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Modern SCADA Solution for Mitigation of Water Losses in Water Distribution Network

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Abstract*— This paper explores the optimization and management of a water distribution network using a SCADA system integrated with DMAs (District Metered Areas) and PMAs (Pressure Management Areas) to improve hydraulic characteristics. The study demonstrates the importance of early fault detection, real-time monitoring, and effective pressure management within high-pressure zones to reduce water loss, enhance operational efficiency, and extend the lifespan of infrastructure. It recommends future improvements, including the addition of a new PMA to further regulate pressure, reduce faults, and decrease water consumption. By implementing these strategies, the network can achieve significant financial and environmental benefits, ensuring sustainable and efficient water supply management.

***Keywords*—PLC, SCADA, RTU, Water distribution network, District metered area, Pressure management area etc.**

I. INTRODUCTION

Water supply systems date back to ancient times, with examples like Persian qanats, Roman aqueducts, and the Machu Picchu water system. Modern developments began in the 17th century, highlighting the evolution of water infrastructure [1]. Maintaining these infrastructures requires calculating and determining the pressure and flow in water supply pipe networks has been, is, and will be of great importance and interest, both for the people responsible for designing, constructing, and maintaining public water distribution networks, as well as for the end consumers themselves.

The "Smart Water Save" project, targeting the Prespa region and encompassing Prespes in Greece and Resen in North Macedonia, aims to reduce water losses. The project was initiated due to the significant discrepancy between pumped water and household usage, as revealed by water bills, which damages underground water sources. The water supply network suffers extensive losses due to pipeline deterioration and illegal connections for agricultural irrigation. It has been estimated that both sides of the lake experience around 50% water loss from the total pumped or delivered water. This necessitates more energy for water purification, increasing greenhouse gas emissions linked to energy use and production.

Water leakage in pipeline networks is most often caused by the inability of the residual resistance of the pipe to withstand the water pressure, which causes small cracks or holes in the pipes. To solve this problem, two solutions will be proposed:

- Reducing the pressure in the pipes;
- Replacing the old, worn-out pipes in the system with new ones.

Managing water pressure in supply networks involves effective strategies to reduce water leakage caused by undetectable pipe damage, thereby lowering the risk of new cracks and extending the pipes lifespan. Water leakage in pipes is directly proportional to water pressure, so reducing the pressure will decrease water leakage.

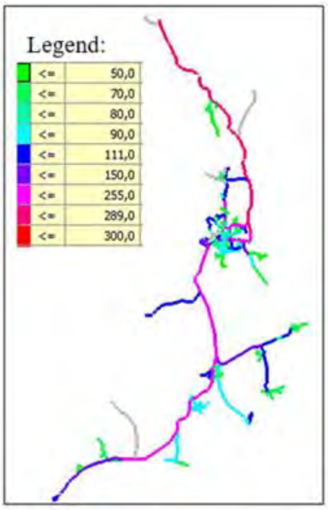

Figure 1 Pressure map of the WDN [1]

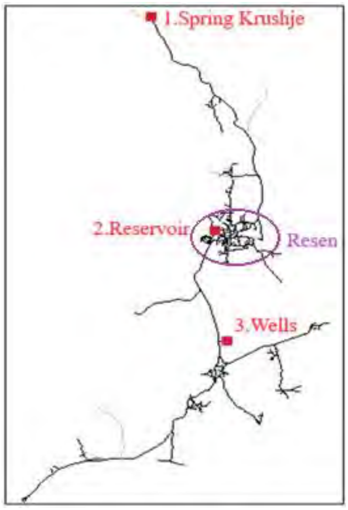

Figure 2 Crucial points of the WDN [2]

The main goal of this project is to reduce the inefficiencies of both water supply systems through the implementation of a SCADA (Supervisory Control and Data Acquisition) system. This system aims to monitor the pressure and flow in the pipes in real-time. It will collect data that will be used for subsequent analyses. Monitoring will involve gathering data from sensors placed at specific measurement points via wireless communication, as shown in Figure 6 Placement of the 19 measurement points. This approach will enable the detection of "critical points" and regionalize potential pipe damage, as well as calculate the total water leakage from the pipes. These critical areas will be replaced with new pipelines, ensuring the prevention of major damages and water losses in the future.

