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Digitalization of Water Distribution Systems in Small Cities, a Tool for Verification and Hydraulic Analysis: A Case Study of Pamplona, Colombia

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Abstract: Digitalization in water networks is essential for the future planning of urban development processes in cities and is one of the great challenges faced by small cities regarding water management and the advancement of their infrastructures towards sustainable systems. The main objective of this study is to propose a methodology that allows water utilities with limited budgets to start the path toward the digitalization and construction of the hydraulic model of their water distribution networks. The small city of Pamplona in Colombia was used as a case study. The work explains in detail the challenges faced and the solutions proposed during the digitalization process. The methodology is developed in six phases: an analysis of the cadastre and existing information, the creation and conceptualization of the base hydraulic model, the development of the topography using drones with a limited budget, an analysis of water demand, the development of a digital hydraulic model, and a hydraulic analysis of the system. The product generated is a tool to assess the overall performance of the network and contributes to the advancement of SDG-6, SDG-9, and SDG-11. Finally, this document can be replicated by other cities and companies with similar characteristics (e.g., limited size and budget) and offers an intermediate position on the road to digitalization and the first steps towards the implementation of a digital twin.

Keywords: water distribution network; water management; digitalization; digital hydraulic model; digital elevation model

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Citation: Bonilla, C.; Brentan, B.; Montalvo, I.; Ayala-Cabrera, D.; Izquierdo, J. Digitalization of Water Distribution Systems in Small Cities, a Tool for Verification and Hydraulic Analysis: A Case Study of Pamplona, Colombia. *Water* **2023**, *15*, 3824. https://doi.org/10.3390/w15213824

Academic Editors: Peiyue Li and Jianhua Wu

Received: 30 September 2023
Revised: 29 October 2023
Accepted: 30 October 2023
Published: 1 November 2023

1. Introduction

Urban water management carried out by water utilities is based on the implementation of various actions allowing the optimization and sustainability of distribution processes through decision-making [1]. Improvement actions should focus on the sustainability and comprehensive performance of the supply and sanitation networks [2]. To this aim, the Sustainable Development Goals (SDG) set clear objectives and diverse actions to ensure the future availability of water and sanitation to communities through the construction of resilient systems and sustainable cities. These actions aim to improve water management and are mainly framed in three objectives, namely SDG-6, SDG-9, and SDG-11 [3].

In some cases, government entities and water companies develop joint actions to ensure water availability, implementing awareness campaigns in the population about water security and creating responsible water citizens, involving state actors, non-state actors, and citizens, conceptualizing and identifying their roles and responsibilities in water use [4].

Cities and their water utilities face diverse challenges to ensure access to drinking water in a safe environment, such as water scarcity and population growth [5], aging infrastructure [6], and climate change [7], among others. A possible solution to address these problems is found in technological innovation and the digital transformation of water distribution systems (WDSs) [8], because digital models allow for achieving knowledge transfer, resilience during atypical events, and improvements in terms of efficiency [9].

Technology and its advances allow the development of several management actions in WDS amenable to being leveraged via the use of optimization techniques for the planning and management of those systems, thus leading directly to the economic improvement of water companies and respect of the environment. The main management actions are aimed at solving optimization problems in designing WDSs, incorporating new methodologies based on minimizing cost factors, and developing intelligent optimization algorithms [10]. Other actions are based on the digital metering of water consumption, which could allow the detection of leaks at the user level and distribution network level [11]. Likewise, the monitoring and measurement of system parameters (e.g., pressure and water flow) improve decision-making and optimize the resources of water utilities and authorities [12], thus minimizing water leakage in their networks [13,14].

The age and quality of water in the WDS is also an important field of research in which different management and optimization actions based on technology have been proposed. The optimization of the operational management of valves has allowed for the minimization of the age of water in pipes via the implementation of a combination of validated algorithms in networks of different complexities, guaranteeing the supply of water with adequate quality [15]. The analysis of the exposure and vulnerability of users to trihalomethanes (THMs) existing in WDSs, carried out using water quality algorithms, has made it possible to identify critical areas with high THM concentrations with different exposure periods, allowing water companies to design public health strategies to reduce risks [16].

The data available from network operation allows the management and operation of water networks and estimates the real state of their non-monitored elements (e.g., pipes), leading to the building of digital twins (DTs). DTs integrate the data monitored in real-time with optimization algorithms and virtual network models through geographic information systems [17]. An essential requirement to build a DT in a WDS is the digitization of its network and, from this stage, the start of a continuous process of adjustments and learning of the system [18].

To support water management, other digital and technological tools—e.g., unmanned aerial vehicles (drones) and satellite images—have been used to quickly and accurately analyze the behavior of some elements of WDSs. Drones have been used to measure reservoir water levels [19] and analyze water quality in reservoirs or supply sources [20]. Satellite imagery has been used for leak detection in WDSs, successfully identifying leaks and saving operational costs [21]. In this sense, digitalization appears to be a powerful tool for WDS management that translates into economic benefits for water utilities.

The digitalization of WDSs is considered an evolving process that is achieved by managing infrastructure through digital technologies. Currently, the impact of digitalization in the drinking water sector is carried out on a smaller scale compared to that in other sectors [22]. There are different factors of complexity, uncertainty, and dynamism in water supply systems that demand a need to revolutionize the water industry and the adoption of new digital technologies that combine monitoring, supervisory control, and data acquisition (SCADA) systems, decision support in real-time water networks, and information and communication technology (ICT)-based solutions [23].

Currently, research on the digitalization of WDSs seeks to meet socioeconomic, environmental, sustainability, and climate needs to improve their efficiency and productivity [24,25], as well as to generate strategic opportunities to address the challenges associated with the SDGs [26]. On this path to digitization, different technologies, called emerging technologies (ETs), are identified as being employed by water utilities worldwide in the digital transformation of their networks. ET can be grouped into five major groups: cyber-physical systems, the Internet of Things (IoT), big data analytics, artificial intelligence, and cloud computing [23].

Research showing the applicability of ETs in WDSs worldwide can be found in the literature. Cyber-physical systems have been applied in Spain [27,28] and India [29]. IoT has had wider application in countries such as Singapore, South Korea, Malta, and South Africa [23]. Big data analytics have been developed in countries such as Morocco [30,31], India [32], Sri Lanka [33] and Italy [34]. Artificial intelligence has been used in Spain [35,36], Mexico [36], Jerusalem [37], United Kingdom [38] and Jordan [39]. Computation has been implemented in Italy [40], the United States [41], Egypt [42], Spain [43], and India [44]. These investigations provide an overview of digitalization in WDSs and the different approaches adopted in different countries around the world.

As a cornerstone, for the implementation of technological actions in WDSs that promote sustainable water management, water utilities need to digitize their supply systems elements. However, the delay in the digitization (and digitalization) process is directly related to the economic costs associated with its implementation [45]. In many cities, mainly in Latin America, the information available from the WDSs is highly vulnerable and susceptible to losses because the information of their networks (location, diameters, and materials) exists in a physical (not digitized) format and, even in some cases, the information only exists in the memory of the most experienced workers [46]. Some water utilities are unaware of some elements of their WDS and do not have accurate information on their oldest pipes, which makes it challenging to start digitizing their networks [47].

