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Departamento de Agronomía
Área Ingeniería Hidráulica

Gestión inteligente de sistemas de distribución de agua

Intelligent management of water distribution systems

Tesis Doctoral presentada por

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para la obtención del título de

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- Pérez-Padillo, J.; Morillo, J.G.; Poyato, E.C.; Montesinos, P. Open-Source Application for Water Supply System Management: Implementation in a Water Transmission System in Southern Spain. Water 2021, 13. Índice de impacto: 3.103. 2º cuartil en la categoría de Recursos Hídricos, posición 36/100.

- Pérez-Padillo, J.; Morillo, J.G.; Ramirez-Faz, J.; Roldán, M.T.; Montesinos, P. Design and Implementation of a Pressure Monitoring System Based on Iot for Water Supply Networks. Sensors 2020, 20. Índice de impacto: 3.576. 1er cuartil en la categoría de Instrumentos e Instrumentación, posición 14/64.

- Pérez-Padillo, J.; Puig, F.; García Morillo, J.; Montesinos, P. IoT Platform for Failure Management in Water Transmission Systems. Expert Syst. Appl. 2022, 199. Índice de impacto: 8.665. 1er cuartil en la categoría de Ingeniería, Electricidad y Electrónica, posición 23/276.

TÍTULO DE LA TESIS: Gestión inteligente de sistemas de distribución de agua.

DOCTORANDO: **José Manuel Pérez Padillo**

INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

El sector del abastecimiento de agua potable en España ha realizado importantes avances en los últimos 20 años renovando parte de las infraestructuras hidráulicas que se encuentran al final de su vida útil. Sin embargo, estas modernizaciones, que en muchas ocasiones se han limitado a la renovación de las conducciones, resultan insuficientes para afrontar los retos actuales a los que se enfrentan las empresas que gestionan el ciclo integral del agua. Para lograr estos retos, es necesario avanzar hacia una gestión inteligente de las instalaciones hidráulicas dedicadas al abastecimiento urbano, debido a su repercusión social pues gestionan un recurso esencial, escaso y vulnerable. Aunque el consumo de agua urbana representa el 14% del consumo total en España, es el sector más destacado por agrupar un mayor número de clientes y por el elevado volumen de negocio que genera (aproximadamente 6.500 millones de euros/año).

Esta Tesis Doctoral se centra en el proceso de digitalización de la gestión de las infraestructuras hidráulicas para abastecimiento urbano. El objetivo que persigue es la creación de un sistema de apoyo a la toma de decisiones que permita a los gestores de estas infraestructuras tomar decisiones basadas en datos registrados en tiempo real de las principales variables hidráulicas y en el conocimiento del comportamiento de la red ante distintos escenarios de operación que puedan ocurrir.

Esta investigación se ha desarrollado dentro de un Convenio de colaboración entre el Área de Ingeniería Hidráulica de la Universidad de Córdoba y la Empresa Provincial de Aguas de Córdoba (Emproacsa), que llevan trabajando desde 2016 en un proceso de digitalización integral encaminado al desarrollo e implementación de un sistema de gestión inteligente de sus infraestructuras hidráulicas.

La Tesis Doctoral se divide en tres grandes bloques claramente diferenciados y que de forma lógica y ordenada dan lugar a la consecución del objetivo general planteado. Los tres bloques se han publicado como artículos científicos en tres revistas con alto índice de impacto, por lo que la tesis se ha elaborado como compendio de artículos:

✓ Pérez-Padillo, J.M., García Morillo, J., Camacho Poyato, E., Montesinos Barrios, P. 2021. Open-Source Application for Water

Supply Systems Management: Implementation in a Water Transmission System in Southern Spain. Water 13, 3652.

En este primer trabajo se crea una aplicación móvil basada en software libre para determinar la ruta de acceso a los tramos averiados de redes de suministro en alta, a la vez permite la constante actualización del Sistema de Información Geográfica, (SIG), de las infraestructuras hidráulicas y del modelo hidráulico de la red. Esta aplicación permite a los técnicos de campo interactuar con el SIG y enviar notificaciones sobre los cambios y renovaciones llevadas a cabo en las redes para modificar el modelo hidráulico en consecuencia y que la base de datos esté siempre actualizada.

✓ Pérez-Padillo, J., Morillo, J.G., Ramirez-Faz, J., Roldán, M.T., Montesinos, P. 2020. Design and implementation of a pressure monitoring system based on IoT for water supply networks. Sensors, 20(15), pp. 1-19, 4247.

En este segundo trabajo, se ha desarrollado un sistema robusto y de bajo coste para la monitorización de la presión que permite detectar fugas y roturas en tiempo real, enviando alertas a los responsables mediante email o SMS. Para ello se ha utilizado una red de largo alcance y baja potencia (LPWAN) con un sistema de comunicación basado en el Internet de las cosas (IoT). El sistema se ha diseñado para utilizar software de código abierto, así como hardware de bajo coste. Esta característica facilita la adaptación a cualquier sistema de abastecimiento de agua y la sustitución tanto de los elementos de software como de hardware por las alternativas más adecuadas para cada situación, gracias a la arquitectura modular del sistema.

- ✓ Pérez-Padillo, J.M., Puig, F., García Morillo, J., Montesinos, P. 2022. IoT platform for failure management in water transmission system. Expert Systems With Applications 199 (2022) 116974.

Para gestionar adecuadamente el gran volumen de información generado en las etapas anteriores, en el tercer trabajo se ha desarrollado una plataforma web utilizando, como en los trabajos anteriores, software libre de código abierto. La plataforma alberga el SIG, el modelo hidráulico, el sistema de monitorización de la presión además de diversos algoritmos de cálculo. Uno de los algoritmos detecta, geolocaliza y clasifica averías a partir de los registros de presión en tiempo real, enviando alertas de avería al personal de mantenimiento de la zona afectada. Un segundo algoritmo utiliza el modelo hidráulico para determinar el tiempo disponible para reparar la avería antes de que haya cortes en el suministro de alguna población. Toda la información necesaria (datos y resultados de los algoritmos) está disponible en una única plataforma que puede ser consultada por los distintos agentes implicados en la gestión del ciclo integral del agua.

La investigación desarrollada en la presente Tesis ha sido implementada en las redes hidráulicas provinciales gestionadas por la empresa pública Aguas de Córdoba, lo que ha permitido llevar a cabo un avance de conocimiento con la investigación desarrollada, y además hacer una labor de transferencia muy significativa en el sector del abastecimiento urbano en la provincia de Córdoba. Esta tesis ha supuesto un claro ejemplo de éxito de colaboración entre la Universidad y la Empresa.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 27 de Octubre de 2022

Firma de los directores

Mª Pilar Montesinos

Jorge

Fdo.: Pilar Montesinos Barrios

Fdo.: Jorge García Morillo

Summary

The United Nations predicts that the world's population in 2050 will reach 9.7 billion people. This exponential growth will mean an increase in the global demand for water available for human consumption. In addition, the advance of climate change is causing the occurrence of more frequent droughts, especially in arid and semi-arid areas. Indirectly, this means an increase in the costs associated with water transport and purification, as water must be drawn from sources that are increasingly distant from the points of consumption and the quality is getting worse. The traditional management of urban water supply is changing towards a more sustainable model aimed at an efficient use of resources (water, energy, labour) that not only reduces management costs but is also more environmentally friendly.

This transformation is taking place due to the development of other transversal disciplines (cloud computing, communication systems, Big Data, electronics, etc.) applied to many fields of science, which applied to water management, can bring considerable benefits. Furthermore, to achieve intelligent management of a water supply network, it is necessary to rely on current tools that provide objective knowledge of the system. For example, geographic information systems (GIS) together with hydraulic models serve as a georeferenced database where the behaviour of any hydraulic network in different scenarios can be simulated. The Internet of Things (IoT) allows the connection of a network of sensors to know the main hydraulic variables at any time, providing key information for hydraulic models to faithfully reproduce the behaviour of modelled

systems in real time. Digitalisation itself favours the use of information and communication technologies (ICT) to convert traditional management into smart management. For these reasons, new studies are needed to assess the potential and applicability of these new tools.

This thesis is organised in 6 chapters focused on the development and application of a decision support system that allow the manager of a water supply network to make decisions based on data recorded on real-time. All the tools developed throughout this thesis have been tested in a real water supply network located in the south of Spain, managed by the Provincial Water Company of Cordoba (EMPROACSA). Chapter 1 shows the trajectory of urban supply management: explaining the starting point and where it is expected to achieve. Then, Chapter 2 describes the main objective and the specific objectives of this thesis, as well as the structure of this document.

Chapter 3 presents a methodology that serves as a basis for starting the digitisation process in water supply networks. The system developed is based on three pillars: the geographic information system, the hydraulic model, and the application for mobile devices. The geographic information system provides a georeferenced database of the infrastructures that compose the hydraulic network; the hydraulic model simulates the response of the network to different operation scenarios; and finally, the mobile application facilitates the feedback of the system to keep it always up to date with changes in the systems. One of the distinguishing features of this work is the use of free software (Qgis,

Epanet and Google My Maps) in all stages, which fosters digitisation in supply companies with a low budget.

Chapter 4 develops an early warning system based on water pressure monitoring. The communication node developed ad-hoc for this work, sends water pressure data to the cloud, where users can visualise them with a device with an internet connection. Among its advantages are its low cost, it allows the use of different communication systems and has a high autonomy powered by batteries, which makes it well adapted to supply systems. The proposed monitoring system detects failures in the network due to pressure drops, alerting managers of the affected zone.

Chapter 5 explains the decision support tool developed to deal with failures in water transmission networks. The web platform that supports this tool is divided into 3 independent modules: fault detection, alerts, and fault repair. The first module is responsible for detecting, geolocating and classifying faults in the hydraulic network using the information recorded in real time by the pressure monitoring system described in the previous chapter. The second module is responsible for sending alerts selectively to the workers in the area of the failure. Finally, the third module estimates, applying the hydraulic model, the maximum time that the manager has to fix failures, avoiding supply cuts using the water stored in regulation tanks when the failure occurs. The fault detection and classification module has demonstrated a 95% accuracy when applied to a real case.

Chapter 6 contains the general conclusions of the thesis, as well as possible lines of future work.

In summarise, water management is experiencing a paradigm shift. This transformation requires sufficiently mature technologies to ensure good results. Therefore, studies are needed that not only advance towards smart management, but also evaluate the tools available now and their integration into the current management model. This thesis presents a decision support system applied to supply networks, which help managers to make decisions based on objective information, not on intuition or experience. The use of open-source software and hardware in all the developments of this thesis must be emphasised. This specific feature allows the adoption of the methodologies proposed by water companies, regardless of size or financial resources, enabling the whole system or only part of it to be adapted to the operation of the company.

Resumen

Las Naciones Unidas prevén que la población mundial en 2050 alcanzará los 9.700 millones de personas. Este crecimiento exponencial supondrá un aumento de la demanda global de agua disponible para el consumo humano. Además, el avance del cambio climático está provocando la aparición de sequías más frecuentes, especialmente en las zonas áridas y semiáridas. Indirectamente, esto supone un aumento de los costes asociados al transporte y la depuración del agua, ya que hay que extraerla de fuentes cada vez más alejadas de los puntos de consumo y la calidad es cada vez peor. La gestión tradicional del abastecimiento de agua en las ciudades está cambiando hacia un modelo más sostenible orientado a un uso eficiente de los recursos (agua, energía, mano de obra) que además de reducir los costes de gestión, es más respetuoso con el medio ambiente.

Esta transformación se está produciendo gracias al desarrollo de otras disciplinas transversales (computación en la nube, sistemas de comunicación, Big Data, electrónica, etc.) aplicadas a diversos campos de la ciencia, que aplicadas a la gestión del agua, pueden aportar considerables beneficios. Además, para conseguir una gestión inteligente de una red de abastecimiento de agua, es necesario apoyarse en herramientas actuales que proporcionen un conocimiento objetivo del sistema. Por ejemplo, los sistemas de información geográfica (SIG) junto con los modelos hidráulicos sirven como base de datos georreferenciada donde se puede simular el comportamiento de cualquier red hidráulica en diferentes escenarios. El Internet de las Cosas (IoT) permite la conexión de una red de sensores para conocer las principales variables hidráulicas en cada

momento, aportando información clave para que los modelos hidráulicos reproduzcan fielmente el comportamiento de los sistemas modelizados en tiempo real. La propia digitalización favorece el uso de las tecnologías de la información y la comunicación (TIC) para convertir la gestión tradicional en una gestión inteligente. Por estas razones, son necesarios nuevos estudios para evaluar el potencial y la aplicabilidad de estas nuevas herramientas.

Esta tesis se organiza en 6 capítulos centrados en el desarrollo y aplicación de un sistema de apoyo a la decisión que permita al gestor de una red de abastecimiento de agua tomar decisiones basadas en datos registrados en tiempo real. Todas las herramientas desarrolladas a lo largo de esta tesis han sido probadas en una red real de abastecimiento de agua situada en el sur de España, gestionada por la Empresa Provincial de Aguas de Córdoba (EMPROACSA). El capítulo 1 muestra la trayectoria de la gestión del abastecimiento urbano: explicando el punto de partida y hacia dónde se espera llegar. A continuación, el capítulo 2 describe el objetivo principal y los objetivos específicos de esta tesis, así como la estructura de este documento.

El capítulo 3 presenta una metodología que sirve de base para iniciar el proceso de digitalización de las redes de abastecimiento de agua. El sistema desarrollado se basa en tres pilares: el sistema de información geográfica, el modelo hidráulico y la aplicación para dispositivos móviles. El sistema de información geográfica proporciona una base de datos georreferenciada de las infraestructuras que componen la red hidráulica; el modelo hidráulico simula la respuesta de la red ante diferentes escenarios de operación; y, por último, la aplicación móvil facilita la retroalimentación del sistema para mantenerlo siempre actualizado con los cambios en los sistemas. Uno de los rasgos distintivos de este trabajo es el uso de software libre (Qgis, Epanet y Google My Maps) en todas las etapas, lo que favorece la digitalización en empresas de abastecimiento con bajo presupuesto.

El capítulo 4 desarrolla un sistema de alerta temprana basado en la monitorización de la presión del agua. El nodo de comunicación desarrollado ad-hoc para este trabajo, envía los datos de la presión del agua a la nube, donde los usuarios pueden visualizarlos con un dispositivo con conexión a internet. Entre sus ventajas están su bajo coste, permite el uso de diferentes sistemas de comunicación y tiene una gran autonomía alimentada por baterías, lo que hace que se adapte bien a los sistemas de abastecimiento. El sistema de monitorización propuesto detecta fallos en la red por caídas de presión, alertando a los gestores de la zona afectada.

El capítulo 5 explica la herramienta de apoyo a la toma de decisiones desarrollada para hacer frente a las averías en las redes de abastecimiento en alta. La plataforma web, que soporta esta herramienta, se divide en 3 módulos independientes: detección de averías, alertas y reparación de averías. El primer módulo se encarga de detectar, geolocalizar y clasificar las averías en la red hidráulica a partir de la información registrada en tiempo real por el sistema de monitorización de presiones descrito en el capítulo anterior. El segundo módulo se encarga de enviar alertas de forma selectiva a los trabajadores de la zona de la avería. Por último, el tercer módulo estima, aplicando el modelo hidráulico, el tiempo máximo del que dispone el gestor para solucionar las averías, evitando los cortes de suministro con el agua almacenada en los depósitos de regulación cuando se produce la avería. El módulo de detección y clasificación de averías ha demostrado una precisión del 95% cuando se aplica a un caso real.

El capítulo 6 contiene las conclusiones generales de la tesis, así como posibles líneas de trabajo futuras.

En resumen, la gestión del agua está experimentando un cambio de paradigma. Esta transformación requiere tecnologías suficientemente maduras para garantizar buenos resultados. Por ello, son necesarios estudios que no sólo avancen hacia una gestión inteligente, sino que evalúen las herramientas disponibles en la actualidad y su integración en el modelo de gestión actual. Esta tesis presenta un sistema de apoyo a la decisión aplicado a las redes de suministro de agua, que ayuda a los gestores a tomar decisiones basadas en información objetiva y no en la intuición o la experiencia. Cabe destacar el uso de software y hardware de código abierto en todos los desarrollos de esta tesis. Esta particularidad permite la adopción de las metodologías propuestas por las empresas de agua, independientemente de su tamaño o recursos financieros, permitiendo adaptar todo el sistema o sólo una parte de él al funcionamiento de la empresa.

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List of Symbols and abbreviations

GIS	geographic information system
DSS	decision support system
WTS	water transmission system
WDS	water distribution system
ICT	information and communication technologies
WSS	water supply system
APP	mobile application
HM	hydraulic model
ES	Eastern System
MRT	maximum repair time
IoT	Internet of things
ITWSM	Integrated Tool for Water System Management
API REST	Representational state transfer application programming interface
AWS	Amazon Web Services
GSM	Global System for Mobile Communications
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
PaaS	Platform as a Service
LoRaWAN	Long Range Wide Area Network
LPWAN	Low-power wide-area network
MDT	Mean detection time
MRT	Maximum repair time

NB-IoT	Narrow Band Internet of Things
SCADA	Supervisory control and data acquisition
SF	Safety factor
SPA	Single page applications
SQL	Structured Query Language
WTN	Water transmission network
wAIter	Artificial Intelligence Water Platform

1. Introduction

1.1 Background

The latest UN predictions estimate the world population in 2050 at 9.7 billion people (Gaigbe-Togbe et al., 2022). This exponential increase in population means that, like other important socio-economic resources, there will be an increasing demand for water worldwide. On the one hand, per capita water needs are increasing considerably. Boretti & Rosa (2019) forecasts an increment between 20% and 30% by the year 2050, to cover mainly basic needs (drinking, hygiene, and food production). On the other hand, droughts, typical of the Mediterranean climate, are occurring more frequently due to the advance of climate change (Allan et al., 2020). Although agriculture is the sector responsible for 70% of freshwater consumption (United Nations, 2017), there is a growing concern to ensure supplies for human consumption in good quality and quantity. In this context, the percentage of the world's urban population facing water scarcity is expected to increase.

Demand growth combined with the increasing frequency of droughts in many areas of the world makes it necessary to search for new sources of water. These sources will be probably less accessible (greater distance and/or depth) from consumption points. Also, many of today's water sources are of poor quality due to pollution problems in many areas. This means an increase both in the cost of transporting water and in the cost of purification. For this reason, budget allocations for integrating new technologies and methodologies are justified in order to avoid this future scenario (Hoekstra et al., 2018). Thus, the aggregate costs of changing current tools to new ones that allow for optimal water supply management in the described scenario would be amortised.

Significant technological advances in recent decades are accelerating a paradigm shift in water management. Traditional management, based on meeting the needs of the population, is changing towards more sustainable criteria to reduce operating costs while minimising water losses. Figure 1.1 shows the high percentage of non-revenue water in European countries, with most of them between 20% and 40% (EurEau, 2021). This can be extrapolated to the rest of the world, with these figures being accentuated in underdeveloped countries (Mutikanga et al., 2010). These trends are contrary to the Sustainable Development Goal (SDG) 6 "Clean Water and Sanitation", which was proposed in 2015 by the UN. To reverse this situation, new approaches and conceptual frameworks are required, which integrate water interventions in a practical way according to the specific situation of each country/region.

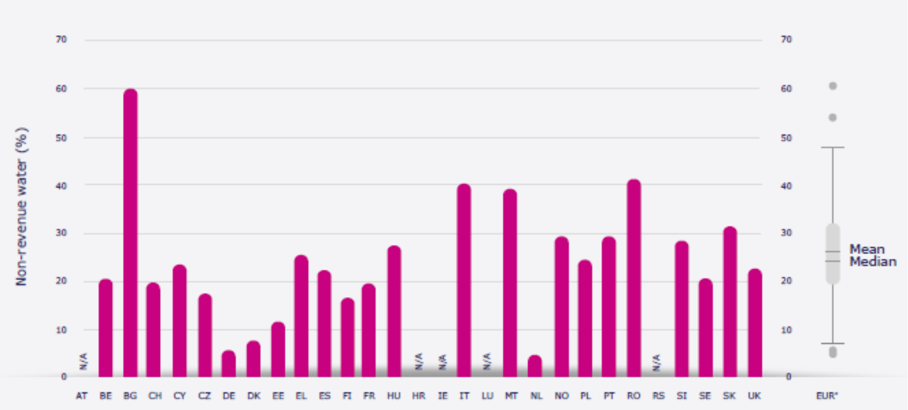

Figure 1.1. Average non-revenue water in percentages. Source: EurEau, (2021).

In the European Region, the World Health Organization (WHO) stated than 63 million people have accessed to safe drinking water services between 2000 and 2017. However, more than 16 million people still lack access to basic drinking water (WHO, 2022). Significant disparities persist between rural and urban areas, and between the richest and poorest countries (Figure 1.2). A significant part of the cost of water supply is related to how to maintain, renew, and extend the infrastructure required to provide the service. Such infrastructure includes visible facilities and buried equipment (supply and sanitation networks). On average, networks represent 75% of maintenance costs, but their invisible nature does not encourage sufficient maintenance (Frérot, 2014). It is estimated that □2,290 millions are needed to make the necessary investments to bring installations in EU countries into line with current water supply directives (Coopers, 2008).

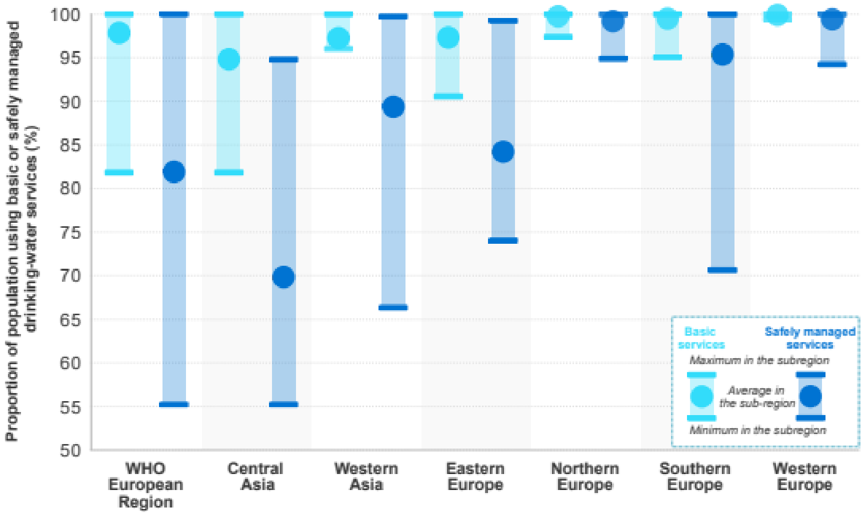

Figure 1.2. Population coverage of basic and safely managed drinking-water services, 2020. Source: WHO, (2022).

At national level, 26% of existing water distribution networks in Spain are more than 40 years. Moreover, the overall percentage of renewal of supply networks represents 0.43%, below the ideal 2% ((AEAS) & (AGA), 2021). In this context, the problem is that not only is water lost, but leaks are also associated with the energy that has been supplied to the water in the upstream part of the system, in addition to that used in the treatment of drinking water. It is crucial to look for strategies aimed at efficiency, i.e. to provide quality service with the lowest consumption of resources (water and energy). For this reason, many companies in the sector are investing in innovations that allow them to manage their facilities in an integrated manner, with the aim of efficiently managing the sources of information associated with any hydraulic network to make decisions based on a comprehensive vision.

1.2 The role of Geographic Information Systems and hydraulic modelling in water network management

One of the main problems faced in the efficient management of a water distribution system is the handling of the large amount of disaggregated information generated around a hydraulic network. The methodologies for the design and analysis of water supply networks have changed with the irruption of new tools that simplify and structure these processes. In this context, geographic information systems (GIS) and hydraulic models are nowadays indispensable instruments for water resources planning.

Water transport networks, which usually occupy large areas of land, generate a large amount of information that needs to be structured and grouped to be used by the different agents involved in their management. For these reasons, GIS play an important role in the capture, storage, manipulation, analysis and presentation of spatial information related to supply and sanitation systems (Tsihrintzis et al., 1996). This tool makes it possible to relate geographic data with other alphanumeric information. Currently, in strategic infrastructures such as water supply and sanitation networks, it is necessary to have a digital cartography that groups all the information in a georeferenced database.

The modern management of water supply systems requires the creation and use of the mathematical model that represents the behaviour of the hydraulic network in specific situations (Abdelbaki et al., 2019). In order to achieve accurate results, it is necessary to perform a prior characterisation of the network to be modelled, entering hydraulic, topological and construction parameters of the network as inputs (Yan et al., 2009). This type of software provides managers with a great help to study in advance the response of the network to operations or future scenarios. Hydraulic models have improved considerably in recent years, focusing on developing a user-friendly graphical interface with the aim of facilitating the utilization of these tools by non-expert modelers. However, it is necessary to implement new methodologies to keep the models updated and to ensure that the results they provide are in line with the real behaviour of the network.

To analyse a hydraulic network comprehensively, it is necessary to have structured and unified data sources, but it is also important to know its behaviour in future operation scenarios. Nowadays, there is an increasing number of computer programmes that combine GIS with hydraulic models, making it possible to update the inventory of existing infrastructures, as well as to calibrate the hydraulic model of the system with real data and simulate its behaviour in different operating scenarios (system failures and enlargements, future demand scenarios). The development of these two pillars, GIS and hydraulic models, is the basis for achieving robust decision support tools (Martínez et al., 2004).

1.3 Internet of Things applied to water transport networks

The concept of the Internet of Things consists of providing connectivity to elements, giving them the ability to make decisions based on context. The Internet of Things consists of a network of physical objects that contain technology to communicate information about their own functioning or about their external environment (Vermesan et al., 2013). This ecosystem offers solutions based on the integration of information technology, which refers to the hardware and software used to store, collect and process data, and communications technology, which includes the electronic systems used for communication between individuals (Soumitra Dutta & Bilbao-Osorio, 2012).

Numerous studies have identified the evolution of the Internet of Things as one of the next big concepts to support societal change and economic growth, which will support the citizen in their daily lives. It is redefining the ways in which networks, data, clouds, and connections are designed, managed, and maintained. The Internet of Things (IoT) has become a predominant system in which people, processes, data, and things are connected to the internet and to each other. Globally, machine to machine connections (M2M) will increase 2.4 times, from 6.1 billion in 2018 to 14.7 billion in 2023 (Figure 1.3). There will be 1.8 M2M connections for every member of the world's population by 2023 ("Cisco Annual Internet Report (2018-2023)," 2020).

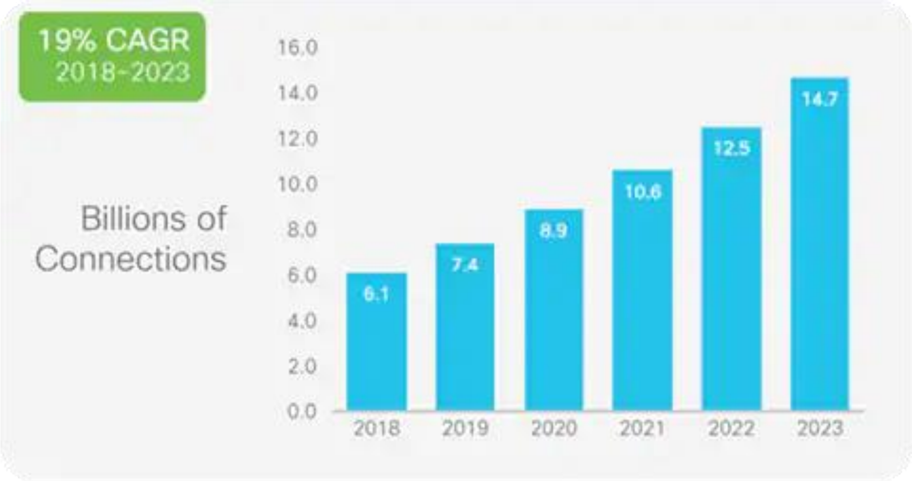

Figure 1.3. Global M2M connection growth. Source: "Cisco Annual Internet Report", (2020).