Further, in this paper, the concepts of pressure management like DMA and PMA will be shown in chapter II, and then in chapter III the actual state of the water supply system will be shown. In chapter IV the modeling principles and the analysis of the expected results will be discussed, and the implementation of the physical layout and SCADA architecture and SCADA system will be shown in chapter V. Finally, in chapter VI the conclusions for the implemented and expected state of the system will be drawn, and some recommendations for further work will be given.

II. Concept of pressure management

Nowadays, with increasing demands for water resources, it is vital to conserve and save them, with aim to avoid overburdening the water sources. Water resource management primarily aims to reduce pressure to the lowest possible operating point while ensuring adequate water supply to the network. Reducing pressure significantly decreases leakage in the pipeline, resulting in substantial resource and economic savings.

Pressure management requires adequate knowledge of the system, including consumer usage patterns, pressures at different network points, network losses, terrain configuration, and even the capacity of potable water sources. While defining the concept may seem straightforward, having a general overview of the system is not as effective as utilizing a modern monitoring system like SCADA. SCADA systems can enable the proper implementation of proven pressure management concepts, such as reducing water consumption, establishing District Metered Areas – DMAs, and pressure management areas PMAs. These zones can then be integrated into the overall management system.

A. DMA

In a water supply network, forming DMAs (District Metered Areas) involves designating certain sectors or areas where the end supply points have similar hydraulic characteristics and are in close proximity. This approach also allows for zoning based on topographical elevation. The division is done using valves at points where two isolated measurement zones meet or by interrupting the pipelines at these points. The resulting DMA zones enable the monitoring of water entering and exiting these measurement zones, allowing for the determination of water loss in a given zone.

Through the established DMAs, water flow entering the zone can be monitored and compared to the flow at the end consumers. Any discrepancies can indicate a defect or water theft in that zone. Analyzing the flows in the DMAs provides a realistic picture of the network conditions within the zones, particularly by observing the state of the zones during periods of low consumption and low flows but high pressure, typically at night. A difference in flow during these times would indicate a possible defect in that zone. Proper utilization of DMAs helps maintain water leakage from the supply network at a low level, allowing for quick intervention and replacement of worn-out infrastructure.

Overall, DMAs are a springboard towards creating an economically efficient and environmentally friendly water supply system, as they provide insights into Non-Revenue Water (NRW) and ensure consistent water supply through zoning by elevation, maintaining constant pressure for end users. DMAs also facilitate defect resolution by allowing immediate isolation and repair without disrupting other zones water supply. Managing water supply systems through isolated measurement zones is a highly advanced concept, widely accepted as standard practice globally. [2]

B. PMA

Certain implemented DMAs in the water supply network may not always achieve consistent pressure, or the consistent pressure may be too high. To address such cases, PMAs (Pressure Management Areas) are introduced, which are upgraded DMAs equipped with appropriate pressure management equipment. Zones at lower elevations often experience significant pressure fluctuations, linked directly to consumption. At night, water consumption is low, resulting in high pressure, while during the day, consumption increases, and pressure can drop below the optimal level for network operation. These fluctuations can cause expansion and contraction of pipes and joints, leading to leaks. DMAs alone may not effectively solve this issue.

To tackle this problem, PMAs are implemented, featuring Pressure Reducing Valves - PRVs. PRVs automatically reduce high inlet pressure, maintaining the desired pressure within the zone despite changes in pressure or flow. PMAs improve on DMAs by not only reducing NRW but also ensuring better pressure consistency. However, the high investment and maintenance costs of PRVs are a drawback. Overcoming this involves considering the long-term benefits of the investment [2].

C. DMA & PMA in SCADA

Implementing PMA and DMA concepts in water supply networks would significantly enhance operational efficiency and ensure consistent water distribution to end users, offering substantial economic and environmental benefits. The benefits of PMAs and DMAs are maximized when locally managed using automated controllers. Using controlling PRV valves instead of static, mechanical ones further reduces pressure, defects, and leaks. Controllers can employ PID (Proportional, Integral, and Derivative) control, optimized with algorithms based on hydraulic models or daily consumption patterns. [3]

However, local control of PMAs and DMAs does not guarantee overall network stability. Sudden, significant demand changes at distribution endpoints can cause system response delays and large fluctuations. Major consumers such as industrial complexes, fire hydrants, operator errors, and pumps in high elevation zones can cause such fluctuations. Integrating PMAs and DMAs into a SCADA system allows for better monitoring and management, preventing fluctuations in main supply lines. [3]

Integrating valves, pumps, reservoirs, and sensors from PMAs and DMAs into a cohesive SCADA system, with well-designed algorithms based on a thorough understanding of the hydraulic model, allows for micro-adjustments within zones. This management approach balances network pressure and prevents hydraulic shocks, reducing pipe damage and leaks.