The operation of WDSs in small cities is commonly conducted empirically or experimentally using the applications of the practical know-how of water utility experts. Future planning related to the expansion and construction of new networks is based on factors affecting water demand, such as population growth or the development of new areas in the city according to their needs (e.g., industrial areas) [48]. A city or a water utility without system digitalization does not have sufficient analytical tools to predict/anticipate potential changes that may affect consumers' needs. For example, in the case of a WDS, it may not even have a hydraulic model of its distribution networks. An appropriate (well-calibrated) model allows simulations and test scenarios to be carried out to estimate the effects generated in the existing networks by changes caused by topological modifications or the occurrence of an event, which may compromise the operation of the system. These events include changes such as variations in pressure or flow at different points in the city due to the incorporation of new users of the system, among others. Therefore, building hydraulic models of a WDS becomes an essential step in developing other actions of technological innovation (e.g., the operation optimization of the current network) to improve water management [49].

This work proposes a methodology to advance towards the digitalization and transformation of WDSs. It is mainly focused on networks with reduced size in the context of a limited budget. The proposed methods for creating a hydraulic model of a real WDS, and how to refine (or incorporate new) elements of the system with the assistance of a low-cost technology (in this case drone) are described in detail herein. The challenges faced and solutions adopted during the construction of the hydraulic model are also explained in this paper. This research attempts to become a base statement, serving as a guide that can be replicated by other cities and companies with similar characteristics and concerns with relatively low economic investment. The hydraulic model for the WDS of Pamplona, Colombia, is created. The results obtained in the hydraulic simulations of the created model are analyzed and compared with pressure measurement data at different points in the network. The work carried out provides the city's water company with a fundamental tool to manage and optimize drinking water distribution.

2. Materials and Methods

The methodology proposed in this paper is presented in Figure 1.

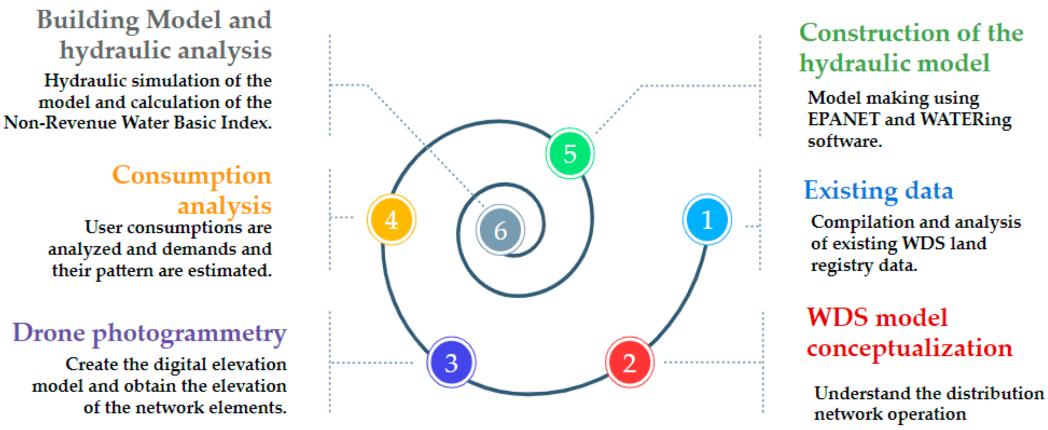


Figure 1. Schematic configuration of the proposed methodology.

In Figure 1, the spiral design of the methodology allows its incorporation at any step of its development. The proposed methodology consists of the following main steps:

Step 1. It begins with collecting and analyzing the existing data related to the land registry of the network infrastructure.

Step 2. The next step is conceptualizing the basic hydraulic model to understand its functioning, such as the direction of the flows and storage volumes.

Step 3. Photogrammetric images are obtained using a drone, which helps create the city's digital elevation model. This digital elevation model is used to obtain the network elevation for both pre-existing and new expansion areas that comprise the city.

Step 4. Existing user consumption data are used in this step to analyze the base demands of the model. The hydraulic model is built using hydraulic computer engines (in this case the EPANET 2.2 software [50–52]) and the model is incorporated into an online platform for monitoring and optimizing water networks (in this paper, WATERing software [53]).

Step 5. The hydraulic analysis of the model is conducted, and the in-field pressure measurements of the water utility are used to compare the obtained results (basic network calibration).

Step 6. Afterward, a preliminary calculation of the non-revenue water index is conducted in this step.

Each step of the proposed methodology is described in detail in the sections below.

2.1. Analysis of Existing Information

Among the main identified problems for building a hydraulic model is the lack of documented information regarding the existing networks and infrastructure of water utilities (this is particularly critical in public institutions) [46]. The lack of standardized processes for storing and documenting public records many times leads to the loss or deterioration of information over time. Therefore, the recorded information is partially reliable and must be verified and updated. In this sense, the first step of the proposed methodology focuses on the collection of the available information from the system and its preliminary digitization. The sources of the information used in this work and essentials of its are as follows.

- Documentary record: In the government offices (technical offices in charge of the infrastructure in each city), physical and digital layouts should be consulted, as well as technical documents related to the land registry of the WDS. Similarly, existing WDS layouts in the water company's technical offices should be found and compiled.

- Urban layouts: The most up-to-date layouts of the city, urban roads, road infrastructure, and land use maps should be obtained from public offices.
- Satellite images: Currently, there is recent, updated, and free-access satellite information that shows the development and urban growth of each community. It is essential to use the existing edited images of the study site and contrast them with the city's physical and digital maps. With these tools, it is possible to identify new neighborhoods (e.g., recent urban developments or unplanned neighborhoods made up of low-income or immigrant families on the outskirts of the city) or non-registered urban settlements in the existing maps. This information should be included and updated.
- Tacit information: Once the existing information is verified and analyzed, field visits should be carried out, preferably with the water utility experts to know the operation of the WDS. The most experienced active personnel in water companies have excellent information in their memory and this information is called tacit information. This type of information is valuable to contrast the information obtained via documentary records, urban layouts, and satellite images with. Fieldwork helps to identify the visible components of the system (valves, reservoirs, reservoirs, pumping stations, hydrants, and sensors) and their physical properties (dimensions, diameters, and materials) to complement the missing information. If necessary, field inspections should be conducted using boreholes to obtain any missing information. Subsequently, this information should be digitized and reflected in an initial layout of the WDS.
- Preliminary digitization: Using the collected information, a preliminary digitization of the WDS is carried out using a computer-aided design (CAD); alternatively, geographic information systems (GIS) can also be used in this activity. It is essential to use several layers in the drawing process to identify and classify the different materials and diameters of the pipes and the existing elements in the network (valves, tanks, and hydrants). This process allows us to roughly understand the general structure of the WDS and to get to know the most important pipes and elements in the network.

2.2. Conceptualization of the Hydraulic Model

It is necessary to understand the WDS's hydraulic operation, identifying the main elements of the network (e.g., main pipes) and the operational hydraulic zones. For the development of the second step of the proposed methodology, it is essential to identify the following.

