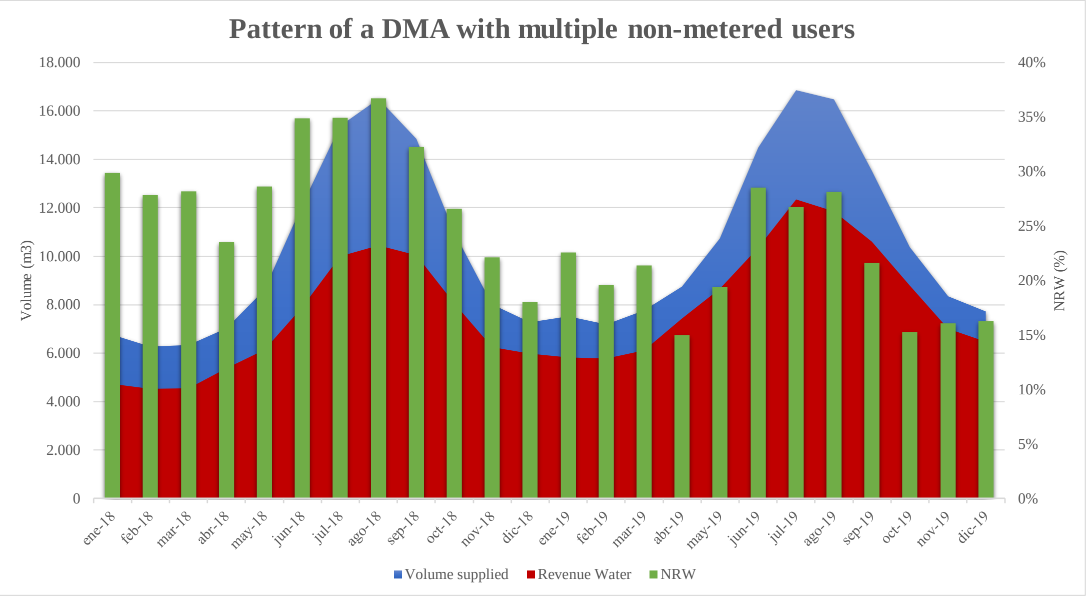

Figure 4. Pattern of a DMA with multiple non-metered users. Note the significant reduction of NRW after several users having been located and metered over winter 2019

Once the catalogue has been built, the subsequent step would be to check, firstly, whether there is any service connection servicing each business; and, secondly, should there be any, if the consumption matches the business activity. Customer Information Systems that have a strong integration with Geographic Information Systems (GIS) are an invaluable help when dealing with this task.

- Secondly, the problem can be dealt with at DMA level. Similarly, as it happened with the under-recording case, there are patterns in NRW over time that identify quite unequivocally a significant amount of fraud. Three of them are worth being described:
    - A high NRW flat level all over the year, after having pinpointed and repaired all detectable leaks.
    - A seasonal NRW peak in summer.
    - An odd NRW peak in one or several periods throughout the year that cannot be explained by bursts.

The second one is the most usual in locations where, like Canal de Isabel II's, demand is highly seasonal, with a significant peak in summer. Examples of these patterns are shown in Figure 4.

Once a DMA with such sort of pattern has been spotted, the same procedure described in the previous paragraph can be applied. The advantage of doing so at DMA level is the size of the area being explored. It must not be forgotten that non-metered users and robbers will show the same pattern in the NRW chart. As a rule of thumb, non-metered parks, ornamental fountains, and public buildings should be ruled out before starting to look for theft.

Theft is not just a commercial or apparent loss. Those who do not pay for water are prone to doing an inefficient usage of it, both through the amount of water they consume and through the losses due to the lack of maintenance of their internal networks. The same happens to any non-metered user. As a consequence, an effective demand management policy should take into account the two following principles:

1. All users must be metered and billed according to their consumption.
2. Theft must be pursued and strongly discouraged through appropriate law enforcement.

2.2.4. Leakage

Undoubtedly, leakage is the most important component of NRW. First and foremost, due to the fact that it is a real loss of water, that has been abstracted, treated, possibly pumped, and conveyed, but used by no one, whereas the other components -especially under-recording- have an effect mainly on revenue. And last, but not least, due to the impossibility of getting rid of it completely. Consequently, it will take the higher amount of resources both to reduce it and to keep it at the lowest possible level over time.

