Araid Journal of Science and Technology (AJST)
Higher Institute of Science and Technology-Al Shmokh

مجلة الرائد للعلوم والتقنية
المعهد العالي للعلوم والتقنية الشموخ

Dynamic Performance Evaluation of the Kiklah Water Distribution Network

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ABSTRACT

This study investigates the transient behavior of three key water supply lines connected to the Western Kiklah pumping station: one directed toward an upper reservoir, another supplying a lower tank, and a third branching off to feed the Awlad Youssef tank. The study focuses on the city of Kiklah, Libya, a region marked by steep elevation differences that pose unique challenges to the operation of its water distribution network. One of the primary concerns was the risk of hydraulic transients, such as water hammer and cavitation, which can occur during abrupt pump shutdowns or sudden valve closures. To understand and address these risks, both steady-state and transient simulations were conducted using the Allievi software, following detailed mapping of pipeline routes based on cadastral survey data—demonstrating the interplay between civil engineering and hydraulic analysis. The pipelines were designed using ductile iron, selected for its strength and resilience. Preventive measures were implemented to reduce transient impacts, including the installation of air valves spaced between 750 and 1200 meters, and the addition of a 20 m³ air chamber placed 20 meters downstream of the pump. These solutions proved effective, particularly along the lines leading to the upper reservoir and the Awlad Youssef branch, in minimizing the effects of pressure surges and vacuum conditions.

KEYWORDS:Transient analysis, Water hammer, Cavitation, Valve operation, Hydraulic modelling.

الملخص

تتناول هذه الدراسة السلوك الانتقالي لثلاثة خطوط رئيسية لإمداد المياه المتصلة بمحطة الضخ في ككله الغربية، حيث يتجه أحد الخطوط إلى خزان علوي، وآخر إلى خزان سفلي، بينما يتفرع الخط الثالث ليغذي خزان أولاد يوسف .تم اختيار مدينة ككله الليبية كموقع للدراسة نظرًا لتضاريسها الصعبة وتفاوت ارتفاعاتها الكبير، مما يشكل تحديًا حقيقيًا لشبكة توزيع المياه ويزيد من احتمالية حدوث ظواهر هيدروليكية ضارة مثل طرقات المطرقة المائية والتجويف، خصوصًا عند الانقطاعات المفاجئة للطاقة أو الإغلاق السريع للصمامات. تم إجراء تحليلات للحالة المستقرة والمحاكاة الانتقالية باستخدام برنامج Allievi، وذلك بعد تحديد مسارات الأنابيب بدقة بالاعتماد على بيانات المسح العقاري، مما يعكس تكامل الجوانب المدنية والهيدروليكية في تصميم النظام. وقد تم اختيار أنابيب من الحديد المطاوع نظرًا لقدرتها العالية على تحمل الضغوط. وللحد من تأثيرات الضغط المفاجئ، تم اعتماد حلول وقائية تمثلت في تركيب صمامات هوائية على مسافات تتراوح بين 750و1200 متر، بالإضافة إلى تصميم غرفة هواء بسعة 20مترًا مكعبًا، تم وضعها على بُعد 20مترًا من المضخة .وقد أثبتت هذه التدابير فعاليتها، خصوصًا في الخطوط المتجهة إلى الخزان العلوي وفرع أولاد يوسف، في الحد من تأثيرات الطرقات المائية والضغط السالب.

1. INTRODUCTION

A city's water network comprises transmission lines (source to main system) and distribution pipelines (main system to consumers). This vital infrastructure demands optimized efficiency and reliability. Fluid mechanics governs water in motion (dynamics) or at rest (statics), impacting numerous applications. Transient flow, characterized by time-varying velocity and pressure, arises from pump/valve operations or tank level changes. This unsteady state, termed surge or water hammer, can cause damaging pressure surges or necessitate steady flow in industries. Transient flow is often analyzed computationally using methods like characteristics and software tools. Cavitation, the formation of vapor cavities due to pressure drops, is another critical concern in such systems. This paper focuses on analyzing and mitigating these transient flow phenomena in a specific urban water distribution network.

2. LITERATURE REVEIW

Transient phenomena in water supply systems, especially water hammer events, have been a focus of hydraulic engineering research for decades due to their potential to cause severe operational and structural damage. The seminal work of Wylie and Streeter [1] provided a detailed theoretical foundation for water hammer analysis using the method of characteristics (MOC), a technique that remains widely used in both academic and engineering applications.

Chaudhry [2] expanded on this foundation by addressing more complex aspects of transient flow, such as unsteady friction, pipe wall elasticity, and multi-phase flow conditions including vapor cavities and air entrainment. These considerations have proven essential for improving the accuracy of transient flow simulations in real-world networks.

With the evolution of computational modeling, simulation tools have become the most popular approach to transient analysis in water distribution networks. These tools support the numerical solution of transient equations and allow for the incorporation of detailed network features, including pumps, valves, tanks, and control systems. Keramat et al. [3] investigated various numerical schemes and emphasized the need for stability and accuracy, particularly in large-scale, branched pipeline systems.

In terms of mitigation, research has highlighted the effectiveness of protective devices such as surge tanks, pressure relief valves, and air valves. Meniconi, Brunone, and Ferrante [4] showed that proper placement and sizing of these devices can significantly reduce the amplitude of pressure surges. Similarly, Lee et al. [5] explored the use of pressure management strategies and automated valve control to limit transient propagation.

Recent studies have begun integrating real-time data acquisition systems and smart sensors into transient analysis. For instance, Colombo et al. [6] proposed using pressure and flow data from sensor networks to detect and localize transient events, offering potential for predictive maintenance and rapid response. The use of machine learning and data-driven techniques for transient event classification and forecasting is also an emerging research direction as demonstrated by Zhang et al. [7].

3. TRANSIENT FLOW IN WATER SUPPLY SYSTEM

In hydraulic systems, transient flow refers to conditions where variables such as pressure and velocity change over time, often in response to system disturbances. Transient analysis is critical for predicting and mitigating the effects of such dynamic events, which may be triggered by actions like pump start-up or shutdown, sudden valve movements, or power failures. Understanding these transient behaviors helps engineers design safer, more resilient systems.

