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Enhancing Operating Rules for Water Pumping Stations Under Transient Flow Conditions by Using Surge Tanks

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Abstract

With an emphasis on Pump Station 1 (PS1) of the Basra Water Project (Open Canal) in Iraq, this study examines the essential hydraulic parameters of water pumping stations under transient flow situations. The study assesses the effects of routine operations, unexpected shutdowns, and surge tank installations on pressure stability and system flexibility using hydraulic modeling with HAMMER V8i. The findings show notable changes in pressure during brief occurrences. An abrupt shutdown without surge tank protection resulted in minimum pressures of 12.5 m in pipes L1 and L2, exposing them to hydraulic transient effects. The maximum pipe pressure under normal circumstances was 17.5 m (L3). Because of its exposure to low-pressure occurrences, the analysis identifies L1 as the most in-danger pipeline. It has been demonstrated that traditional operating procedures, which frequently ignore transient dynamics, increase the probability of service disruption and lead to inefficiency. In contrast, adding surge tanks reduces pressure variability and lessens the impacts of the water hammer, significantly increasing pressure stability, especially when three tanks are used. The results highlight how adaptable operational procedures are essential for employing and managing water delivery systems. According to the study findings, adding surge tanks improves durability and performance while lowering the risks of transient flow occurrences. This offers a guide for restructuring water pumping station operations.

Keywords: Water Pumping Station; Transient Flow Condition; Bentley's HAMMER V8i; System Reliability.

1. Introduction

Water pumping stations are considered functional substructures that play a relevant role in water supply within urban and rural areas. They are critical for relatively continuous water supply requirements, but for assessing and predicting system behaviors under other probable demands. With continuous increment of population, climate change, and the increasing rate of urbanization, the transient flow condition—the variation in flow rates and pressures—has become a

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critical consideration [1, 2]. Such changing conditions may be caused by rapid changes in usage associated with facilities, often accompanied by unexpected increases or decreases in water usage needs, equipment failures, emergencies, and other factors that can be critical to efficiency [3, 4]. Current operating practices in water pumping stations often rely on pre-programmed procedures that do not account for the system's dynamic behavior, leading to inefficient operations [5]. Moreover, traditional hydraulic methods for evaluating pressures do not adequately accommodate the complexities within the interconnections between individual pumping stations within a system, especially in decentralized networks [6].

Therefore, there is a high probability of an urgent need to redesign and strengthen these operational guidelines to be put into practice strategies for change that are sensitive to transient conditions [7, 8]. Recent works explain the remaining higher-order optimization methods to optimize the design of surge tanks. A dimensionless transient model was proposed and embodied this model with particle swarm optimization to investigate the best surge tank areas concerning diverse pipeline networks [9]. It offers a generic solution for flow conditions across the flow regime maps and models the pressure response as kinetics after employing either point or line integrations of the data. Other works can be identified exploring specific emptying tank configurations in the context of the general pumping station design, including pump designation, energy usage, and costs [10, 11]. These combined strategies are designed to enhance the system's performance within the lowest feasible costs.

The following research studies indicate the effectiveness of the utilization of surge tanks for enriching operating rules in water pumping stations. The effects of surge tanks on the transient flow occurring were simulated due to variations in turbine gate openings of a hydroelectric power plant [12]. When comparing the pressure oscillations in both systems, surge tanks were proven beneficial since they reduced the pressure variations and maintained a comparatively constant downstream pressure while extending the time availability of maximum and minimum pressures. A new stability criterion for mass oscillation in surge tanks was developed by including velocity head and throttle loss to make the substantial reduction of surge tank size possible while improving safety [13]. The simulation was used to demonstrate that a comparatively smaller surge tank would suffice for stability, which would mean savings [14]. The efficiency of surge tanks with other types of surge protection in a water delivery system has been studied [15]. From the research details, the authors concluded that surge tanks were the most useful in addressing the pressure surges since they displayed the least maximum pressure compared to flywheels and check valves. Using advanced sensors and other monitoring systems, as well as data collecting and analysis methods to aid in decision-making is one of the main areas of research. Bello et al. [16], for instance, emphasize that real-time monitoring systems connected to machine learning algorithms could be useful in noticing patterns of demand variability and modifying pump operating time plans accordingly [17]. This method offers protection against service interruption during peak hours, even though it improves resource consumption [18].