III. State of the Water Supply System in Resen

The goal of this paper is to demonstrate the implementation of a SCADA system in a real water supply system. It will cover hydraulic aspects, including the system's condition, physical characteristics, models, and strategies. Additionally, it will explain the mechanical features, management of the system, the SCADA system's communication, and architecture.

The water supply system of the town of Resen, also known as Krushje-Resen-Sirhan, serves the local population in Resen and 17 other surrounding settlements with drinking water, managed by the public utility company "Proleter." This system comprises a network of pipelines totaling 97 km in length. Constructed in the 1980s, the current network consists of 67% PVC pipes, 23% HDPE pipes, 8% asbestos, and only 2% ductile iron, as shown Figure 1 [2].

Figure 2, illustrates the water supply system of Resen and its three crucial points essential for ensuring continuous and adequate water flow and pressure:

- The Krushje spring, located at 985 meters above sea level, has a capacity of 35 liters per second.
- The Resen reservoir, located at 934 meters above sea level, stores excess water during the day to be reused at night. Its location and role make it functional both as a pre-settlement and post-settlement reservoir.
- The wells near the village of Carev Dvor, used during summer when water demand increases. Three deep wells, equipped with three pumps, can provide an additional flow of up to 30 liters per second. These wells boost flow and pressure in the network, particularly for southern villages. Excess water is stored in the Resen reservoir when demand is met.

According to data from JKP "Proleter," the system is gravitational, flowing naturally from north to south. However, geographical variations, especially in the city of Resen, cause pressure differences. Higher areas (900 meters) experience lower pressure, while lower areas (875 meters) face higher pressure, leading to potential pressure differences of several bars. This discrepancy complicates the supply of consistent pressure and increases the likelihood of defects in lower areas due to high pressure.

According to calculations in [2], based on available data, the invoiced water quantities for households and commercial properties suggest a norm of 100 [l/day/per], which is acceptable. However, calibration measurements reveal that the actual norm is higher, at 150 [l/day/per], reflecting the system's true state.

IV. Modeling and Analysis of the WDN

A. Modeling

To perform a hydraulic analysis of a water supply system, a reliable mathematical model is essential. The model of the system is acquired by using modern EpaNET software package and data from crucial measurement points of the system, by solving nonlinear systems of equation, after that the model can be accurately calibrated to reflect the system's real state. The calibration process involves using least squares method for optimizing and adjusting the model based on measured data, such as geodetic height, pipe profile, pressure, water flow, and timestamps, ensuring the model closely matches actual conditions. This calibrated model can then be used for various analyses and optimizations. Data for this system is obtained from continuous measurements of pressure and flow at several points, as shown in Figure 3 [2].

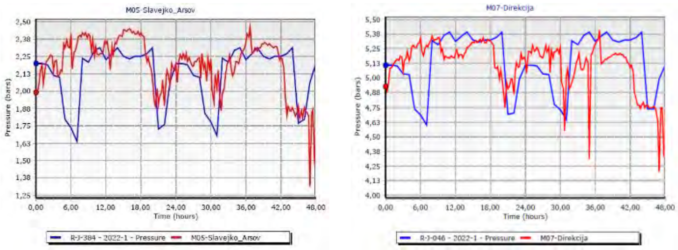

Figure 3 Comparison between real data (RED) and calibrated model (BLUE)

The graphs above illustrate the differences and deviations of the model compared to the real state of the system. According to [2], the calibrated mathematical model appropriately reflects the system's actual condition and remains within acceptable deviation limits. In other measurement points, the dynamics of the calibrated mathematical model correspond well with the real system's dynamics. Although there are noticeable spikes in the graphs, these should not be considered for calibration. Instead, the general dynamics of the system should be calibrated to avoid increasing the model's sensitivity in general cases.