The low-cost technology available nowadays has been one of the factors that have allowed the society to access to this type of technology applied to different fields. When implementing IoT devices, the communication technologies used are key to their successful operation. The evolution of communication systems has been another reason for the rapid development of IoT (Figure 1.4). Today, to accommodate the diversity of connected objects, there is a heterogeneous mix of communication technologies, which are adapted to suit application needs such as energy efficiency, security, and reliability.

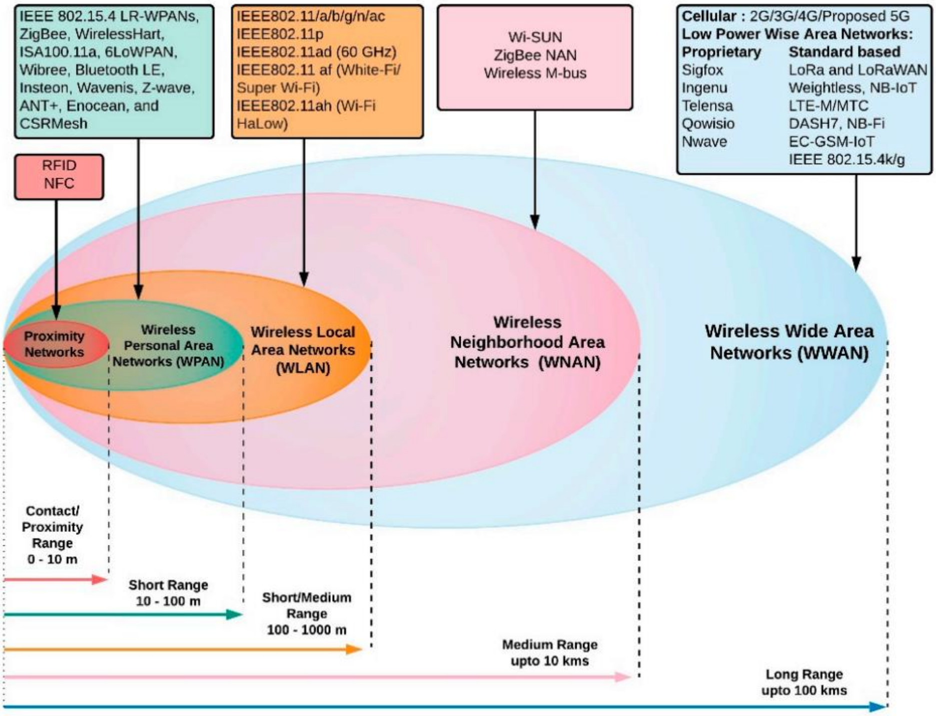

Figure 1.4. Existing communication systems according to range and transmission rate. Source: B. Chaudhari & Zennaro, (2020).

In many cases, energy consumption is a problem for many of the connected objects. This problem is accentuated in the specific case of monitoring water transport networks, which are often dispersed over large areas, crossing territories far from urban areas with little or no coverage. The progression of low-power wide-area communication networks (LPWANs) has enabled the use of sensors with minimal energy consumption per sending data cycle (Mekki et al., 2019). This is allowing battery-powered sensors to have a long autonomy. Such networks, which have a star topology, can achieve a coverage range of 10-50 km. In addition to their low information transmission capacity, these communication systems are characterised by their low cost, which makes it possible to connect a large number of devices with a low initial investment (B. S. Chaudhari et al., 2020).

The use of IoT in water supply networks has the potential to overcome key challenges for sustainable water management (Salam, 2020). Water supply is facing new challenges due to increasing demand. The use of real-time data, together with decision support tools, allows comprehensive real-time analysis of system behaviour by network managers. In addition to improve the management of water supply networks, the use of IoT sensors helps to make more sustainable use of water and energy resources (Monks et al., 2019). Numerous works have shown how IoT sensors has reduced water losses in leakage (Ferrarese & Malavasi, 2022; Gong et al., 2016), reduced electricity bills with optimal scheduling of pumping stations (Bagloee et al., 2018; Quintiliani & Creaco, 2019), or even improved planning with accurate demand forecasting (Brentan et al., 2018; Pesantez et al., 2020).

1.4 Digitalisation in the integral water cycle management sector

Every year the percentage of people moving from rural to urban areas is increasing. Currently, the United Nations (UN) reports that, for the first time in history, more than half of the world's population lives in cities. By 2050, 68% of the world's population is expected to live in urban areas (United Nations, 2018). As the world continues to urbanise, sustainable development increasingly depends on the effective management of urban growth (Melchiorri et al., 2016). In this sense, transforming "traditional cities" into Smart Cities is an essential demand. A Smart and Sustainable City is an innovative city that uses Information and Communication Technologies (ICT) to improve decision-making, efficiency of operations and delivery of urban services (Padmavathi & Aruna, 2022).

The significant impacts of climate change on water resources and the current critical energy scenario are forcing the water sector to face a transformation towards a new digital era. Urban water cycle management is a key part of this transformation. Structural changes are currently taking place in the water sector. As a result, water management has been drastically transformed by the development and application of new forms of automation and monitoring, as well as the use of artificial intelligence and knowledge management tools (Becker et al., 2019). This is known as the "digital revolution" (Garrido-Baserba et al., 2020).

In recent years, digitisation activities in the water sector have increased and digitisation has become a central theme (Wehn & Montalvo, 2018). The increase in funding sources indicates a widespread recognition of this need. Examples in Europe are the "Horizon 2020" and its successor "Horizon Europe" programmes (for research, development and, innovation activities) and the LIFE 2021-2027 Structural Funds (the EU funding instrument for the environment, climate action and the objectives of the EU Green Deal). At the national level, the Strategic Project for Economic Recovery and Transformation (PERTE) for digitalising water management in Spain aims to provide approximately □3 billion over the period 2022-2026. This grant is mainly focused on transforming and modernising water management systems.

Although more than 60% of the publicly presented digitisation solutions can be qualified as market-ready, there is still a long way to go in this area. It is estimated that 7% of the digitising elements in the water sector are in an advanced stage of development (test/prototype phase) and 30% are at a very early stage (figure 1.5). Further research is therefore needed in this field to be able to offer companies in the sector products that guarantee to work properly.

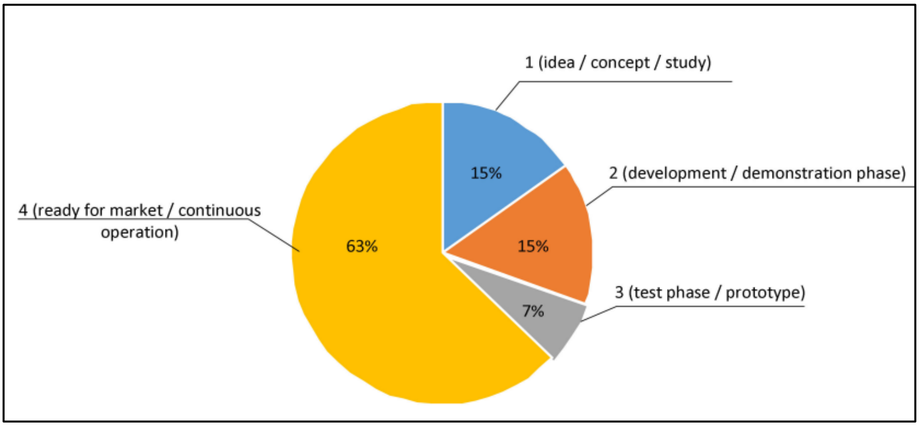

Figure 1.5. Development status of identified digitization elements. Source: Müller-Czygan et al., (2021).

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2. Objectives and thesis structure

2.1 Objetives

The general objective of this thesis is to develop a smart management system for water distribution systems, based on open-source software, using real-time data processed by mathematical models.

To achieve this purpose, the following specific objectives are detailed below:

- Creation of a methodology for obtaining digital mapping water distribution systems based on open-source software, that includes the physical and hydraulic characteristics of the system components, input data for the hydraulic model of the water distribution system.
- Development and implementation of a low-cost monitoring system that records and transmits key information for the management of this type of infrastructure in real time.
- Creation of a comprehensive digital tool based on open-source software for analysing and interpreting the data collected by the monitoring system to propose optimal management recommendations.

2.2 Thesis structure

In order to achieve the proposed objectives, this document is organised in six chapters. The first two chapters correspond to the introduction and the objectives of the thesis respectively. The following chapters are explained below:

Chapter 3 presents a system called "Integrated Tool for Water Supply Systems Management" (ITWSM) that facilitates the daily work of managing a water transport network. This system has been built on three interconnected modules (Geographic Information System, hydraulic model and application for mobile devices) based on open source software. This work has been published in the paper "Open-Source Application for Water Supply System Management: Implementation in a Water Transmission System in Southern Spain" (2021) by Pérez-Padillo, J., Morillo, J. G., Poyato, E. C., & Montesinos, P. in the journal Water (https://doi.org/10.3390/w13243652).

Chapter 4 consists of a pressure monitoring and warning system using low-cost hardware and open-source software. The main objective of the monitoring system proposed in this chapter is to detect malfunctions in water supply network. This chapter corresponds with the paper "Design and implementation of a pressure monitoring system based on IoT for water supply networks" (2020) by Pérez-Padillo, J., Morillo, J. G., Ramirez-Faz, J., Roldán, M. T., & Montesinos, P. in the journal Sensors (https://doi.org/10.3390/s20154247).

Chapter 5 describes a web tool that support in the decision-making process in the management of failures in water transmission networks. This work represents a step forward with respect to the previous chapter. This tool detects and classifies the failure and provides the manager with essential information to efficiently manage the repair the fault. This chapter has been published under the title "IoT platform for failure management in water transmission systems" (2022) by Pérez-Padillo, J., Puig, F., García Morillo, J., & Montesinos, P. in the journal Expert System With Applications (https://doi.org/10.1016/j.eswa.2022.116974).

Finally, chapter 6 contains the general conclusions of the thesis, as well as the future lines of work in the optimisation of the management of drinking water transport networks.

3. Open-Source Application for Water Supply System Management: Implementation in a Water Transmission System in Southern Spain

This chapter has been published entirely in the journal "Water", José Pérez-Padillo, Jorge García Morillo, Emilio Camacho Poyato and Pilar Montesinos (2021).

Abstract: Sustainable water use has become a critical issue for the future of the planet in face of highly probable climate change. The drinking water supply sector has made significant progress over the last 20 years, although improvements in the management of urban hydraulic infrastructures are still required. The proposed system, Integrated Tool for Water Supply Systems Management (ITWSM), built on three interconnected modules (QGIS database, Epanet hydraulic model, and Google My Maps app), was developed on open-source software. The core of ITWSM allows analyzing the behavior of water supply systems under several operation/failure scenarios. It facilitates decision making supported by the mobile application ITWSM-app. Information flows easily through the different decision levels involved in the management process, keeping updated the georeferenced database after system changes. ITWSM has been implemented in a real public water supply company and applied to manage breakdown repairs in water transmission systems. The use of the proposed methodology reduces the average cost of failure repair by 13.6%, mainly due to the optimal planning of the resources involved.

Keywords: digitalization; geographic information system (GIS); hydraulic modeling; information and communication technologies (ICT); decision support system (DSS)

3.1 Introduction

Sustainable water use has become a critical issue for the future of the planet in face of highly probable climate change. Current hydroclimatic data support the hypothesis of the occurrence of climate change (prolonged periods of drought and severe flooding in different parts of the world) (Vargas & Paneque, 2018), which causes alterations in the availability of water resources. The large number of factors involved in water management makes it difficult to take decisions to minimize the adverse effects of future water use scenarios and ensure the long-term sustainable use of water resources (Cabrera, 2007).

The drinking water supply sector in Spain has made significant progress over the last 20 years by renovating hydraulic infrastructure near the end of its useful life (Fernández Landa et al., 2018). However, these modernizations are insufficient to confront the current challenges related to the efficient use of water resources (ONU, 2015). To accomplish these challenges, it is necessary to implement smart management of water facilities, especially those devoted to urban water supply, due to their social repercussion. Although urban water consumption accounts for 14% of total consumption in Spain, it is the most prominent water supply sector as it groups together a larger number of customers and a high turnover (approximately 6500 million EUR). The Spanish urban water sector is a combination of public, private, and mixed water companies. This makes it difficult to standardize the measures to be implemented in the sector, as infrastructure funding comes from different sources.

The main objective of decision support systems (DSS) applied to water transmission (WTS) and water distribution systems (WDS) is the efficient management of these infrastructures. The achievement of this objective entails making efficient use of available resources (water, technology, labor, and funding). Current technological advances at affordable prices (Sadler et al., 2016), including communication systems (Puig et al., 2017; Tomas Robles et al., 2014), data cloud storage (Fazio et al., n.d.), data analysis tools, and hydraulic network modeling (Léon-Celi et al., 2018; Sela et al., 2019), facilitate the attainment of this objective.

DSSs applied to territorial systems are constructed from geographic information systems (GIS), which combine digital cartographic information and alphanumeric information. Current cartographic analysis tools (Hoffmann et al., 2018), both online and offline, facilitate the transformation of traditional cartography into digital and collaborative cartography (Corbett et al., 2009; Liu et al., 2018) and allow the updating and consultation of information for GIS users (e.g., water service departments) (Motiee et al., 2007).

Thus, water supply companies need a detailed knowledge of the infrastructures that make up their WTS/WDS to know their actual state and set improvement plans (Triantafyllidis et al., 2018). Water companies are concerned by the aging of the hydraulic infrastructure as many pipelines, valves, or pumps are beyond or near to the end of their lifetime and should be renovated. The system improvements will allow sustainable use of water and energy resources, especially in the current scenario of a continuous increase in energy prices and a reduction in greenhouse gases emissions (Blasco & Bejerano, 2016).

The digitization process of the water supply sector has been accelerated in recent years. The adoption of disruptive technologies is changing the business models that have prevailed for decades. The digitization process is completed by integrating all available information about the system into a hydraulic model to estimate hydraulic variables (flow rate, pressure, tanks levels, etc.) at any point of the system (Aydin et al., 2015). Hydraulic models simulate the behavior of WTS/WDS systems in multiple operating scenarios, facilitating decision making (Venkatesh et al., 2017).

To reap the full benefits of digitization, it is essential to provide the company with tools to obtain all the advantages of this approach. Currently, there are applications for mobile devices applied to water resource management (e.g., drought prediction (Hao et al., 2017), water quality analysis (Ostfeld, 2005), flood warnings (René et al., 2014; Sermet & Demir, 2018), and sanitation system monitoring (Berretta et al., 2007)), but their implementation is not generalized.

With the use of this technology, the management of hydraulic infrastructures is improved and cost reductions can consequently be achieved. The widespread use of mobile phones and tablets is based on information and communications technology (ICT) tools to send and receive information (text messages, photographs, videos, geolocation, etc. (Sowmyaa et al., 2021)) anywhere. In short, applications for smartphones applied to water supply companies benefit both end-users and managers, responding to current market challenges. In many cases, the correct operation of water supply systems (WSS) is based on the experience of the field workers. However, many times, this knowledge is not captured in a digital structured database, and, over time, this valuable information may be lost. This entails a risk due to the generational change occurring in a high number of water supply companies. Recording information in a structured way reduces the adaptation process of new workers by providing, in a simple way, a complete overview of the different tasks to be performed. A structured digital database with the main hydraulic infrastructure and its management and operation rules is critical for the success of these companies.

Today, there are different types of DSSs used in WSS management (Mysiak et al., 2005). Most of them are based on only one of the factors involved in the management process (demands, pressures, flow rates, leaks, etc.). To achieve optimal management of a WSS, it is necessary to develop DSSs based on the joint analysis of involved factors (Gonzalez Perea et al., 2017). Therefore, the ideal DSS should be built on the georeferenced hydraulic model and the WSS operating rules, fed with the information stored in the linked GIS.

As the implementation cost of new technologies is one of the most restrictive factors in medium- and small-sized water supply companies, the main goal of this research is to develop a methodology based on open-source software (Arias et al., 2015), which brings together a hydraulic model and a GIS, linked by a mobile application (APP) to support the digitization process of water supply networks. The developed system, named Integrated Tool for Water System Management (ITWSM), stores and uses categorized information of WSS, including the workers' know-how, to improve the operation and management of these facilities. It can be used to manage either WDS or WTS regardless of size. The implementation of this methodology provides an easy-to-use decision support tool, whose main benefits are the reduction in both failure repair costs and supply interruptions to end-users, due to better planning of the resources needed to fix breakdowns. ITWSM has been applied to a provincial WTS in Spain, managed by a public water company, as the starting point for the digitalization process needed in the management of urban water supply companies.

3.2 Methodology

The development of a DSS requires a previous digitization process of the WSS. This procedure starts georeferencing all the elements that comprise these systems, as well as their characterization (Poorazizi & Alesheikh, 2008). For this purpose, all available information (cartography, hydraulic installation plans, hydraulic device location and features, operation rules, etc.) is gathered and revised. These initial data are completed with in situ inspections of the WSS to verify, complete, and update them before their storage in a GIS. In this work, the free GIS software "Qgis" was used (Team, 2002).

From this information, the hydraulic model of the WSS was created using the open-source software "Epanet" (Rossman, 2000). Operation rules should also be introduced into the model. To validate the results, it is necessary to calibrate the hydraulic model with real flow and/or pressure data. The hydraulic model (HM) provides the distribution of flows and pressures at any point in the network. These variables are required to analyze the behavior of the WSS under different operation and water demand scenarios.

The HM was generated in a quasi-automated manner with the GIS data using the Qgis plugin "QWater" (Almeiro, 2007). The link between the GIS and the hydraulic model is a dynamic database (Moody & Ast, 2012) that is updated automatically when new information is introduced.

In order to facilitate communication between field workers and managers, the open-source and general-purpose app linked to a cloud-based cartographic representation platform, Google My Maps (Palen et al., 2015; Taylor et al., 2015), was adapted to support operation and maintenance tasks of WSSs (Google Development, 2007). This app allows the field workers to consult the GIS of the system and send information in real time about operations carried out in the WSS (e.g., pipe replacement, valve opening/closing, and leak repair) to the system managers.

3.2.1 ITWSM as Decision Support System for Urban Water Management

The proposed system, ITWSM, facilitates low-cost digitization of any water supply network. ITWSM is based on the three pillars present in all digitization processes: a geographic information system, a hydraulic model, and an app for data consultation. The system is characterized by the use of free software in all its stages. It also offers versatility and facility to progress without making frequent mistakes in the digitization process.

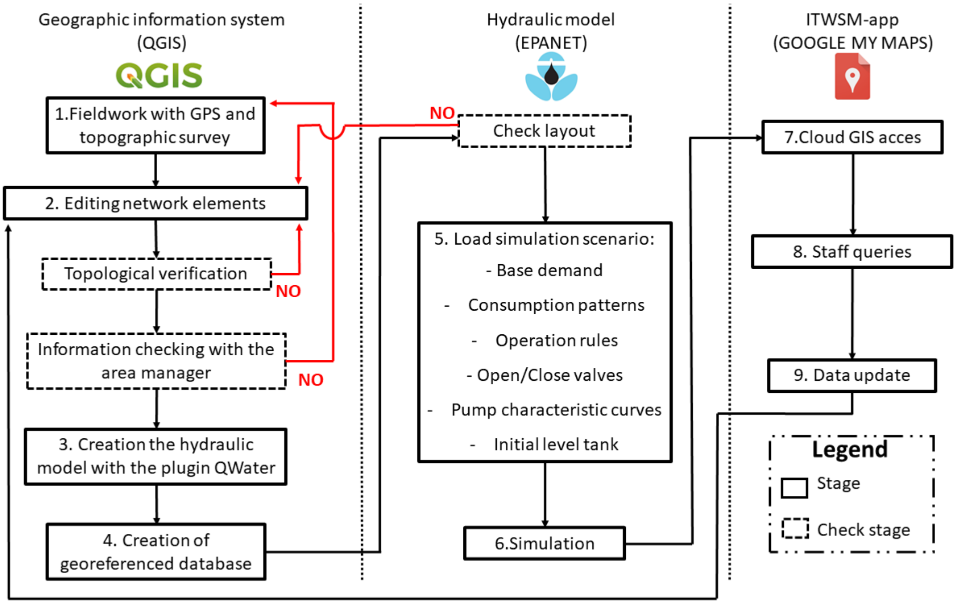


Figure 3.1. ITWSM flow chart.

ITWSM operational stages are shown in Figure 3.1. Information can either flow between consecutives stages or flow back to previous stages. There are several stages of control to check the quality of the information input. In case of error, it will be necessary to restart the process from previous stages. This diagram identifies the DSS modules with their main objectives: the creation of a reliable georeferenced database, the creation of a reliable hydraulic model, and the use of a mobile application to facilitate the data transfer and the communication between workers to keep the GIS information updated. Figure 3.1 shows the flow chart of ITSWM.

The proposed DSS, Integrated Tool for Water Supply Systems Management (ITWSM), consists of three interrelated modules: geographic information system, hydraulic model, and mobile application. All of them use free software: Qgis, Epanet, and Google My Maps. The functions and contributions of each module in the system are detailed below.

3.2.2 GIS Database

The territorial aspect (spatial location) of the components of a WSS is recorded in its GIS. For this reason, the dynamic database was developed within the GIS, which allows consulting data associated with georeferenced elements stored by thematic layers (Wienand et al., 2009). This facilitates the creation of statistics and reports on the status of the hydraulic devices and the operation of the hydraulic network. In addition, this type of software shows the data classified, facilitating its understanding by both field workers and decision-makers (Khadra & Lamaddalena, 2010).

Qgis is an open-source software in the field of GIS that has been commonly used in recent years (Sui, 2014). This is due to the existence of an active community that continuously improves the program and develops plugins that complete the software with specific functions, such as the possibility of spatial analysis with GRASS (Neteler et al., 2012) and the availability of various topological editing tools (Salata & Szylar, 2018).

For this reason, Qgis was considered suitable for the development of ITWSM.

First of all, available data were assessed and supplemented with data recorded in the field using a GPS device with a spatial resolution of centimeters (Czerniak & Genrich, 2002). Then, the information was exported in shapefile format to Qgis, creating an easily manageable point cloud. The next step was to assign an element to each GPS-marked point (drains, inlets, pipes, valves, pumps, tanks, or water meters). Next, each element was assigned hydraulic characteristics collected from project documents and field trips. In this process, additional GIS layers were included with information about the location of the municipalities (to identify their supply pipes), high-resolution orthophoto (to identify WSS elements), and a digital elevation model (to know the elevation of WSS elements).

In this way, each element is georeferenced by its coordinates and defined by its hydraulic characteristics. This information is the key element for the development of the HM, as well as the operation and maintenance of the WSS. A dated photograph completes the information of each element, as a reference of its current state. Once the network elements are identified, the piping layout is digitized. In order to minimize errors during the HM generation, it is necessary to carry out a topological correction of all the network elements, eliminating duplicated elements and incorrect layouts, using the Qgis topology tester. It is important to perform this process thoroughly due to the large number of elements to be analyzed. The WSS characterization process ends with the verification of the information stored in the GIS by its managers, to minimize the occurrence of errors in the next stages due to the large volume of data handled.

Table 3.1. Data model. Water supply system geospatial components.

WSS Components	***GIS Geometry***	***HM Geometry***	***Numeric Attributes***	***Text Attributes***
pipe	polyline	line	id, diameter, length, roughness coefficient, installation date	material, status, initial node, final node
localized consumption	point	node	id, coordinates, elevation, daily consumption	status, consumption frequency
drain valve	point	-	id, coordinates, elevation, diameter	status, receiving stream
suction cup	point	-	id, coordinates, elevation, diameter, nominal pressure	status, type
reservoir	point	node	id, coordinates, elevation, maximum flow, minimum flow, water level	status, type, watershed
valve	point	line	id, coordinates, elevation, diameter, nominal pressure	status, type, function
water meter	point	-	id, coordinates, elevation, diameter, nominal pressure, min flow, max flow, reading frequency, installation date	status, type
tank	point	node	id, coordinates, elevation, capacity, last cleaning date, height, diameter/side, maximum level, initial level	status, type, shape, chlorination, material, name
pump	point	line	id, coordinates, elevation, no. of pumps, electrical power, nominal pressure, nominal flow	status, name, connection type

It is important to store both hydraulic and geographic data in an orderly format in the geodatabase. Knowing the relationships between the geodatabase and the future hydraulic model will minimize the risk of making mistakes during the time-consuming process of creating the GIS.

Table 3.1 shows the components of the WSS, the geometry of each element in both the hydraulic model and the GIS, and the alphanumeric attributes associated with each element. Each hydraulic element is stored in a separate vector layer. Therefore, the GIS geometry of the elements corresponds to polylines or points.

The geometry of the elements in the hydraulic model suffers substantial changes due to the line-node topology (all nodes must be connected by linear elements). Some elements that are represented with a point geometry in the GIS correspond to a linear geometry in the hydraulic model. It should be noted that some elements identified in the GIS (drain valve, suction cup, and water meter) are not included in the hydraulic model. For this reason, the column "HM geometry" has some unfilled gaps.

The attributes considered to characterize the WSS elements are divided into data with a numerical format and data with a text format. The attributes marked in red are required to run the hydraulic model. The remaining attributes provide complementary information of the network studied. Some of the attributes not marked in red, which are considered important, can be introduced in the hydraulic model in the "label" section (e.g., the material of the pipes and the name of the tanks).

3.2.3 Hydraulic Model

The distribution of pressures and flows in WSS depends on the loading conditions of the system that change during the day and throughout the year. Previous knowledge of the evolution of both nodal pressures and pipe flows allows making opportune decisions to avoid service failure for users. Consequently, a permanently updated mathematical model of the WSS is needed to faithfully reproduce its actual operating conditions.

The geometry of the hydraulic model (layout) is obtained from the previously created GIS using intrinsic functions of the system (e.g., pipe direction tester, pipe connection repairer, selection by location, dimension assignment, and topology tester). Such functions can be programmed to automatically update the system layout when an element of the system is introduced, removed, or relocated.

The data required to generate the HM of a WSS are geometric (network layout, length and diameter of pipes, location of valves and pumps, nodes elevations, etc.) and hydraulic (material, roughness, coefficient of pressure loss in valves, etc.).

The open-source hydraulic simulator Epanet (Rossman, 2000) was used to create the model of the WSS. The QWater plugin of Qgis was applied to export the WSS geometry to the inp format, readable by Epanet. QWater automatically creates fictitious nodes in the HM to convert GIS point elements into HM linear elements. This process mainly affects valves and pumps. In addition to this important task, this plugin has a set of tools to facilitate the creation of the hydraulic model. These tools allow automatically obtaining the elevations of the elements from the digital elevation model, generating the identifiers of the elements of the hydraulic model, and locating errors due to duplicity of the identifiers. It is an intermediate step to obtain the mathematical model in Epanet from Qgis data.

To complete the HM generation process, it is necessary to introduce base demands and demand patterns of each consumption node, the operating rules of the pumps and tanks, the state of the valves (open/closed), and the characteristic curves of each pump installed in the WSS. These data are specific to each simulation scenario. Finally, Epanet is run to simulate the operation of the WSS under different operating scenarios and to detect possible failures before continuing with the digitization process.

In order for the hydraulic model faithfully reproduce the real behavior of the network, calibration of the model is necessary. Each modification of the GIS database requires the creation of a new hydraulic model. Consequently, it is necessary to calibrate each of the new models that are generated. The data for calibration can be provided from either telemetry systems or from periodically collected manual data, depending on the circumstances of each network and technique selected for calibration (Hossain et al., 2021; Tabesha et al., 2011).