- Continuity of service: This is determined to know the actual time of service offered by the system during the day, to know if the service is continuous or intermittent, and in the case of the intermittent systems, to identify the service shifts and the areas supplied in the different shifts that may exist. This information is relevant to determining consumption patterns and should be consulted with the water company's experts; if possible, the company's records of pipe damage and repair times should be consulted.
- Pipe information: It is necessary to know the diameter of each pipe, length, type of material, and approximate age. Knowing the age allows for the establishment of an approximate roughness coefficient, which is necessary for the loss equations of the hydraulic model.
- Network fittings: These comprise the location, diameter, and material of strategic valves used by workers to operate the network, as well as pressure regulating valves, need to be identified. Hydrants and other relevant accessories for hydraulic operation should also be identified.
- Storage tanks: It is essential to know the existing tanks, their location, volume, and internal dimensions, as well as the variation in water levels throughout the day. It is also necessary to have an idea of the supply areas of each tank.
- Pumping equipment (if any): The pumping stations that operate in the network must be identified; it is necessary to have clarity on the number of pumps installed, power

characteristics, and models installed to determine the operating curve of each pump and to know the suction and discharge pipes.
- District metered areas: If there are metered district areas in the WDS where flow or pressure data are available, they should be detailed and similarly shown in the network plans and in the hydraulic model to be built. If there is no sectorization, the company's experts should be consulted on how the network is operated, whether it supplies all users continuously and without district zones, or whether there are service shifts in defined areas determined on an experimental basis with valve management. Intermittent service provision should be analyzed based on a thorough knowledge of intermittent water distribution, as recommended [54].
- Monitoring data: The existence of measured data on pressure, flow, and water quality in the network should be investigated. These data can help understand the behavior of the network and will be used to perform the calibration process. In water utilities that do not have this information, it is recommended to implement monitoring campaigns—preferably pressure and flow—at some points of the network and according to the limited budget that can be allocated for these activities.

From all these data, a more approximate idea of the real functioning of the networks will be obtained which is called the "conceptualization" of the hydraulic model.

2.3. Drone Assistance

For building the hydraulic model of a WDS, a detailed topography is needed to obtain topographic elevations of the roads or streets and visible elements of the network. The costs associated with georeferenced topography work increase depending on the area, generally charged per hectare and georeferenced. For some companies with low budgets, the total value of this activity can be costly. In the city of Pamplona, the urban area is approximately 580.30 ha. Using new technologies allows alternatives to obtaining topographic and geospatial information based on photogrammetry with the assistance of unmanned aerial vehicles (drones) to be found. Currently, drones perform high-precision processes to obtain topographies relevant to water management. The general process of drone photogrammetry can be divided into six main activities, according to [55], as follows.

- Flight planning: The areas of interest must be identified, delimiting the general perimeter of the location from which information will be obtained. Mobile applications (e.g., DJI GO o PIX4Dcapture Pro) are used to plan the number of flights to be carried out, called missions, according to the size of the total area. Flights should be made on sunny days; the drone should not be flown on rainy, cloudy, or foggy days, as this affects the quality of the images and the drone's reception signal.
- Configuration of flight parameters: Flight altitude, maximum flight time, and photo capture interval are configured. These parameters depend on aspects such as the height of the buildings or existing infrastructure in the city (telephone towers, electric power antennas, etc.) and the state of the batteries that limits the maximum flight time per mission.
- Image acquisition and processing: Planned flights are carried out to obtain photographs. The information taken by the drone is downloaded to a computer and the quality of images is verified by checking that there are no blurred or distorted photographs due to clouds or any external element around the drone. Subsequently, the images must be processed to obtain the sense and orientation of each picture, which is carried out by analyzing the pixels of each image and the similarity of these pixels in the other photographs to obtain the overall picture of the area. Finally, 3D spatial data are generated, with points containing geographic and elevation information. There are different tools to analyze the photographs taken with a drone. In this case, the Agisoft Metashape photogrammetric application [56] is used to process and orient the images based on the GPS information of the drone and the relative position in each mission. It is necessary to verify that all pictures have information to guarantee the quality of the result. If, due to signal reception problems (e.g., a loss of connection

with GPS satellites or interference with radio or mobile phone signals), information is not obtained from any area, a new mission must be planned for that sector.

- Checkpoints: With the information of the national geodetic network "https://redgeodesica.igac.gov.co/redes/red_geodesica.html (accessed on 17 January 2023)", the existing georeferenced points within the flight area must be located and the elevation of the points and their coordinates, at least, must be obtained, as well as the geodetic coordinate system in which they are located. If these points are unavailable, a high-precision GPS should be used to obtain that information. This information will minimize the error and increase the accuracy of the elevation model obtained.
- Creation of the point cloud: The following process consists of creating the point cloud, which allows for the identification of points with the same pixel information in the photographs and the construction of a first 3D image with the data captured with the drone. From this, the mesh is created, which is the base element with which to obtain elevations of the model; it is recommended to work at a high resolution (a face count parameter equal to 180,000). It is necessary to carry out the process of classification of points to purge elements that are not of interest in the model to be generated.
- Digital elevation model (DEM): Finally, processing is performed to obtain the DEM, contour lines, and orthophoto. These three products can be exported in independent files in shapefile, DWG, or JPG format, among others, so that they can be visualized in software such as AutoCAD, QGIS, or ArcGIS.

Figure 2 summarizes the described process of drone photogrammetry.

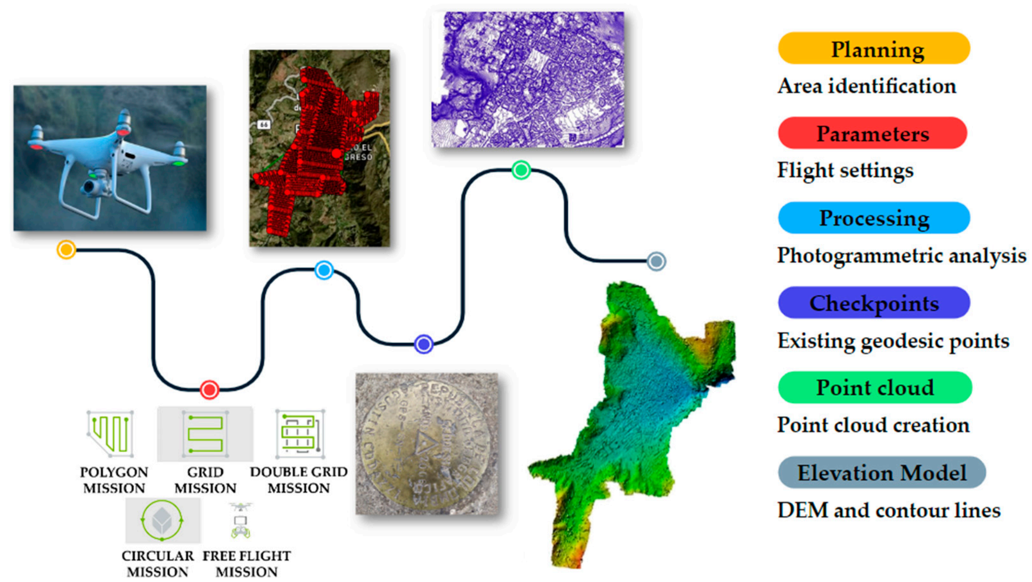


Figure 2. Photogrammetry with drone assistance to update elevation data in a WDS.

2.4. Consumption Analysis and Demand Pattern

Consumption analysis is performed to determine the actual water consumed by the inhabitants of a population. It allows the obtention of an approximate value of the base demand to be used for the hydraulic simulations of the WDS model. To obtain the demands of each node of the hydraulic network, a unit flow is used based on the types of existing users (domestic, commercial, institutional, and industrial) according to the total area supplied by the WDS. Those flows are calculated as described in Equations (1)–(4):

$$Qu_{RES} = \frac{CM_{RES}}{30 \times 86{,}400 \times A_{TOTAL}} \quad (1)$$

$$Qu_{IND} = \frac{CM_{COM}}{30 \times 86{,}400 \times A_{TOTAL}} \quad (2)$$

$$Qu_{IND} = \frac{CM_{IND}}{30 \times 86{,}400 \times A_{TOTAL}} \quad (3)$$

$$Qu_{INST} = \frac{CM_{INST}}{30 \times 86{,}400 \times A_{TOTAL}} \quad (4)$$

Here, QU_{RES} is the unit domestic flow in liters per second per hectare (L/s × Ha), QU_{COM} is the unit commercial flow in L/s × Ha, and QU_{IND} is the unit industrial flow in (L/s × Ha), QU_{INST} is the unit institutional flow in L/s × Ha. CM_{RES}, CM_{COM}, CM_{IND} and CM_{INST} are the monthly average consumptions for each type of user in cubic meters per month (m^3/month × user) and A_{TOTAL} is the total supplied area in hectares (Ha).