3.1 Water Hammer

Water hammer is a specific type of pressure transient resulting from sudden acceleration or deceleration of fluid in a pipeline. The term reflects the hammer-like effect of pressure waves striking system boundaries. Water hammer can exert extreme dynamic loads on pipes, valves and pumps. The effects of water hammer can be delayed and often become evident only after repeated events, leading to pipe ruptures, disconnected flanges, buckled or collapsed pipelines. Water hammer, while unavoidable in dynamic systems, must be controlled through design and operational strategies to prevent damage [8].

3.2 Cavitation

Cavitation occurs when local pressure in a fluid falls below its vapor pressure, causing vapor bubbles to form. These bubbles typically arise in high-velocity zones, such as pump impellers, turbine blades, and valve contractions. When these bubbles move into higher-pressure regions, they collapse violently, causing erosion of metallic surfaces, vibration and noise or reduced pump efficiency. These effects can severely damage mechanical components and reduce system lifespan [9].

4. METHODOLOGY

4.1 Overview of Kiklah City Water Supply System

The water distribution system of Kiklah City was analyzed to assess its behavior under transient conditions. The network comprises a main pumping station, elevated storage tanks, transmission mains, and distribution pipelines supplying residential and commercial zones. The focus was on a representative portion of the system with high demand variability and operational complexity.

4.2 Data Collection and Network Configuration

Detailed system data were collected from the local water authority, including pipe diameters, lengths, materials, storage tank dimensions and valve types. The network topology was mapped using GIS data and verified through site visits and consultation with local operators.

4.3 Modeling Approach and Software

The system's transient behavior was analyzed using the **Allievi** software, a specialized tool designed for simulating hydraulic transients in both pressurized and free-surface flow conditions. This software has evolved over many years and incorporates a proprietary algorithm that has been applied successfully in numerous engineering consultancy and technical advisory projects. Due to its robust performance and proven reliability, Allievi is regarded as one of the few tools globally capable of accurately modeling transient phenomena in complex hydraulic systems.

5. RESULTS AND DISCUSSIONS

5.1 Water Distribution Network

A transient analysis was conducted on the water supply network of the city of Kiklah, with some input data obtained from Excel-based datasets. The study focuses on two main transmission lines under different operational scenarios, including their interaction through a shared branch. These lines were selected to represent typical challenges observed across the city's water distribution system. The stations and lines analyzed in this study include:

- Western Kiklah Pumping Station (J): supplying water to the upper storage tank
- Washan Mosque Pumping Station (F): feeding the lower storage tank
- Al-Naher to Awlad Youssef Branch Line (A): a branch line.

These components were chosen due to their significance in the network and the recurrent operational issues they face. The existing system was analyzed for transient-related problems such as water hammer, cavitation, and negative pressure. The simulation aimed to identify the causes of these issues and evaluate possible protective measures. Several mitigation strategies are explored in the analysis and discussed in this section.

Figure 1: Kiklah's Water Distribution Network.

5.2 Washan Mosque Pumping Station

In the first phase of the study, the Washan Mosque Pumping Station was analyzed under its current configuration, without any protective devices installed. The transient simulation, as illustrated in the figure, revealed the presence of cavitation and negative pressure near the tank connection point.

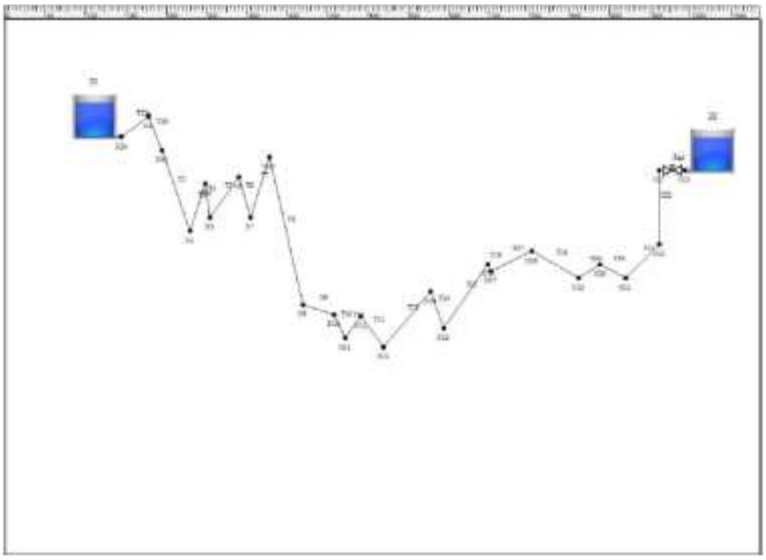


Figure 2: Washan Mosque pumping station before the installing.

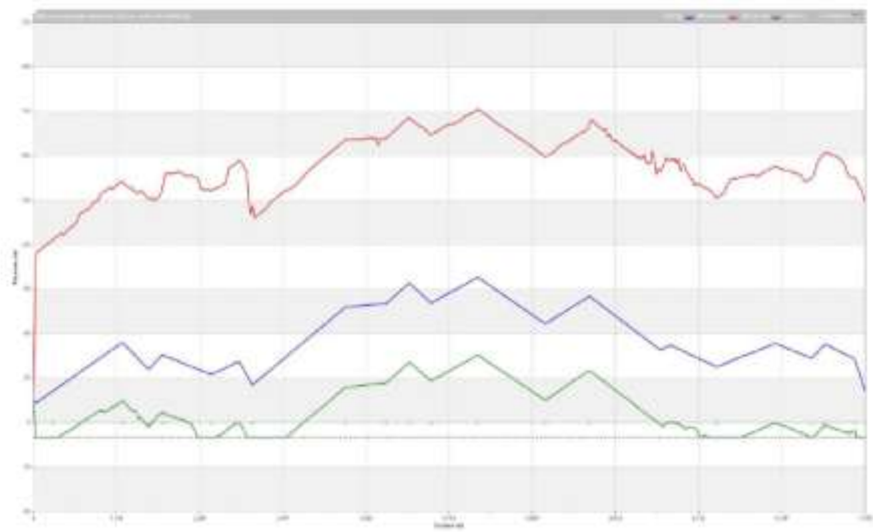


Figure 3: Pressure curve for Washan Mosque pumping station before the installing.