Epanet is a free tool created by the United States Environmental Protection Agency (USEPA) to perform hydraulic simulations. It is characterized by calculating the pressure at the nodes and the flow in the pipes by solving the mass conservation equation for each node (Equation 3.1) and the energy conservation equation for each pipe (Equation 3.2) and for each pump (Equation 3.3) (Hossain et al., 2021; Muranho et al., 2015). To solve the equations simultaneously, Epanet uses the gradient algorithm (Todini & Pilati, 1988). To complete the linear equations that make up this system, Epanet uses the water demand assigned to each node (multiplying this by the hourly coefficient). To provide an accurate result, this software also needs the characteristic curve of the existing pumps.

$$\sum q_{ij} - D_i = 0, \tag{3.1}$$

$$h_{ij} = h_i - h_j = rq_{ij}^n + mq_{ij}^2, \tag{3.1}$$

$$h_{ij} = -w^2\left(h_o - t\left(q_{ij}/w\right)^n\right), \tag{2.3}$$

where q_{ij} is the flow rate in the pipe between node i and j, D_i is the demand at node i, h_{ij} is the head losses in the pipe between nodes j and i, h_i and h_j are the head at nodes i and j, r is a resistance coefficient, m is a minor loss coefficient, w is the relative speed of the pump, h_0 is the pump head when the pump is not operating, and t and n are coefficients of the pump characteristic curve.

Epanet allows simulating the operation of a WSS under different loading conditions both in stationary (permanent regime) and in nonstationary mode (extended period). Permanent regime simulations are used to know the flow and pressure at a concrete moment in time. This can be useful to understand the loading conditions at a particular point prior to any management and control work. Extended period simulations, on the other hand, provide insight into the operation of the network over a period of time. This can be useful to understand the evolution of the tank level over the hours of the day. With this tool, it is possible to study future situations by creating simulation scenarios that are close to reality. In this way, the situation is evaluated, and the best possible solution for each problem is studied.

The MRT is calculated using the hydraulic model. This requires georeferencing the failure and studying the municipalities affected by the failure. Each municipality affected will have an MRT, i.e., the MRT of the failure the minimum of the municipalities involved. To calculate the MRT, an extended period simulation is carried out and the time is determined from the start of the simulation (equivalent to the time the failure occurs) until each of the regulation tanks in the affected municipalities is empty (and, therefore, the end-users are affected by the failure). In order to carry out this process with guarantees of obtaining correct results, the rapid response of the operators in all the links, the correct georeferencing of the fault, and the availability of a calibrated hydraulic model are essential.

3.2.4 Mobile Application

The WSS database in GIS format is updated when the system is modified (new pipes, pipe relining, pipe rehabilitation, new valve, changes in operating rules, etc.).

In this work, the free mobile application "Google My Maps" was adapted to provide detailed information about the network elements to field workers and system operators within ITWSM. This app is a free Google service that allows the customized creation and edition of maps (Quirós & Polo, 2018). It is linked to Google Drive (Google Drive, 2012) to store data in the cloud and share information between different users. The customized app, ITWSM-app, allows field workers to consult the characteristics of the system elements and send to the manager of the system an online warning about changes in the WSS (leaks, breakdowns, repairs, etc.) to update the information in the database. The manager will analyze the information received before updating the database.

This tool is aimed at the following:

- Being a consulting tool of the network elements (pipes, valves, drains, tanks, catchments, pumps, flow meters, etc.), facilitating maintenance tasks.
- Recording system changes before updating the GIS database. Field workers will be able to report georeferenced changes in the system, through the app, filling in new questionnaires for new elements, and updating failure repairs in existing questionnaires. The app will create historical records of incidents for future studies and analysis.

ITWSM-app has been adapted to the management of a standard water supply company. Coordination between the field work teams and system managers requires smooth communication between both parties. A key aspect of this information is its spatial character that can be easily analyzed with ITWSM-app.

Its specific functions are as follows:

- Access from any mobile device with internet connection to the WSS database.
- Hierarchy of permissions to access information (query and/or permission to edit).

- Selection of the base map that best suits the query made (political map, relief map, or satellite map).
- Activation or deactivation of layers to improve the visibility of the map. Each layer collects the location and information of the same type elements. In other words, there will be as many layers as types of elements in the system. Each of these layers can be represented with a different icon and color, improving the readability of the map.
- Online/offline operation. Workers have access to the characteristics of the elements even if the mobile device is in an area without internet connection.
- Access to photographs stored in Google Drive (or the cloud) through the GIS attribute table to visualize each element.
- GPS guidance to locate any element with Google Maps (Google Maps, 2005).

The aim of the app is to facilitate the database update with the knowledge of field workers, who best know the location and state of the hydraulic infrastructures, as well as to detect the errors or changes in the database information. In this procedure, it is essential to have a GIS-HM operator to verify and filter the information before entering it into the system. Periodically, the contents of the GIS are revised to rectify the errors detected and are transmitted through the app to improve the database over time.

3.3 Results

3.3.1 Study WTS

The case study WSS is a WTS operated by the Córdoba's provincial water supply company (EMPROACSA), located in Southern Spain. This system is composed of three independent systems. The proposed methodology was implemented in the Eastern System, ES, covering an area of about 600 km^2 (Figure 3.2).

The number of inhabitants within the 10 municipalities in the ES area varies between 140 and 9635, with 60% of the population being concentrated in three municipalities.

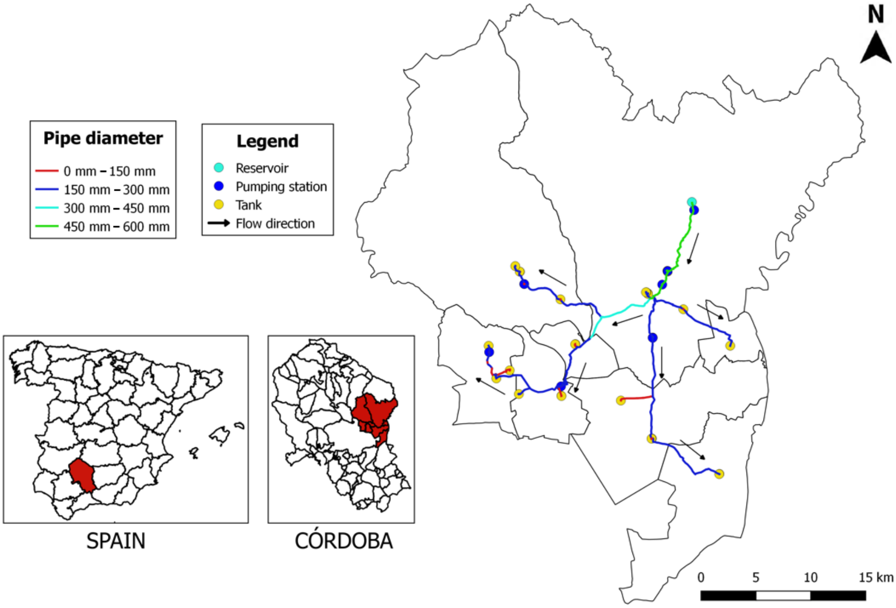


Figure 3.2. Location and layout of ES.

The Martín Gonzalo reservoir (280 m above mean sea level) is the water supply source for this WTS, which is purified in a drinking water plant with a capacity of 25,920 m^3/day to supply water to 44,200 inhabitants (Figure 3.3). The population varies seasonally, due to the recreational use of many houses in the area. The main industrial activity of the zone is the extraction of olive oil, whose maximum water demand occurs during the harvest period of olives (November to February), although it only represents 3% of the total consumption (Guadalquivir, 2015).

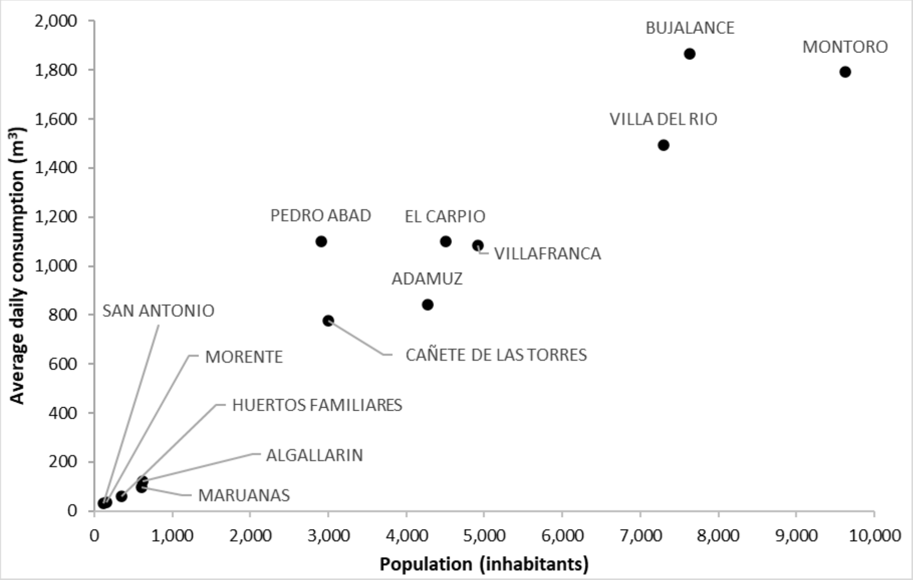


Figure 3.3. Population vs. average daily consumption.

Initially, the HM module was applied to estimate the pressure distribution in the 1219 nodes of the ES. When the consumption in the demand nodes is the daily average demand, the simulated pressure of 36% of the nodes is above 75 m, while 10% of them exceed 120 m. This high percentage of nodes with high pressure is due to the topography of the terrain. In this WTS, the most used material for pipes is ductile iron (67%), although 30%

of the pipes are made of fiber–cement. The age of the pipes using this disused material favors the risk of failures.

The average daily water demand is 250 L/hab/day. The annual mean consumption per municipality ranges from 12,733 m^3/year to 681,572 m^3/year, with the peak water consumption occurring during summer (from July to September).

The topology of the ES is branched, consisting of a main pipeline, with three secondary and several tertiary pipes. The network is made up of a total of 88.79 km of pipelines with different materials and diameters. In the ES, there are four pumping stations with horizontal centrifugal pumps that pump water between 69 mamsl and 180 mamsl to supply water to different municipalities. The ES also has 18 tanks with capacities between 80 m^3 and 7500 m^3.

3.3.2 Georeferenced Database

Each component of the system is located geographically and introduced to the database by storing its characteristics in an attribute table. Several site visits were carried out to inventory and characterize the hydraulic facilities in the ES. During the fieldwork, supported by EMPROACSA's staff, the most relevant elements were photographed, and their technical characteristics and current state were recorded. All this information was introduced into Qgis (Figure 3.4). Therefore, this tool allows joining dispersed information in a single database. The GIS facilitates the integral management of the ES. The accuracy of this procedure is critical to create a reliable hydraulic model.

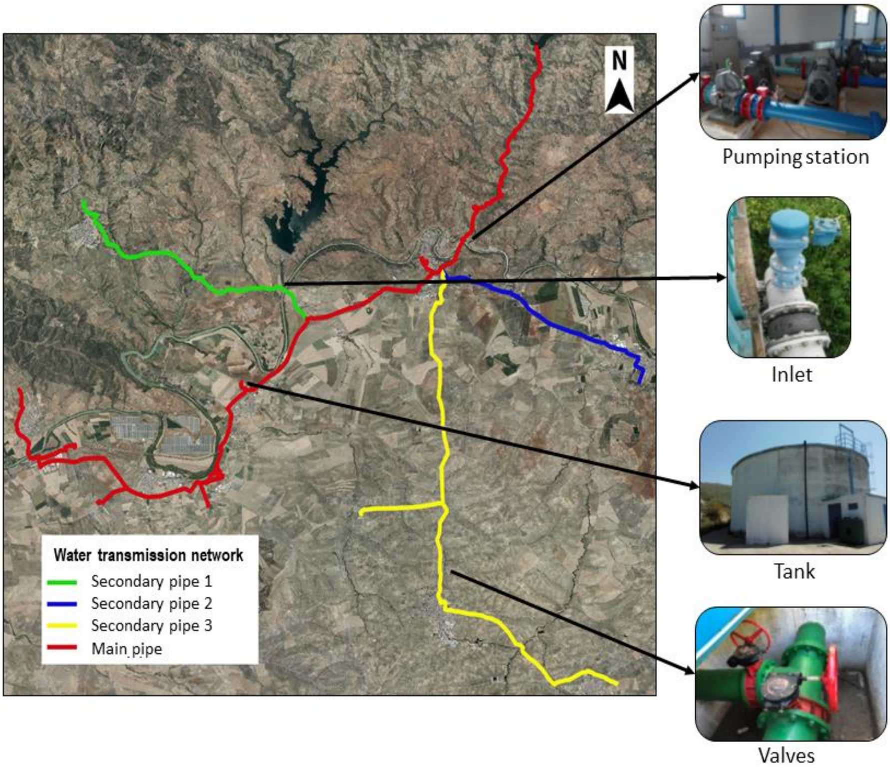


Figure 3.4. Geographical information system of the Eastern System.

3.3.3 Hydraulic Model

The hydraulic model, generated by Epanet, reproduces the working conditions of the network under different operating scenarios. The model's correct operation requires the inclusion in the model of all its components (Figure 3.5) such as pumping stations, tanks, reservoirs, valves, and pipes, as well as the operating rules of the system. The use of the QWater plugin allows generating the detailed hydraulic model of a real drinking water supply network in a simple way. This plugin serves to automate many tasks in this process, which would be difficult to perform manually.

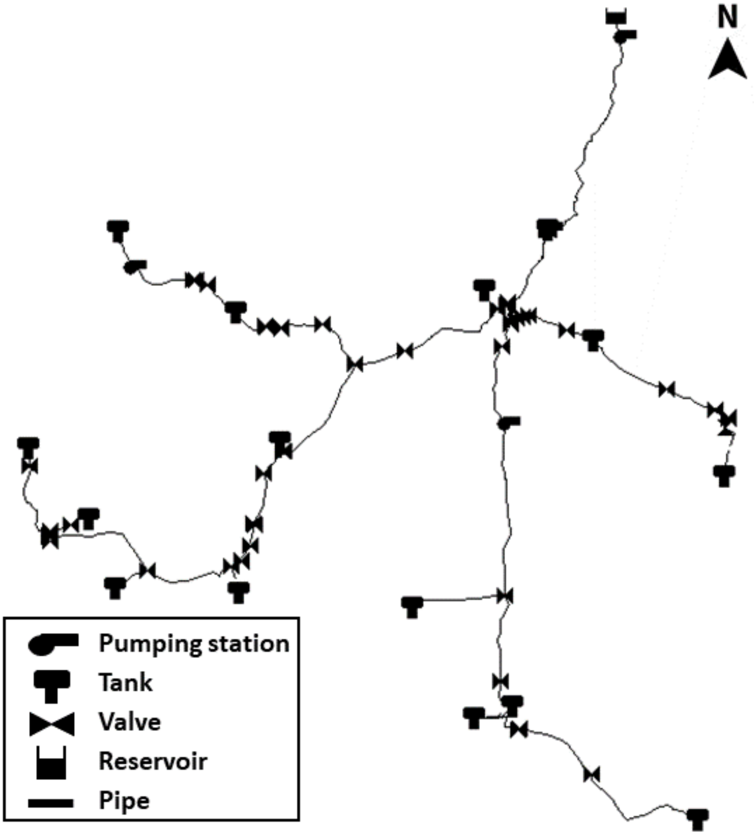


Figure 3.5. Hydraulic model elements.

The simulation of the hydraulic model provides the value of the main hydraulic variables in steady state or the evolution of these values over time at any point in the network when the nonstationary operation option is selected (Figure 3.6). This information must be processed by a qualified operator who analyzes pressure and flowrate distributions to take the appropriate decisions for each situation.

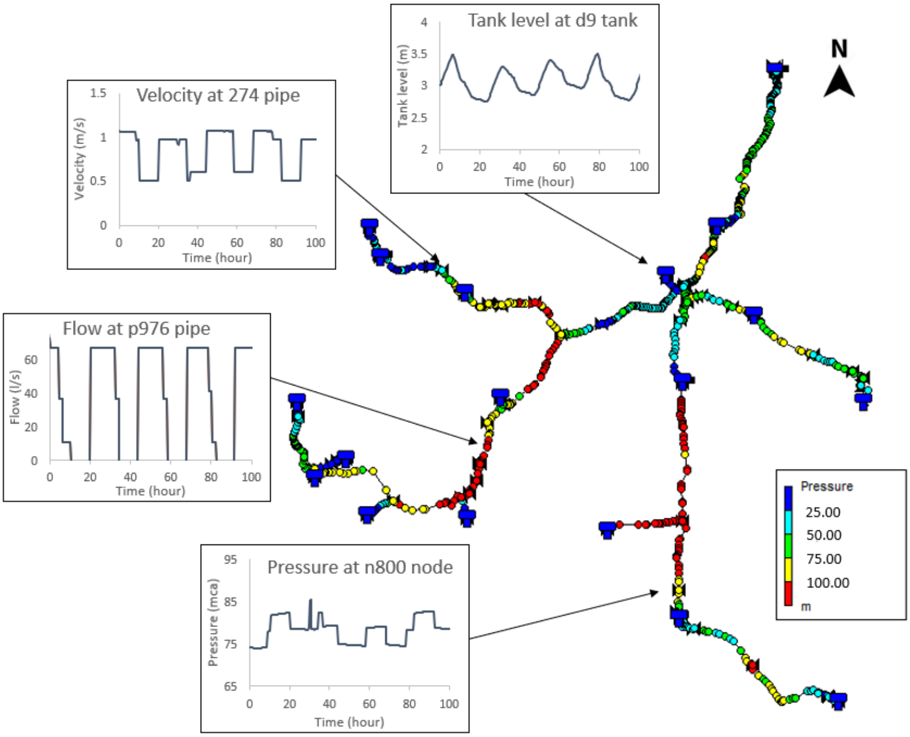
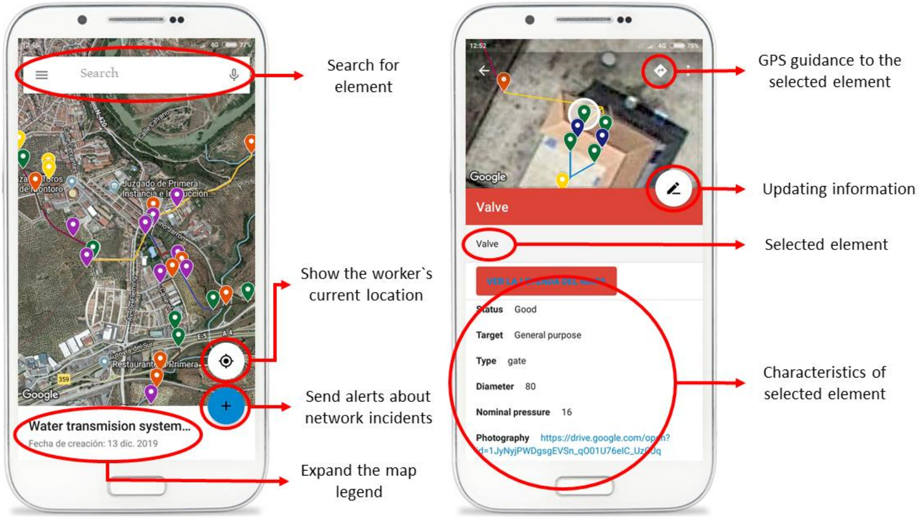


Figure 3.6. Results simulations of the ES HM (extend simulation period).

3.3.4 Mobile Application

ITWSM-app is a customized application of Google My Maps for WSS management. It has been applied to facilitate access of field workers of the ES to its GIS database with a user-friendly interface (Figure 3.7). This app allows maintaining the GIS updated with worker contributions, a highly valuable information source. The quality of GIS updates is critical for correct hydraulic model simulations. Users can update existing information and send warnings about network incidents, GPS guidance, etc.



Search for element

Show the worker`s current location

Send alerts about network incidents

Expand the map legend

GPS guidance to the selected element

Updating information

Selected element

Characteristics of selected element

Status Good
Target General purpose
Type gate
Diameter 80
Nominal pressure 16
Photography https://drive.google.com/op[illegible]n?id=1JyNyjPWDgsgEVSn_qO01U76elC_Uz[illegible]Jq

Figure 3.7. ITWSM-app graphical interface.

3.3.5 *ITWSM Application*

ITWSM has been applied to manage the breakdown repairs occurred in the study WTS. During 2019, 23 severe failures that required water supply interruptions were recorded. ITWSM is aimed at facilitating decision making when any failure occurs in the WTN as soon as the technical staff is informed of the incident. Then, the operation protocol (Figure 3.8) is followed.

The field operator detects the problem, performs an initial evaluation of it on site, and then, using ITSWSM-app, sends a description (including photographs) of the incident to the GIS-HM manager. The location of the incident is also recorded, using the GPS function of the operator's smartphone. The GIS-HM manager receives this information and identifies the elements and users affected in the GIS. After that, the HM is then updated to simulate the georeferenced failure in extended period mode to calculate the MRT as described previously. According to these results, the GIS-HM manager plans the repair of the failure. The database is continuously updated with the introduction/modification of elements after fixing the failure.

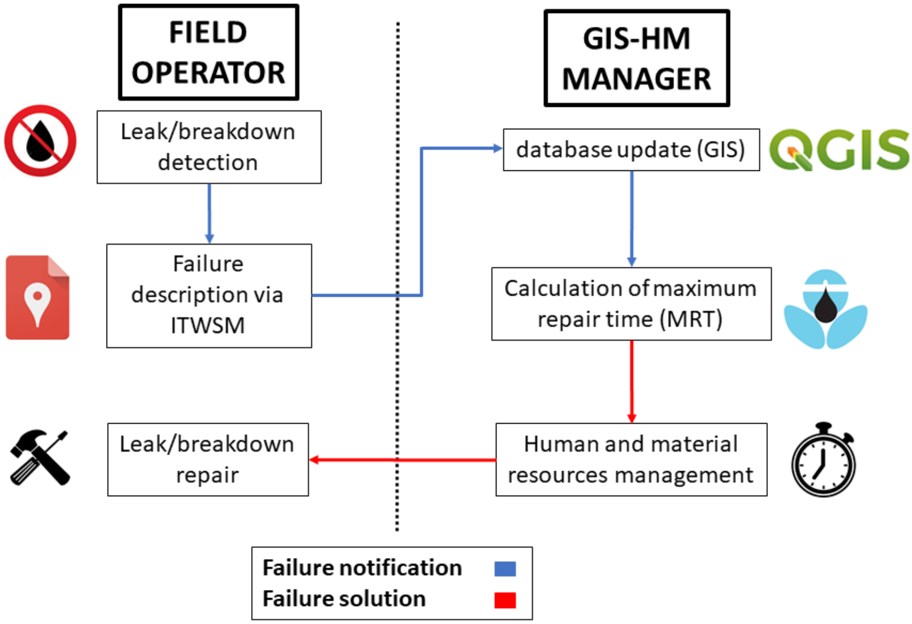


Figure 3.8. Failure fixing protocol.

The main objective of this methodology is to conduct an optimal management of human and material resources to minimize the repair time to avoid that any municipality could be affected by the failure.

ITWSM was applied to manage repair tasks of a breakdown occurrence in the main pipe of the WTS on 10 February 2020 (Figure 3.9). This breakdown affected four tanks when failure occurred. Firstly, once the leak was detected, the water supply was interrupted downstream of the failure point in the main pipe by field works and communicated through ITWSM-app to the system managers. Then, the hydraulic model was run to calculate the MRT.

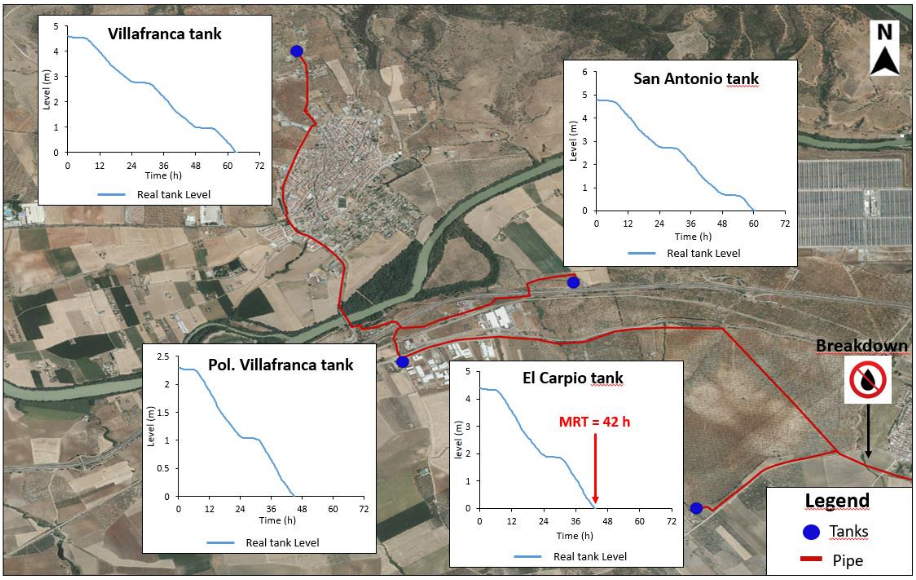


Figure 3.9. MRT estimation for the failure that occurred on 10 February 2020 in the studied WTS.

The water level in the affected tanks at the failure time must be known to identify which tank is more restrictive. The most restrictive tank is determined according to different criteria aimed at minimizing the impact of failures on the end users. Thus, the MRT could be the shortest time for emptying the reservoirs of the affected municipalities or the emptying time of the tank of the municipality with the largest population, as examples of criteria for defining the MRT. In this case, the emptying of the El Carpio tank was considered the most restrictive; therefore, it determined the MRT of the studied failure. Figure 3.9 shows the location of the tanks and the hourly evolution of the tank levels after the water supply was cut.

ITWSM facilitates the communication of incidents between personnel involved in decision making and breakdown repair workers and speeds up the repair process reducing reaction time.

3.3.6 Assessment of the ITWSM DSS

To demonstrate the effectiveness of the proposed DSS, Table 3.2 shows a comparison of the failure records for the years 2019 and 2020. The difference between the 2 years was the implementation of ITWSM. In 2019, there was no management system available, whereas, in 2020, the ITWSM was implemented.

Table 3.2. Comparison of breakdown repair costs in 2019 and 2020.

	2019 Season	**2020 Season**
Number of failures	23	21
Average repair time (h)	14	25
Average cost of part replacements (EUR)	1,498	1,472
Average cost of machinery (EUR)	278	114
Average labor cost (EUR)	344	247

In order to objectively evaluate the advantages/disadvantages of ITWSM, the following parameters were compared: number of failures (leaks or breakages that implied supply interruptions), the average repair time (time elapsed since the failure was detected until the supply is restored), the average cost of part replacement (pipes, valves, pumps, etc.), the average machinery costs (backhoe, truck, trailer, etc.), and the average labor cost, which depends on the number of workers (own or external) involved in the repair and their working time.

The number of failures in both years was similar. These data justify the objective comparison between the two periods. The average repair time was much higher in 2020 compared to 2019. The main explanation for this difference is the correct time management. Whereas, in 2019, all failures were repaired as quickly as possible, in 2020, once a breakdown was detected and the water supply was interrupted from the affected pipe, the situation was assessed and the MRT was calculated by ITWSM. Then the repair tasks were planned to use the available resources in an effective way. The increase in the average repair time did not imply a shortage of water for end users, as the repair times were smaller than the MRT of each failure. The increase in the average repair time did not lead to an increase in water losses. As soon as the breakdown were detected, the affected pipe was closed, and water losses were avoided.

This correct time management due to the implementation of ITWSM allowed a reduction in the machinery and labor costs (59.0% and 28.2%, respectively). The element replacement cost was very similar in both years. To achieve these results, the repair of leaks/breaks was planned in such a way that the repairs were carried out during the normal working hours of the workers (avoiding cost overruns due to overtime hours). A longer observation period is needed to validate these good rates. It is also necessary to implement the same methodology in other types of hydraulic networks (distribution water networks, meshed water network, large- and medium-sized companies, etc.).