Moreover, effective coordination between the different pumping stations is also considered a fundamental process interface that decides transient flow management [19], and is pointed out that decentralized water supply systems can use the integrated models of potential coordination between several pumps to improve total system reliability and functionality. These results further emphasize the need for synergistic approaches to enhance the effectiveness of integrated pumping systems. It is stated that knowledge of transient conditions is critical for enhancing the efficiency of pump systems, especially those utilizing pump-as-turbine (PAT) technology, such as water hammers, which, if not controlled appropriately, can cause operational difficulties and harm equipment [20]. It was stated that the use of hydraulic modeling to predict transient conditions is an efficient tool to simulate and assess system responses during transient flow and understand pressure patterns and flow behavior to improve operational durability [21]. Thus, the need to improve the operational guidelines will remain of high value as water faces climate change and resource scarcity [22]. Accordingly, flexible data-enabled operating protocols represent vital advances with the potential to increase operational efficiency and reliability significantly [23]. In summary, it is suggested that high-time management practices in water pumping stations were changed to provide more flexibility in responding to the features of transient flow.

This research aims to assess the hydraulic characteristics of the PS1 of the open canal of the Basra Water Project, south of Iraq, under transient flow conditions and the effects of using surge tanks as a protective tool. The study also comprehends a determining of the expected relevant factors of the pipes and equipment before and after surge tank usage to provide protective measures that should be adopted to increase the water supply system's safety, efficiency, and reliability. This was done through the evaluation of transient flow conditions in water pumping stations using hydraulic modeling employing Bentley's HAMMER V8i. It emphasizes the need to understand hydraulic transient processes, including water hammer effects, since they cause operational problems and damage to hydraulic equipment.

2. Material and Methods

2.1. Study Area

The pump station no.1 (Ps1) is one of the pumping stations for the Basra Water Project (BWP) which was constructed on the Basra Open Canal that supplies water for domestic use and drinking water to Thiqar and Basrah Governorates [24]. It is located in station 300+63 of the open canal and it was established in 1993. The station lifts water from the canal and pumps it through pipes to cross the Euphrates River via a siphon. The pipe continues for a length of 1100 m to reach the outlet basin. The station consists of 19 metric pumps. Now, it is rehabilitated and developed to 15 pumps. Each pump has a discharge of 1.5 m^3/sec and a head of 16 m [25].

The station plays a vital role in addressing water shortages, improving public health through access to clean water, and supporting economic development in a region that has historically struggled with water quality and availability. However, it faces ongoing challenges related to maintenance and environmental impacts, making its effectiveness critical for the future of Dhiqar and Basrah water management and overall community well-being. Figure 1 shows the location of the case study.