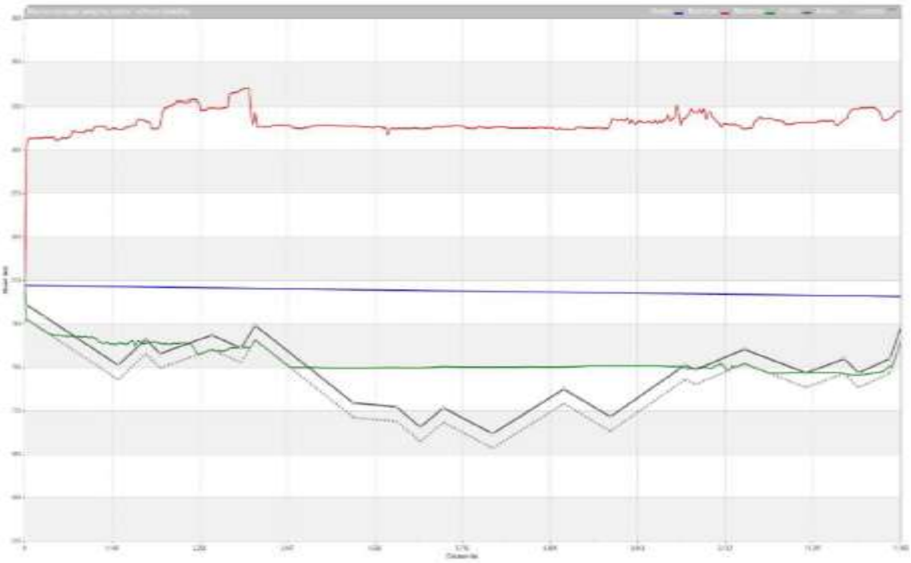


Figure 4: Head curve for Washan Mosque pumping station before the installing.

To address the pressure issues, ten relief valves were strategically installed in the most critical sections of the pipeline. This intervention effectively reduced pressure spikes and eliminated all occurrences of cavitation. Since the flow in this line is gravity-driven, there was no need to install an air chamber or a booster pump, which significantly lowered the overall cost.

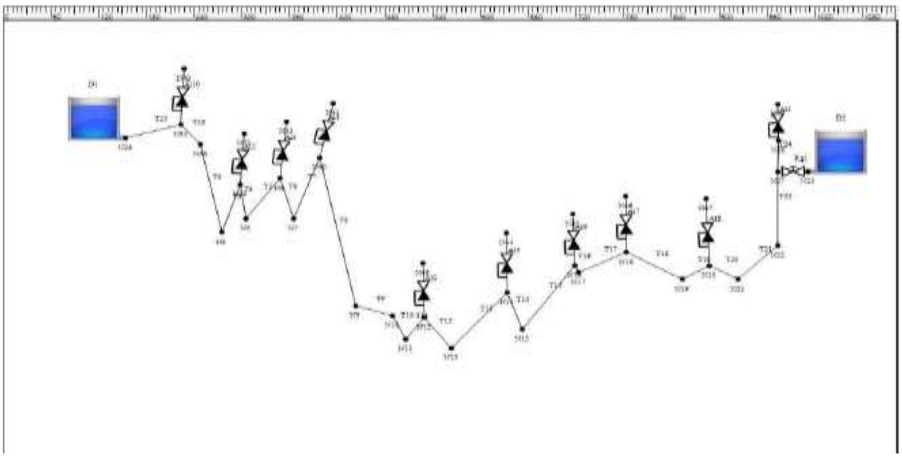


Figure 5: Washan Mosque pumping station after the installing.

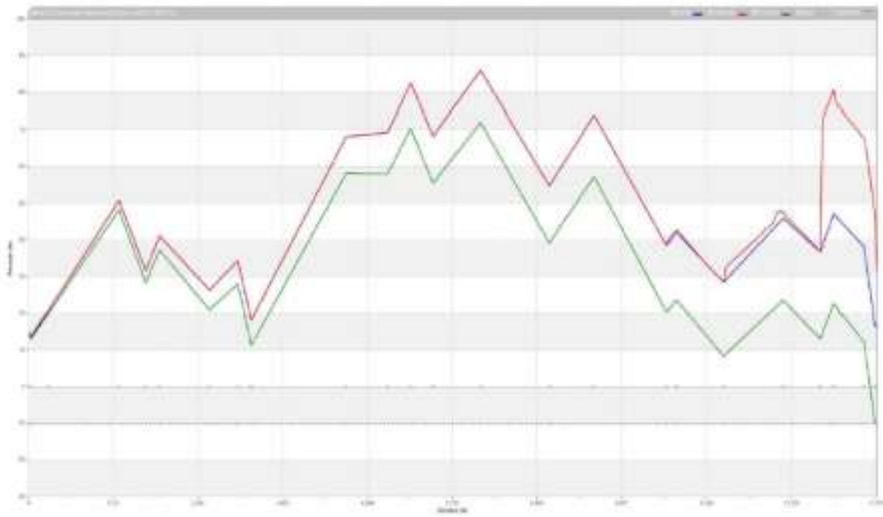


Figure 6: Pressure curve for Washan Mosque pumping station after the installing.