3.4 Conclusions

ITWSM helps to reduce repair costs and water supply interruptions for end users. Through easy and quick communication between field workers and decision-makers, it is possible to improve decisions about where and how to act on each failure. The GIS and the hydraulic model integrated in ITWSM provide a source of knowledge for managers that can help to save water by an efficient failure management. An effective planning of available resources (human and material) can be carried out to fix failures before MRT is reached to avoid water outages. Efficient use of resources entails cost savings.

ITWSM allowed cost reductions in the presented case study. Average breakdown repair costs were reduced in the year that the proposed tool (ITWSM) was used. Mainly, machinery costs (59.0%) and labor costs (28.2%) were reduced due to better resource planning once the maximum repair time (MRT) was known. ITWSM allows improving the management of repair processes and, consequently, reducing water supply interruptions to end-users, thanks to the information provided by the hydraulic model on which it is based.

The ITWSM-app user can log failure data (e.g., breakdowns) in digital format. Information about location, staff, machinery, and material used in each repair is stored. The economic analysis of repair costs of the network elements that have undergone frequent repairs can be used to estimate the timing of their replacement by new elements.

The developed DSS and its app facilitate sharing information among different departments of the water service. The user-friendly interface of ITWSM-app facilitates the visualization of complex data, reducing the adaptation time of new workers who can make informative queries (location, hydraulic features, etc.) about any system element. The availability of ITWSM-app allows the continuous update of the database of all the network elements. The participation of the company's staff in the implementation of ITWSM is essential for the optimal management of the WSS.

The high costs of implementing new technologies increase the digital divide between large and small companies. The proposed DSS, based only on open-source software, allows the digitization of companies with limited financial resources. ITWSM provides users independence from commercial DSSs for water. A key feature of ITWSM is its modular nature as it is made up of separate open-source modules that can be replaced at any time by a new, more advantageous alternative.

The costs related to the implementation of this digitization methodology are low. This methodology does not have any costs associated with software (only free software is used: Qgis, Epanet, and Google My Maps) or material. The only resource required is personnel with the necessary knowledge to carry out these tasks. Currently, the need for knowledge related to open-source software is compensated for by the large amount of information available on the internet. In addition, the use of free software allows the company to have the control over the digitization process. Once the system has been implemented, there should be one or more people (depending on the number of hydraulic networks to be managed) in charge of updating the GIS/hydraulic model.

ITWSM has been successfully implemented in a real public water supply company to manage its WTS. A breakdown repair in this WTS was analyzed as a case study. ITWSM provides WTS managers with the parameter MRT, i.e., the time available to fix the failure to avoid water outages on end users. The comparison of the repair costs in 2019 and 2020 showed that the average repair cost was reduced by 13.6% in 2020 mainly due to the optimal planning of personnel and machinery involved in the repair works. This methodology is currently being implemented in other water networks of Córdoba's provincial water supply company in order to verify these values.

The WTS management approach described herein should be introduced progressively according to the staff characteristics of each water service. Younger staff can easily adopt technological tools, unlike workers close to retirement age that are often reluctant to use new technologies. This drawback could be minimized by offering training courses to show the advantages of mobile apps in daily work.

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4. Design and Implementation of a Pressure Monitoring System Based on IoT for Water Supply Networks

This chapter has been published entirely in the journal "Sensors", José Pérez-Padillo, Jorge García Morillo, José Ramirez-Faz, Manuel Torres Roldán and Pilar Montesinos (2020).

Abstract: Increasing the efficiency of water supply networks is essential in arid and semi-arid regions to ensure the supply of drinking water to the inhabitants. The cost of renovating these systems is high. However, customized management models can facilitate the maintenance and rehabilitation of hydraulic infrastructures by optimizing the use of resources. The implementation of current Internet of Things (IoT) monitoring systems allows decisions to be based on objective data. In water supply systems, IoT helps to monitor the key elements to improve system efficiency. To implement IoT in a water distribution system requires sensors that are suitable for measuring the main hydraulic variables, a communication system that is adaptable to the water service companies and a friendly system for data analysis and visualization. A smart pressure monitoring and alert system was developed using low-cost hardware and open-source software. An Arduino family microcontroller transfers pressure gauge signals using Sigfox communication, a low-power wide-area network (LPWAN). The IoT ThingSpeak platform is used for data analysis and visualization. Additionally, the system can send alarms via SMS/email in real time using the If This, Then That (IFTTT) web service when anomalous pressure data are detected. The pressure monitoring system was successfully implemented in a real water distribution network in Spain. It was able to detect both breakdowns and leaks in real time.

Keywords: digitalization; information and communication technologies (ICT); low power wide area network (LPWAN); Arduino microcontroller; ThingSpeak; web service

4.1 Introduction

Increasing the value of water as much as possible, especially in the arid and semi-arid zones of southern Europe (Kingdom et al., 2006) means improving the performance of water distribution networks. These regions frequently suffer prolonged drought periods (Vargas & Paneque, 2018) and this makes it increasingly difficult to secure and maintain sufficient quantities of drinking water, sometimes limiting water use in the area. A high percentage of the water distribution networks that operate in large cities have leaks that cause significant water losses. These inefficiencies are contrary to the European Commission's reference document (Lambert et al., 2015), which declares that water is a resource that must be managed sustainably and reasonably.

The current management models of water distribution systems aim to control the main hydraulic variables and ensure that these infrastructures are used efficiently. The decision-making process is based on objective data (Hollands, 2008). For this reason, numerous technologies have been developed to monitor hydraulic and water quality variables. Substantial progress is now being made in the development and implementation of intelligent water meters (digital water metering) based on an electronic core (Gosavi, 2017) and different communication systems to perform remote accurate readings (Alvisi et al., 2019). Several studies have focused on the benefits of these meters (Monks et al., 2019), which can be improved with a complementary set of pressure sensors located in optimal positions (Cheng et al., 2017; Sela & Amin, 2018) to detect and locate leaks (Lee et al., 2015; Rayaroth & Sivaradje, 2019). These sensor networks have led to the development of algorithms for real-time leak detection (Kayaalp, 2017). These advances have been implemented in pilot tests in water supply companies in order to check the reliability of these technologies and any issues related to their implementation (Beal & Flynn, 2014; March et al., 2017; Thiemann et al., 2011).

Digitization and the implementation of the concept "Industry 4.0" has created a new dimension in the management of hydraulic networks. The control of hydraulic parameters through the installation of sensors requires the storage and analysis of a large amount of data (Poljak, n.d.; Sedlak, 2017), opening the door to big data for water supply companies (Fazio et al., n.d.). These companies can obtain numerous benefits as a result of the correct analysis of the stored data, such as knowing the state of the infrastructure in real time (Díaz et al., 2017), detecting uncontrolled water leaks or losses (Britton et al., 2013; Farah & Shahrour, 2017), the ability to bill their clients more accurately and periodically (Raykar et al., 2015), and predict consumption to anticipate possible problems (González Perea et al., 2018; Li, 2011).

The success of current monitoring systems applied to water distribution networks is based on the adoption of new technologies related to the Internet of Things (IoT) (Tomás Robles et al., 2015). The IoT allows wireless connectivity between elements of the system in order to process data and make the best decision (Abdelhafidh et al., 2017). Conventional monitoring systems based on SCADAs (Dobriceanu et al., 2008), PLCs (Bayindir & Cetinceviz, 2011), etc., have been replaced by modern IoT systems, and have moved from centralized systems to decentralized systems where data are accessible from anywhere with an Internet connection. According to (Tomas Robles et al., 2014) the IoT applied to water management helps to increase productivity without cost increases, improves system efficiency and fosters the creation of new business models based on full control of the network.

The communication networks best suited to water supply systems are low-power wide-area networks (LPWAN) (Cheng et al., 2017). The companies responsible for these supply systems generally have some commonalities: hydraulic infrastructures that occupy a large surface area, work areas with little or no mobile coverage, very diverse topology that makes it difficult to access certain points, etc. LPWANs can be easily adapted to different scales, which facilitates their implementation in water supply networks, therefore, the correct functioning of the system is not constrained by a possible future extension of the network or an increase in the monitoring variables.

LPWAN networks are characterized by low energy consumption and low cost, and they allow for connection between far-away objects. This telecommunication system fits perfectly with applications that require little transmission information (Sanchez-iborra & Cano, 2016). This communication architecture is now implemented frequently due to the ease of its development, the online available resources, and the existence of a community of developers who share their projects and results. The low cost of developing these wireless networks has led to an increase in their use, and they are favored by the growing number of compatible modules offered by major companies in the electronics sector (Paul & Buytaert, 2018). The LPWAN networks that are currently used are Sigfox, LoRaWAN and NB-IoT.

In recent years, the use of open source technologies in sensing projects has increased for two main reasons: low component prices and the easy use of these technologies (Raza et al., 2016). Open source platforms allow the development of large monitoring and telemetry projects at an affordable price. Technological obsolescence can be avoided because they are versatile and able to install new improvements to update libraries or improve the codes. Additionally, there is a growing community of developers (makers) who facilitate rapid self-learning due to the large amount of online resources. There are several examples of the application of open source platforms to solve real problems including a hydrological monitoring system based on Arduino Mega (Hund et al., 2016), an intelligent irrigation system that uses an IoT sensor network with Arduino Uno (Abba et al., 2019) and the monitoring of water quality with wireless communication using Arduino Leonardo (Yu et al., 2019).

To ensure the success of a monitoring system, it is necessary to properly store the data that is generated (Gubbi et al., 2013). Currently, low-cost cloud databases (IoT platforms) are emerging and these require low complexity in order to facilitate their manipulation among users (Zdravkovi et al., n.d.). In addition to their main function, the orderly storage of information, they provide other secondary services such as friendly data visualization, the generation of results reports, search for patterns that follow similar behaviors, data analytics, etc. (Botta et al., 2015). Hence, it is necessary to use these tools to manage large amounts of data and information.

The main goal of this research was to develop a low-cost and robust system for pressure monitoring in water transmission systems to detect leaks and breaks in real time. This system requires a measuring and signal transmission device that must be able to operate in locations without connection to the grid and the number of these devices should not affect the operation of the monitoring system. For this purpose, a low power wide area network (LPWAN) was used with a communications system based on the internet of things (IoT). The system was designed to use open source software as well as low-cost hardware in all its functions (data collection, data transmission and data visualization). This feature makes it easy to adapt to any water supply systems and to replace both software and hardware elements with the most appropriate alternatives for each situation, thanks to the system's modular architecture. In comparison with other conventional pressure monitoring systems, the proposed system allows pressure data with a high frequency (fundamental characteristic to develop an alert system in real time) to be obtained; this offers great autonomy (the data collection device manages the optimal energy needed for its operation). The reliability of the developed prototype was tested in a real water transmission network to detect and locate leaks in real time, reduce the duration of system failure periods and maintain costs (improving its efficiency), which are key factors in the optimal management of water distribution systems.

This manuscript is structured as follows. Section 4.1 introduces the problem of the inefficiency of water distribution networks and presents studies related to the monitoring of hydraulic variables. Section 4.2 describes the architecture and components of the proposed pressure monitoring system, as well as their operation. Then, the case study is presented in Section 4.3. It characterizes an actual water distribution network where three measuring devices have been tested. Section 4.4 shows the actual results of leak detection under different working conditions, followed by a discussion of the strengths of the proposed system versus other commercial systems (Section 4.5). Finally, the conclusions are provided in Section 4.6.

4.2 Material and Methods

The architecture of LPWAN networks is simple: the final nodes collect the data recorded by the sensors and connect directly to the base station to transmit the information and store it in a cloud database, where the data are analyzed and then sent to be visualized by internet-connected devices (computers, tablets or mobile phones) (Figure 4.1). This architecture makes the system modular. The data acquisition nodes work independently, so the installation of a larger number of nodes does not affect the behavior of the system. Another advantage is the low power consumption of each node, which improves the autonomy of the connected devices. This type of communication network allows limited transmission of information bytes, but enough to guarantee the detection of water leaks.

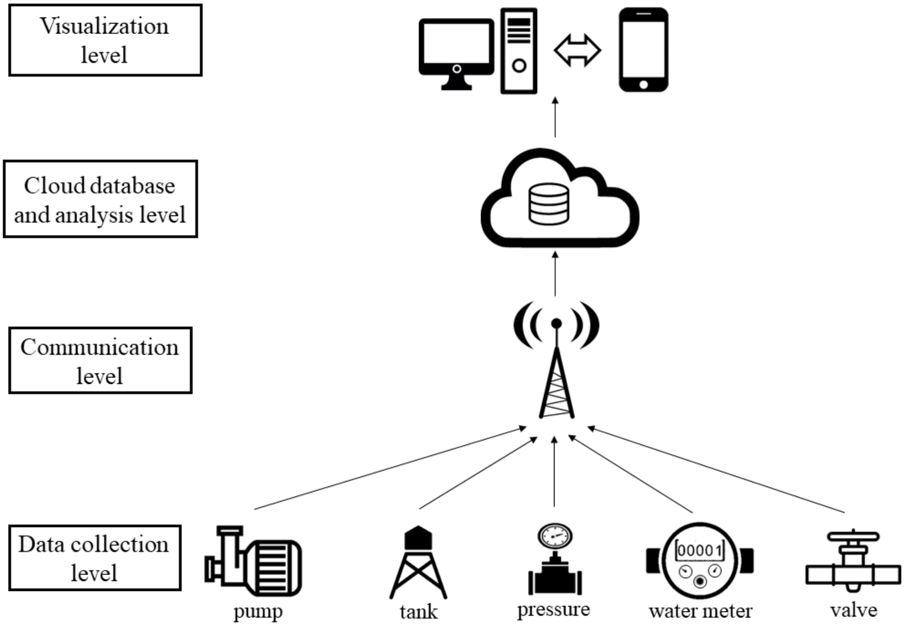

Figure 4.1. Typical low-power wide-area (LPWAN) network architecture for water supply systems.

This type of architecture has four levels:

- Data collection level (DCL). This is the basic level of the system. This level contains the sensors that transform hydraulic variables into electrical signals. It is possible to measure the water level in the tanks, the pressure and flow inside pipes, the state of valves, the number of operating pumps in a pumping station, etc. The collection data nodes, where information is recorded and sent are independent from each other.
- Communication level (CL). The communication system chosen must be suitable for the application of the information recorded in the sensors. LPWAN networks are oriented to communicate distant elements using a narrow band. This has the advantage of using very little energy during the transmission process. Each device forms an independent node based on the IoT technology. In this way, the error of one node does not affect the correct operation of the others.
- Cloud database and analysis level (CDAL). The elements of storage and the interpretation of data coincide at this level. Cloud data storage allows remote access to the collected data.
- Visualization level (VL). The information is accessible by computers and smartphones/tablets.

The following diagram (Figure 4.2) shows the architecture of an IoT pressure monitoring system (IPMS). The different elements that make up the system are organized in the levels described above. A detailed description of each level of IPMS is given next. The system is characterized by its low cost and the use of widely available technologies. This facilitates the replication of this system in any water supply network. The system for collecting and sending data works independently of the analysis and visualization platform, which facilitates its integration into existing monitoring systems.

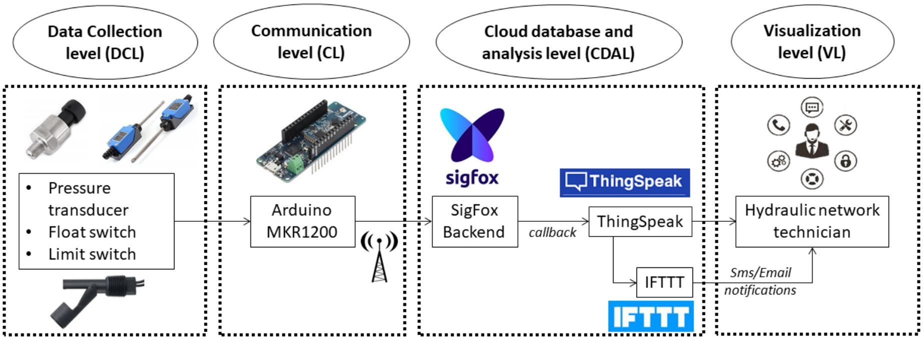

Figure 4.2. Internet of Things (IoT) pressure monitoring system (IPMS) architecture.

4.2.1 Data Collection Level

Each node is composed of a pressure transducer that converts the hydraulic pressure into an electrical signal. Its measuring range should cover the range of possible pressures at the sensor location to ensure a reliable reading of the variable and to avoid damage to the rest of the electronics. Any change in the operational conditions of the system affects the pressure in the pipes according to the energy conservation equation between two points of the network (Equation 4.1).

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 + H_A - H_L - H_E = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 \qquad (4.3)$$

where P is the pressure; v is the flow velocity; z is the elevation; γ is the specific weight of water ; H_A is the energy added by a pumping station; H_L are friction losses in pipes and H_E is the energy extracted by turbines. This demonstrates that leaks or breakdowns in the water supply network (modify v in Equation 4.1) will give pressure readings out of their ordinary range at downstream points. This monitoring system will detect and locate leaks in real time, thus improving the hydraulic performance of the system. The pressure measurement is also used to understand the behavior of the hydraulic system in different operation scenarios, in order to improve the management of adverse situations.

A Honeywell transducer (PX2AN1XX250PSACX model) was used to measure the pressure. This device converts the pressure into a voltage signal ranging from 0.33 V to 2.97 V. The supply voltage is 3.3 V and the supply current is 4 mA, being fully compatible with the output voltage of most microcontroller boards that exist on the market. It also has an IP69K degree of protection, which allows it to be in contact with water without being damaged. The working range of this transducer ranges from 0 bars to 17.23 bars, which covers the normal operating pressure range in the case study network.

In addition, two sensors were included in the pressure measuring node to make it robust. As electronics will be set inside a box, these sensors are used to control its status. A limit switch will send alarms in case of theft of electronics material and a float switch will also send alarms if the box is flooded, which may occur in nodes located in the lowest elevation points of the network.

4.2.2 Communication Level

Communication Network:

The chosen solution is based on the use of Sigfox network operator. Sigfox is a LPWAN and it allows for both sending and receiving messages from any Sigfox device. In this case, one-way communication is used, i.e., only sensor readings will be transmitted. The 140 daily messages allowed by the Sigfox network are sufficient to monitor the pressure evolution in water supply networks, and data are obtained every 11 min.

The main reason for choosing this communication system is its ease of application. The Sigfox network is used as a service. The customer pays per year and per connected device. Users do not have to install and maintain a communication network. Therefore, this wireless communication system is suitable for water management companies that cover a large area, and they can avoid the major investment required to implement and maintain their own communication network.

It is important to study the coding structure of the messages transmitted by Sigfox network in order to minimize the space required (Sigfox, 2018). This strategy reduces the time of transmission of the message, thus increasing the autonomy of the device. Long messages mean long radio signals, and this implies greater use of the battery. The size of each section is determined by the number of circumferences (4 bits).

Hardware platform:

The hardware platform chosen to build the prototype was the Arduino MKRFOX 1200 (Arduino, 2019). It can be connected to the Sigfox network with a free subscription for a period of one year. This board consists of the Atmel SAMD21 microcontroller and the ATA8520 radiofrequency module with Sigfox connection. The main specifications are: 48 MHz speed, 256 Kb Flash memory and 32 Kb SRAM memory, 28 digital pins and 10 analog pins, and 3.3 V power supply. Figure 4.3 shows the layout of the output pins on the board chosen for this project, the Arduino MKR FOX 1200.

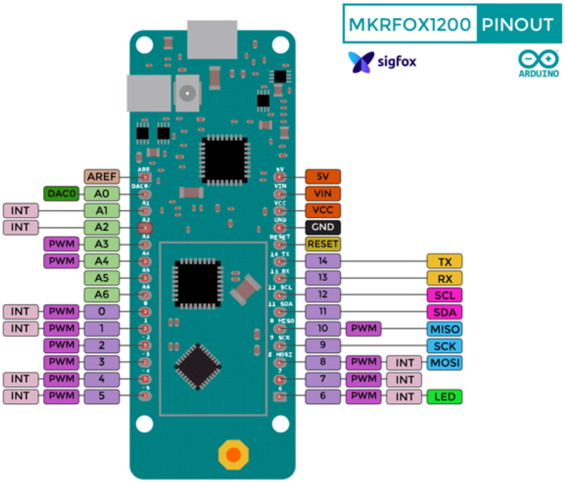

Figure 4.3. Arduino MKR FOX 1200 pinout scheme.

The Arduino microcontroller collects the information provided by the sensors and periodically sends data via the Sigfox network. To do this, it has been programmed in C++ language through its integrated development environment (IDE) following the activity diagram shown in Figure 4.4.

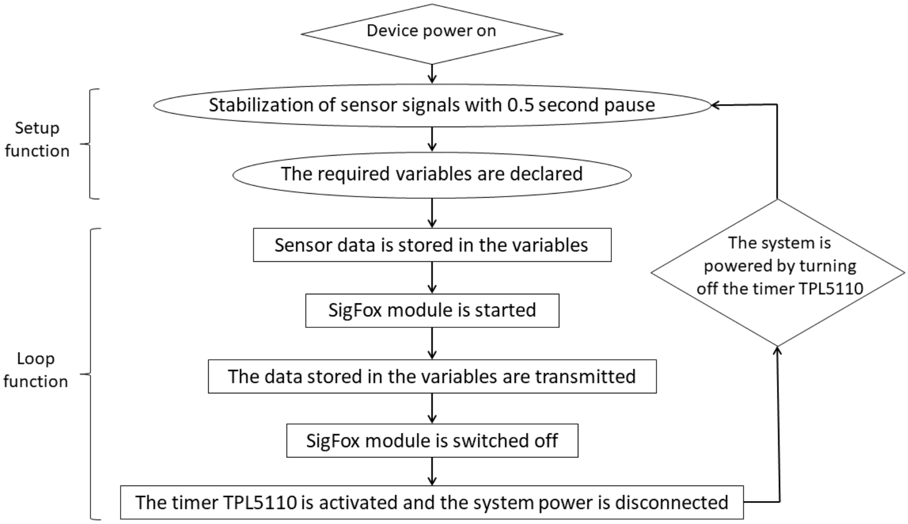

Figure 4.4. Activity diagram showing the functions performed by the Arduino microcontroller.

Arduino does not perform data storage functions. It just reads the information generated by the sensors and transmits it. The data are stored together in the cloud with data from other nodes. The designed code is aimed to send information efficiently with low energy consumption and minimal execution time. After two consecutive cycles, the energy supply to the microcontroller is interrupted by the timer to extend the autonomy of the batteries.

Timer:

As the Arduino MKR1200 board has a deep sleep consumption of approximately 12 mA, it is necessary to equip the prototype with a low power timer like TPL5110 to save battery power during each sending cycle. This element is placed between the energy supply source and the rest of the components. This element aims to cut the current supply to the whole device, thus avoiding energy consumption by the rest of the components between sending cycles.

The TPL5110 allows power interruptions in periods ranging from 100 ms to 7200 s, and it consumes 35 nA during these periods. The duration of each interruption is determined by the value of the resistors connected to a timer pin. The TPL5110 is able to manage a voltage range between 1.8 V and 5.5 V (which is compatible with the Arduino MKR FOX 1200 board that operates at 3.3 V).

Battery:

Li-ion 18650 rechargeable batteries were chosen as the supply source. These batteries have a nominal voltage of 3.7 V and a capacity of 2900 mAh (Hallaj et al., 2000). This type of battery is ideal for IoT devices because they have a low level of self-discharge and they require minimum maintenance.

The nominal voltage of the Li-ion 18650 batteries is consistent with the operating voltage of the Arduino MKR FOX 1200 board (up to 6 V via the VIN pin), the supply voltage of the pressure transducer (3.3 V) and the operation of the TPL5110 timer (1.8 V–5.5 V). For this reason, it is not possible to install several batteries in series. A set parallel cells was used in order to increase the capacity and improve the autonomy of the device.

Autonomy:

The device´s consumption was monitored using a YOKOGAWA DL850E oscilloscope (Figure 4.5). It is necessary to know its consumption during each data transmissions cycle to estimate the battery autonomy. Each transmission period has a duration of 12 s in which the device goes through four different stages:

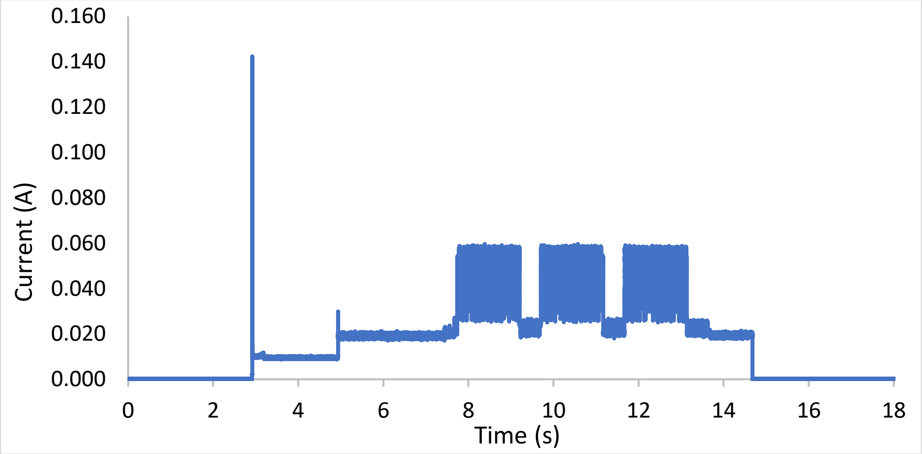

Figure 4.5. Device consumption per data transmission cycle.

- Timer on: this is the status of the device between message sending cycles. The intensity during this period is 0.05 mA because only the timer TPL5110 uses energy.

- Peak consumption: this occurs when the microcontroller starts the Sigfox connection module with a peak intensity of 0.14 A.

- Signal stabilization: this period always last 2 s during which the signal is stabilized for a correct reading of the sensor data. In this period, the intensity of the prototype reaches 0.010 A.
- Sending information: this period varies according to the length of the message. The duration of the sending is approximately 10 seconds while the current ranges between 0.020 A and 0.060 A.

In order to quantify the number of Li-ion 18650 batteries, which are arranged in parallel and required to provide the device with reasonable autonomy, the following sensitivity analysis was carried out. Table 4.1 shows the autonomy of the device according to the number of cells arranged in parallel, the frequency of sending messages and the electric consumption at each stage of data transmission.

The results obtained in the theoretical simulations of the autonomy of the device are gathered in Table 4.1 and show that the best option is to connect four batteries in parallel. The set of four parallel cells has a total capacity of 11,600 mAh and the autonomy of the device is up to 3 years, sending information every 15 min (which is suitable for monitoring pressure in water supply systems). After this period, the batteries must be replaced by fully charged batteries. Autonomy is a key issue when IoT devices are scattered over large areas, as in the case of water transmission systems. This dispersion combined with the inaccessibility of certain monitoring points requires maximizing the battery lifespan for the applicability of the device.

Table 4.1. Autonomy of the device expressed in days and years depending on the number of batteries connected in parallel.