Multiple approaches exist for tackling leakage control (European Commission, 2015, Hamilton et al, 2020) with many of them not mutually exclusive. Nevertheless, a one-size-fits-all strategy remains elusive. Various factors, including financial standing, distribution network design, and pressure dynamics, wield substantial influence over policy selection.

To begin, the equilibrium between capital investment and operational expenses demands careful consideration. Given that newly implemented networks are essentially leak-free and enjoy extended lifespans, courtesy of advancements in materials and construction techniques, pipe replacement emerges as the optimal avenue, provided the company possesses the financial capacity to cover the requisite capital outlay (Skaar, 2023). This approach is exemplified by Canal de Isabel II, which has been renewing approximately 1% of its networks annually for the past decade, with plans to elevate this rate to 2% per annum over the forthcoming five-year period. The palpable impact of this strategy materialises in quantifiable terms, manifesting as a decline in burst incidents and a reduction in tangible loss levels, as expounded upon in chapter 3.

Figure 5. Map coloured by replacement risk index

Once this path is chosen, the subsequent question that necessitates an answer pertains to the identification of pipes meriting replacement. A customary and astute methodology for this entails calculating a risk index for each pipe and subsequently targeting those with the highest indices. Presently, the market boasts an array of tools that facilitate this risk assessment, underpinned by either statistical or artificial intelligence methodologies. Canal de Isabel II boasts its proprietary in-house tool, an outcome of its two-decade employment of this technique, which stands as a pioneering solution in the market (see Figure 5).

The process of selecting pipes for replacement can be further enriched by undertaking condition assessment campaigns. A range of technologies is available in the market to ascertain a pipe's state, indicating whether prompt replacement is imperative. Employing this approach on the pipes earmarked for replacement prior to commencement of work can potentially augment the overall efficiency of the undertaking.

A secondary consideration necessitates the determination of whether to partition the network into distinct metering areas (DMAs) or not. In essence, this involves dividing the water distribution network into smaller segments, each with measurable input and output flows. This approach effectively mitigates the challenge of leak detection by dealing with a more manageable network. The adoption of DMAs has emerged as one of the most effective strategies for addressing the issue of leakage. However, it is worth noting that not all water utilities are opting for this solution.

To begin with, implementing DMAs requires certain prerequisites that may not be feasible for every company: a precise Geographic Information System (GIS) encompassing all pipes, valves, and service connections; seamless integration of a Customer Information System (CIS) with the GIS to enable linkage of water bills to specific service connections on the GIS; a Supervisory Control and Acquisition System (SCADA) for the acquisition and storage of flow measurements, also integrated with the GIS; and, finally, an hydraulic model derived from the aforementioned systems for conducting calculations essential to the establishment and maintenance of the DMAs. Some additional software might be helpful in order to attain this target (Di Nardo et al, 2020)

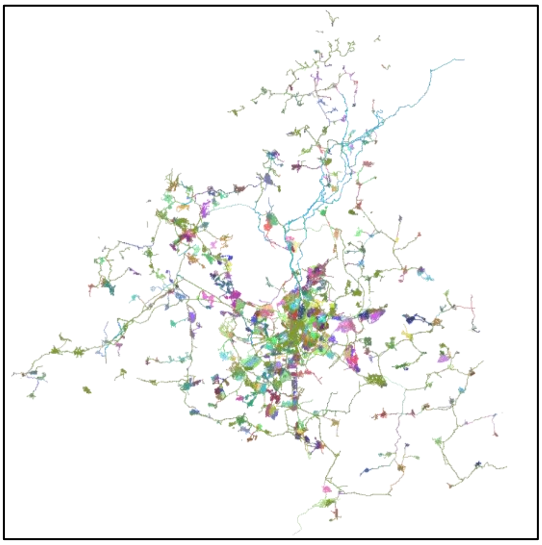

Figure 6. Canal de Isabel II's DMAs map

Moreover, once the DMAs are established, data processing becomes imperative, entailing the computation of various performance indicators to evaluate and identify leakage. Furthermore, the network's design could potentially pose an overwhelming impediment, stemming from concerns related to quality, pressure, or the substantial number of sensors or infrastructure works required to prevent such issues.