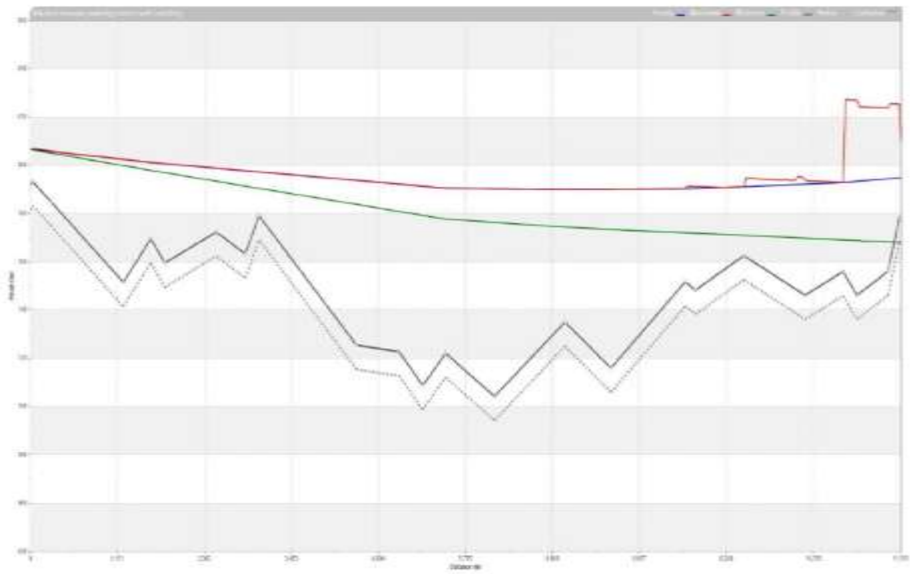


Figure 7: Head curve for Washan Mosque pumping station after the installing.

5.3 Western Kiklah Pumping Station

In the initial phase of the analysis, the Western Kiklah Pumping Station was evaluated in its original condition, without any protective measures or system enhancements. The transient simulation revealed the presence of cavitation and negative pressure, particularly near the tank connection point. The figure below illustrates the system's behaviour before any improvements or installations were implemented.

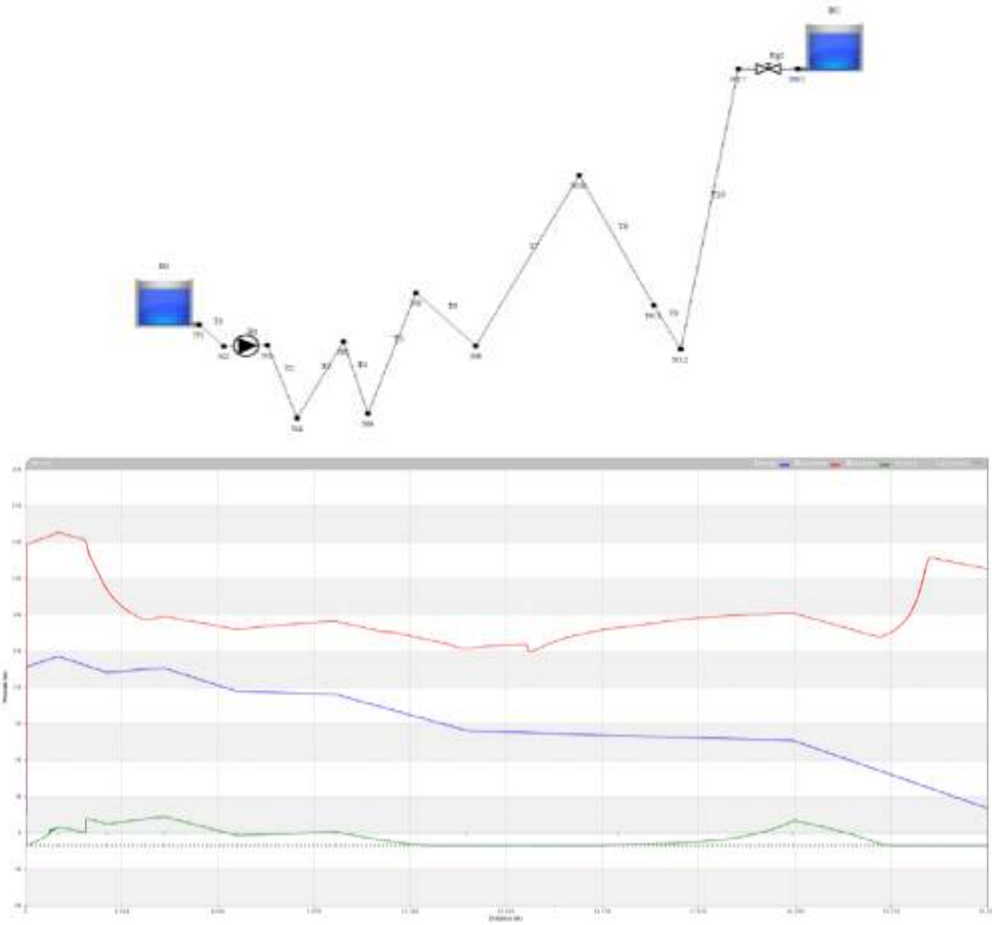


Figure 9: Pressure curve for Western Kiklah pumping station before the installing.