Message Frequency	Sending Consumption	Standby Consumption	1 Battery		2 Batteries		3 Batteries		4 Batteries	
(minutes)	(mAh)	(mAh)	(days)	(years)	(days)	(years)	(days)	(years)	(days)	(years)
11	0.5304	0.05	208	0.57	416	1.14	625	1.71	833	2.28
12	0.4862	0.05	225	0.62	451	1.23	676	1.85	901	2.47
13	0.4488	0.05	242	0.66	485	1.33	727	1.99	969	2.65
14	0.4167	0.05	259	0.71	518	1.42	777	2.13	1036	2.84
15	0.3890	0.05	275	0.75	551	1.51	826	2.26	1101	3.02
20	0.2917	0.05	354	0.97	707	1.94	1061	2.91	1414	3.88
30	0.1945	0.05	494	1.35	989	2.71	1483	4.06	1977	5.42
40	0.1459	0.05	617	1.69	1234	3.38	1851	5.07	2468	6.76
50	0.1167	0.05	725	1.99	1450	3.97	2175	5.96	2900	7.94
60	0.0972	0.05	821	2.25	1641	4.50	2462	6.75	3283	8.99

Control circuit module:

Figure 4.6 shows the connections between the different elements that compose the printed circuit board (PCB). Five terminal blocks were arranged to facilitate the connection of the sensors and the battery. A nano-switch was also installed to disconnect the power supply for repair or maintenance of the device.

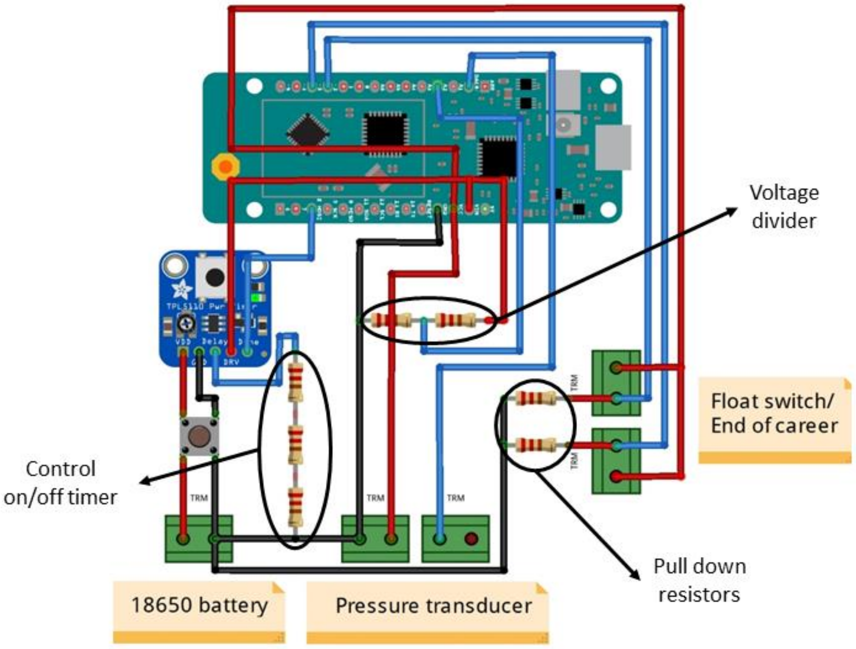

Figure 4.6. Prototype printed circuit board (PCB) wiring diagram.

The resistors shown in Figure 4.6 have various functions. There are three resistors arranged in series to control the timer on/off. The two resistors connected in series form a voltage divider to measure the battery level (4.2 V at maximum capacity), without damaging the Arduino board (input of 3.3 V maximum). Finally, the two remaining resistors are pull down resistors, which establish a logic state (LOW) on an Arduino input pin when it is on standby to avoid false input pin states caused by noise generated in electronic circuits.

Register box:

All the elements of the prototype were placed in a waterproof register box to protect and isolate them from the adverse weather. The box has an IP65 degree of protection to guarantee the device durability (Figure 4.7). Three cable hoses were used to connect the PCB and the sensors. Each cable exits the box through a cable gland to maintain the water-tightness of the prototype.

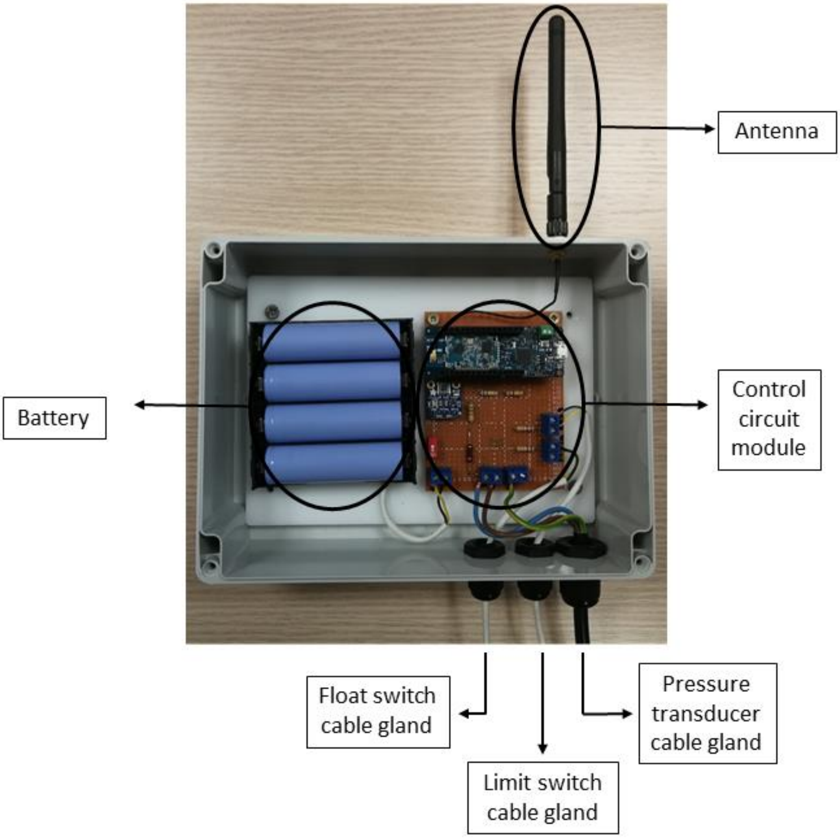

Figure 4.7. Internet of Things pressure monitoring system (IPMS) electronics.

To improve the quality of the radio signal, the antenna was placed outside of the register box using a rubber gasket to maintain the water-tightness. An adapter was used to convert the ufl output from Arduino to sma to facilitate the installation of an antenna that best suits the location of the device. The antenna is the only element that affects the quality of Sigfox connectivity, hence its importance in the device. For this specific case, an omnidirectional antenna with8 dB power was used.

4.2.3 Cloud Database and Analysis Level

Sigfox backend:

As described above, the maximum amount of information that can be transmitted per message is 12 bytes, and up to 140 messages per day and per node can be sent. The information included in each message is as follows:

- Battery level: this parameter varies between 3.2 V (lower limit) and 4.2 V (upper limit). The lower limit is determined by the Arduino power supply voltage. The upper limit is determined by the maximum capacity of the battery. This value is transmitted as an unsigned integer in decivolts to increase its accuracy. This variable controls the replacement of the batteries to prevent the device from not sending information.
- Pressure: indicates the pressure of the water inside the pipe. The measurement range is between 0 bar and 17.23 bar. The data is transmitted as an unsigned integer in centibars.
- Cover status: indicates the status of the manhole cover where the pressure transducer is installed. The data is transmitted as an unsigned integer with values of 0 (open door) and 1 (closed door).

- Flooding: indicates the state of the manhole where the pressure transducer is installed. The data is transmitted as an unsigned integer acquiring values of 0 (good conditions) and 1 (flooded sump).

Table 4.2 summarizes the measured variables and the type of data used for transmission via the Sigfox network.

Table 4.2. The variables and their format transmitted in each message.

Message	Possible Values	Category	Byte Position	Units
Battery level	0–255	uint8	0	decivolts (dV)
Pressure	0–65.535	uint16	1 2	centibars (cbar)
Manhole cover status	0–255	uint8	3	0 = open door; 1 = close door
Flood sensor	0–255	uint8	4	0 = good conditions; 1 = flooded manhole

The data from the different nodes installed in the network are collected in the Sigfox backend. This platform is a tool to manage messages and check that the communication is correct but it is not able to visualize the data. The information is received in a hexadecimal format.

To facilitate the display of data, callbacks redirect the data from the Sigfox backend to an alternative storage and visualization platform. In this case the ThingSpeak platform was used. The callbacks are made by identifying the URL of the ThingSpeak platform in the Sigfox backend, pointing out the variables to be transmitted. So, every time a message arrives at the Sigfox cloud, the chosen data are redirected to the ThingSpeak platform where they can be easily managed and displayed.

ThingSpeak platform:

ThingSpeak is an IoT platform developed by MathWorks to receive, visualize and analyze data in the cloud. This platform is very intuitive, so it is widely used. It has two versions: the free version that connects up to four devices and a maximum of 8200 messages/day; and the paid version can be adapted to the needs of each client depending on the number of connected devices and the number of messages per day.

This work is based on the free version. The messages are received via REST API calls and stored in the cloud database. The data are accessible from any device with an internet connection. In addition, ThingSpeak allows the use of the following modules to perform extra functions:

- Matlab Analysis: to analyze the information received using Matlab tools.
- TimeControl: this plugin is used to program actions in a regular schedule, relaying the performance of some functions with the data on other modules. For example, every 30 minutes an analysis is programmed to detect pressure drops with Matlab Analysis.
- React: this module continuously analyzes the input data to perform actions when events occur. This module analyses the data

to send an alarm when there is loss of data due to coverage problems

- ThingHTTP: it uses the HTTP communication protocol to transmit messages to other devices or web services.

Pressure information can follow two paths through the ThingSpeak platform (Figure 4.8):

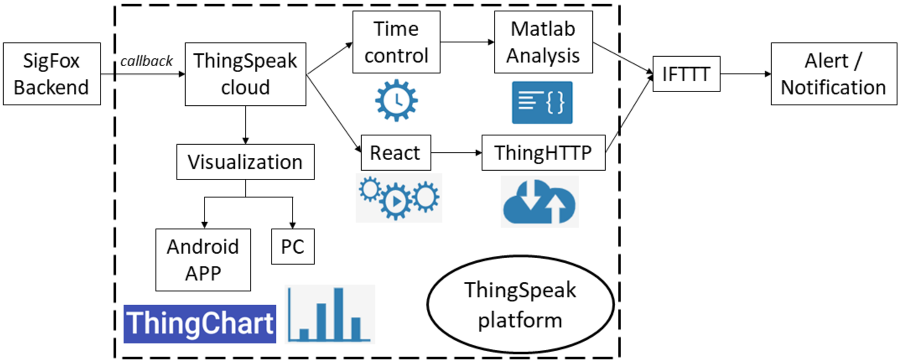

Figure 4.8. ThingSpeak platform functions in IPSM.

- A quick analysis of the information can be performed with the React module based on previously defined pressure threshold values. If the pressure exceeds these thresholds, HTTP calls are made to send alerts via email to an external platform.

- For more complex analyses it is necessary to use the TimeControl module, which performs periodic analyses of historical or live data linked to the Matlab Analysis module. Matlab Analysis has great analysis potential as it uses functions from additional MATLAB toolboxes. The outcome of these analyses may prompt a HTTP call to an external platform to send warnings to the operation and maintenance personnel of water service companies. For instance, the following code is aimed at detecting sudden pressure drops and their return to normal values (Figure 4.9).

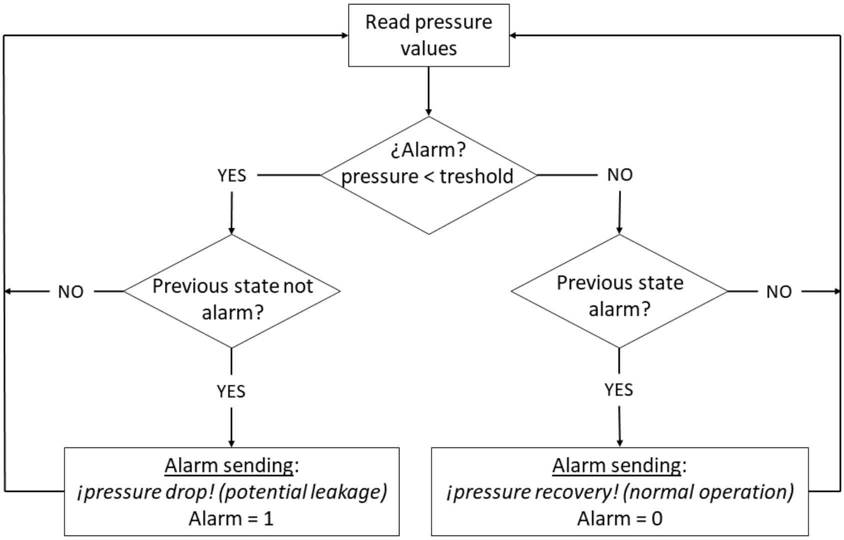

Figure 4.9. Flowchart to detect pressure variations.

IFTTT (If This, Then That):

The last element in the cloud database and analysis level is the platform, ”If This, Then That” (IFTTT). This web service programs actions to automate different tasks. The user must formulate a condition and define a reaction to that condition. The objective of this tool is to identify anomalous situations from the received data and to automatically send alerts via e-mail.

The IPMS includes warnings in response to out-of-range pressure oscillations, if the manhole cover where the device is installed is opened, if the sensor box is flooded or when the battery is almost discharged. Water utility managers will receive emails with real-time information on the occurrence of these events. They receive instant information about failures that enable them to make decisions to revert these situations as quickly as possible.

4.2.4 Visualization Level

At this level, the water utility staff have access to pressure data in real time. Data must be shown in a friendly and intuitive way. The IPMS allows data consultation from any device with internet access through its website. The ThingSpeak platform also has an APP to take queries from smartphones (Figure 4.8). This facilitates data-based decision making in any case: for the staff in the office and for the maintenance personnel that work out of the water service offices.

The IPMS sends email warnings when anomalous system performances occur. This ensures a quick response from the water service staff. Both data and emails can be visualized on web platforms and smartphone APPs, which facilitates the communication of information to decision makers.

4.3 Case Study

The developed prototype was installed in the water transmission system (WTS), which supplies drinking water to the municipalities in the province of Córdoba (Spain). This WTS transports water from the Martín-Gonzalo reservoir to the municipalities located in the eastern part of the province with a population of 44,200 inhabitants in an area of about 600 km^2 (Figure 4.10).

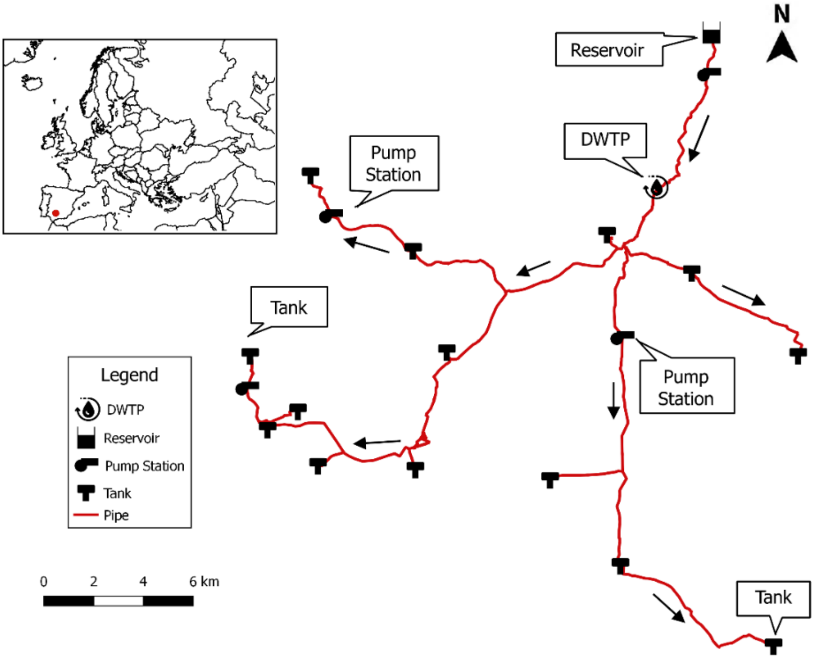

Figure 4.10. Location and layout of the hydraulic network studied.

The number of inhabitants varies between 140 and 9635 in the 10 municipalities that comprise the study area. Sixty percent of the population is concentrated in three municipalities. The average water demand is 250 L/hab/day, with an average annual consumption ranging from 12,733 m^3/year to 681,572 m^3/year in the municipalities in the area.

The WTS consists of a total of 88.79 km of pipes of different material and diameter, as well as 18 tanks with a capacity of 80 m^3 to 7500 m^3, 2 pumping stations and a drinking water treatment plant (DWTP).

The Sigfox signal quality in the study area was accurately measured before the sensors were installed. The results are shown in the Sigfox signal level map (Figure 4.11) and provide key information for choosing the optimal location for the sensors.

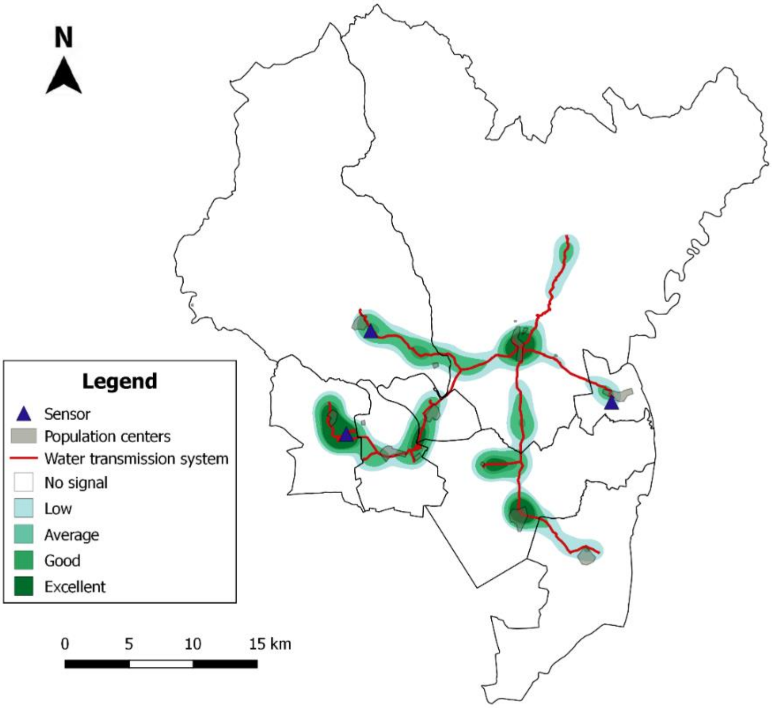

Figure 4.11. Distribution of Sigfox coverage intensity over the water distribution network.

Figure 4.11 divides the signal quality into five categories: no signal, low, average, good and excellent. These categories were constructed according to two parameters: the received signal strength indicator (RSSI) and the number of stations receiving the message. The signal quality is better in areas close to towns with larger population and worse when the distance from them increases. Seventy-five percent of the WTS has acceptable coverage, allowing the Sigfox system to be used as a communication network for the designed pressure sensors.

4.4 Results

Three pressure measuring devices were installed at different locations to test the performance of the designed prototype: a tank, a pump station and an inlet (Figure 4.12). In each location, a valve isolates the installation point of the device from the water flow. The different locations were selected to check if the prototype works properly under different operating conditions.

Figure 4.12. Prototype installation.

Once the devices are installed, they begin to store data in the cloud database. If the pressure values are in the range previously estimated as optimal, the system will continue to store values. These can be consulted from any PC or smartphone/tablet with internet connection. In this way, it is possible to see the real-time response of the hydraulic network to the different regulation operations or the seasonal changes typical in this type of network. If there is a drop in the pressure below the defined threshold in any of the data recording nodes, the system will send an alert via SMS or email to the corresponding operators depending on the area of occurrence. Therefore, it is necessary to have the email and phone number of the responsible operators in each zone. The system tries to unify data and simplify its visualization in decentralized hydraulic networks such as transmission supply systems.

Leakage/breakdown detection:

Figure 4.13 shows the pressure data recorded at an inlet during a leakage in the main pipe of the water transmission system. A leak event consists of four stages:

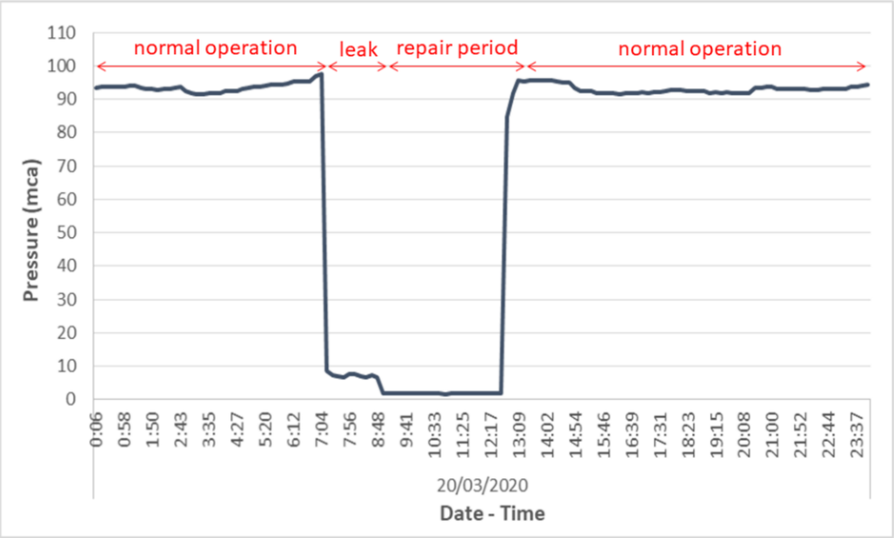

Figure 4.13. Pressure diagram in a leak event.

- Regular operation: the recorded pressure data are in the expected range during this period.

- Leak occurrence: pressure data recorded by the sensor are not in the expected range.
- Leak repair period: the pressure recorded during the pipe fix period will be 0 due to the interruption of the water supply by the leaking pipe and the repair work is carried out.
- Back to normal operation: once the leak has been repaired, the pipe flow is restored to the usual operating pressure.

The IPMS is intended to detect the occurrence of leaks and breakdowns and locate where they occur when a warning is received from any of the sensors installed in the WTS. The rapid and accurate location of the leakage/breakdown point in pipeline networks crossing large unpopulated areas is key to leakage control. Real-time information about the pressure levels reduces the failure time (detection, diagnosis, and repair) and therefore the volume of water losses, thus improving the performance of these systems.

Detection of anomalous pump operation:

The pumping station studied is located on a secondary pipe that supplies water to a municipal tank. The start/stop of the pump depends on the level of the tank. The pressure sensor was installed in the pipe connecting the pump to the tank. Analysis of the pressure variations allows the detection of a malfunction of the pump and the correction of possible system failures. As Figure 4.14 shows, false start events were detected, and were repeated at certain periods of time. This can cause long-term pump deterioration, as well as unnecessary energy consumption. By studying the pressure record, the cause of the false starts was identified, that is, an erroneous signal from the tank level sensor that sent a start command to the pump control system.

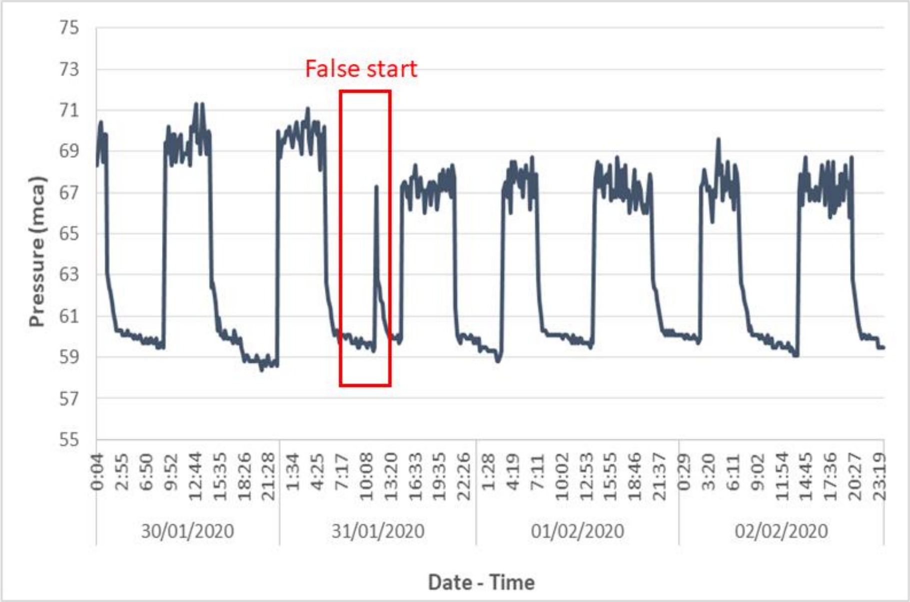

Figure 4.14. Pump false start.

Analysis of the pressure evolution records in the previous pumping station also revealed other unusual operations. The pump was found to be running at one-hour intervals, when the normal duration of periods of non-operation of the pump was 7–8 h. This situation was due to the existence of a leak in the distribution system (from the municipal tank to the final consumers) with the consequent continuous drop in the level of the tank fed by the studied pumping station. Therefore, the pump had to increase its frequency of operation to compensate for leaks in the water distribution system. This anomaly was quickly detected by the IPMS (Figure 4.15).

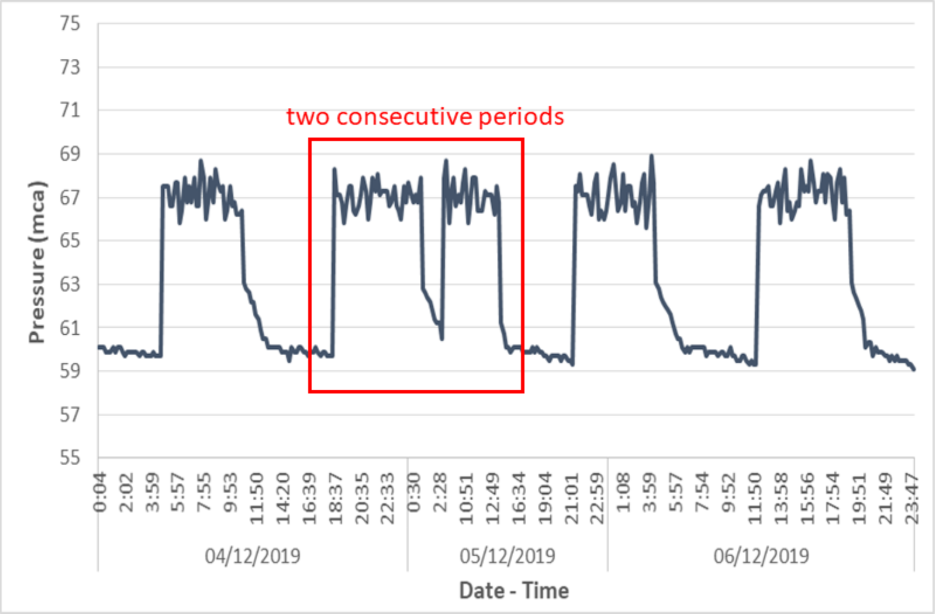

Figure 4.15. Two consecutive pump periods at a pumping station.

IPMS costs:

The production costs of a single sensor of IPMS is detailed in Table 4.3. In this work, the cost of the communications system (Sigfox) was not considered as Sigfox use is free for the first year. The free version of the ThingSpeak platform was also used. Finally, the IFTTT tool is free, so there was no additional cost.

Table 4.3. Production costs of the IoT pressure sensor.

Concept	Price (€)
Arduino MKRFOX1200 board	35.0
TPL5110 timer	4.5
Li-Ion Battery	12.0
Enclosure	15.0
Battery holder	2.5
Antenna	3.0
Limit switch	4.0
Float switch	2.0
Pressure transducer	83.0
Others	3.5
Total costs	164.5

4.5 Discussion

The results confirm the adaptability of the Sigfox network for the communication of sensors located in different elements of a WTS, despite their dispersion over a large number of territories. No telecommunication infrastructure is required to use the Sigfox system, only the payment of an annual (17 □approx.) fee per connected device from the second year of use.

The proposed IoT platform, ThingSpeak has many advantages (for example, powerful advanced calculation engine, easy data visualization, online database, etc.) but the free version used in this work is limited to four devices at most. Therefore, when IPMS is composed of more than four sensors, it is necessary to have a paid subscription, whose annual cost can vary between 70 □and 580 □depending on the functions subscribed.