As demonstrated in the preceding sections, the utilization of DMAs yields significant benefits, extending beyond NRW reduction and encompassing the effective management of leakage. In the latter context, the conventional approach stems from the premise that the minimum night flow (MNF), calculated as the average flow between 3 and 5 am, serves as an upper limit for leakage within the DMA. The overarching procedure unfolds as follows:

1. Employing some leakage detection methodology – which will be expounded upon in subsequent discussions – leaks are identified and repaired across the DMA.
2. Alternatively, or concurrently, a theoretical MNF can be computed by incorporating an estimation of night-time consumption for each customer within the DMA.
3. As a result of one or both of the aforementioned steps, a baseline MNF is established for the DMA. This foundational flow can be subject to monitoring, and any unjustified increase – whether sudden or gradual – prompts the inference of a leak's presence and its approximate magnitude (see Figure 7).

The emergence of smart meters represents a significant advancement concerning this issue, as it enables the calculation of flow balance for each DMA, typically on an hourly basis. In this scenario, the disparity between the incoming flow and the measurements recorded by customers' meters not only serves as an upper bound for leakage level but also offers an estimation of the actual leakage magnitude, provided that the presence of fraud or unmeasured consumption has been ruled out, as elaborated in preceding paragraphs.

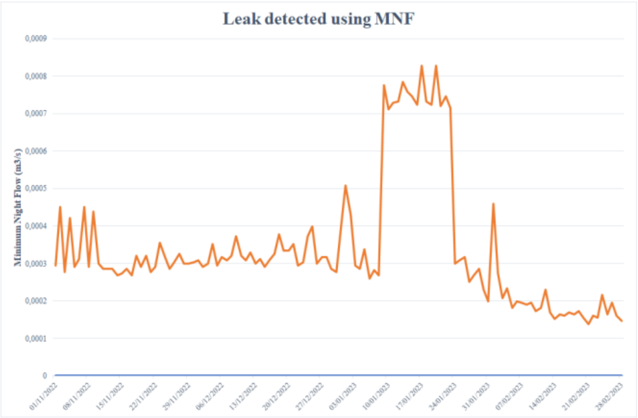

Figure 7. Leak detection using minimum night flow in a DMA.

Once the existence of a leak is ascertained, the subsequent course of action involves precise localisation and subsequent repair. The forthcoming sections will delve into the various techniques at hand for accomplishing this.

In the event that DMAs are excluded for any reason, alternative approaches to leakage detection remain viable. Generally, a combination of the detection techniques outlined below can be tailored to align with the specific requirements of the company. As a guiding principle, the subsequent procedure can be adopted:

1. Establish a network of permanent sensors, typically noise loggers, strategically positioned in areas with an elevated likelihood of leaks, and where replacement is not currently under consideration.
2. Conduct periodic surveys across the remaining network. The frequency of these surveys can be fine-tuned based on the anticipated condition of pipes. This can involve prioritizing those segments with a higher probability of failure or subjecting them to more frequent inspections than the rest. Ultimately, these frequencies can be adjusted based on the outcomes in terms of the quantity and scale of detected leaks.

In the realm of leak pinpointing technologies, a roster of the most prevalent options unfolds. To commence, a clear demarcation must be made among trunk mains, distribution pipes, and service reservoirs. Focusing on trunk mains, three distinct technological avenues come to the fore:

1. Technologies predicated on the insertion of specialized devices within the pipe, capturing various physical parameters – typically encompassing noise, and occasionally encompassing electrical measurements or video imagery. Through post-processing of the recorded data, these methodologies can pinpoint the leaks' locations and magnitudes, occasionally even furnishing insights into the pipe's condition.
2. Approaches founded on stationary noise-logging devices, predominantly hydrophones for trunk mains. The noise data collected by these devices is commonly transmitted via mobile networks to a cloud infrastructure, where meticulous calculations are undertaken to accurately deduce leak locations and sizes.
3. Innovations rooted in fibre-optics. By analysing the behaviour of unique signals conveyed through fibre-optic cables – either within the pipe itself or positioned above its surface – precise determinations regarding leak existence, location, and magnitude can be meticulously gauged.

Solutions two and three are fixtures within the network and typically entail higher costs compared to the first solution, particularly the fibre-optics variant. Consequently, the conventional approach involves deploying the fixed technologies for particularly critical pipelines, while the first solution can be employed in other locales, either periodically or whenever a suspicion of leakage arises.