B. Analysis

The analysis of the water supply system focuses on how consumption changes with pressure levels. Three scenarios are considered: the first reflects the current system state, the second introduces two pressure zones (high and low) based on identified high-pressure areas from the first scenario, and the third enhances the second scenario by adding two new PMAs with PRVs.

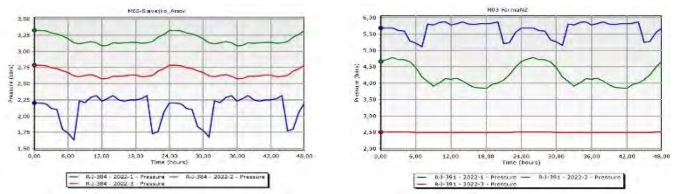

Figure 4 Model results (blue-scenario 1, green-scenario 2, red-scenario 3) [2]

To obtain a general picture of the system's dynamics, measurement points are selected at various locations and pressure zones, tracking pressure changes over 48 hours. The obtained data represent a set of information for the measurement point, such as its geodetic height, pipe profile, pressure, total volume of water passed, current flow rate, timestamp of the record, etc. This helps observe the differences and dynamics in the models from different scenarios and their impact on pressure at these points. The pressure changes for the three scenarios are shown in Graphs 11-14, with node positions in Figure 4.

1) Scenario 1 – Current situation

To establish a good reference point for comparing the proposed scenarios, the current state of the water supply system must be identified and modeled, determining all its hydraulic characteristics. This allows identifying system deficiencies that need resolution and recognizing system strengths. Using the geographical characteristics mentioned earlier, computer simulations can set up measurement nodes within the water supply system. These nodes help identify high-pressure zones, and the obtained information can be used to reduce this high pressure, thereby proportionally decreasing water loss [2].

The network in this scenario experiences high pressure ranging from 5 to 7 bars, with a water consumption rate of 70.82 l/s. In Resen, due to its geography, high areas experience low pressures (2 to 3 bars), while lower areas have much higher pressures. To address this, high and low-pressure zones are established.

2) Scenario 2 – High and low-pressure zones

This scenario is based on the previously explained isolated measurement zones, or DMAs. It is the most economical solution, requiring minimal modifications and being easy to implement. Two pressure zones—high and low—are proposed. The high zone is influenced by the pressure from the Krushje spring, extending from Krushje to the higher parts of Resen. The reservoir in Resen, located in the higher areas of the town, acts as a "low pass filter" for pressure, nullifying the pressure influences from the Krushje spring. This allows new pressure boundaries to be set for the low zones of the city, creating the new low-pressure zone.

In the first scenario, pressures ranged from 5 to 7 bars. After implementing the second scenario, pressures are reduced to between 4 and 5.5 bars. The expected pressure in the low zones of the city accounts for the elevation difference of 50 to 60 meters between the reservoir (934 m ASL) and the lowest parts of the city (875 m ASL). Simulation results for the reduced pressure in the nodes of the low zone are shown in Appendix 3, with an average pressure reduced from 5.5 to 4.9 bars, equating to a 10.3% pressure reduction. Calculations in [2] result in 14.2% decrease in network defects, 2.06% reduction in user water consumption, 10.3% reduction in water losses, and the total water consumption in the system for this state is 53.92 l/s, representing an approximately 24% reduction compared to the current state [2].

3) Scenario 3 – PMA

To improve the given system, the next step is to introduce PMAs by installing PRVs to regulate the pressure in the high and low zones. Building on the previous scenario, two PRVs will be placed according to the DMA established in the second scenario, with their positions shown in Figure 5. Since the connected buildings are mostly houses with low height, the output pressure at the regulators is set at 2.9 bar, ensuring adequate pressure for firefighting requirements [2].

Figure 5 Placement of PRVs in the city of Resen [2]

Comparing this to the previous scenarios, where the first scenario had pressures ranging from 5 to 7 bar with an average of 5.5 bar, and the second scenario had pressures from 4 to 5.5 bar with an average of 4.9 bar, scenario 3 shows pressures between 2.5 and 3.5 bar with an average of 3.1 bar, representing a significant reduction. This amounts to a 37.9% pressure reduction compared to scenario 2 and a 44.4% reduction compared to scenario 1.