Compared to the existing pressure monitoring systems on the market, the proposed IPMS is 45%–65% cheaper. In addition, some of the commercial pressure measurement systems often require an initial investment in telecommunication infrastructure. By using the SigFox network, this type of initial cost is avoided. According to the proposed architecture, the maintenance of servers is also avoided, which is a problem for most water service companies as they usually do not have specific staff to perform these tasks. This saves indirect costs in the implementation of the IPMS. The proposed architecture is easily scalable by increasing the number of information logging nodes. Each node acts independently, so the failure of one of them does not entail the collapse of the entire system.

The versatility of the Arduino MKRFOX 1200 microcontroller makes the proposed prototype easily upgradeable. The correction of operating errors of the device or an extension of its functions can be done by replacing the code loaded on the Arduino board. In addition, the use of this microcontroller is becoming more widespread and more detailed documentation on its operation is available. The large community of developers, along with its low cost are the main advantages in the use of this microcontroller.

Another notable aspect of the proposed prototype is its adaptability to different communication technologies. Although Sigfox technology has proven its suitability for this case, it is possible that in the near future there will be another technology more suitable for urban water supply systems. According to the layout of the control module, only the Arduino MKRFOX 1200 microcontroller should be replaced by a board that can communicate using another technology. The operation of the selected auxiliary components is not affected by the installed microcontroller.

Currently there are boards in the Arduino family that are compatible with several telecommunication technologies: WiFi (MKR 1000, MKR 1010), LoRa (MKR WAN 1300, MKR WAN 1310), GSM (MKR GSM 1400), Narrow Band IoT (MKR NB 1500) and audio and video processing (MKR Vidor 4000). All these boards have the same input and output pin layout as the chosen MKR FOX 1200 board. This would facilitate adaptation to future change in communication technology.

4.6 Conclusions

The IoT pressure sensor prototype, as an IPMS node, as well as the architecture of the communication, processing and information display system based on open source and low-cost technologies proved their applicability as a real WTS pressure monitoring and warning system. IPMS is a robust and reliable low-cost pressure monitoring system that is able to sends alerts regarding leaks, breaks and abnormal operation in pumping stations.

The system developed is versatile as the nodes can be operated in locations without connection to the conventional electrical grid with autonomy for up to 3 years thanks to the use of the TPL 5110 timer, which reduces energy consumption. The prototype, based on the Arduino MKR FOX 1200, provides data every 15 minutes on the pressure, the battery level and the state of the manhole where it has been installed (open/closed cover and flood warning).

IPMS architecture is modular (including information collection, data transmission, storage and display). In each module, any element and/or software can be replaced by another of similar characteristics to facilitate the updating/upgrading of the technologies used and the integration of these data into another existing telemetry system. In addition, dependence on trademarks is avoided.

The combination of low-cost and open source technologies implemented in IPMS minimizes the initial investment and maintenance costs of monitoring key hydraulic variables in the operation and maintenance of water supply services. These are very important incentives for the digitalization of the management of water supply companies, especially for companies with limited economic resources.

The evolution of IPMS in the near future could be directed to the reinforcement of its autonomy with the incorporation of a connector for photovoltaic panels in nodes in suitable locations. Also, the time between measurement cycles could be reduced by using a (non-volatile) EEPROM memory, which accumulates the data recorded in several measurements and sends them every 11 minutes (minimum period between sending cycles in Sigfox).

Finally, the IPMS functionality could be extended by incorporating an advanced ThingSpeak calculation module (MATLAB) to calibrate the hydraulic model of WTSs and simulate the behavior of the system under different operating scenarios based on pressure measures.

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5. IoT platform for failure management in water transmission systems

This chapter has been published entirely in the journal "Expert System with Application", José Pérez-Padillo, Francisco Puig, Jorge García Morillo, Pilar Montesinos (2022).

Abstract: In aging water supply systems, many components have exceeded their service life. Consequently, tools are needed to efficiently manage the failures in these systems. This work describes the development and implementation of a web tool for the management of breakdowns in water transmission networks. The proposed tool, called wAIter, consists of a network of wireless water pressure sensors that send real-time data to an IoT platform. The core of the platform consists of a rule-based decision algorithm, which detects and classifies failures based on the recorded pressure values and then sends an alert to repair them. In addition, wAIter uses the mathematical model of the hydraulic network to estimate the maximum repair time without causing supply interruptions. This information is key in the decision-making process to repair breakdowns and facilitate repair work management. Finally, the results of the implementation in a real water transmission network are presented.

Keywords: decision support system, wireless sensors, artificial intelligence, web services, information and communication technologies (ICT), digitization.

5.1 Introduction

The current growth of the world's population requires the careful management of available resources. The United Nations predicts that up to 6.5 billion people will live in urban areas by 2050. This upward trend in population density in large cities increases exposure to extreme weather events (Herrera et al., 2016) and longer periods of drought are alerting researchers to the importance of good water resource management (Butler et al., 2014).

The age of many water distribution systems considerably affects their operation. These systems have been in service for more than 50 years, so a significant number of their components (pipes, valves and pumps) have exceeded their lifespan, in addition to being manufactured with obsolete materials. Consequently, the frequency of failures tends to increase over time (Winkler et al., 2018). This has a negative impact on the performance of water supply networks which, together with the increasing trend of energy prices, makes the modernization of these infrastructures essential (Hernandez & Kenny, 2010).

The operation of water transmission networks (WTN) that convey water from sources to regulation tanks in municipalities is conditioned by their dispersion in the territory. These networks are made up of long pipes (tens of kilometers in length) located in non-urban areas, which makes it difficult to monitor all the key points of the network on site daily. In addition, given the large diameter of the pipes to adequately transport large flows, leaks in WTNs result in the loss of substantial volumes of water.

Numerous techniques have been developed to improve the performance of large water supply networks. In addition to the traditional techniques of periodic acoustic measurements (Cody et al., 2020; Fuchs & Riehle, 1991) and minimum night flow analysis (McKenzie & Seago, 2005), there are techniques to analyze data from the SCADA data acquisition system in real time and detect leaks (Romano et al., 2014; Wu et al., 2010) or compare real data to the data generated by hydraulic models (Al-Khomairi, 2008; Shao et al., 2019). The optimal placement of sensors in hydraulic networks to maximize fault detection in the network has also been studied (Soldevila et al., 2018).

However, these techniques have important limitations to implement them in real systems. On numerous occasions the technology has only been validated in the laboratory (Fereidooni et al., 2020). The implementation costs are high, since they require a large number of sensors to ensure acceptable results. In addition, to apply current machine learning techniques, historical data series are needed at several points in the network.

The development of new telecommunication systems based on low power wide area networks (LPWANs) is driving the development of telemetry and data acquisition systems to collect large amounts of information (Lalle et al., 2019). Systems based on the Internet of Things (IoT) are enabling the decentralized monitoring of large hydraulic networks and providing access to information in real time from any point with an internet connection (Apostol et al., 2021; Narayanan et al., 2020). To efficiently manage these large hydraulic infrastructures, their digitization is essential.

Digitization is the only way to apply Big Data techniques to the recorded data and facilitate the daily management tasks of this type of facilities, thus making them safer and more resilient to adverse situations (Makropoulos & Savic, 2019).

This paper describes the development and implementation of an IoT platform aimed at fault detection in drinking water transmission networks using open-source software. The core of the platform is a rule-based decision algorithm, which detects and classifies faults using only the pressure data recorded by the linked network of low-cost wireless pressure sensors. Upon detection of a fault, the system sends alerts and estimates the maximum repair time without causing supply outages, facilitating the management of repair works. The applicability of the proposed system has been tested in a real WTN.

The rest of this article is organized as follows. Section 5.2 describes the architecture of the IoT platform for WTNs. Section 5.3 explains the functions of the different modules of the platform. Section 5.4 presents a case study of the implementation of the platform. Section 5.5 discusses the results and Section 5.6 concludes.

5.2 IoT platform architecture

The architecture of the IoT platform proposed in this work is organized into three independents but connected layers (Figure 5.1). The platform is called wAIter, a combination of the words “water” and “artificial intelligence”. The wAIter platform architecture allows adding, deleting, or updating the modules and components of the layers without affecting the system architecture. These layers are described below.

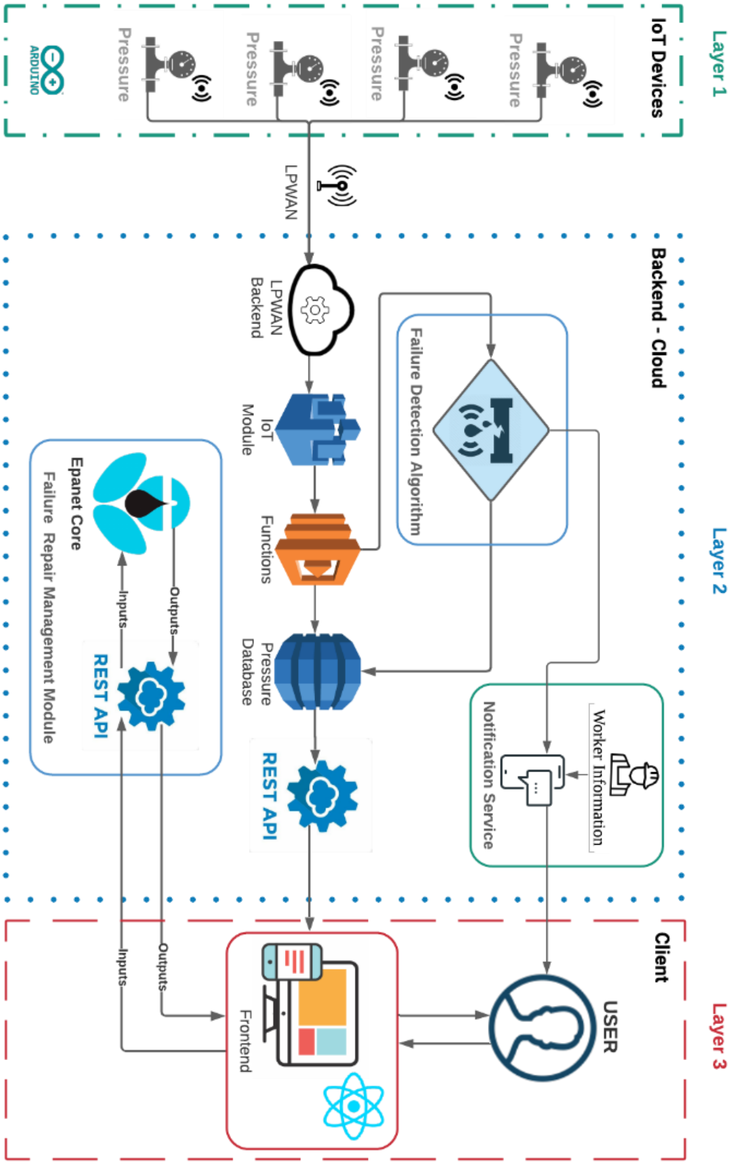


Figure 5.1. Architecture of the pressure monitoring system.

5.2.1 Layer 1: Data collection

Layer 1 contains the IoT sensors that record the required variables in WTNs. The sensors are controlled by Arduino-type microprocessors and send the information to the cloud using LPWAN technology. Each device has a unique identifier that allow the elements in the other layers of the platform to identify the sensor that captured each data.

5.2.1.1 Pressure sensor network

This level contains the sensors that transform the hydraulic variables involved in failure detection (e.g., pressure) into electrical signals. Ad-hoc communication nodes have been developed for this research (Pérez-Padillo et al., 2020). These nodes can read different types of signals (4-20 mA, analogue signal, digital signal, I2C signal) and can also be powered in three ways: with batteries, with a small photovoltaic module or by connecting the device to the conventional electrical network (Figure 5.2).

Each device is equipped to host an Arduino MKR family hardware board. These boards are composed of an Atmel SAMD21 microcontroller. All of them have the same input and output layout and are compatible with the rest of the electronics of the measurement device. The Arduino microcontroller collects hydraulic data at different periods and disconnects the system between measurements to save battery power. This helps to reduce the energy consumed in each reading cycle and increase the autonomy of the device.

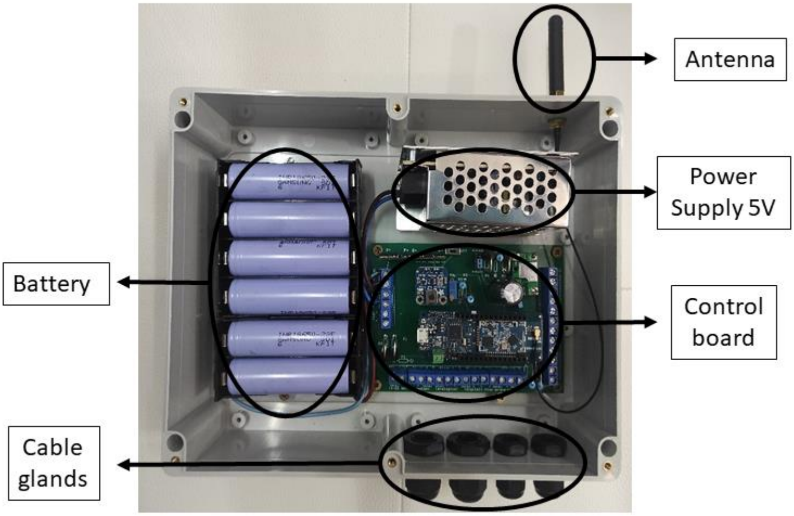


Figure 5.2. Communication node components.

The communication node acquires and periodically transmits the pressure data recorded by the pressure transducer. The pressure records are used to characterize the operation of the system. Thus, pressure values out of the normal range indicate system malfunctions.

5.2.1.2 Wireless communication network

The expansion of IoT systems is driving the development of LPWANs. Due to the range and power consumption of these networks, they are ideal for communicating scattered points in large and often difficult to access territories, where WTN monitoring systems are often located (Singh et al., 2020). The most widely used LPWAN communication networks are Sigfox (Purnama & Nashiruddin, 2020), LoRaWAN (Cesana & Redondi, 2017; Semtech Corporation. Lora Overview, n.d.) and NB-IoT (Chen et al., 2017), whose main features are shown in Table 5.1.

Table 5.1. Comparison of low power wide area networks.

Attribute	**NB-IoT**	**LoRa**	**SigFox**
Operation frequencies [MHz]	700-900	868	868
Band	Cellular, licensed	ISM, unlicensed	ISM, unlicensed
Transmit power [dBm]	23/35	14	14/27
Bandwidth [kHz]	180	125	0.1/0.6
Range (km)	<15	9 km (Urban) 50 km (Rural)	10 km (Urban) 50 km (Rural)
Data rate	DL 50 kbps UL 50 kbps	DL 50 kbps UL 980 bps	DL 600 bps UL 100 bps
Infrastructure deployment	No	Yes	No
Expansion	Low	High	High
Compatible Arduino microcontroller	MKR NB 1500	MKR FOX 1200	MKR WAN 1310

The selection of the most suitable communication technology depends on each application case. The IoT sensor described in the previous section is versatile, so it can communicate with any of the LPWANs in Table 5.1 using the corresponding microcontroller. The Arduino MKR family has different boards, each of which is adapted to a communication system: LoRa (Arduino MKR 1300), Sigfox (Arduino MKR 1200), Wifi (Arduino MKR 1000), GSM (Arduino MKR 1400), and Narrow Band IoT (Arduino MKR 1500).

5.2.2 Layer 2: Backend

The backend layer provides the platform services and contains the utilities for sensor control, data analysis and storage, notification, application programming interfaces that conform to the constraints of representational state transfer architectural style (REST API) allowing for interaction with REST web services (Kumar Polu, 2018), and the failure identification algorithm. The development of the backend in the cloud allows new services to be added without affecting the system architecture, as well as to scale and/or replicate the platform on other servers and connect it to any client or service with their own interface.

In this work, the Amazon Web Service (AWS) platform has been chosen to offer PaaS (Platform as a Service) type services, thus avoiding the need to manage the web infrastructure (hardware and operating systems). This feature facilitates platform development and implementation. The architecture has been developed to easily add or remove modules, thus ensuring the scalability of the system. The modules that form the backend are:

- LPWAN-Backend: the measurement devices are connected to the LPWAN cloud where the values arrive in hexadecimal format. The call-backs that redirect the sensor value through the Hypertext Transfer Protocol (HTTP) to the backend of the platform are configured from the LPWAN cloud. This system allows managing several devices together, which facilitates the process.

- IoT service: in addition to storing sensor data in the cloud, this element permits processing a variety of data in an easy manner. The service facilitates the management of large amounts of information, such as tools for developers, data security, administration tools, data analysis, etc.
- Functions: This element manages and redirects the data transferred from the LPWAN to the different cloud services: database and calculation algorithms. Each pressure value has an identifier associated with the sensor that registered it.
- Database: The DB Dynamo database (NoSQL type) stores both the data recorded by the sensors and the results of the calculation algorithms. This database was selected due to its ease of integration with other cloud services.
- Failure Detection Algorithm: This algorithm detects possible faults in the WTN and analyzes the pressure data to determine whether the values are within the normal operating range of the pipe. If the values are not within the normal range, it sends an alert command to the notification module which is also stored in the database. This algorithm is described in Section 5.3.1.2.
- Notification services: This module sends failure alerts to the platform users.
- Failure repair management module: The availability of the mathematical model of the network is required for using this

module. It contains an ad-hoc algorithm written in Python programming language (Python Software Foundation. Python Language Reference. Version 3.6.11 Available at Http://Www.Python.Org, n.d.) that is connected to the EPANET open-source hydraulic simulator (Rossman, 2000) as a calculation engine to analyze the behavior of the system during different failure scenarios. The algorithm is hosted in a cloud server and accessed through a REST API created with the Django open-source framework (Django, 2020). The API was configured to receive HTTP calls through a POST method that sends the necessary parameters for the algorithm execution (Kumar Polu, 2018). A detailed description of this module is given in section 5.3.3.

5.2.3 Layer 3: Frontend

The frontend layer contains the platform's graphical interface for the user and establishes the connection between the database, the user, and the calculation algorithms. It enables users to operate the platform and visualize all its functionalities in a simple and efficient manner. The frontend interacts with the REST API (backend) by the HTTP protocol for the user to make requests for information to the database and the analysis algorithms hosted in the backend.

To develop the interface, the open source ReactJS library for creating single-page web applications (SPA) was used (Gackenheimer, 2015). This library allows the platform utilities to be divided into components, each with its own logic and independent operation.

Depending on their category, users can use the frontend functions described in section 5.2.3. The user categories are administrator, who has access to all the functions, and qualified and basic users, who are permitted different levels of accessibility to the platform functions. The access levels are given in the description of the functions.

The role of administrator is reserved for the platform developers, who are the only ones that can add and remove users and manage databases. Administrators have full access to the functions allowed to users in the other categories. WTN managers have the role of qualified users. They are enabled to create, remove sensors, and edit the pressure range of each sensor. Finally, maintenance staff are basic users. They can view the sensor data and query flow and pressure values of damaged pipes, as well as calculate maximum repair times automatically from the information recorded in the system.

5.3 wAIter function modules

The proposed platform facilitates the comprehensive management of failures in WTNs, enabling the analysis of each incident from different points of view and estimates of the time available to carry out repairs. Its functional modules are described next.

5.3.1 Failure detection module

This module analyzes sensor pressure data to detect failures in real time in branched WTNs with a single water supply source. Likewise, no pumps may be in operation in the sector(s) where the pressure sensors are installed. Moreover, when data logging is started, the WTN must be operating correctly. The type of pressure deviation incidents and the failure detection algorithm are described next.

5.3.1.1 Type of incidents

There are four typical pressure variation incidents in WTNs as described below.

a) Incident 1: Sensor failure. This incident occurs when some data sending cycles are not performed correctly for any reason. Pressure data transmission failures cause erroneous pressure fluctuations that must be analyzed. Although situations of this type are rare in robust data logging devices, it is important to be aware that they may occur. Even if the duration of a fault is short, it must be identified as a sensor failure to avoid generating a false failure alert. This type of incident can be easily detected because the pressure fluctuation is associated with a fluctuation of the device battery (Figure 5.3). This incident does not cause water losses.

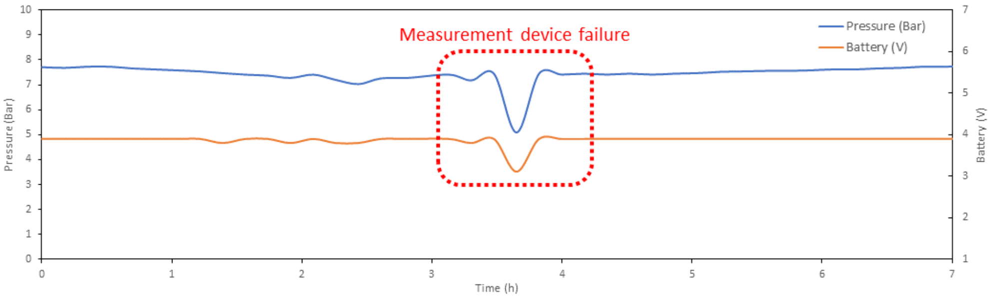


Figure 5.3. Sensor failure incident.

b) Incident 2: Supply cut-off. A cut-off in water supply in the sector where the sensor is located causes the water to drop (Figure 5.4). These interruptions of supply are necessary to perform cleaning and maintenance operations in the network. When the shut-off valve located upstream from the sensor closes, the pressure line shows a sudden drop in pressure from normal values to zero pressure. After maintenance is completed, the valve reopens, and the pressure returns to its normal range of values. As in the previous case, this incident does not involve water losses.

Figure 5.4. Supply cut-off incident.

c) Incident 3: Leaks/breaks downstream from the sensor. This incident is characterized by the evolution of pressure over time when a leak occurs downstream from the pressure measuring device. Figure 5.5 shows four distinct periods in the evolution of pressure data. In the first stage, the pressure is within the normal operating range and ends with a sudden drop in pressure when the leak/break occurs. In the next period, the pressure stabilizes at a lower pressure value than normal until the repair begins. The duration of this phase determines the amount of water losses caused by the leak/break in the pipe. Once the problem is detected, the upstream shut-off valve is closed and the repair period begins. The repair period ends when the pipeline is put back into service. The locations of the shut-off valve and the sensor, as well as the topology of the damaged pipe, determine the minimum pressure recorded by the sensor during the repair period. As shown in Figure 5.5, the pressure returns to normal values once the fault has been fixed and the shut-off valve has been reopened.

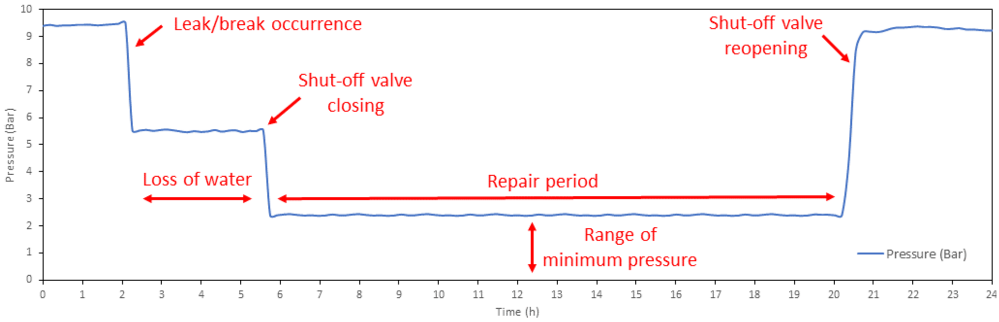


Figure 5.5. Occurrence of leaks/breaks downstream of the sensor.

d) Incident 4: Occurrence of leaks/breaks upstream from the sensor. This type of incident is detected in a similar manner to the previous one (Figure 5.6). In this case, leak/break is detected by a sudden drop in pressure values, which continue to decrease progressively as the flow rate in the damaged pipe is reduced due to water losses. The repair period begins with the shutdown of the supply by closing the corresponding shut-off valve. The locations of the shut-off valve and the sensor, as well as the topology of the damaged pipe, determine the minimum pressure recorded by the sensor. As in the above type of incident, the pressure record values return to normal levels after reopening the shut-off valve once the leak/break has been fixed.

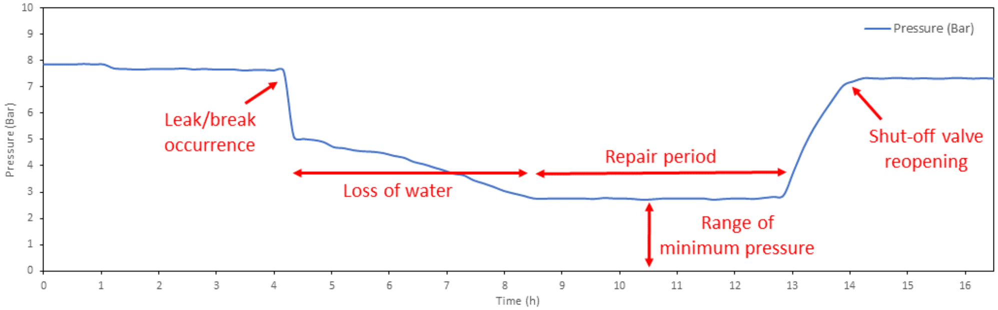


Figure 5.6. Occurrence of leaks/breaks upstream of the sensor.

5.3.1.2 Rule-based decision algorithm for failure detection

A rule-based decision algorithm has been developed to detect failures in WTNs using pressure data analysis. This type of algorithm has a similar structure to that of a decision tree. Its behavior is based on making decisions related to the values of the input data. This methodology is a supervised self-learning algorithm for solving classification problems (Safavian & Landgrebe, 1991). Fault detection is a binary classification problem whose solution determines whether the fault exists or not.

The proposed algorithm has tree-like flowcharts in which an internal node represents a feature (or attribute), the branch represents a decision rule, and each child node represents the decision (Breiman, 2001). The nodes in the tree act as a test case for some attribute, and each branch descending from those nodes corresponds to one of the possible responses to the test case. Finally, the terminal nodes of the tree indicate the final classification. Logical structures of this type convert complex decisions into a set of several simpler decisions.

The flowchart shown in Figure 5.7 is designed to determine the type of failure that occurs in a WTN due to deviations of pressure values from normal values. In the figure, the orange elements represent the nodes, the green ones represent the branches, and the blue ones represent the terminal nodes. In this case, as four possible incidents have been considered, the blue nodes identify the type of failure in the pressure records described in the previous section. The pressure and the battery of the measuring device are the attributes considered to define the branches starting from each node.

This algorithm is executed each time the database receives new data (pi(t), pressure at time t). After the algorithm is executed, the data are stored in the database. Subscript i identifies the sensor that recorded the data. Likewise, pi(t-1) is the pressure data before time t stored in the database of sensor i; pi(t+1) is the pressure data after time t recorded by sensor i; bi(t) is the battery level of the measuring device i at a given time, t: bi(t-1) is the battery of sensor i at the instant immediately before time t.