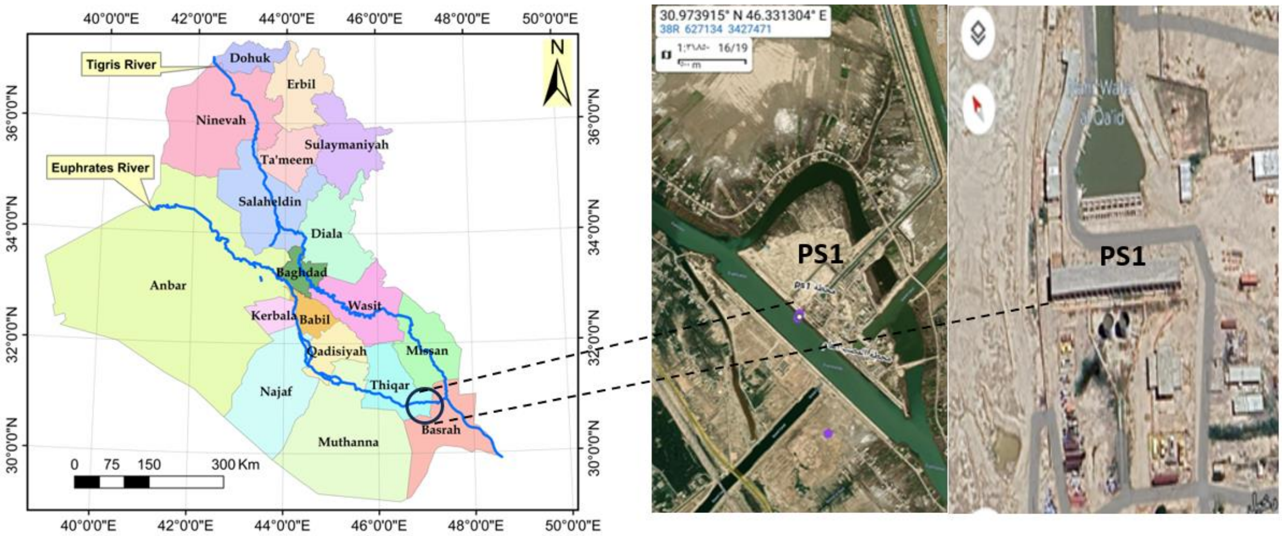

Figure 1. Location of the study area

2.2. Methodology of Data Analysis and Simulation

The analysis has been addressed in two phases:

- Steady state analysis

To determine the system's initial states, a preliminary equivalent linear steady-state analysis must be carried out utilizing Bentley's HAMMER V8i platform. In this instance, the major pipes' maximum and minimum pressures were computed in relation to their distance.

- Transient Flow analysis

The system's hydraulic transient characteristics will be simulated. The system is divided into three scenarios:

  - Sudden shutdown (S) without tank protection.
  - Treatment with two tanks, placed after the pumps for the two main pipes L1 and L2.
  - Treatment with three tanks placed after the pumps for the three main pipes L1, L2 and L3.

The water network for the main transmission pipelines, as well as some pipes before and after the pumps, is analyzed to show the effect of each case on the pressures and other hydraulic parameters. The results could be classified into three cases, as they will compare the system of the water hammer and its control measure at different conditions. The purpose of these scenarios is to evaluate the efficacy of tank use as well as the initial potential threats to the system in the absence of protective tanks. The hydraulic system was equipped with extra tanks to lessen the water hammer's abrupt pressure to lessen its impact and improve the system overall.

Figure 2 displays the general framework of the methods employed in this investigation. Figure 3 shows the pump station's layout under various conditions.