Several firms are endeavouring to pioneer drone-based solutions. Nonetheless, none among them has thus far presented an alternative superior to the aforementioned ones.

Regarding distribution networks, the most common techniques are as follows:

1. The utilization of geophones by specialised personnel to approximate the location of a leak. While this technique is becoming outdated, it remains a viable choice in areas where access to more modern technologies is challenging.

2. The implementation of noise sensors. Typically, this involves deploying noise sensors in direct contact with pipelines, often magnetically attached to valves. During night-time hours when ambient noise is minimal, these sensors record transmitted noise from the conduits. Data files can be downloaded either by connecting to a computer or via the mobile network. By employing various data analysis technologies, in conjunction with network maps provided by the GIS, leaks can be approximated with varying degrees of accuracy in terms of their existence and location. Generally, this technology necessitates a sensor approximately every 200 meters of network. Temporary deployments, spanning one or two nights, can be conducted within a DMA where leaks have been identified, or alternatively, networks of these fixed sensors can be established, linked to the cloud through the mobile network. In general, the deployment of fixed networks is practical only when the number of leaks is high, in locations where replacement has been ruled out, or at points of exceptionally high criticality where the swift identification of concealed leaks is imperative before they escalate into visible ruptures.

   Frequently, the information provided by both geophones and noise sensors falls short of pinpointing the exact location of a leak. To address this, they are complemented by the use of noise correlators, which can determine the location with precision down to pressures below one meter.

   Systems based on noise sensors significantly lose effectiveness when the pipelines are metallic, particularly in the case of asbestos-cement or PVC pipes, which transmit noise less effectively.

   With the advent of smart meters, there are companies beginning to integrate noise sensors within them, effectively serving the purpose of the aforementioned fixed networks. This facilitates the deployment of these networks, as it introduces only a modest cost to the meter. Given the typically high density of connected meters within the network, they also naturally incorporate communication capabilities. The drawback lies in the necessity for the meter to be equipped with higher-capacity batteries to accommodate the functioning and data transmission of both the meter and the noise sensors.
3. Currently, there are several providers offering satellite-based leak detection services. These systems typically rely on changes in terrain reflectivity at specific wavelengths when the ground is moist at a certain depth. When combined with network maps provided by a GIS, moisture "spots" detected by the satellite located above pipeline routes serve as an indicator of a potential leak in the area. The effectiveness of this technology remains uncertain, seemingly yielding favourable results on certain occasions, although at times it fails to achieve reliable detection.
4. In cases where the aforementioned techniques yield no results, helium injection into the network can be employed. After creating holes in the ground at regular intervals along the pipeline route, the escape of helium through a specific hole is measured to ascertain the location of the sought-after leak. This method is highly costly and typically serves as a last resort in situations where other techniques have proven unsuccessful.
5. If a pressure measurement network and calibrated hydraulic mathematical models are available within a DMA, achieved either through pressure sensors integrated into the network or incorporated into smart meters – another emerging technology in this field –, these data, in conjunction with flow meters and customer meters, can be utilised to determine the locations of these leaks using said models. These techniques have not yet achieved significant levels of implementation due to the requirement for meticulously refined data, a substantial number of sensors, and considerable computational resources (Yipeng et al, 2017). Nevertheless, the results they yield are not of substantial precision and necessitate supplementation with one of the techniques mentioned above.

Another approach for leakage reduction, which does not rely on its detection and localisation, involves the utilisation of smart pressure management systems. Its operational principle is based on attempting to minimise undetectable leaks by adjusting the pressure to the absolute minimum necessary. To achieve this, pressure regulating valves (PRVs) need to be installed at the inlet(s) of the DMAs where it is desired to implement this approach, along with a control system that maintains the pressure as low as possible without impacting the customer. There are three types of implementation (not mutually exclusive) that can be applied: the simplest one is based on pressure regulation using hourly schedules, maintaining higher pressure during the day when consumption is higher and significantly lowering it at night when demand is minimal; the second, more sophisticated approach, regulates pressure based on data from a flow meter located at the DMA inlet, aiming to maximize reduction while aligning with demand; finally, the most sophisticated method involves installing a pressure sensor at the DMA's point where pressure is lowest (critical point), and the control system continuously adjusts pressure to maintain the essential minimum at that point.