Such a reduction in pressure results in improved water supply and reduced consumption. According to [2], based on the computed results in 26.5% decrease in network defects, 3.8% reduction in user water consumption, and 18.9% reduction in water losses.

It is important to note that the initial state of the system assumes most of the defects have been resolved and total water consumption has been reduced. In scenario 3, total water consumption is 50.78 l/s, representing a 6% reduction compared to scenario 2.

V. IMPLEMENTATION

A. Physical layout

The implementation of the project involves gathering data from 19 different locations distributed across the water distribution network as shown on Figure 6. Given that this network primarily consists of off-grid manholes, the following solution was implemented: pressure is measured at 17 locations, flow rate is measured at 2 locations on the main water distribution pipeline from the water spring Krushje and the water wells at Carev Dvor, and water level is measured at 2 locations in the reservoirs at Carev Dvor and the city reservoir. Out of these, 12 locations are powered by an off-grid solar panel. Furthermore all of the locations are monitored via the SCADA, but only the reservoir in the city of Resen has an implemented control, i.e. 2 electric motor valves are installed for redirecting the flow of water from the reservoir and to it, when certain peaks in the demand or surplus of pressure occurs.

B. SCADA architecture

The SCADA architecture consists of 19 points, as mentioned, with one point being the SCADA center that communicates with the other 18 points through wireless communication in a multi-point architecture in star topology. This architecture, as shown in Figure 7, in general assumes only one master device for several slave devices, where data is passed between the master and each one of the existing slaves. In the case of two of the slaves need to exchange data between each other, it must be sent to the master device first, which acts as a moderator on the communication. The physical application of the architecture includes 16 measurement points equipped with RTUs, and the other 3 equipped with 3G/4G routers. The SCADA center uses these routers to initiate communication with all 18 points in the system via the means of wireless network. The other 2 measuring points are the reservoir in the city and the wells or pump station at Carev Dvor. Their configuration consists of PLCs and HMI screens for local monitoring and control by the operators there.

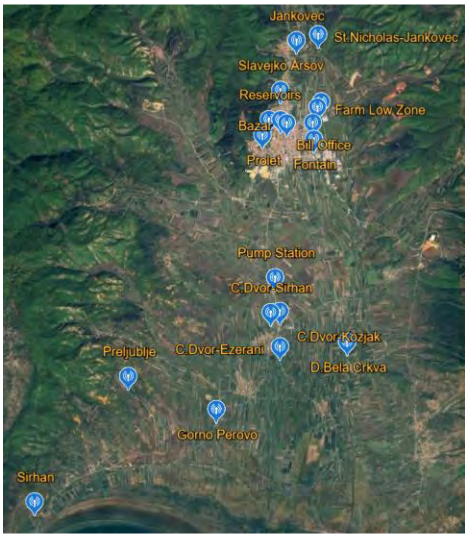

Figure 6 Placement of the 19 measurement points

The communication protocol of choice for this case is the MODBUS. Modbus is considered one of the main used and most popular protocols in the industrial field, using not just traditional serial protocols, but also Ethernet protocols, allowing different devices to use this protocol as their main communication method. When communications are placed between serial and Ethernet networks, there is a need to use a gateway in order to properly handle the connection [4]. More precisely the communication protocol used in the SCADA system is MODBUS RTU wrapped in a MODBUS TCP/IP header [5]. This means that the RTUs use the MODBUS RTU communication protocol, but since the communication is done via GPRS technology, they receive the messages from the master router via the MODBUS TCP/IP protocol. The RTUs will handle the conversion and read out the message. When configuring the RTUs, a slave address must be assigned for them to be reached by the SCADA. On the other hand, the 3G/4G routers use only MODBUS TCP/IP and need to be configured with proper tunneling between them to enable data transfer.

It is worth mentioning that all 19 points are in a private IP range or APN domain, and connection to the outside internet is nearly impossible. This increases the security against potential breaches in the system. Additionally, the SCADA interface consists of a map with all the measurement points, alarms and alarm history, historical trends, proper indicators for the measured values, detailed insights for each measuring point, and admin access to the parameters for each point.