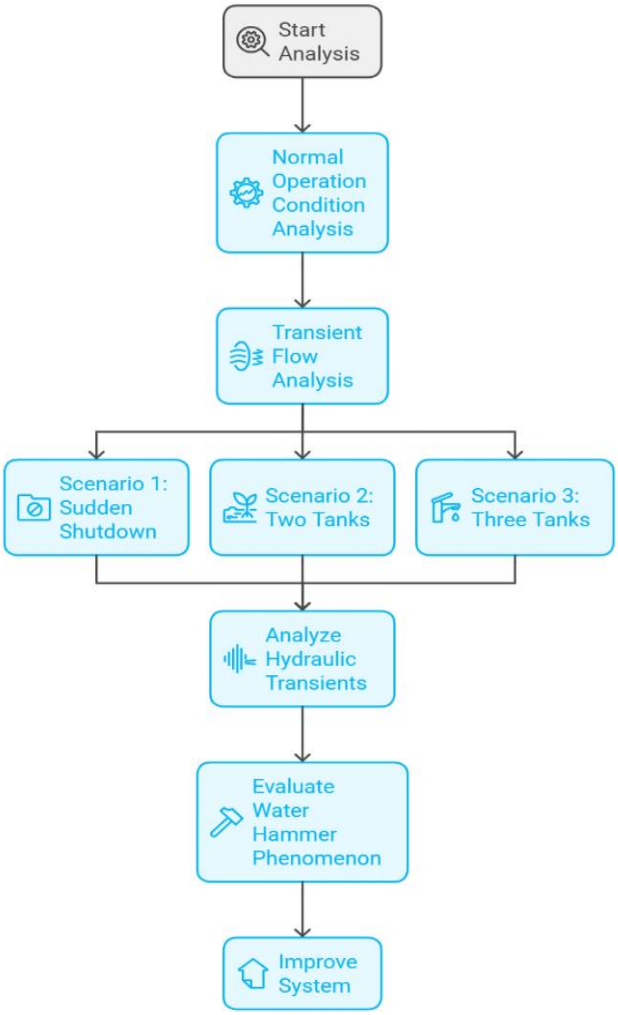

Figure 2. The methodology's scheme

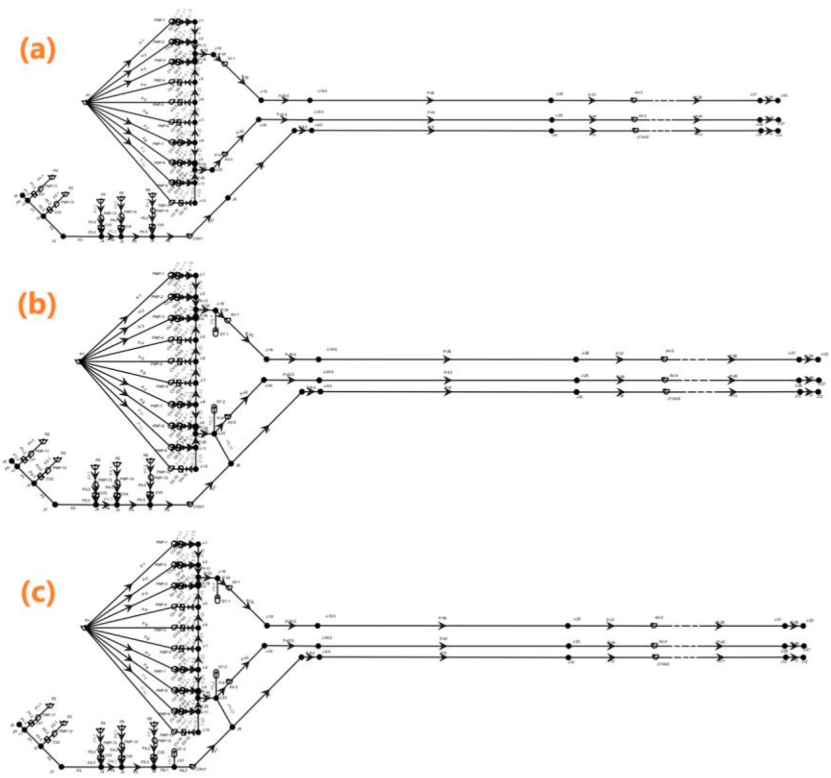

Figure 3. Hydraulic system with (a) sudden shutdown and without tank protection, (b and c) two tanks

2.3. Numerical Modeling of the Hydraulic Transient Flow Conditions

Reviewing Bentley's HAMMER V8i software's ability to assess numerical hydraulic transient flow situations and how much it takes pressure transients into account in water distribution systems is crucial nowadays. With its advanced algorithms, HAMMER V8i, a transient flow solver analysis program made specifically for transient flow analysis, can be used to represent the majority of hydraulic events, including surge and water hammer. Among other things, this feature lets engineers assess the impact of abrupt variations in flow or pressure brought on by pump failures and valve actions. In the method of characteristic lines, the governing equations' transient flow modeling was done using HAMMER software. Additionally, characteristic lines that show wave propagation in the time-location plane can be graphically displayed by this software. Partial differential equations are rearranged into ordinary differential equations using the characteristic approach. The finite difference method (FDM) is used to discretize these ODEs, and the resulting numerical issues are resolved. Accurately determining the boundary condition data at the transmission line's upstream and downstream spline points is one of the essential components of the numerical solution procedure [26]. Other components such as pumps, water hammer control components such as air tanks, connection components, and other kinds add to the system's "more unknowns" in a complicated water supply system. The system's boundary condition is the pump's Head-Discharge Relationship H-Q curve, which is applied at the boundary where the pumped flow is [26, 27].

The water hammer effect occurs when the flow velocity abruptly changes. The basic formula for a water hammer is given by the conservation of momentum and is as follows [2]:

$$\Delta p = -\rho \, c \, \Delta v \tag{1}$$

where c is the wave speed, Δv is the fluid velocity change, ρ is the fluid density, and Δp is the change in pressure.

$$c = \sqrt{\frac{k}{\rho}} \tag{2}$$

where K is bulk modulus of the fluid, and ρ is density of the fluid.

Pressure wave propagation in the pipeline is described by the wave equation, which is essential for examining transient flow [28].

$$\frac{\partial^2 p}{\partial t^2} = c^2 \frac{\partial^2 p}{\partial x^2} \tag{3}$$

where *t* is the time proceeding, and x is the distance along the pipeline.