Smart pressure management yields immediate and measurable outcomes on leakage levels, resulting in a reduction of minimum night-time flow rates. Moreover, it has a positive side effect: as pressure decreases, consumption is also reduced, impacting not only leaks but also overall usage, leading to sustainability benefits. However, it is only feasible for use in segmented networks and in DMAs where there is sufficient pressure margin to justify the investment and operational expenses.

Additional details and other techniques for leak detection can be found in Hamilton and Charalambous (2020).

In the particular case of Canal de Isabel II, the approach to leakage reduction employs a combination of various of the strategies previously outlined. On one hand, the company's strong technological foundation led to the decision, in the first decade of the century, to adopt the DMA-based approach. On the other hand, the company's remarkable financial health allows for high rates of pipe renewal. Additionally, the comprehensive service provided by the company across a vast area (over 8,000 km^2), characterised by a high degree of redundancy, necessitates the management of an extensive transport network, with leaks in this network requiring specific treatment. With that being said, Canal de Isabel II approach can be summarised as follows:

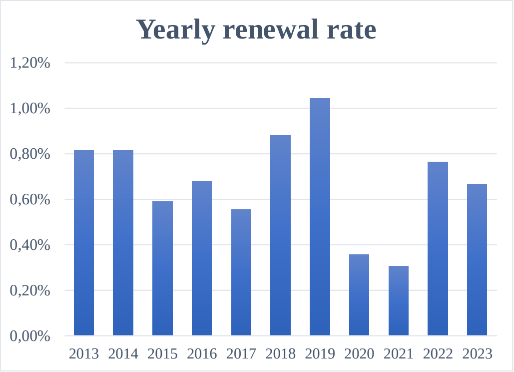

Figure 8. Yearly renewal rate at Canal de Isabel II as of June 2023.

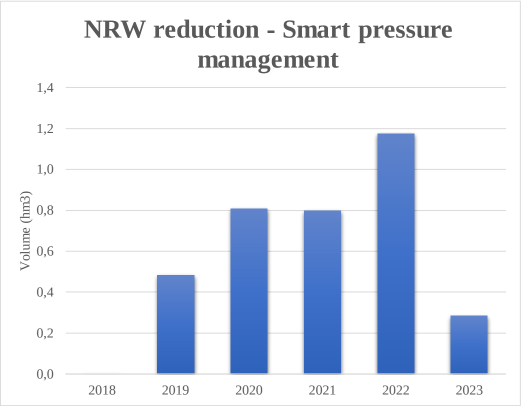

Figure 9. Reduction in NRW due to smart pressure management as of April 2023

- Given that Canal de Isabel II implemented its first GIS-based network maintenance system in 1997, it possesses an extensive history of information regarding the characteristics of pipe bursts. As mentioned earlier, the company employs its own system for assessing breakage risks for each conduit, which informs the creation of annual network renewal plans. Over the next 5 years, the goal is to replace 2% of the network annually (see Figure 8).
- The division of the network into DMAs—currently, 600—facilitated the implementation of smart pressure management systems. Initially, 200 DMAs were selected as potential candidates for this solution. Following detailed examination, this solution was deployed in 68 of them, with the results detailed below. The specific configuration employed varies based on the unique characteristics of each DMA, encompassing both hourly schedules and regulation based on flow or critical points (see Figure 9).
- Furthermore, the company utilises monitoring of minimum night-time flows to determine the presence of leaks within a DMA. When this indicator suggests a leak, temporary networks of noise sensors are deployed for a few days to locate the leaks, in conjunction with the use of correlators, followed by necessary repairs. Occasionally, when no other option exists, geophones or helium-based detection systems are employed. In those locations where

the deployment of smart meters has been completed, the minimum night-time flow ceases to be the parameter under observation. Instead, in this scenario, the hourly calculation of the difference between the volume supplied to the DMA and the reading from the meters becomes the new approach. This transition brings about a significant increase in accuracy, as actual consumption is accounted for, thus eliminating a variable that might impact potential shifts in night-time flow trends (see Figure 10). This holds particular significance for Canal de Isabel II, given the highly seasonal nature of consumption. During the summer period, the minimum night-time flow increases to levels at which leaks, unless excessively substantial, would remain imperceptible without smart meters' hourly readings.