The afferent area influencing each node of the WDS hydraulic model is calculated, the number of dwellings associated with each hydraulic node is determined, and the afferent area is estimated from the urban plans mentioned in numeral 2.1. The products of these areas and the estimated unit flows provided by Equations (1)–(4) enable a calculation of the base demand of each node using Equation (5):

$$Q_{Ni} = Qu_{RES} * A_{RES(Ni)} + Qu_{COM} * A_{COM(Ni)} + Qu_{IND} * A_{IND(Ni)} + Qu_{INST} * A_{INST(Ni)}, \quad (5)$$

where Q_{Ni} is the base demand of each node of the hydraulic model in L/s. $A_{RES(Ni)}$, $A_{COM(Ni)}$, $A_{IND(Ni)}$ and $A_{INST(Ni)}$ are the areas afferent to each domestic, commercial, industrial and institutional node, respectively, in hectares (Ha).

To obtain the demand pattern that represents the hourly variation of flows in the WDS, the use of flow data from the flow record at the drinking water treatment plant (DWTP) outlets is proposed. An hourly increase factor (HIF) based on the flow measured at each hour of the day and the average daily flow, the latter being understood as the average of the daily flows, can be calculated as shown in Equation (6):

$$\text{Hourly Increase Factor(HIF)} = \frac{\text{Flow measured each hour}}{\text{Average daily flow}} \quad (6)$$

2.5. Hydraulic Model, Hydraulic Analysis, and Non-Revenue Water Basic Index

For the building of the hydraulic model, the digitized information is converted into DXF format (drawing exchange format). This file, in turn, is converted into INP format to generate the pipes and network nodes according to those described in [57]. The created file can be edited in EPANET and will only have pipe layouts. Lengths, diameters, and roughness must be added. Additionally, reservoirs, tanks, and valves, and the properties of these elements must be inserted.

The base demands in the network nodes are estimated using Equation (5). The demand pattern can also be included in EPANET and the model is configured for extended-period modeling. The changes made are saved to an INP file.

The DEM obtained with the drone and the last INP file modified to include the topographic elevations based on the methodology proposed in [58,59] are used. The physical properties of the hydraulic model are completed and the first hydraulic simulations are performed in EPANET to test the functionality of the network. The WATERing software and the INP file are then used, loaded, and synchronized with an OpenStreetMap satellite base map. A simple graphical interface is obtained once its correct geographical implementation is verified. This software allows water utilities to have an online hydraulic model that offers several analysis options and the possibility of multi-user editing.

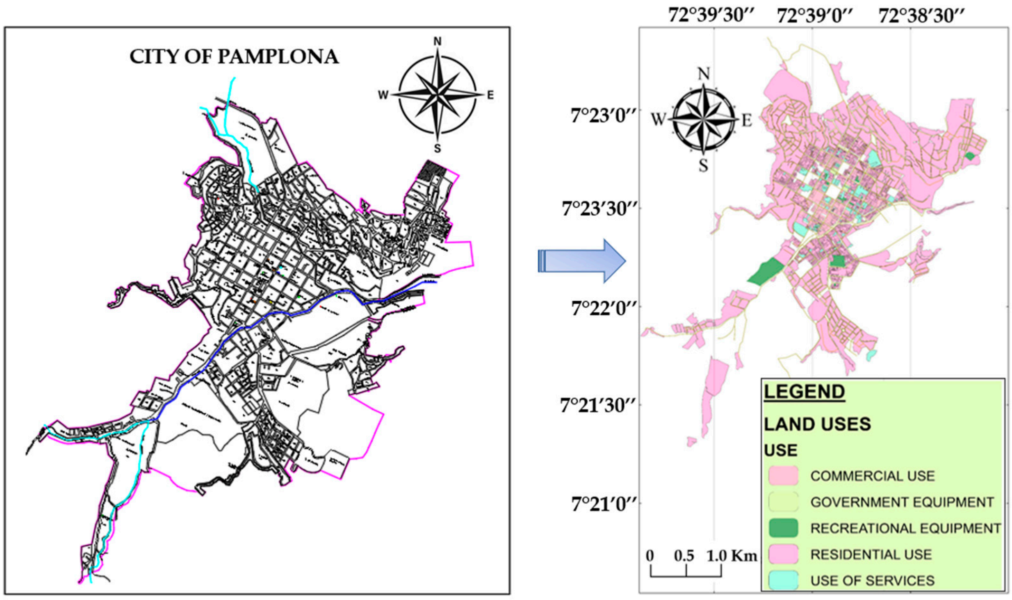
With the historical record of the billing and consumption of the users and the measurements of the flow supplied to the WDS by the DWTP for the last three months, the non-revenue water basic index (NRWB) of the system is calculated using Equation (7) described in [60], as follows:

$$NRWB = \left(\frac{SIV - BAC}{SIV}\right) * 100\%, \quad (7)$$

where SIV (system input volume) is the water supplied to the network (m^3/year) and BAC (billed authorized consumption) is the water sold (m^3/year).

2.6. Study Location

The city of Pamplona is located in the state of Norte de Santander in Colombia. Its geographical location is at the coordinates 72°39′ west longitude and 7°23′ north latitude, with an elevation that varies between 2200 and 2600 m above sea level and an estimated population of 51,292 inhabitants for the year 2023. Pamplona is considered a small city and its urban area is approximately 580.30 ha; its main economic activities are education, tourism, and agriculture. According to the different land uses, the city has residential, commercial (e.g., restaurants, stores, cafeterias, and supermarkets), governmental and institutional, and recreational uses (e.g., parks; sports areas) [61]. Figure 3a shows an urban map highlighting the urban perimeter in purple and Figure 3b shows the city's land uses.



(**a**) (**b**)

Figure 3. Pamplona, Colombia. (**a**) Urban map and (**b**) land uses.

3. Results

3.1. Existing Data and Conceptualization of the Hydraulic Model in Pamplona

In Pamplona, the WDS was not digitalized. There was no hydraulic model that correctly represented the actual behavior of the network and its physical infrastructure. The most relevant existing information consisted of physical plans and the information existing in the memory of the most experienced workers. Physical and PDF (portable document format) layouts provide information on the existing networks in the city up to the year 2016, where the locations of the pipes, materials, and diameters are described, as well as the location of tanks and their storage volumes, valves, pumping stations, and DWTPs. It has been necessary to update information on the cadaster regarding new network zones (installed in recent years in replacement and expansion works).

The updated information up to the year 2021 is in DWG digital format (AutoCAD files) and shapefile format. Using satellite images, new urban settlements were identified that were not registered in the physical or digital plans and currently have water networks installed and in operation. These settlements are observed in the city's northwest, northeast, and southeast areas, as shown in Figure 4.