The momentum equation, which links changes in velocity and pressure, is useful for figuring out the forces operating on the fluid [29].

$$\frac{\partial Q}{\partial t} + \frac{\partial \, (A.V)}{\partial x} = -gA \frac{\partial h}{\partial x} - f \frac{Q|Q|}{2gD} - \sum P_{loss} \tag{4}$$

where Q is the flow rate, A stands for the pipe's cross-section area, h for the hydraulic grade line, f for the Darcy-Weisbach friction factor, and D for the pipe's diameter, and P_{loss} is Losses brought on by bends, fittings, etc.

3. Material and Methods

The analysis under normal operation conditions and for three different scenarios was utilized: the 1st is a sudden shutdown without any protective equipment (tanks addition) as shown in Figure 3-a; the 2nd is that the hydraulic system has been equipped with two tanks placed behind the pumps and at the inlet of each the main pipes $L_1, and\ L_2$. The 3rd scenario is the hydraulic system equipped with three tanks placed behind the pumps and at the inlet of the three main pipes L_1, L_2, and L_3. The results of the hydraulic analysis performed on the main pipelines were planned and investigated and present the results on the relative performances of various applications, with and without surge protection.

3.1. Normal Operation Condition of the Model

To creates a point of reference for comprehending how the system operates independently of regular occurrences or outside interferences. The goal is to determine the maximum and minimum pressure values attained during routine operations by examining the pressure profiles of the main pipes, namely $L_1, L_2, and\ L_3$. The results will form the basis for further hydraulic transient evaluations, enabling a more transparent comparison of the system's response to abrupt changes, including demand fluctuations or pump shutdowns. The pressure for main pipes under typical operating conditions is displayed in Figure 4.

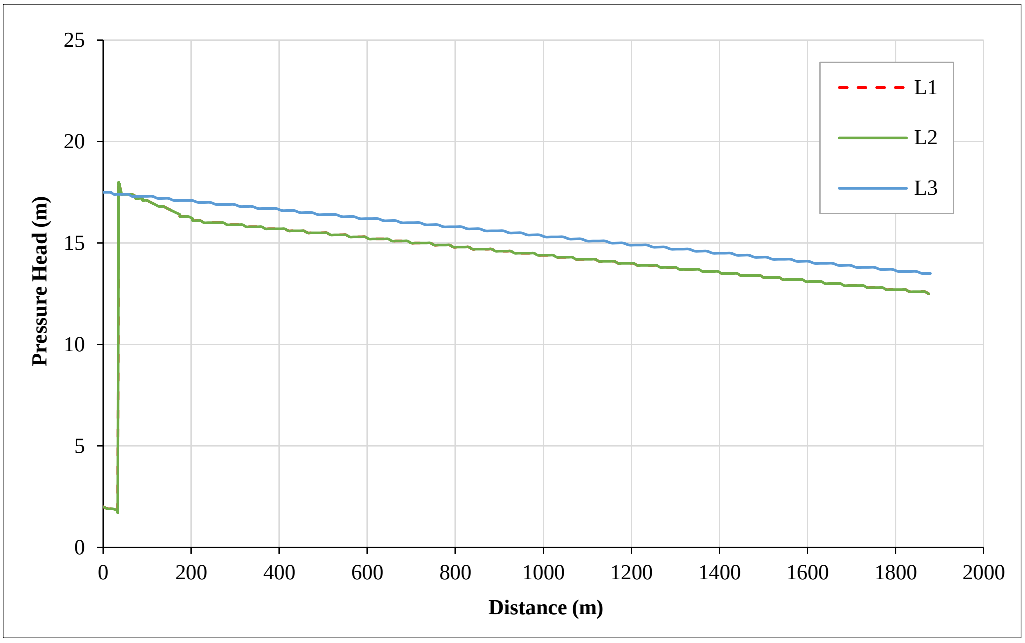

Figure 4. Pressure under normal operation conditions for the main pipes

Figure 4 illustrates that the initial pressure under the normal operation condition of the three main pipes pressure is 17.5 m, and the minimum was found to be 12.5 m in the pipes L_1 and L_2 and 13.5 m in the pipe L_3. Additionally, before examining the consequences of irregular situations like the pressure of water hammer rise, bent losses…etc, this assessment allows the network's pressure transient conditions to be determined at any given time. Operating the hydraulic system in normal conditions without a water hammer provides an understanding of what happens after the pressure changes due to the water hammer before and after the hydraulic system is supplied with protection tanks.