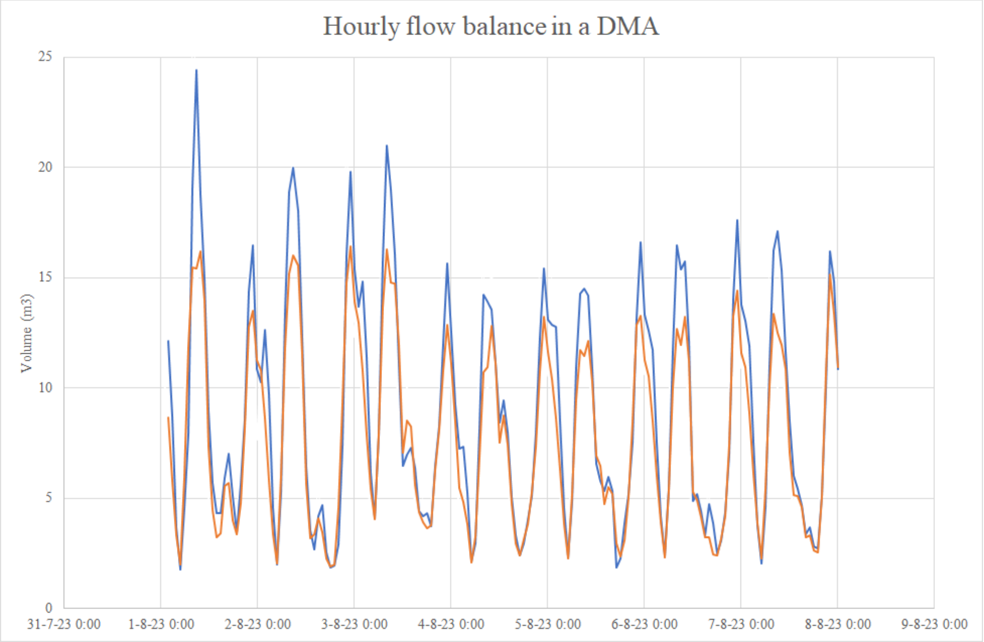

Figure 10. Hourly Flow balance in a DMA. Note that the balance at night is null. Therefore, the DMA is leak free. The difference at peak times might be due to the fact that there are still 2% of smart meters to be rolled out in the DMA.

- Concerning the transport network, a small selection of highly critical trunk mains has been equipped with a fixed detection system utilising hydrophones and artificial intelligence. In the remaining cases, periodic inspections are conducted through the introduction of noise recording devices into the pipeline.

All of these measures combined, over the course of more than a decade, yield the excellent results discussed subsequently.

3. Results and Discussion

The effective fight for NRW reduction necessitates, as has been observed, the combined implementation of numerous measures. Three factors are indispensable to ensure the success of their implementation. Firstly, selecting the appropriate strategy for each case. As elucidated in the preceding chapter, financial health, network topology, and the availability of information and telecontrol systems are the most significant factors to be taken into account. Secondly, employing a comprehensive performance indicator system to apply these measures where they are expected to be most effective. And lastly, but by no means less important, assessing the actual effectiveness of these implemented measures and taking appropriate action.

Under this heading, a different approach is used depending on the outcome of each action: a reduction in total water supply, albeit pipe replacement, pressure management or leakage control; an increase in revenue water, such fraud control or unmetered consumption. In the former, results are assessed by calculating the difference between night flow and baseline values, both before and after the action has been executed. Conversely, in the latter, it is the actual meter reading which provides an evaluation. In either scenario, the total water recovered is calculated for a period of one year from the time the action was completed.

That said, leakage is an exception: accounting for it starts from the date a leak is detected and repaired and is thereon effective for one year. Making these calculations does not mean that the outcome is the actual amount of water recovered. It is simply a way of providing a means to have a performance indicator that is fully aligned to show the individual effectiveness of every action in place, and which of these actions are worth pursuing.

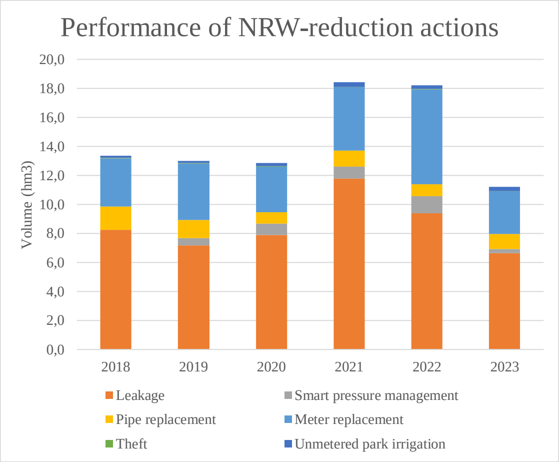

Figure 11. Performance of NRW-reduction actions, as of June 2023

In addition, this performance indicator turns out to be an appropriate answer to the question: how much NRW would have increased, had no actions been taken. As such, the yearly sum of this PI affords a good approximation of the effectiveness of NRW reduction policy. It is also a means of comparing the global throughput in subsequent years (see Figure 11).