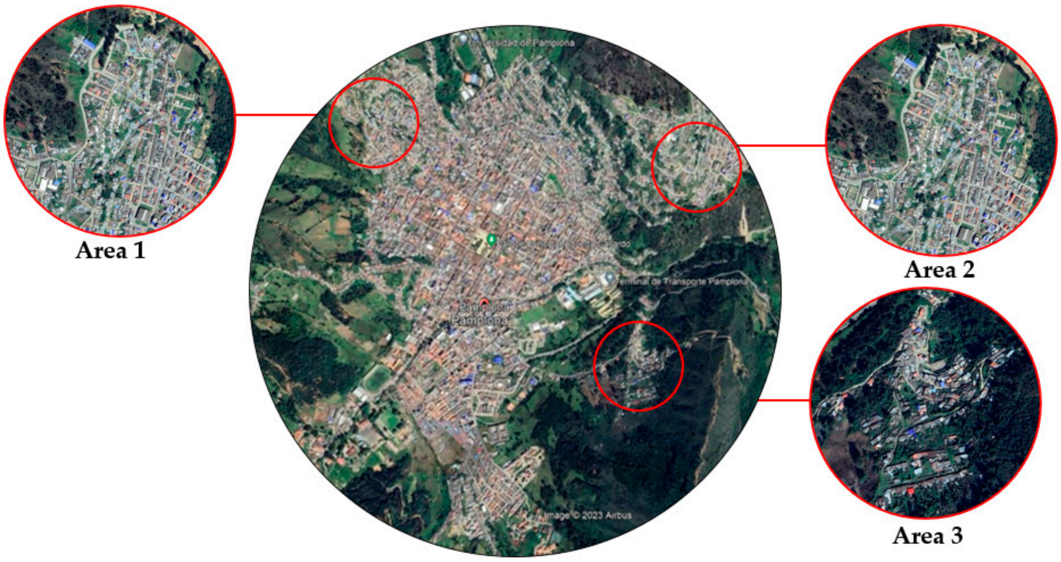


Figure 4. New urban settlements identified in Pamplona.

Due to the incomplete information on the cadaster of the networks installed in recent years, it is necessary to carry out fieldwork to identify and verify some elements and layouts. Figure 5 shows some of the details verified in the field. Figure 5a shows piping and valves and Figure 5b illustrates one pressure-bursting chamber. Once the missing information was confirmed, a preliminary digitization of the WDS was performed.

(**a**) (**b**)

Figure 5. Record of field inspections. (**a**) Piping and valves; (**b**) pressure-bursting chamber 4.

The distribution system is operated by the water company EMPOPAMPLONA SA ESP "https://www.empopamplona.com.co/ (accessed on 30 January 2023)". It is a gravity-fed system providing continuous service. Two DWTPs supply water to the piping networks. The Cariongo DWTP has an average operating flow of 104.7 L per second (L/s) and the Monteadentro DWTP has that of 37.8 L/s. The DWTPs are designed as reservoirs and distribute water directly to the network and 12 storage tanks or reservoirs totaling 3530 cubic meters (m^3). The network supplies an area of 3.76 square kilometers (km^2) with an average flow of 142.5 L/s. The water company in the year 2022 had 15,587 users, of which 92% were domestic, 7% commercial, 0.25% industrial, and 0.75% institutional. Figure 6 shows the digitized map of the networks in DWG format.

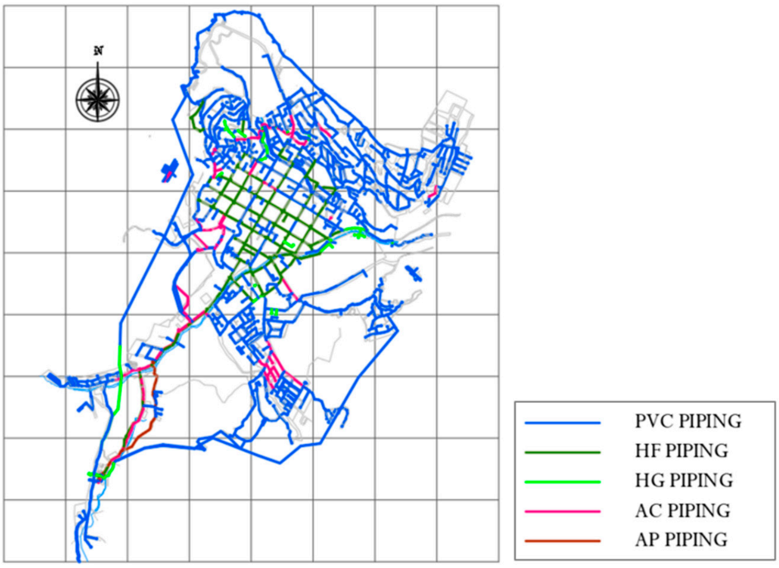


Figure 6. Digitization and updating of the WDS cadaster map.

The main network pipe diameters vary from 150 mm to 400 mm and interconnect to smaller networks with diameters varying from 50 mm and 100 mm. The water network is compounded by polyvinyl chloride (PVC), asbestos cement (AC), cast iron (CI), galvanized steel (GI), and American pipe (AP). There are pressure rupture chambers at some points in the network because there are areas with highly variable topography and differences in elevation between the tanks and the network that can exceed 150 m. There are no pressure-reducing or regulating valves in the WDS. The network lacks hydraulic sectorization, areas with district meters, or a macro measurement of the network's internal flow. It only has a micro measurement for each user.

The water company installed 19 piezometers at different points of the network, which were located after an engineering report, where pressure data are manually recorded at two times of the day, at 9:00 and 16:00 h. These measurements are used to control the hydraulic operation of the WDS. According to existing data, the pressure measured varies between 14 m of the water column (mH_2O) and 105 m of mH_2O. Isolation valves are distributed along the network and used to close subsystems when pressure problems cause damage and failure. Figure 7 shows the conceptualization scheme of the Pamplona WDS.

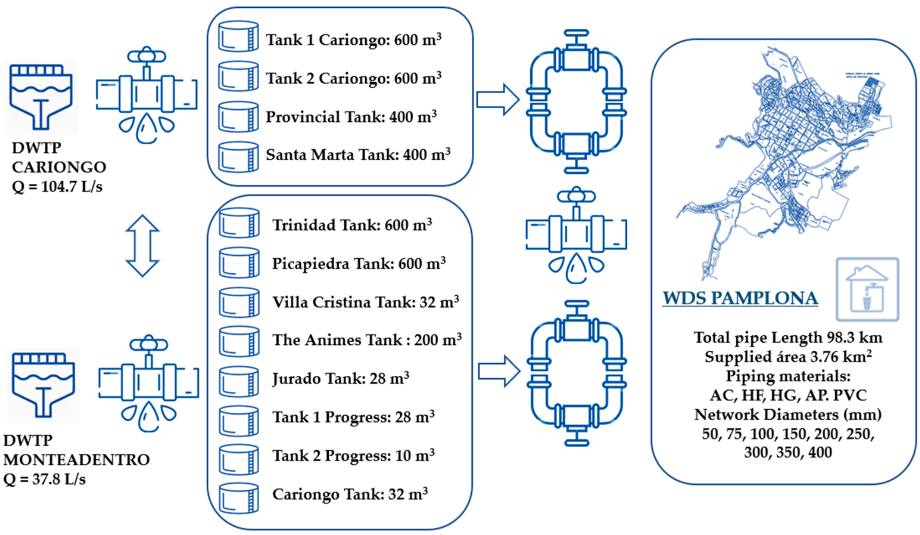
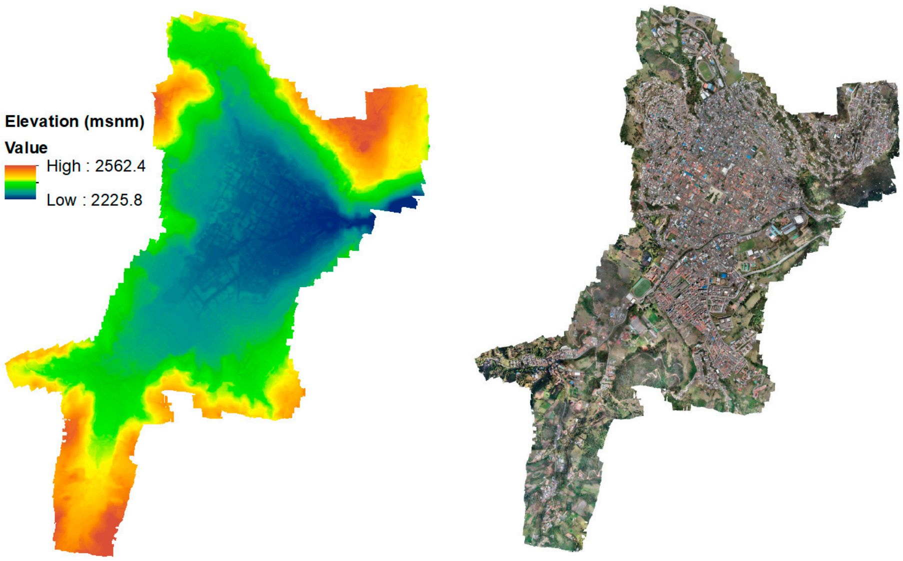