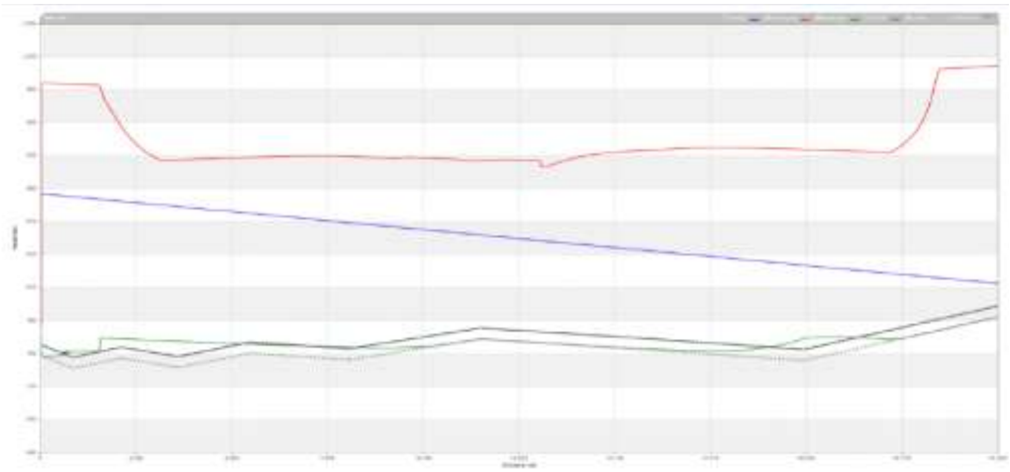
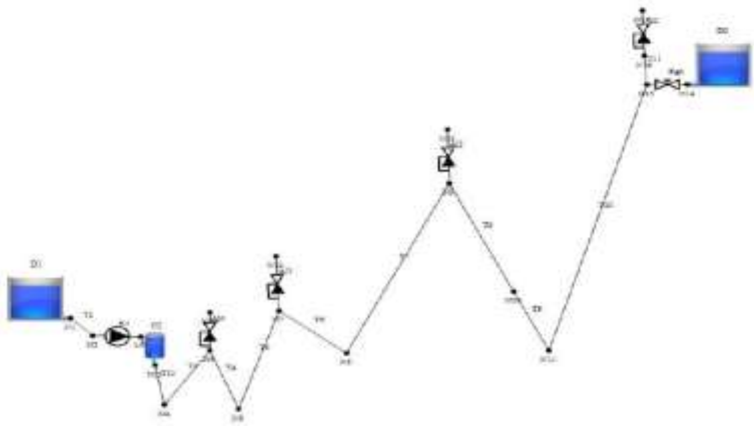
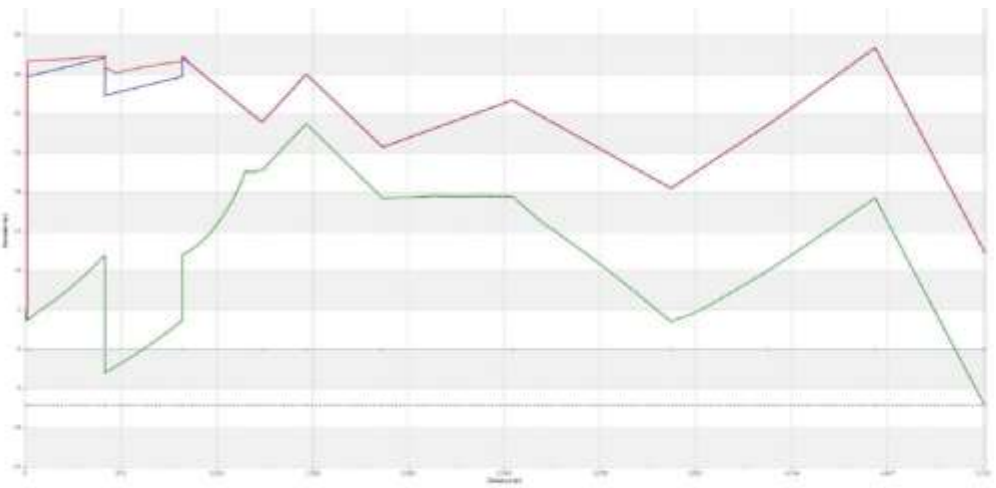


Figure 10: Head curve for Western Kiklah pumping station before the installing.

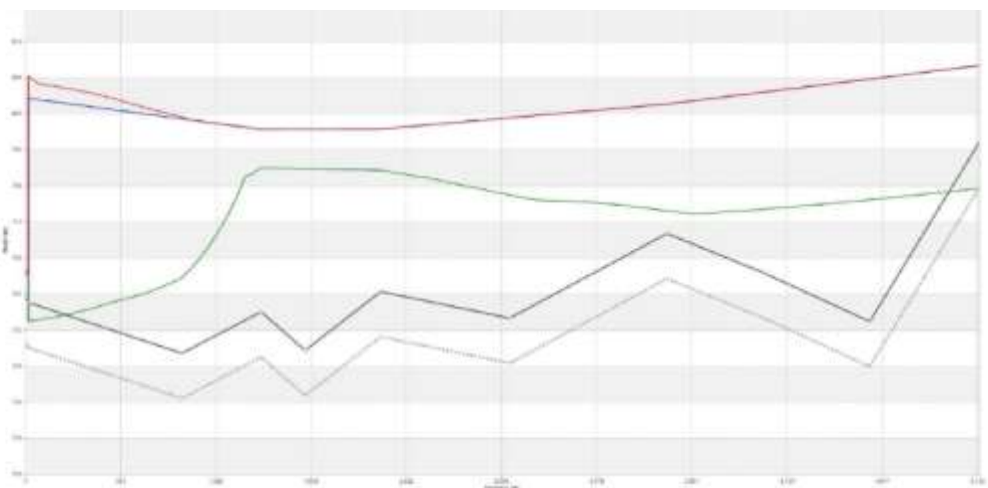
During the analysis, several critical zones were identified along the pipeline. To address the issue, air valves were installed at key points spaced approximately 750 to 1200 meters apart. Despite these efforts, the negative pressure persisted and showed little improvement. As a next step, double air valves were tested in the same positions, but this approach also proved ineffective. Ultimately, the problem was resolved by installing an air chamber located 20 meters downstream from the pump, which successfully stabilized the system and eliminated the transient pressure issues.



1: Western Kiklah pumping station after the installing.1Figure



2: Pressure curve for Western Kiklah pumping station after the 1Figure installing.



5.4 Al-Naher tank to a branch of the Awlad Youssef tank line

An analysis was carried out on the pipeline extending from the Al-Naher reservoir to a branch of the Awlad Youssef reservoir line, focusing on the section between reservoir D1 and D2. This initial assessment was performed without any modifications or protective devices installed.During the transient simulation, a severe water hammer was observed. Pressure levels spiked to approximately 130 bar, far exceeding the pipe's tolerance, which was limited to 98 bar. In addition, negative pressure zones were also detected along the line, indicating serious risk of structural damage if unaddressed.