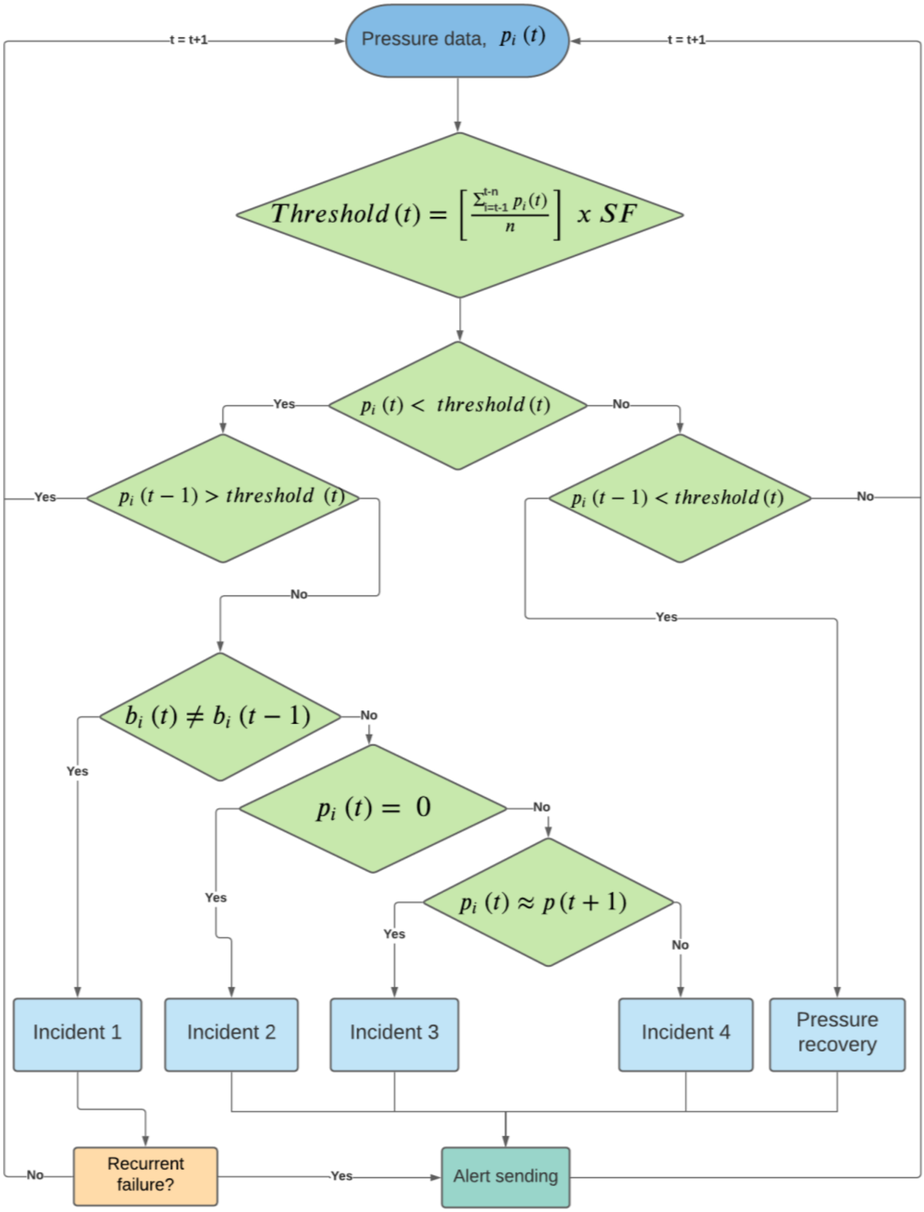


Figure 5.7. Flowchart of the leak detection algorithm.

The algorithm starts by checking whether pi(t) is below a certain pressure threshold, which is calculated in each time step (described in section 5.3.1.2.1). If it is under this value, it is checked whether this situation had occurred for pi(t-1). Thus, if pi(t-1) is higher than the threshold, the battery condition is checked, otherwise the failure detection process finishes. When bi(t) is not equal to bi(t-1), the sensor is not operating properly (incident 1). Then pi(t) is rejected and not stored in the database to avoid false data being recorded and no alert is sent to the WTN managers. This type of failures does not occur continuously and are of a short duration. Otherwise, if the failure occurs repeatedly, the algorithm can detect it and alerts the users to repair it.

Conversely, when bi(t) equals bi(t-1) (the sensor performance is correct) and pi(t) equals 0, the algorithm identifies that water is not circulating through the pipe because of the supply cut-off upstream of the sensor (incident 2). An alert is then generated and sent through the alert module (section 5.3.2) and the algorithm ends.

Finally, leaks and breaks (incidents 3 and 4) can be detected when pi(t) is not equal to 0. The algorithm sends a first notification that a leak has occurred. In the next data sending cycle, the algorithm determines whether the leak/break has occurred downstream (incident 3) or upstream (incident 4) of the sensor by comparing pi(t) to pi(t+1). If pi(t) is almost equal to pi(t+1), incident 3 is detected. However, if pi(t) is lower than pi(t+1), then the leak/break has occurred upstream of the sensor location. Once the failure has been classified, a second notification is sent to the

WTN managers informing them if the leak/break is located upstream or downstream of the sensor.

In addition, the algorithm detects that the pressure has returned to its ordinary values after the failure has been fixed when pi(t-1) is below the threshold, but pi(t) is above it. At that time, an alert is sent indicating that the pressure values have returned to their normal levels. In this way, the WTN managers are informed in real time when the network is back to its normal operation.

The algorithm described can be applied with a single sensor, but the denser the pressure sensor network, the easier it is to locate WTN failure points.

5.3.1.2.1 Threshold definition

The pressure threshold is the key parameter (attribute) for the performance of the rule-based decision algorithm described above. This parameter defines the lowest pressure limit for detecting failures in WTN when the recorded pressure is below this limit. The accuracy of the incident classifier depends on the precision of the pressure threshold determination, as it is the decision-making attribute of the first node.

The pressure changes over the year and time of day (Figure 5.8). Therefore, the pressure threshold is a dynamic parameter. The threshold value is calculated as the mean of the last n pressure values recorded in the database weighted with a safety factor, SF, ranging from 0 to 1, according to Equation 5.1. The shape of the threshold time evolution curve is similar to the pressure curve, since the threshold value depends on the last received pressure values, thus adapting to changes in the WTN loading conditions.

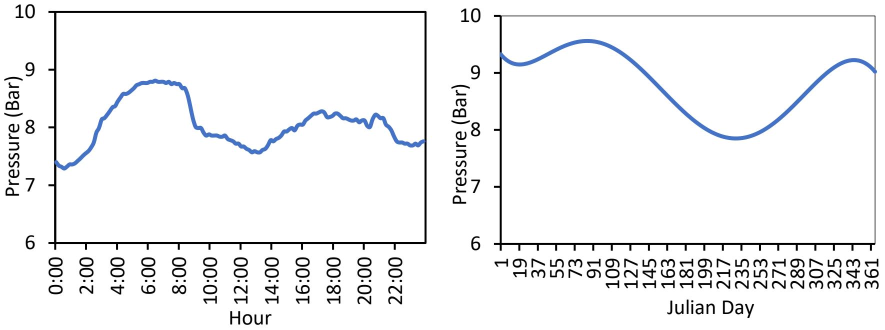
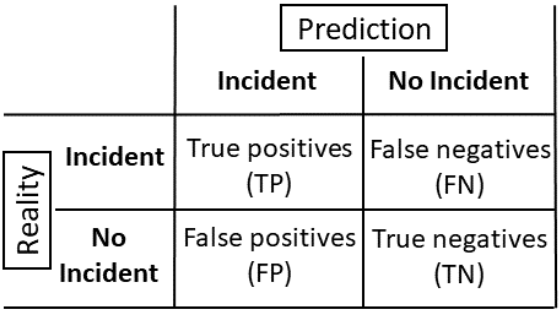


Figure 5.8. Real pressure data from the ad-hoc pressure measuring device.

$$threshold(t) = \left[\frac{\sum_{i=t-1}^{t-n} p_i(t)}{n}\right] x\ SF \qquad (5.1)$$

The values of n and SF are estimated based on the pressure variability at the monitoring points. Each sensor in the network is defined by a different SF and n. Hence, the threshold is adapted to the pressure conditions at each specific measurement point. The value of n depends on the type of network to be studied. In a network with sudden pressure changes, it is necessary to set a relatively low value of n, to quickly adapt the threshold to the changes. In networks with constant pressures, a higher value of n can be set to avoid false positives of network failures. The choice of the optimal SF is a complex process that is mainly based on the performance of the algorithm (measured by the confusion matrix and the calculation of the mean detection time, MDT). This parameter is key for adapting the fault detection algorithm to the network.

The accuracy of the algorithm that calculates the SF and n parameter is evaluated by the confusion matrix as it is a classification algorithm (Figure 5.9) (Fawcett, 2006; Sokolova & Lapalme, 2009). The rows of the matrix indicate the actual class and the columns indicate the predicted class. The elements that form the confusion matrix are: true positives, TP, which are the number of times the algorithm correctly detects incidents; false positives, FP, which are the number of times the algorithm detects non-existent incidents; true negatives, TN, which are the number of times the algorithm does not detect incidents because they have not occurred; and false negatives, FN, which refers to the number of times the algorithm does not detect real incidents.



		Prediction	
		Incident	**No Incident**
Reality	**Incident**	True positives (TP)	False negatives (FN)
	No Incident	False positives (FP)	True negatives (TN)

Figure 5.9. Confusion matrix.

The last aspect to evaluate is the mean detection time (MDT) of the incidents (Equation 5.2). MDT is the period from the beginning of any incident until it is detected by the algorithm. This parameter indicates how quickly the algorithm detects incidents in the network and is directly proportional to SF. An increase in SF will decrease the threshold that determines the occurrence of an incident and consequently increases the average time that the algorithm takes to detect it.

$$MDT = \frac{\sum_{i=1}^{N}\left(t_d^j - t_p\right)}{N_d} \tag{5.2}$$

Where t_d^j is the exact time that the measurement device j takes to detect an incident; t_p is the exact time the incident occurs; and N_d is the number of total incidents. High MDT values indicate delayed detection of faults. When these faults are leaks/breaks, significant amounts of water can be lost in an uncontrolled manner. Therefore, it is important to adjust the threshold value to minimize the number of false negatives and reduce MDT.

To calculate the SF parameter, an iterative process is followed starting with a value close to 0 and increasing this parameter according to the results of the confusion matrix (TP, TN, FN and FP) and MDT. The user can define minimum requirements (TPreq, TNreq, FNreq, FPreq and MDTreq) that stop the algorithm when it exceeds them. Once the SF is optimized, the previous results are improved by performing a similar process, but this time by modifying the value of the parameter n. The objective is to improve the previous results of the confusion matrix (TP1, TN1, FN1 and FP1) and MDT (MDT1) with an optimal value of parameter n.

These two parameters, SF and n, are updated weekly to learn from new failures that occur during that period and thus optimize the calculation of the threshold. The optimization process of the parameters involved in the calculation of the threshold (SF and n) is explained in the flowchart in Figure 5.10.

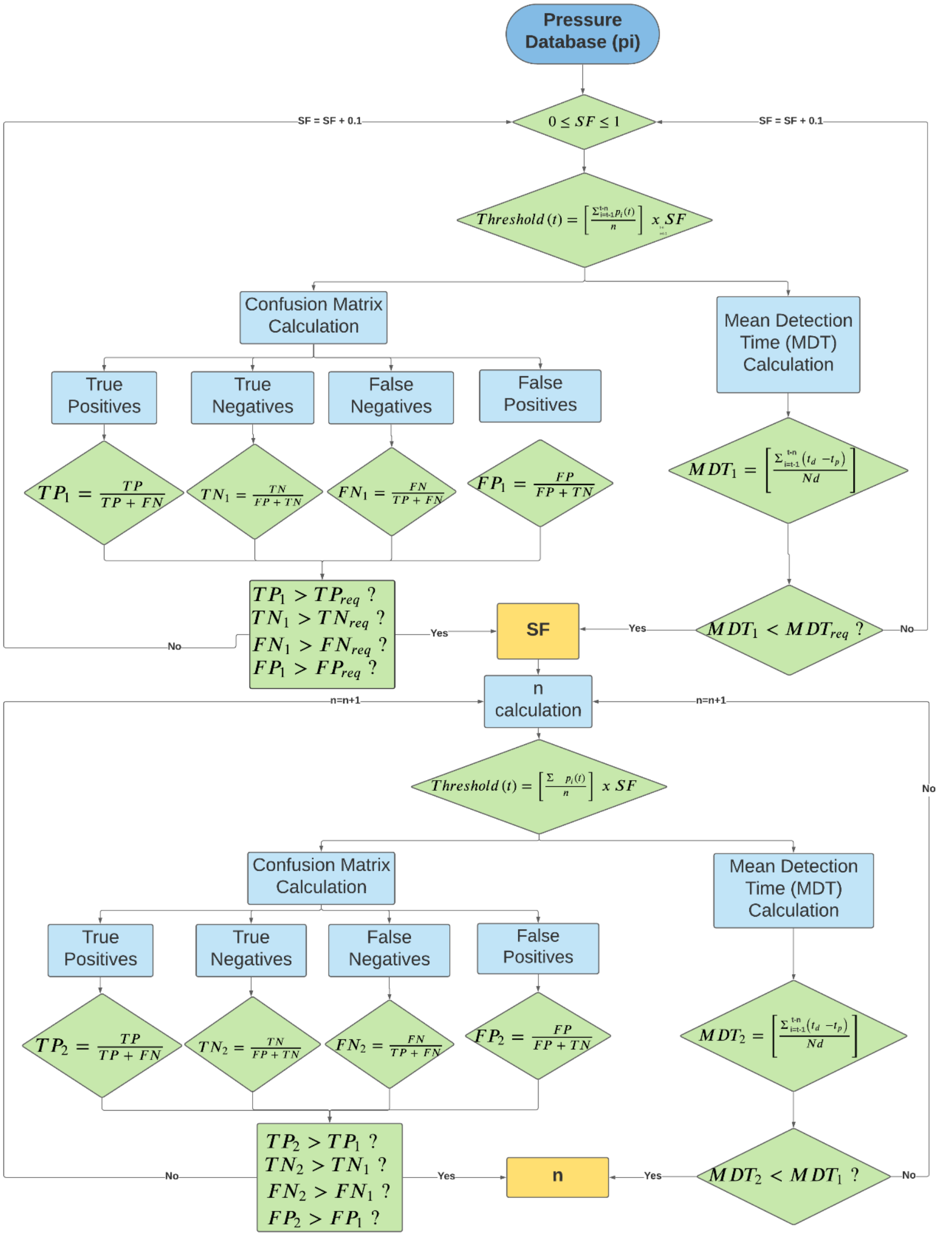


Figure 5.10. Flowchart for the estimation of SF and n.

Fixed thresholds require a relatively large dataset to fix their value and do not detect small leaks linked to small drops in pressure records (Venkatasubramanian et al., 2003). The proposed threshold is a dynamic threshold that updates its value with each new data sending cycle, thus adapting to the evolution over time of the WTN loading conditions (Figure 5.11). With the dynamic threshold, the fault detection algorithm proposed in this work can detect small leaks that would not otherwise be detected if a fixed threshold were considered.

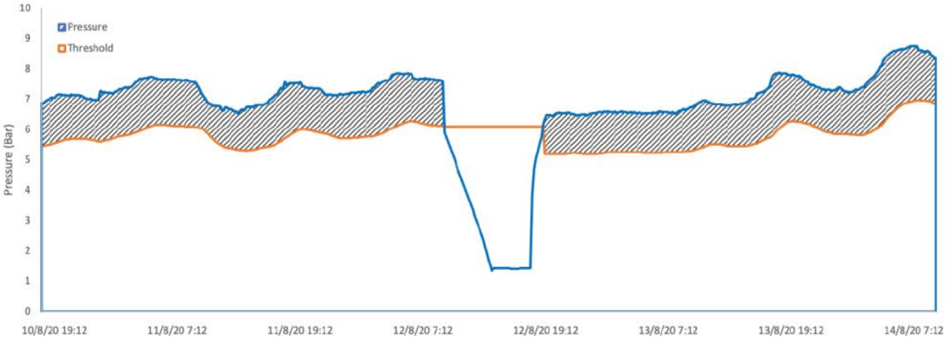


Figure 5.11. Pressure and threshold evolution during a pressure variation incident.

Figure 5.11 shows the evolution of pressure and threshold during a pressure variation incident. For the duration of the incident, the threshold value remains constant at the value it had at the time of the incident. This prevents the threshold from taking excessively small values, which would not allow the identification of failures resulting from smaller pressure variations.

5.3.1.2.2 Algorithm performance evaluation

The parameters precision, recall, accuracy and F1score, which are calculated from the elements of the confusion matrix, are used to complete the evaluation of the algorithm (Rijsbergen, 1979). Recall is the fraction of the true positive values that are predicted to be positive (Equation 5.3). Precision is the fraction of positive predictions that are positive (Equation 5.4). Accuracy is the ratio of correct predictions to all predictions (Equation 5.5). F1score measures the accuracy of the proposed classification algorithm as a function of precision and recall (Equation 5.6). F1score is used to minimize false positives and false negatives in unbalanced datasets.

$$Recall = \frac{TP}{TP+FN} \tag{5.3}$$

$$Precision = \frac{TP}{TP+FP} \tag{5.4}$$

$$Accuracy = \frac{TP+TN}{TP+TN+FN+FP} \tag{5.5}$$

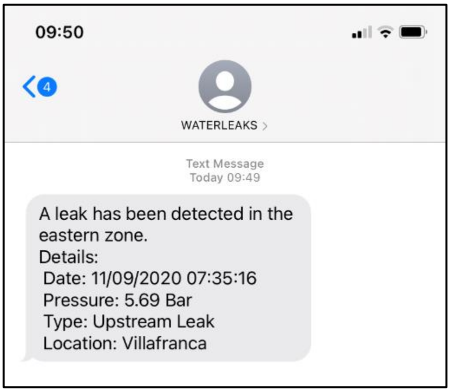
$$F1score = \frac{2 \cdot precision \cdot recall}{precision+recall} \tag{5.6}$$

5.3.2 Alert module

This module receives the results of the fault detection module when it detects a fault and generates the corresponding alert message via SMS/email. Its purpose is to allow users to visualize the results of the failure detection module as soon as the failure occurs and to act accordingly.

This is a selective alert sending module. Alert messages are only sent to the staff responsible for the area affected by the fault. To do this, the module integrates a database with information about the maintenance personnel responsible for each sector in which a sensor has been installed. To perform this process, the sensors are georeferenced so that when the fault detection module triggers an alert, the module identifies the appropriate staff.

Each alert message sends information about date and time of failure detection, recorded pressure value, type of incident and location of the sector where the failure has been detected (Figure 5.12).



A leak has been detected in the eastern zone.
Details:
Date: 11/09/2020 07:35:16
Pressure: 5.69 Bar
Type: Upstream Leak
Location: Villafranca

Figure 5.12. Example of alert message.

5.3.3 Failure repair management module

The purpose of this module is to determine the maximum repair time of a failure, MRT, or the duration of a maintenance task. MRT is equivalent to the interval between the time the failure is detected and the time users (inhabitants of a municipality) are unable to meet their demands because of the supply failure. This concept is the basis for the optimal management of the human and material resources needed to resolve failures. Once MTR is known, the WTN manager makes the necessary arrangements to carry out the repair, which must be solved in less time than MRT.

The consumption nodes of a WTN are the tanks that supply drinking water to the municipalities. When a supply network fails, the time to empty these tanks determines the value of MRT. To estimate MRT, it is necessary to have a hydraulic model of the WTN, which is a set of mathematical equations that simulate the behavior of the network. The hydraulic model reproduces the evolution of tank levels over time using an extended simulation period approach (Paez & Filion, 2020).

The Django Rest Framework (DRF) open-source tool is used to implement the REST API. The design of the REST API is based on three essential components: serializers, views and routers (Figure 5.13). These components connect the frontend and the EPANET core. Because the frontend and the repair module are written in different programming languages, serializers are used to transform the data from EPANET into the JSON format used by DRF so that the data can be visualized using ReactJS. Views is the module in charge of the logic and manages all the communications between the API and the EPANET core. The routers define the API URLs. There is one router per view, which takes as parameters the name of the view and the URL of the API created. The computing procedure was developed in Python to use the EPANET hydraulic simulator (open-source software) as a calculation engine. A description of the hydraulic simulation process is given below.

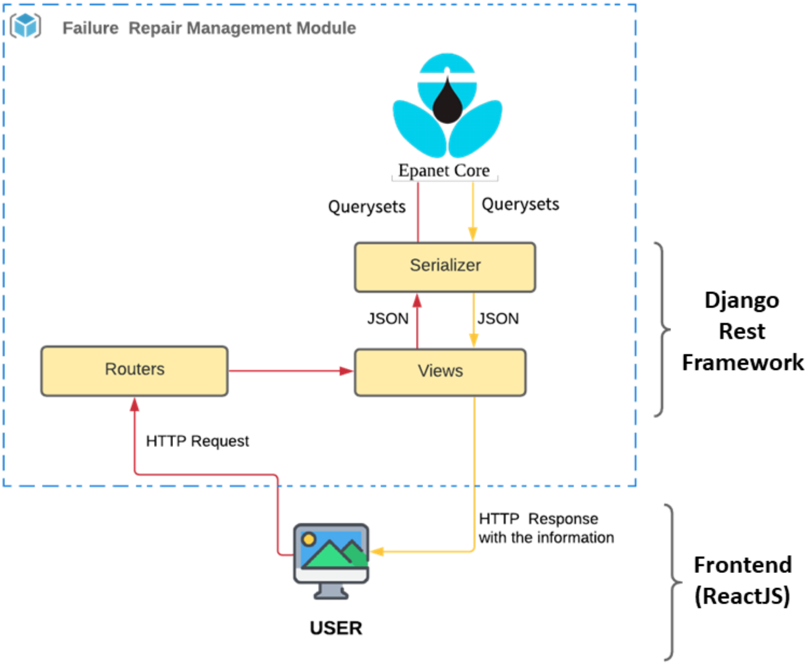


Figure 5.13. Communication between the frontend and the EPANET core.

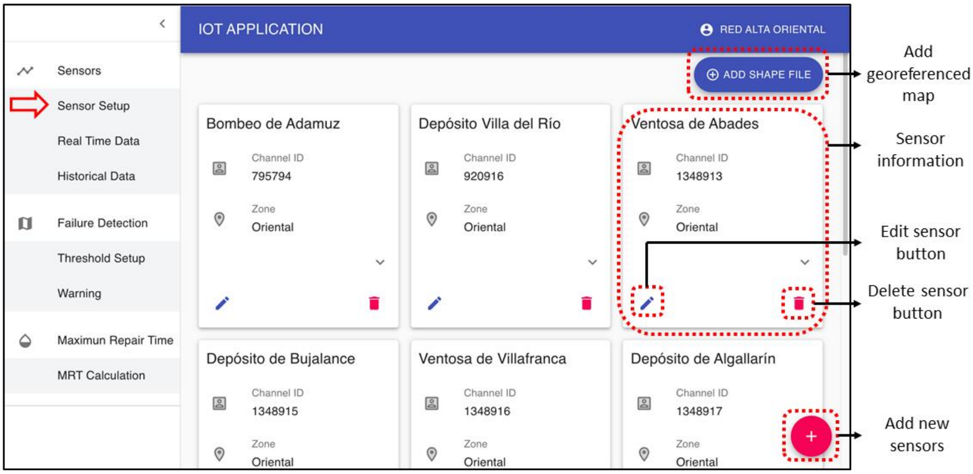
5.3.4 MRT calculation mode

WTN managers can analyze the behavior of the network under different fault scenarios by manually entering the input data to perform the MRT calculation and simulate hypothetical fault situations in the WTN.

This calculation option is complex and requires minimal knowledge of hydraulic modelling. The only requirement to implement this option is to have the hydraulic model of the WTN. The user must manually enter the pipe affected by the failure, the level of each tank at the time of the failure and the demand of the affected municipalities. Then, using the extended period calculation of EPANET (Rossman, 2000), the maximum time available to avoid disrupting the supply of the most critical tank in the simulation scenario can be calculated.

5.3.5 Business solution

This section describes the design of the graphic interface of the wAIter platform. The platform includes the functionalities of the three modules explained above. A simple and intuitive interface has been designed to facilitate its replication for any water service.



Bombeo de Adamuz
Channel ID
795794
Zone
Oriental

Depósito Villa del Río
Channel ID
920916
Zone
Oriental

Ventosa de Abades
Channel ID
1348913
Zone
Oriental

Depósito de Bujalance
Channel ID
1348915
Zone
Oriental

Ventosa de Villafranca
Channel ID
1348916
Zone
Oriental

Depósito de Algallarín
Channel ID
1348917
Zone
Oriental

Add georeferenced map

Sensor information

Edit sensor button

Delete sensor button

Add new sensors

Figure 5.14. Sensor configuration tab.

In the first tab (Figure 5.14), the sensors are set up to display the information they record. There is a specific button to add, edit and delete the sensors. It is necessary to enter basic information for each sensor: geographic coordinates, password to access its database, type of installation and altitude. This option is only available to the platform administrator, who is responsible for managing the sensors' basic settings. To have a background map with the layout of the georeferenced pipe network, it is necessary to upload a file with a shapefile extension containing this information.

Figure 5.15 shows the location of the pressure sensors in the WTN. The platform provides users the latest recorded data of the selected measurement device by clicking on the sensor displayed on the map. With just a glance, it is possible to know the pressure in real time at the WTN monitoring sites.

Depósito de Algallarín

Presión 3.44 Bar

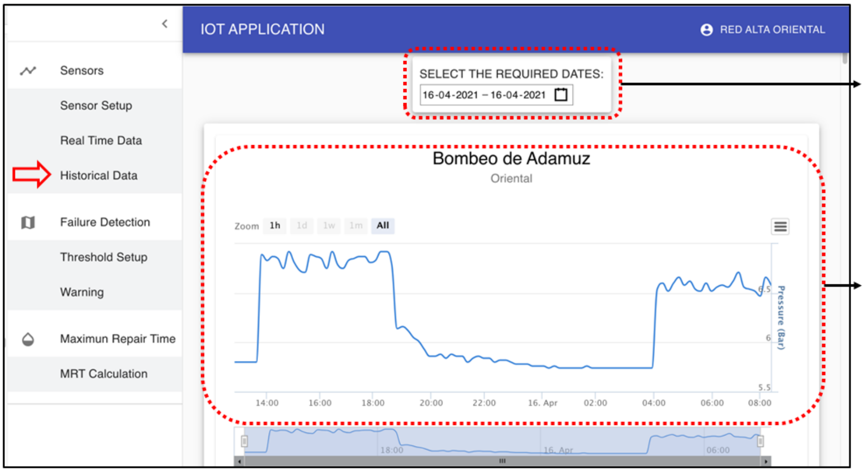
Batería 4.1 V

Real-time values

Sensor location map

Figure 5.15. Real time data tab.

Knowledge of the water pressure evolution over time in WTNs is important to gain a better understanding of how these systems operate. In many cases, historical data series are needed to analyze past time periods. The wAIter platform permits data to be consulted for a selected date interval (Figure 5.16). This information can be used for the advanced calculation mode of MRT under different operational scenarios. Data can be downloaded in different formats (CSV, PDF and PNG) to adapt the query to the user’s needs.



SELECT THE REQUIRED DATES: 16-04-2021 – 16-04-2021

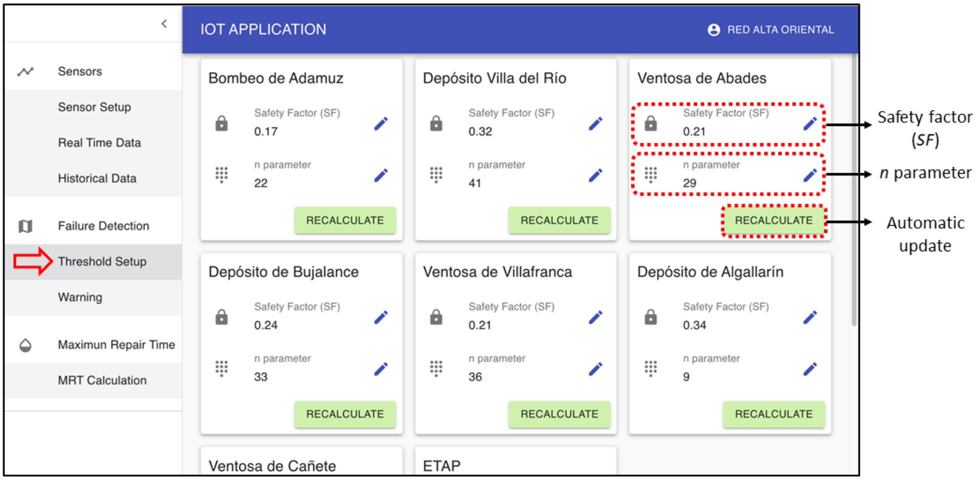
Time period selection

Pressure values for the selected period

Figure 5.16. Historical data tab.