Figure 7. Conceptualization of the WDS of Pamplona.

3.2. Drone Assistance

In this research, a Phantom 4 Pro drone "https://www.dji.com/global/phantom-4-pro (accessed on 2 February 2023)" was used to obtain the digital elevation model to determine the topographic elevations of nodes and elements such as reservoirs and tanks of the network. In this work, 19 missions are planned in "polygonal mission" mode. The minimum flight altitude was selected as 50 m, the maximum height was 150 m above ground level, and the complete transmission range was 7 km. The missions were configured for flight times between 12 and 15 min. These parameters were selected according to the heights of the buildings, the variation of the topography in the city, and the duration of the drone's batteries.

The city of Pamplona has five geodetic control points. This information, included in the Agisoft Metashape software, increased the accuracy of the elevation model. Figure 8a shows the DEM generated with the topographic variation in the city, its minimum height of 2225.8 m above sea level (masl), and its maximum height of 25,652.4 masl. Figure 8b shows the orthophoto of Pamplona.



(**a**) (**b**)

Figure 8. Pamplona, Colombia. (**a**) Digital elevation model; (**b**) orthophoto.

3.3. Consumption Analysis and Demand Pattern

The consumption analysis is based on the water company's billing information. The billing records are analyzed to estimate the average consumption of users and categorized according to the use's type (residential, commercial, institutional, or industrial). This analysis allows the obtention of the average monthly consumption of each user per cubic meter (m^3/month × user). These values are obtained through a descriptive statistical analysis of the different types of users proposed by [62] and allow the obtention of the values of CM_{RES}, CM_{COM}, CM_{IND}, and CM_{INST}, which are mentioned in Equations (1)–(4). The analysis results show that the average monthly consumption for institutional users was 10.50 m^3, that for industrial users was 10.00 m^3, that for commercial users was 8.25 m^3 for, and that for domestic users was 9.00 m^3.

Another essential element for building a hydraulic model is the hourly demand pattern of the network. For this purpose, the flow values measured in the DWTPs for the last three months are used. The hourly increase factors were calculated using Equation (6) and thus, the demand pattern shown in Figure 9 was obtained.

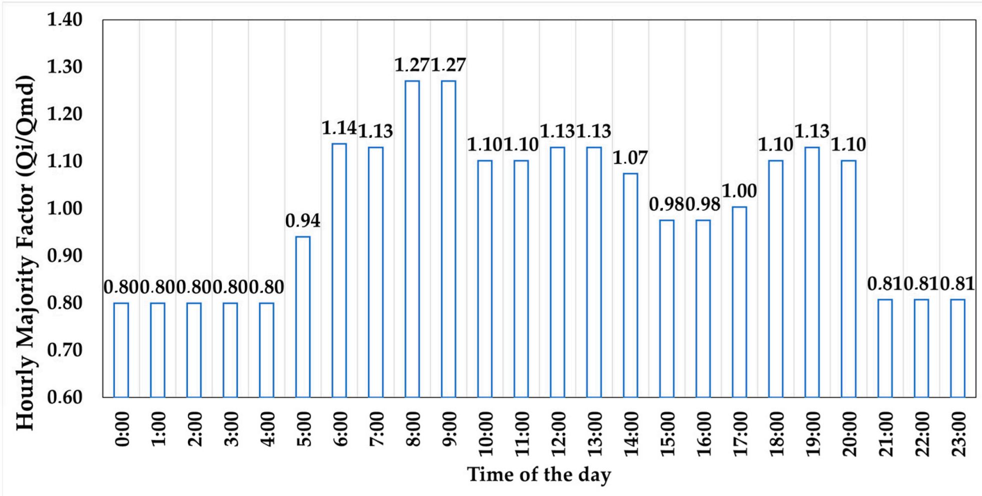


Figure 9. Daily demand pattern of Pamplona WDS.

It is observed that the peak of consumption in the network occurs at 9:00 h and 19:00 h when the population consumes the most significant amount of water. It is also observed that the hours of lower consumption occur between 22:00 h and 4:00 h the following day. During these hours, consumption is relatively low and operations in the DWTPs are reduced to their minimum operation. The HIF was obtained with a value of 1.27. This analysis was performed by averaging the records supplied by the water company. The calculated pattern has a behavior directly related to the habits of the inhabitants of Pamplona.

3.4. Building of the Model for Hydraulic Analysis

The network map shown in Figure 6 is converted into an INP file as indicated in Section 2.5, and an offline model is created and exported to EPANET; some properties such as diameters, roughness, base demand, and demand pattern can be added initially. This file and the DEM generated in Section 3.2 complete the preliminary hydraulic model with the topographic elevations. The first hydraulic simulations are performed in EPANET to test the functionality of the network. The created hydraulic model is loaded and synchronized in WATERing.

Figure 10 shows the WDS network's implementation and general layout in the WATERing software on the Open-Street Map base map.