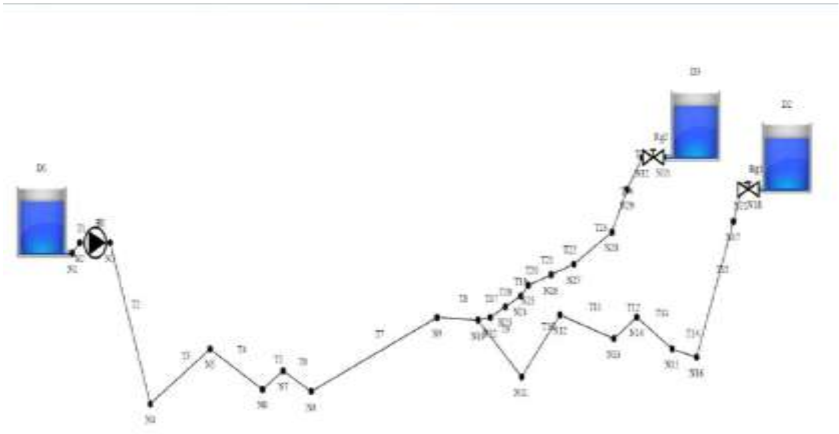
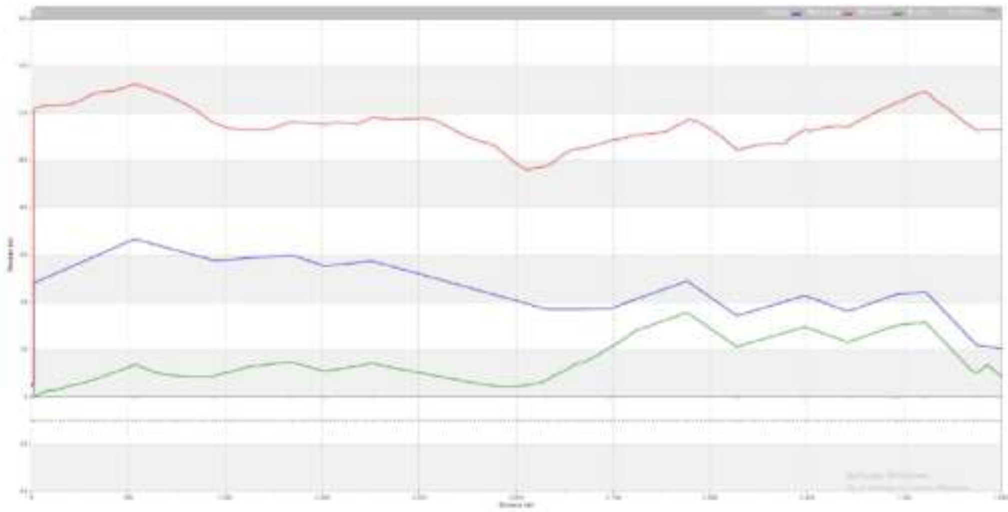
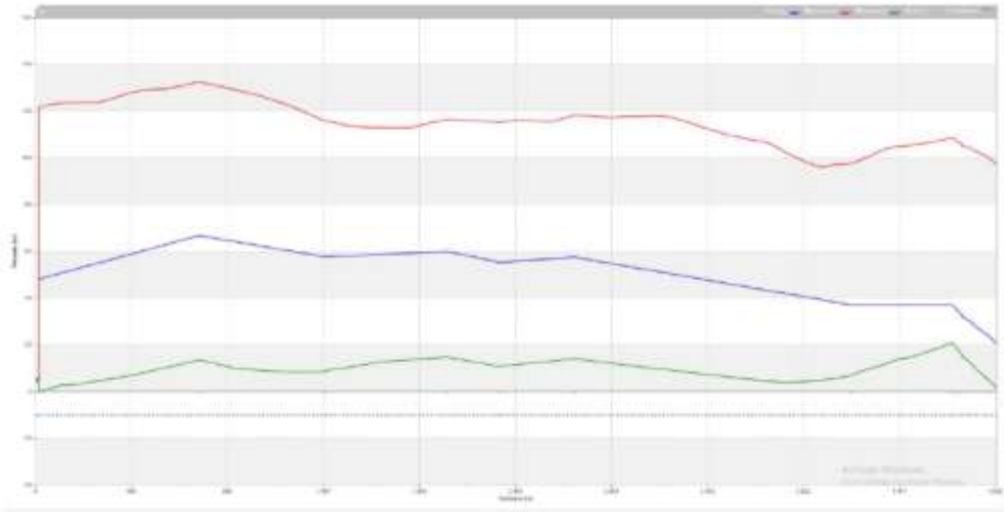


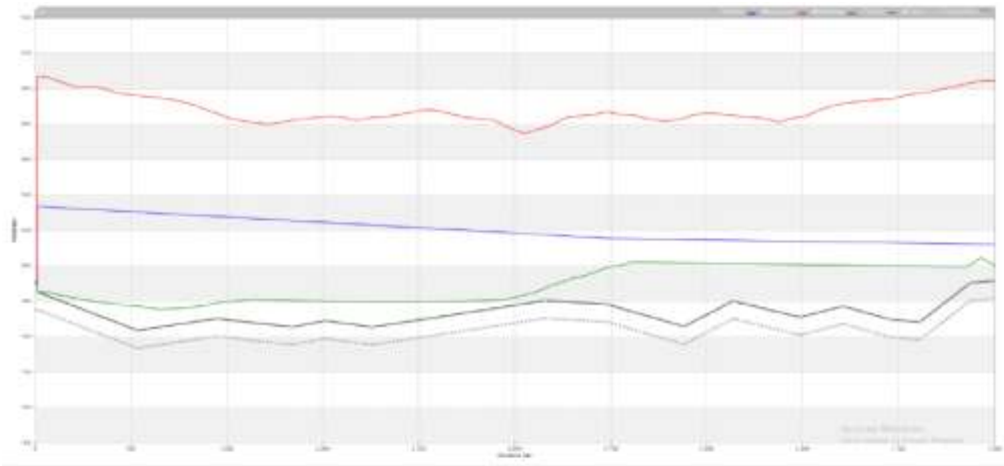
Figure 14: Al-Naher tank to a branch of the Awlad Youssef tank line before the installing.