This tab configures the key parameters for the failure detection algorithm (SF and n) to calibrate the failure detection module (Figure 5.17). There are two setup procedures. For sensors that have recently been installed in a location with no previous records, SF and n are entered manually. The automatic update button is for sensors that have been operating for a minimum period and have detected failures in their sector. SF and n are recalculated to take into account the last failures. Like the Sensor Setup tab, this option is only available to administrators.

The Data labelling tab (Figure 5.18) has been created to label the pressure data and store detailed reports of every event occurring in the network. Data labelling is essential for fine-tuning the dynamic threshold to improve the performance of the failure detection algorithm. This way, the algorithm learns from past incidents and will self-adjust to the behavior of each network. The parameters defining the dynamic threshold (n and SF) are updated weekly according to the new data entered in the system's event database.

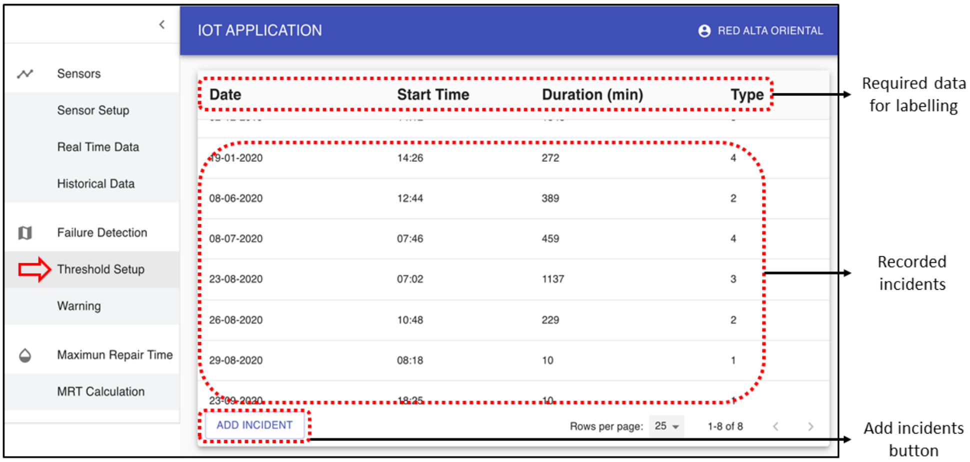


	Safety Factor (SF)	n parameter
Bombeo de Adamuz	0.17	22
Depósito Villa del Río	0.32	41
Ventosa de Abades	0.21	29
Depósito de Bujalance	0.24	33
Ventosa de Villafranca	0.21	36
Depósito de Algallarín	0.34	9

Ventosa de Cañete

ETAP

Figure 5.17. Threshold setup tab (1).

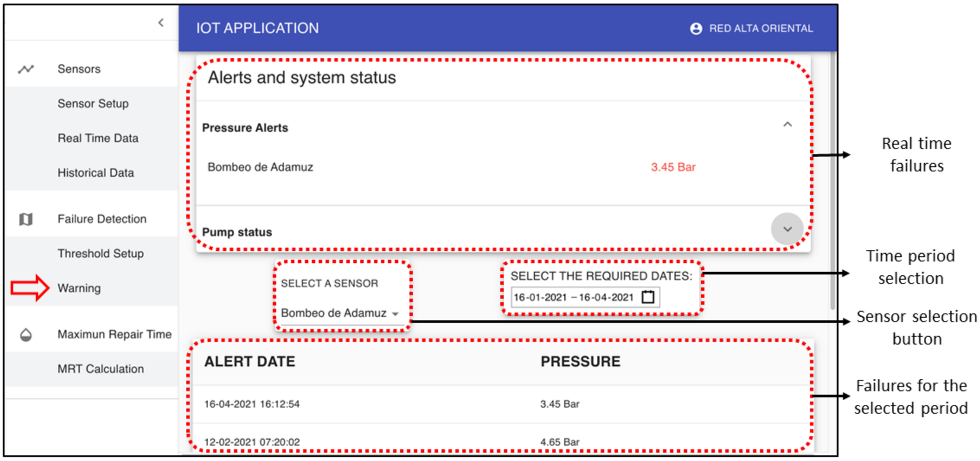


Date	Start Time	Duration (min)	Type
19-01-2020	14:26	272	4
08-06-2020	12:44	389	2
08-07-2020	07:46	459	4
23-08-2020	07:02	1137	3
26-08-2020	10:48	229	2
29-08-2020	08:18	10	1
23-09-2020	18:25	10	1

Figure 5.18. Threshold setup tab (2).

To describe an incident, it is necessary to enter the starting date and time, the duration of the failure from start to full repair and the type of incident (based on the classification shown in section 5.3.1.1)

The alerts tab collects information about faults detected by the system (Figure 5.19). This tab is divided into two sections. The upper part of the screen contains the failure register in real time (i.e., based on the latest data collected from each sensor). The lower part of the screen contains a failure history. The platform displays the failures of the selected sensor for the selected period. This option allows users to carry out advanced studies on the recurrence of failures in the same sector.



Bombeo de Adamuz 3.45 Bar

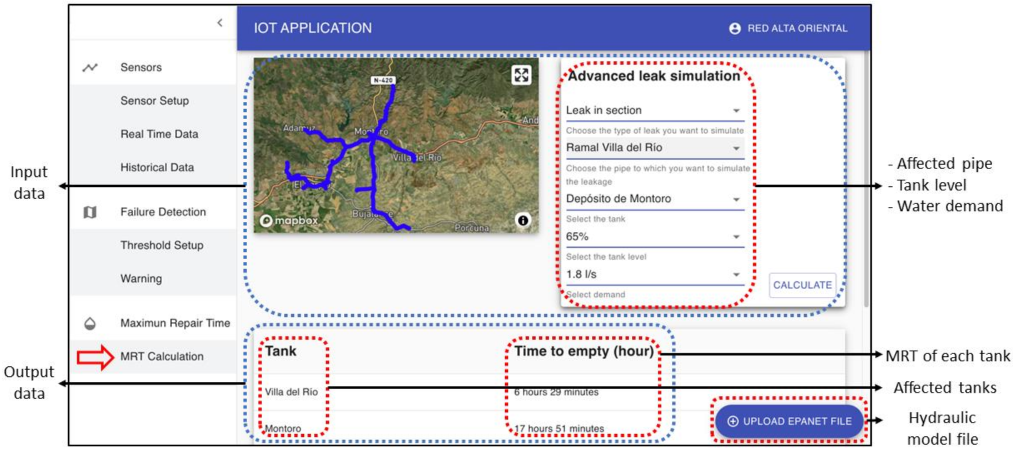
SELECT A SENSOR: Bombeo de Adamuz

SELECT THE REQUIRED DATES: 16-01-2021 – 16-04-2021

ALERT DATE	PRESSURE
16-04-2021 16:12:54	3.45 Bar
12-02-2021 07:20:02	4.65 Bar

Figure 5.19. Warning tab.

The MRT tab is suitable for users with some knowledge of hydraulic modelling (Figure 5.20). To use this function, a text file with the hydraulic model must first be created in EPANET.inp format and then uploaded by clicking on the lower right button. To create several loading conditions scenarios for each incident detected in the WTN, the hydraulic model of the network must be uploaded previously. Data on the pipeline, the level of the affected tanks and the base demand of the consumption nodes must be entered manually.



Advanced leak simulation

Choose the type of leak you want to simulate: Leak in section

Choose the pipe to which you want to simulate the leakage: Ramal Villa del Río

Select the tank: Depósito de Montoro

Select the tank level: 65%

Select demand: 1.8 l/s

Tank	Time to empty (hour)
Villa del Río	6 hours 29 minutes
Montoro	17 hours 51 minutes

Figure 5.20. Advanced MRT tab.

5.4 Results

5.4.1 Study Area

The proposed methodology has been implemented in a WTN operated by EMPROACSA, the provincial water supply company of Cordoba, southern Spain (Figure 5.21). The network covers an area of around 600 km^2 and supplies drinking water to ten municipalities with populations ranging from 140 to 9,635 inhabitants. The three largest municipalities account for 60% of the total population (44,200 inhabitants).

The Martín Gonzalo reservoir (280 masl) is the water source of this WTN. The water is purified in a water treatment plant with a capacity of 25,920 m^3/day. The population varies seasonally as many of the houses in the area are used for recreational purposes. The main industrial activity of the area is olive oil extraction, whose maximum water demand occurs during the olive harvesting period (November to February), although it only accounts for 3% of the total water consumption (Guadalquivir, 2015).

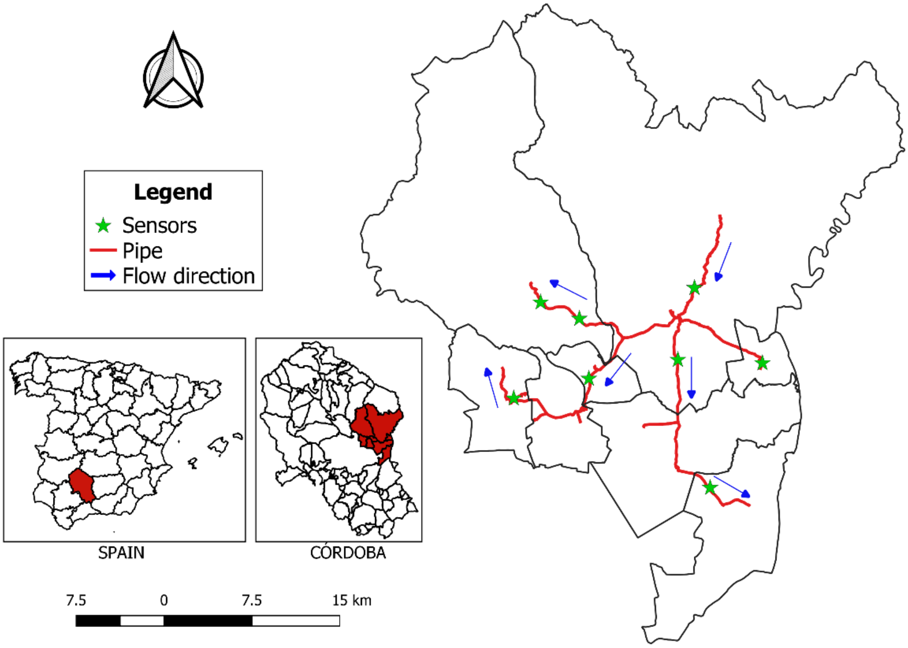


Figure 5.21. Location and layout of the WTN and the sensors.

The average daily water demand is 250 l/hab/day. The mean annual consumption per municipality ranges from 12,733 m^3/year to 681,572 m^3/year and reaches the highest values in summer (July to September).

The topology of the network is branched and consists of a main pipeline with three secondary and several tertiary pipelines. The network is made up of pipes of different materials and diameters with a total length of 88.79 km. Water is pumped through 4 pumping stations with horizontal centrifugal pumps between 69 masl and 180 masl. The municipal water supply networks are fed by the 18 tanks of the WTN with capacities between 80 m^3 and 7,500 m^3.

5.4.2 Sensor network

Due to the state of the WTN, the Sigfox communication network has been chosen and consequently the microcontroller of the IoT sensor is Arduino MKR 1200 (Arduino, 2019). Sigfox has a range of 50 km and does not require the installation of a communications network as it can be accessed by paying the connection service with an annual fee per device. These features make Sigfox the most suitable LPWAN alternative for monitoring WTNs scattered over large territories at a low cost. A one-way communication is established between the sensor and the LPWAN network, so only the sensor readings are transmitted. This communication system is limited to a maximum of 140 messages per day and a payload of a maximum of 12 bytes. This is a sufficient frequency to monitor the water pressure and obtain data approximately every 11 minutes.

Eight pressure measurement devices were installed in the network. The location has been conditioned by the coverage of the Sigfox network and by the proximity to sectors with a high failure rate. The entire WTN has been covered by installing a pressure sensor in each branch of the pipe system. The technical characteristics of the pipes (diameter and material) where the sensors have been installed are varied but have not affected the quality of the pressure records.

The core of the sensors is the pressure transducer, which measures the water pressure inside the pipes. This device converts the pressure into a voltage signal ranging from 0.33 V to 2.97 V. The supply voltage of the transducers is 3.3 V with a current consumption of 4 mA and is fully compatible with the output voltage of the microcontroller used (Arduino MKR FOX 1200). In addition, transducers have an IP69K degree of protection, which provides them protection against water and avoids damage. To improve the accuracy of the pressure measurement, two transducers with a different full scale (0-17.23 bar and 0-34.47 bar) have been used. Thus, the pressure transducer that best suits the operating range of each monitoring point has been chosen.

5.4.3 Pressure threshold calculation of the failure detection algorithm

Using the sensor network described above, pressure data were collected from the study area over a period of 12 months. To show a more concrete case, the results will focus on one of the pressure sensors mounted on the WTN. Thus, the procedure can be extrapolated to the other sensors. In this series of pressure data recorded by this representative sensor, a total of 40 incidents (20 incidents of type 1, 5 incidents of type 2, 9 incidents of type 3 and 6 incidents of type 4) have been detected. Each of the failures is described according to its pressure, date, time and duration, location and type of incident. As an example, Figure 5.22 shows how an incident can be detected by studying the evolution of the pressure. Table 5.2 shows how some of the incidents during the study period have been labelled to include them in the database that feeds the fault classification algorithm.

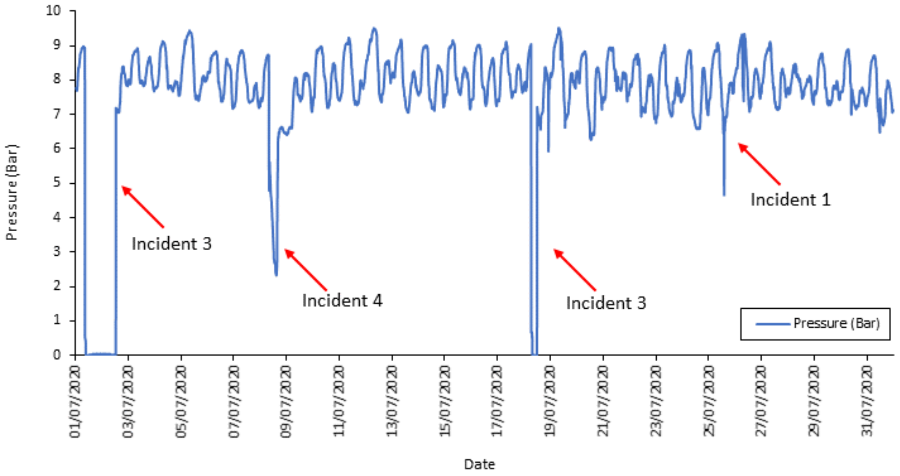


Figure 5.22. Pressure evolution in July in a representative sensor.

Table 5.2. Example of incident characterization.

Failure label	Type	Start Date (day/month/ year)	Start Time (h:min)	Duration (min)	Location		
					ID	Diameter (mm)	Pipe Material
1	Incident 3	02/12/2019	14:12	1348	p512	150	Asbestos cement
2	Incident 3	23/08/2020	7:02	1137	p822	150	Cast iron
3	Incident 4	19/01/2020	14:26	272	p1019	400	Cast iron
4	Incident 4	08/07/2020	7:46	459	p77	350	Asbestos cement
5	Incident 2	08/06/2020	12:44	389	p263	150	Asbestos cement
6	Incident 2	26/08/2020	10:48	229	p471	350	Cast iron
7	Incident 1	29/08/2020	8:18	10	p512	150	Asbestos cement
8	Incident 1	23/09/2020	18:25	10	p368	150	Asbestos cement

One of the key parameters in calculating the threshold of each sensor is the safety factor (SF). The data in Figure 5.23 show that the optimal SF is close to 30%. This study has been carried out with data collected for 12 months, accounting for the number of false positives, false negatives and true positives with each of the SFs considered. The dashed line indicates the actual incidents that have occurred during the period analyzed. For this study, sensor failures have not been considered, as they are considered irrelevant and because these failures are due to a problem of the sensor electronics rather than the malfunctioning of the WTN.

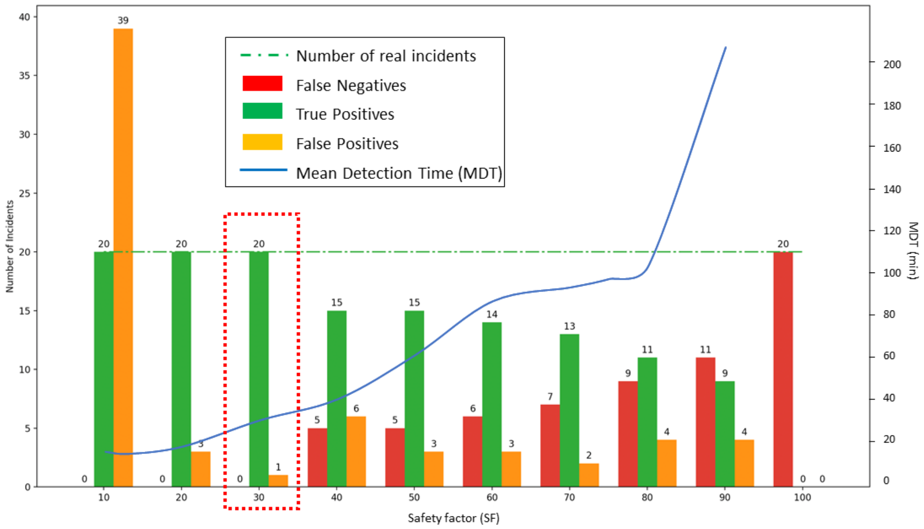


Figure 5.23. Threshold safety factor and the mean detection time estimation.

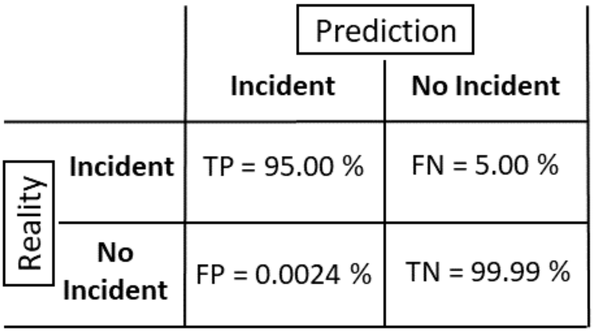
False positives are represented by the number of times the algorithm considers an incident that has not occurred. With a low SF, there will be a high number of false positives because any small variation in pressure will be considered an incident. Conversely, a high SF implies a low rate of false positives. True positives and false positives behave symmetrically, i.e., as one increases, the other decreases proportionally. As the SF increases, the true positives decrease. This is because the threshold decreases, and the pressure drop must be greater to be detected by the algorithm. The rate of false negatives will behave in the opposite way.

The MDT, which is an important parameter for measuring the performance of the algorithm, has also been evaluated (Figure 5.23). A decrease in the response times leads to a rapid action on any leak or fault and hence an improvement in the overall performance of the network.

The SF may change over time depending on the type of variable of interest to the user. For example, if the user wants to decrease the response time in summer due to water scarcity, the SF should be decreased. In contrast, false positives will increase. In addition, the algorithm learns from new incidents and the SF will be modified to adapt to new types of failures. An SF of 28% was chosen for this study as it detects the maximum number of incidents and provides an acceptable response time.

5.4.4 Performance analysis of the failure detection algorithm

Figure 5.24 shows the results confusion matrix. The low rate of FN shows that few incidents were not detected by the algorithm. The high rate of TP and TN is a measure of the robustness of the algorithm and indicate that the system has not generated unnecessary alarms.



		Prediction	
		Incident	**No Incident**
Reality	**Incident**	TP = 95.00 %	FN = 5.00 %
	No Incident	FP = 0.0024 %	TN = 99.99 %

Figure 5.24. Dataset confusion matrix.

The evaluation of the algorithm performance parameters is shown in Table 5.3.

Table 5.3. Performance parameters of the failure detection algorithm.

	Recall	**Precision**	**Accuracy**	**F1score**
Failure Detection Algorithm	0.950	0.974	0.999	0.962

As can be seen in Table 5.3, the high value of Recall (0.95) indicates that the number of false negatives is very low. A Precision of 0.974 indicates that the number of predictions that are false positives is very low. The Accuracy value (0.999) indicates that the algorithm's predictions are almost 100% correct. The F1score is also considered since the classes are not balanced (only 40 events in 12 months of data). The F1score (0.962) is close to 1, showing that the algorithm is working properly.

5.4.5 Business solution cost for the case study

The cost of the platform and the associated sensor network has been determined considering the sensor cost and platform maintenance cost. The research and development costs of the platform and the sensor network installation have not been considered.

Each IoT pressure sensor was developed using low-cost technologies and open-source software. The total cost of each sensor was □125 for the communication node and □83 for the pressure transducer.

The number of pressure monitoring devices depends on the topology of the WTN, as well as the financial resources of the corresponding water service. The system described in this work allows for the progressive incorporation of sensors if the monitoring network is implemented in phases.

The maintenance costs of the monitoring network and the platform are shown in Table 5.4. In this case, the sensor communication costs correspond to the system used, Sigfox. The annual connection of each device costs a maximum of □16.10, which can be reduced depending on the number of devices to be connected. On the other hand, the maintenance costs of the web infrastructure include the databases, the frontend, the servers where the hydraulic model is stored and the service for sending SMS alerts.

Table 5.4. Annual system maintenance costs.

Concept	**Price (€/year)**
Sigfox (8 un.)	128.80
Database	5.60
Frontend	9.30
Servers	84.00
SMS Alert system	11.75
Total cost	239.45

The total acquisition cost of the 8-sensor network and wAiter installed in the studied WTN was □1664 and the annual maintenance cost was

□239.45. This amount is a low percentage of the annual maintenance costs of the WTN. Compared to other commercial alternatives, the cost of the system is 25-35% lower than the average price. In this case study, the payback period of the wAIter system is one year after its implementation due to the reduction in the network failure time. This has been calculated considering only a reduction in the volume of water lost in breaks.

5.5 Conclusions

The web platform presented in this work is a comprehensive support tool to manage failures occurring in WTNs. The most relevant function of this platform is the detection and classification of incidents in the network. The main elements of the proposed tool use open-source software, so water companies can control all the stages of the failure detection process (data collection, storage, analysis, visualization and warning) without the support of an external service. The platform has been successfully applied to the studied WTN during a one-year trial period.

The monitoring system linked to the web platform is fully scalable and allows increasing/decreasing the number of data collection nodes that gather information on water pressure according to the size of the WTN. Each node operates independently, so that the failure of one node does not affect the correct operation of the rest. The communication node is designed to host different communication technologies depending on the microcontroller used. The microcontroller Arduino MKR family has different boards with different communication systems, which ensures that the system will not become obsolete in the short-medium term. The platform allows accessing data from any point with an internet connection and shows the results in an intuitive and user-friendly way.

The core of the platform failure detection function is a rule-based decision algorithm. The detailed characterization of typical incidents in WTNs has allowed the development of a simple rule-based decision algorithm that efficiently detects failures in this type of hydraulic networks, as corroborated by the results obtained. The algorithm has been successfully used to classify pressure data and detect failures in the case study WTN. The performance of the algorithm depends on a dynamic pressure threshold to classify pressure records. Each pressure measurement point is defined by a different threshold. In this way, the system ensures optimal adaptation to detect pressure variations. Furthermore, the threshold is considered dynamic as the parameters defining the threshold (SF and n) can be updated to improve the detection of faults based on the faults occurring up to that moment. The proposed dynamic threshold has proven to be more reliable than traditional fixed thresholds. For the case study, the high accuracy of the fault detection algorithm (recall = 0.950, precision = 0.974, accuracy = 0.999, f1score = 0.962) was obtained with SF and n values of 0.28 and 17, respectively. Both parameters are necessary to calculate the dynamic threshold.

The MRT calculation is a useful tool for planning leakage repairs. This platform function allows optimal planning of the resources needed to carry out the repair. In this way, technical staff can simulate actual and hypothetical demand scenarios to evaluate the evolution of the tank level. When the MRT is known, it is possible to establish the maximum period for repairing faults to manage the necessary resources and prevent users from being left without supply. The proposed algorithm can be applied to WTNs with similar characteristics to the studied network, although its adaptation to other types of networks (looped networks, pumping, distribution networks, etc.) needs to be studied.

When working with real datasets of water transmission network pressure, it is time consuming to collect long series of incidents. So far, good results have been obtained with the existing data, although the system will be improved with the addition of new failure records. wAiter has great potential for future developments such as incorporating flow and level sensors in the tanks and the addition of a decision-making module based on the analysis of historical failure records to determine pipe renewal criteria according to the frequency and magnitude of failures.

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6. Conclusions

6.1 General conclusions

In this thesis, a decision support system for smart management of water supply network has been developed. The tool has been designed by applying open-source technologies and software, adapted to the management of water supply networks. Scientific rigour combined with low-cost technologies has allowed the development and implementation of a robust system, whose applicability has been demonstrated by its successful application in real networks.

6.2 Specific conclusions

- The integration of a GIS with the hydraulic model provides a source of knowledge to the managers to manage breakdowns efficiently by properly planning the use of the available resources (human and material). Failures are located in the GIS and, the hydraulic model allows to evaluate the situation to know the time available to carry out the repair before any user becomes unsupplied.

- The application for mobile devices that stores the GIS information facilitates the exchange of information between the staff involved in management. This APP serves as feedback, ensuring that the system is updated when the network is extended or renewed.

- The IoT pressure sensor, as well as the communication architecture, information processing and visualisation system based on open source and low-cost technologies, has demonstrated its robustness as a true pressure monitoring and warning system.
- The communication node developed is designed to host different communication technologies depending on the microcontroller used, which guarantees that the system will not become obsolete in the short-medium term. This allows the system to be adapted to the site to be monitored.
- The web platform is a comprehensive support tool for failure management. The main functions of this platform are the detection and classification of faults in drinking water supply networks. The performance of the algorithm depends on a dynamic pressure threshold that has demonstrated an accuracy above 95%.
- In each module of the web platform any element and/or software can be replaced by another with similar characteristics to facilitate the updating/improvement of the technologies used. In addition, dependence on commercial brands is avoided.
- The use of open-source software in the four pillars of the proposed system (GIS, hydraulic model, APP, and web platform) enables the digitization of the management of water supply systems operated by companies with limited financial resources.

This helps to reduce the digital divide between large and small water companies.

6.3 Avenues for future research

After the results obtained throughout this thesis, some of the possible lines of future research are detailed below:

- Adaptation of the proposed intelligent management system to other hydraulic networks such as collective irrigation networks or drinking water distribution networks.
- Implementation of the monitoring system developed, based on the Internet of Things, to sewerage networks to record the main hydraulic variables that characterise the behaviour of these networks in real time. In this line, a first prototype has already been developed, which has been validated in the lab and it is being tested in a real wastewater discharge point.
- Until now, the detection of failures and support in the process of repairing them has been addressed. An algorithm could be proposed to plan the renewal of the network considering the failure history of each sector of the network.
- Incorporate into the proposed intelligent management system the monitoring of a larger number of hydraulic variables (flow rate, tank levels, etc.) to detect other types of failures that cannot be identified using only pressure data.

- Due to the large amount of water pressure data collected until now, points with potential for energy recovery due to excess water pressure could be studied for the suitability of installing microturbines or PATs. A preliminary analysis has already been carried out using the hydraulic model, which needs to be supplemented with real data (pressure and flowrate) from the hydraulic network.