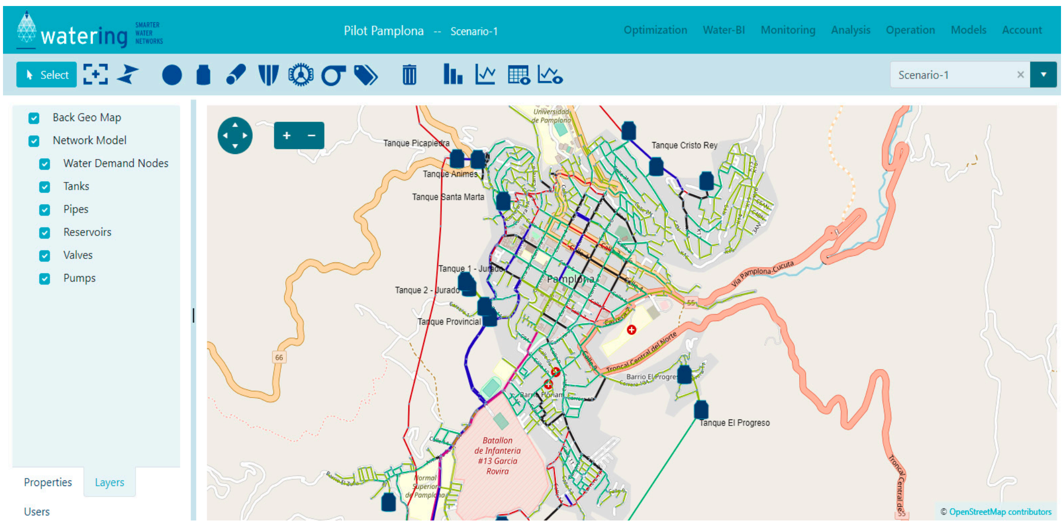
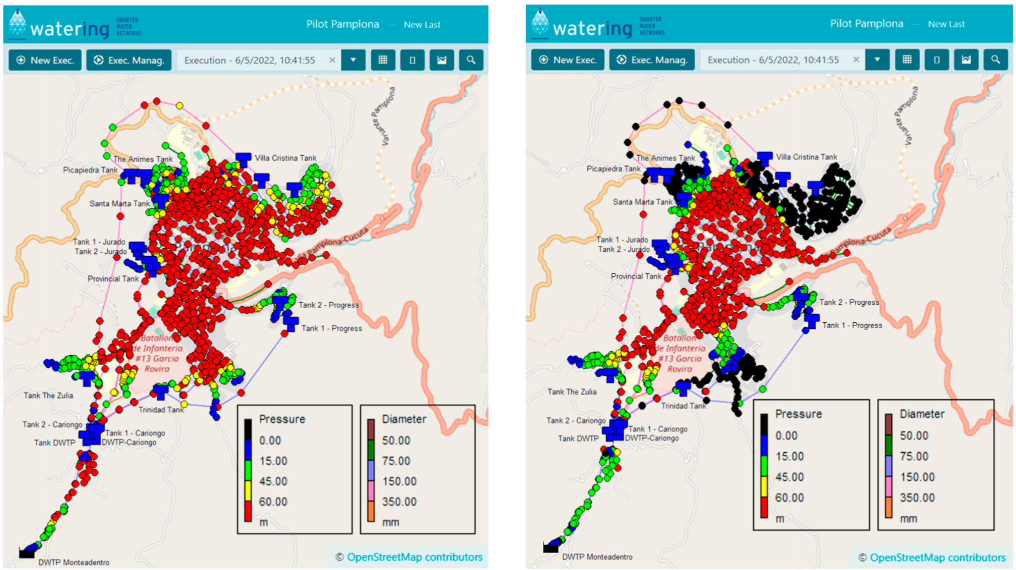


Figure 10. Hydraulic model of the network in the WATERing software platform.

The hydraulic simulation to determine the initial state of analysis of the network was performed in the WATERing software. The hydraulic calculation options were configured and verified that the parameters of all model elements were correctly incorporated. A demand-driven hydraulic analysis (DDA) was performed. WATERing uses the EPANET calculation engine. Once the extended-period simulation was run including the pattern described in Figure 9, the results of the hydraulic behavior of the network were obtained, e.g., the pressure results at the nodes were obtained.

The hydraulic simulation leads to results that are very close to the pressure measurement records. Figure 11a shows the state of the ODS at 0:00 h; at the lowest points of the network (the city valley), the maximum pressures exceed 60 mH_2O, and at the highest points, the pressures are between 10 and 15 mH_2O. Figure 11b shows the simulation at the time of maximum consumption, at 9:00 h, and the results show low- (pressure less than 15 mH_2O) or zero-pressure values in four specific zones of the network. Three of these zones coincide with the areas shown in Figure 4; zero pressures are observed in areas 1 and 2, and in area 3, low pressures are observed. These urban settlements have emerged recently and have grown uncontrollably, having in common that the communities have built their homes in the vicinity and places with topographic heights close to the existing storage tanks in those areas of the city. For this reason, during peak consumption hours, pressures near these tanks are low or non-existent. The inhabitants usually store water at night for daytime consumption.



(**a**) (**b**)

Figure 11. Hydraulic simulation of WDS (**a**) at 0:00 h; (**b**) at 9:00 a.m.

Similarly, Figure 12 shows the contour plot of network pressures at the hour of minimum consumption (0:00 h). It can be seen that the pressure in the city's center exceeds 80 mH2O, and at the extremes (highest points), the pressures are less than 20 mH_2O.

The pressure results obtained are close to the average of the measured pressure data; the data corresponding to the last month were used to obtain the average. The differences observed in the model vary between 83 and 123% concerning the data recorded in the field. The root means square error (RMSE) obtained was 4.31 for the measurements for 9:00 h and 5.18 for the data for 16:00 h. The pressure values obtained were compared with the existing data set, and it was observed that there was a significant dispersion between the monitored and simulated values. The absence of flow measurements within the system does not allow the development of a flow-based calibration methodology at this research stage.

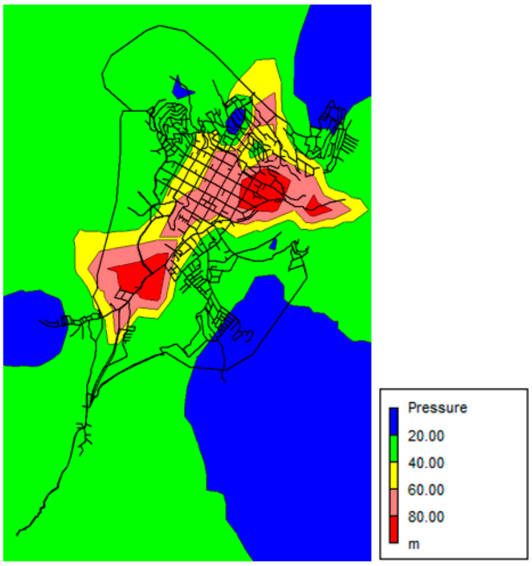


Figure 12. Pressure contour plot of Pamplona WDS at 0:00 h.

For the Pamplona network, based on the existing pressure data measured at some points of the network, which are shown in Figure 13, general calibration was performed, and the results shown in Figure 14 were obtained, where the simulated pressures are observed against the pressures measured in the network.

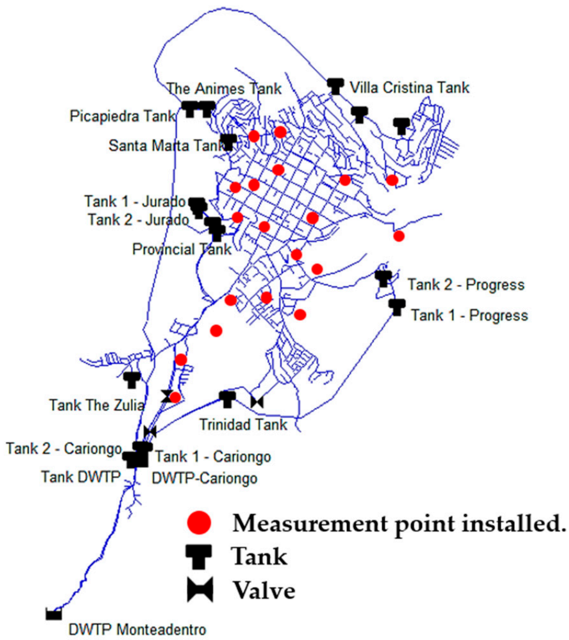
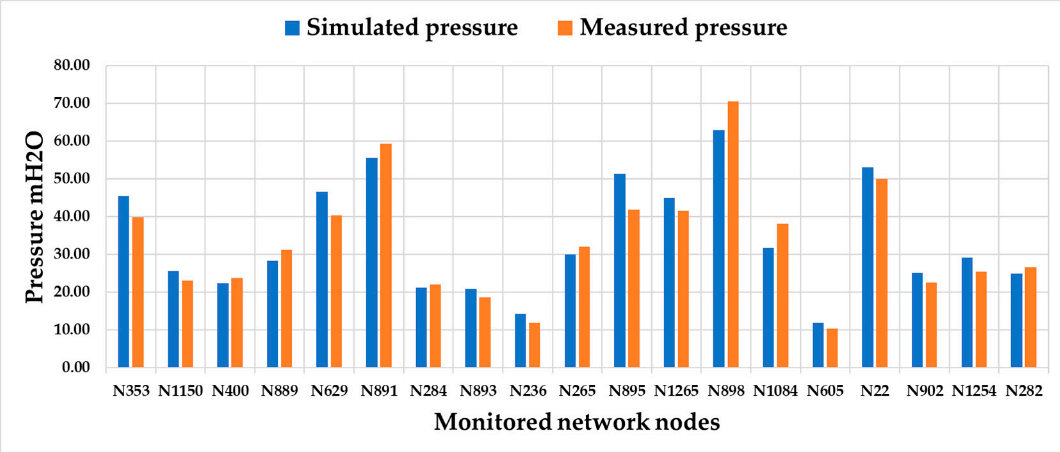