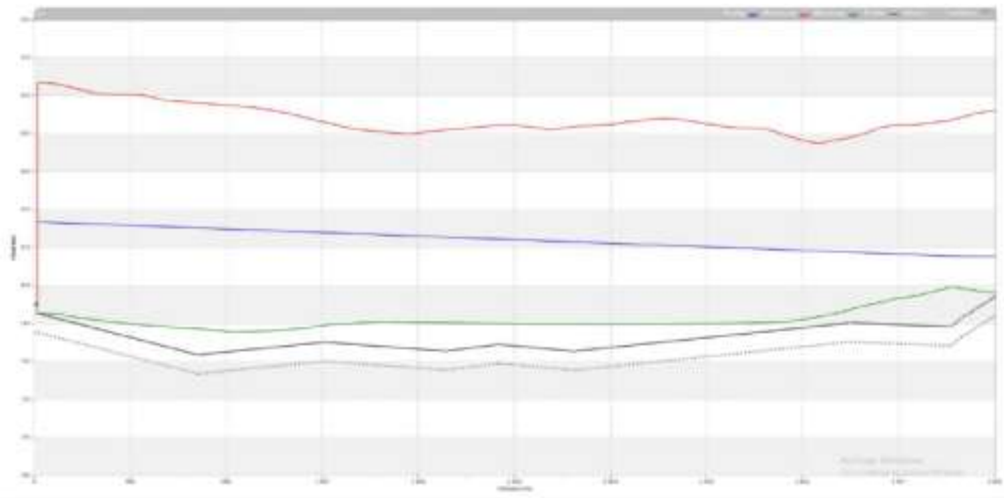
5: Pressure curve from D1 to D2.1Figure



6: Pressure curve from D1 to D3.1Figure



7: Head curve from D1 to D2.1Figure



8: Head curve from D1 to D3.1Figure

In the second phase of the analysis, air valves were installed throughout the pipeline linking the Al-Naher tank to the A branch of the Awlad Youssef tank line, taking into account the interaction between the connected lines. This intervention effectively resolved the water hammer issue. However, a small amount of negative pressure remained near the pump side of the system.

In the final phase of the analysis, an air chamber was installed approximately 20 meters downstream from the pump. This addition, combined with the previously installed air valves, effectively addressed the system's earlier issues. Most of the problems that had been observed before the branching point, including negative pressure and water hammer, were successfully resolved. The air chamber eliminated the remaining negative pressure, while the air valves mitigated the pressure surges caused by transient events.

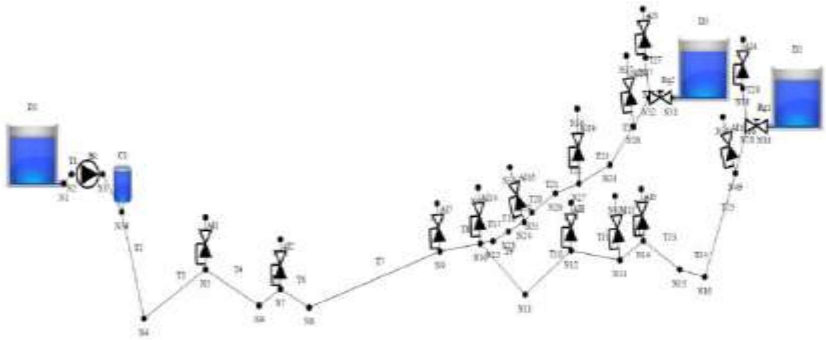


Figure 19: Al-Naher tank to a branch of the Awlad Youssef tank line after installing.

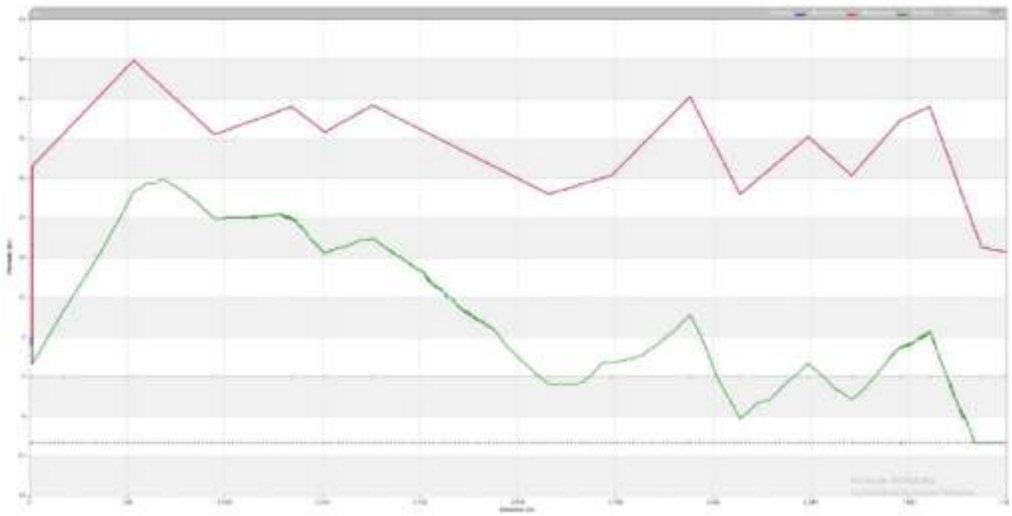


Figure 20: Pressure curve from D1 to D2.