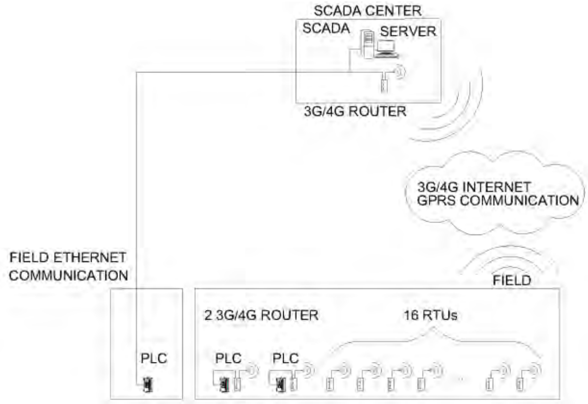

Figure 7 SCADA Architecture of the system

VI. Conclusion

From everything that has been developed and presented above in this paper, a conclusion can primarily be drawn based on the SCADA system and the hydraulic system of the water supply network. This means that progress in both areas should go hand in hand, as poor implementation in one field cannot be compensated by excessive investments in the other.

A. Conclusion based on the hydraulic model

If scenarios 2 and 3 are implemented properly and DMA and PMA are formed as prescribed, the following results can be expected: a 44.4% reduction in pressure, a 62.2% decrease in the number of network failures, an 8.9% reduction in water consumption by users, and a 44.4% decrease in water losses.

B. Conclusion on overall SCADA system

To achieve the desired effects from implementing these scenarios, cohesion among all segments of the system is necessary. The ability to detect network faults early allows the SCADA system to provide real-time information on abnormalities in measured values or errors in executive elements. The benefits of implementing a SCADA system and establishing DMAs and PMAs include a reduced number of faults due to lower pressure in the network, the ability to identify areas with water loss (such as illegal connections), increased financial efficiency by reducing the amount of non-revenue water, and greater financial benefits due to reduced water production and a decreased need to activate the wells, resulting in lower electricity consumption. Additionally, end users can benefit from lower water bills, there is an extended lifespan of the pipeline network, and there are greater environmental benefits.

C. Recommendations for further work

Further works can be done if the proposed 2 scenarios are realized and implemented properly. In terms of enhancing hydraulic characteristics, if the recommendation from [2] is considered an additional PMA can be introduced, pressure regulation and management could yield even greater benefits. This is particularly relevant given that the proposed area of interest falls within a high-pressure zone as shown in Figure 8.

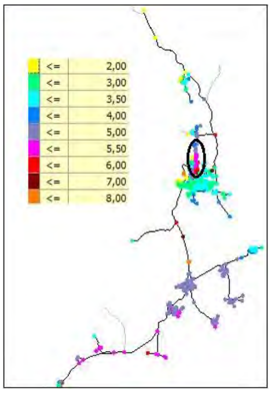

Figure 8 Proposed PMA after scenario 3 [2]

Implementing DMAs in water supply networks not only reduces water losses but also provides early indications of pipeline conditions. By comparing network pressures and detecting deviations under specific working conditions, early maintenance of pipelines and sensors is possible, thus requiring advanced SCADA system complexity. Different approaches to managing quality rely on statistical processes, including univariate and multivariate methods.

Univariate methods use control charts for monitoring a single variable, identifying potential defects through deviations from expected values based on simple mathematical models. Multivariate methods, such as Principal Component Analysis (PCA), analyze correlations among multiple variables to detect anomalies, thoroughly explained in [6].

Multivariate approaches can also validate measurement accuracy through crosschecks with feedback from valves and pumps. Significant deviations across multiple sensors or changes in valve/pump states indicate anomalies, often due to sudden water demand spikes or pipeline ruptures.

These methods lead to advanced machine learning algorithms, such as anomaly detection, crucial for timely and efficient equipment maintenance.

Furthermore implementing the PMA elements such as PRVs and the existing booster pump stations in the SCADA can enhance the control dimensionality of the systems by implementing and upgrading the system with proper control methods for real-time control and monitoring, such as reinforcement learning or neural network controllers.

Integrating such algorithms into SCADA systems creates intelligent systems, aligning with Industrial Internet of Things (IIoT) standards when connected to the internet or implemented to the cloud [7] [8].

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