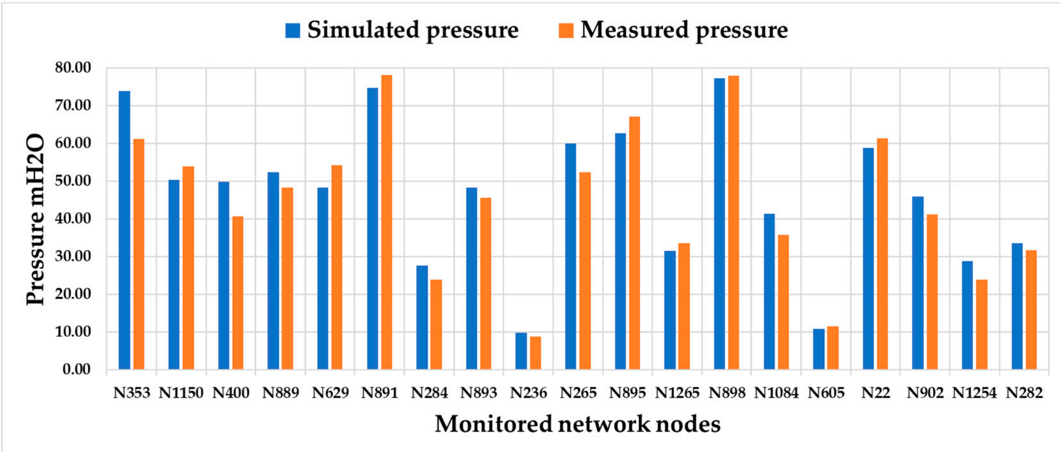
Figure 13. Points in the Pamplona WDS with pressure measurement.

Figure 13 shows the 19 points of the network with pressure measurements, as a reference point the WDS storage tanks and some valves of the network are observed.

Figure 14a shows the results at 9:00 h, and Figure 14b shows the results at 16:00 h. At those hours, pressure records are taken in the network at the 19 points indicated in the graph. The results are for the behavior of the consumption pattern shown in Figure 9; as consumption increases, network pressures decrease.



(**a**)



(**b**)

Figure 14. Simulated pressures vs. measured pressures (**a**) at 9:00 h; (**b**) at 16:00 h.

Finally, using the flow records at the outlets of the DWTPs for the last three months of the year 2022, a SIV of 382,419.22 m^3 and a BAC of 221,038.31 m^3 were obtained. This represents an NRWB of 42.20% for the WDS of Pamplona. The value obtained is high but typical of Colombian cities. In Colombia, the NRWB values reported by different cities and their water companies vary between 23.90% (Tunja) and 67.00% (Villavicencio). The national average of NRWB between 2007 and 2011 was 45.3% and between 2011 and 2017, it was 43.60% [63].

4. Discussion

The results of this work show an important advance in the path towards digitalization. A digitized network was obtained, and the hydraulic model should be improved by implementing a form of telemetry that allows a comparison of the model results and the pressure and flow values monitored at different points of the network defined by the water company experts or based on optimal sensor location methodologies. Flow and pressure measurements at the sensors should be performed continuously and in constant intervals. To develop a monitoring phase, sensors must be installed to transmit data in real time to the WATERing platform to obtain a time series of data to calibrate the network, analyze hydraulic sectorization scenarios, and identify leaks in the pipes. These recommendations will improve water management in the city of Pamplona and increase the operational efficiency of the existing infrastructure.

The work was designed according to the digitalization needs of water utilities in small cities with low budgets. Describing in detail the necessary steps to obtain the base information required to create the hydraulic model of a WDS is a fundamental step to digitalizing a distribution system. This experience developed in Pamplona teaches other companies and cities the path that will allow them to obtain important results.

The research proposes a guide structured in six steps, taking as a case study a small city in Colombia, which represents to a large extent the typical case of a water company in Latin America and developing countries. A company that has few resources and operates its WDS under the technical decisions made by its engineers was studied. This research explains in detail how to digitize the water network and obtain a useful verification and analysis tool that could be replicated and extended as a guide to companies in other cities and/or countries. The development of traditional actions such as the search for existing data, the conceptualization of the model, and the analysis of water consumption, together with new digital tools such as photogrammetry with drones, cloud computing, and the use of online software to digitize a WDS at low cost are some of the novelties in this research.

5. Conclusions

This research has generated a final product that serves as a fundamental water analysis and management tool for the small city of Pamplona. The hydraulic model created on an online platform can be used from a web browser. The DDA performed on the network yielded good initial results. It is necessary to consider the numerical solution of the network under other approaches such as pressure-driven hydraulic analysis (PDA), as this would allow us to determine if there is a variation in the pressure of the network nodes, specifically in the low-pressure zones evidenced in this study. The results may vary when performing a hydraulic solution based on the assumption of a pressure–demand relationship at the junctions. This tool should be complemented with a set of pressure and flow monitoring measurements of the existing network to determine the analysis option that adequately represents the Pamplona WDS. This would allow an evaluation of the overall performance of the network and contribute to the advancement of SDG-6, SDG-9, and SDG-11. The aim is to ensure the availability of water to the population of Pamplona with a supply system that can be managed and sustained, and that can evaluate resilience scenarios in the face of adverse effects that may arise. The process explained in this work to create a hydraulic model with the assistance of a drone can be applied in small and medium water companies and will allow them to take significant steps towards digital transformation with a low investment cost and few limitations.

Good results can be obtained on the road to water digitalization with the support of current technological elements, such as drones and free-use software, plus the knowledge of the water companies' experts. The creation of hydraulic models of a WDS allows access to network information and the permanent updating of existing elements. It also allows us to permanently evaluate the state and functioning of the network to be able to solve more robust problems using analytical tools. The total investment cost of this research was below USD 1400, not including the cost of the time spent by the researchers, since professionals from the water companies could carry out this work.

The development of this case study shows an important advance in the path to a digital twin; it indicates that there are different options to create value from hydraulic models and the optimal management of drinking water distribution systems.

Author Contributions: Conceptualization and methodology, B.B., I.M. and D.A.-C.; data collection, software, data analysis, and editing, C.B.; writing and preparation of the original draft, C.B., B.B. and J.I.; visualization, I.M. and D.A.-C.; conceptualization, review, and supervision, J.I. All authors have read and accepted the published version of the article. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: There is no need for a data statement.

Conflicts of Interest: The authors declare no conflict of interest.

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