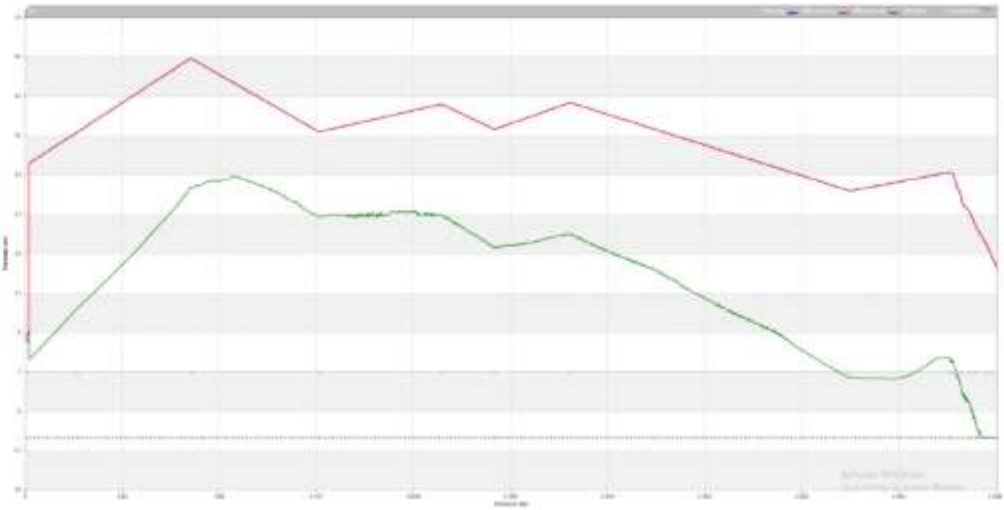


Figure 21: Pressure curve from D1 to D3.

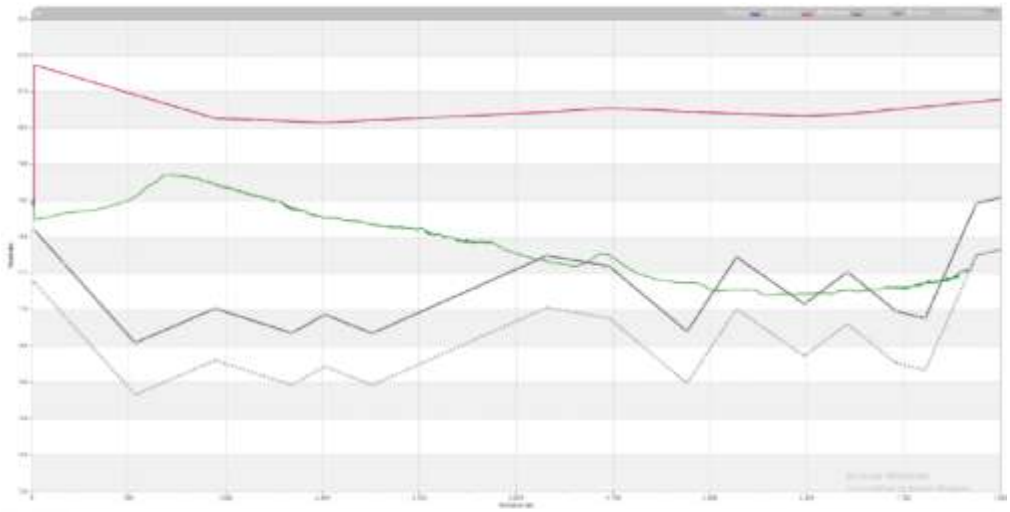


Figure 22: Head curve from D1 to D2.

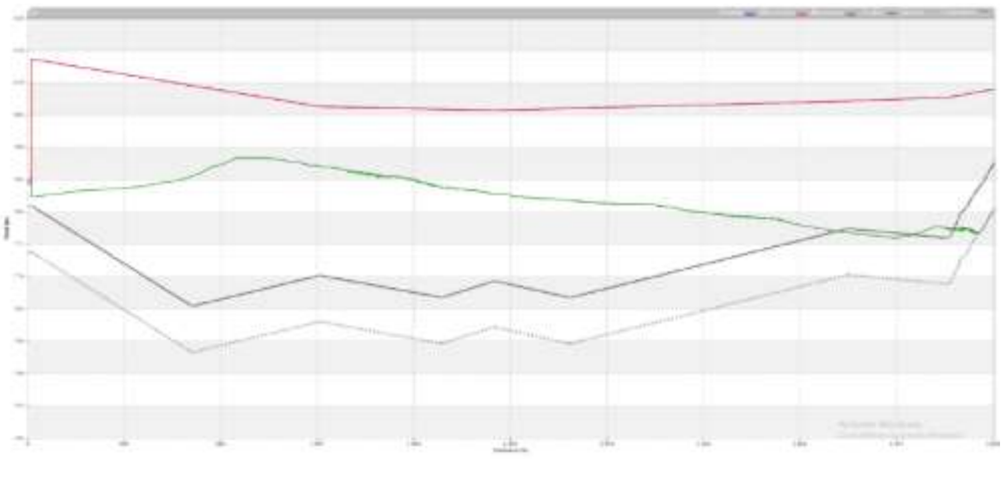


Figure 23: Head curve from D1 to D3.

6. CONCLUSION AND RECOMMENDATIONS

This study focused on examining the impact of water hammer on a pumping system. The findings highlight that several factors, such as the size of the air chamber**, its** placement relative to the pump, and the capacity and position of the water tank, play a critical role in determining the intensity of pressure surges. The study also emphasized the value of using advanced hydraulic modeling software to predict and understand transient behavior in pipeline systems. Additionally, results indicated that installing inline valves along branching sections of the network can contribute significantly to minimizing the effects of water hammer.

Based on the analysis, the following measures are recommended to help control and reduce water hammer in similar systems:

1. Increase the air chamber volume to adequately absorb the energy from pressure surges.
2. Position the air chamber as close to the pump as possible to maximize its effectiveness.
3. Install the water tank near the pump to stabilize flow and reduce pressure fluctuations.
4. Utilize advanced hydraulic simulation tools to anticipate potential transient issues and inform design decisions.
5. Install inline valves in branching pipelines to help moderate pressure changes and mitigate the risk of water hammer.

By implementing these strategies, the likelihood of damage caused by water hammer can be significantly reduced, enhancing the reliability and longevity of the pumping system.

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