From the offset of the assessment, using this method has been invaluable to continuously and consistently improve performance in the fight against NRW.

4. Conclusions

From the above results and discussion, three main conclusions can be drawn:

1. Reducing NRW is an enormous, unending task. An appropriate procedure is of the essence.
2. Assessing performance is vital in order to make the most of it and continuously tweak and streamline the action plan. The smaller the network segment the better the outcome of an assessment.

3. Without doubt, the results obtained hitherto, support such a procedure, as outlined in Figure 12. The necessary reduction in apparent losses is expected to be achieved by means of the smart metering programme, which is due to be completed by 2026. Note that the decrease in UfW surpasses that of NRW. This phenomenon can be attributed to the circumstance that metered unbilled consumption, largely out of the company's control, is experiencing an increase rather than a decrease. Consequently, this increment compensates for the reduction observed in the remaining constituents of NRW.

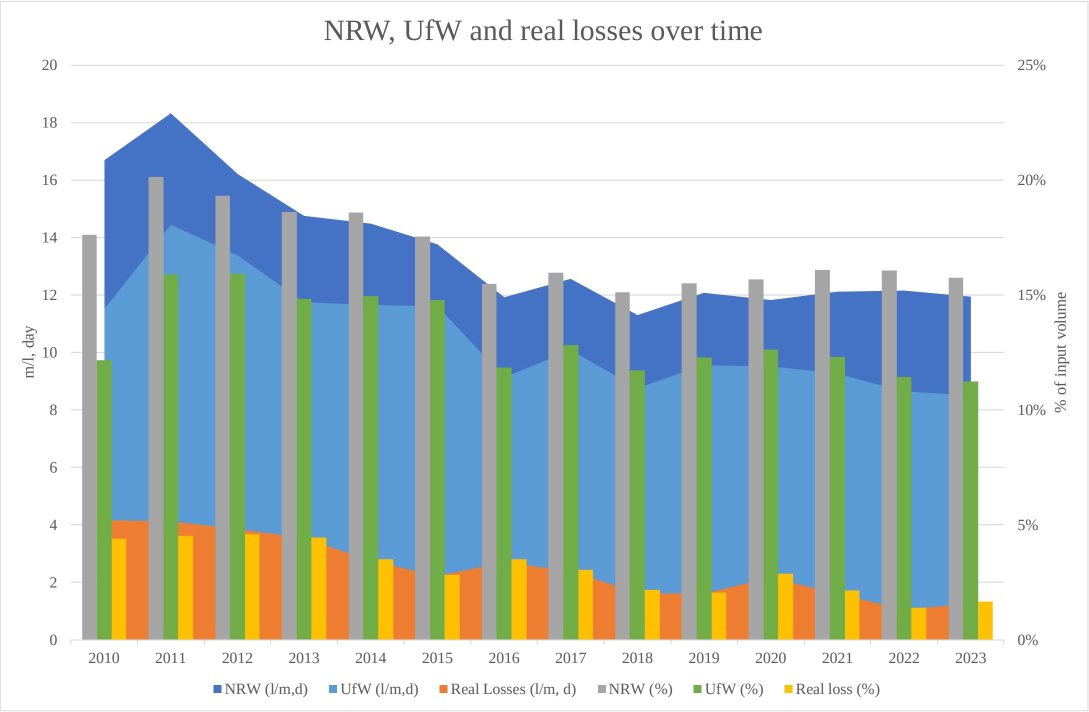

Figure 12. NRW, UfW and real losses over time. Values in litres per metre of pipe and day (left axis) and percentage of input volume (right axis). Data as of June 2023

As regards the effectiveness of reducing each individual component, leakage reduction continues to be the salient contributor, though meter replacement, bolstered by the smart metering programme, is steadily growing. (Figure 11).

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