3.2. Transient Flow Analysis

The behavior of the pressure distribution system during different transient flows, such as pump failure and surge tank installation, is covered in this section. Additionally, it will try to investigate the system's hydro transients, which result in pressure changes and operating difficulties. The effects of such transient events—specifically, the conditions without tank protection with two and three surge tanks—on the pressure stability and flow characteristics across the main pipelines are compared in this analysis using several pretended scenarios. Figure 5 describes the behavior of the pressure values under normal operation conditions and at a sudden shutdown (S) case without tank protection of the main pipes of the hydraulic system.

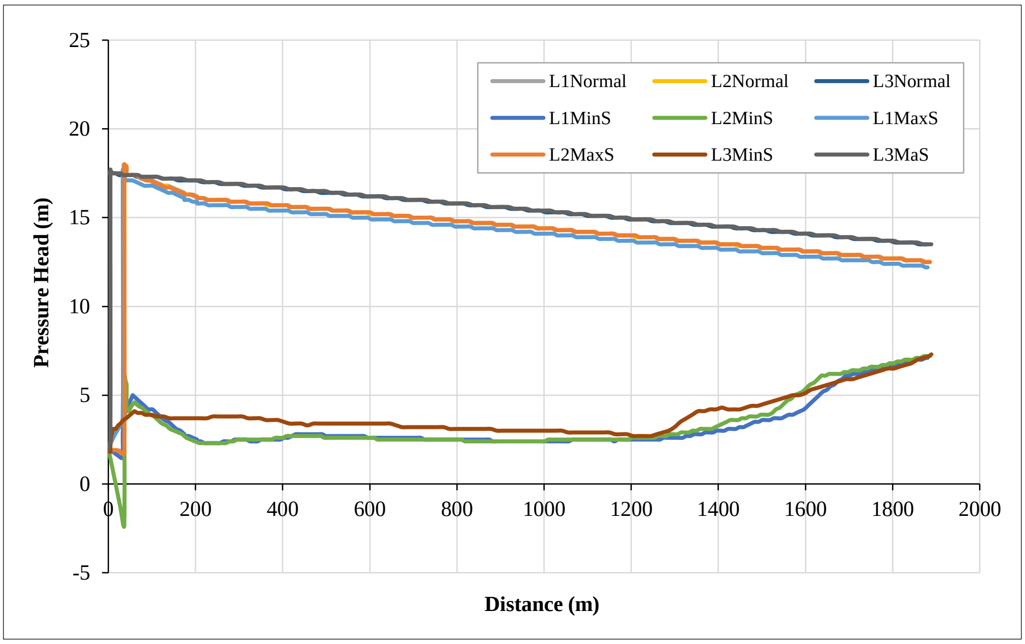

Figure 5. Pressures under normal operation conditions and a sudden shutdown (S) for main pipes

In Figure 5, L_3 has achieved the maximum pressure value under normal operation conditions, meaning that the system can effectively manage flow and hydraulic pressures. On the other hand, L_1 offers the minimum pressure during a sudden shutdown situation without tank protection. This scenario shows the sensitivity of all hydraulic system pipes to pressure variations due to the shutdown condition, but line 1 offered the most sensitivity according to the lowest pressures. This may lead to several expectations, including backflow and pipe collapse due to very low pressure.

Peak pressures, on the other hand, are often good indicators of effective flow under normal operating conditions; however, they have the disadvantage that high peak pressures risk reaching the design limit, exposing the pipes to the risk of bursting and equipment failure. Similarly, another important parameter, the minimum required pressure, indicates the lowest pressure used as working pressure in the system. It can cause negative consequences, such as backflow, reduced flow rate, and pipe collapse due to poor hydraulic consideration. Furthermore, the tripping pressure value provides a benchmark against which the performance of the system can be compared before it is affected by operations or disturbances.

Figure 6 shows the pressure variation in different cases including normal operation conditions, sudden shutdown without tanks, and an operation with two tanks installed at the main pipes. Figure 6 indicates that the pipe L_3 is exposed to pressure rise during operation with two tanks scenario fulfilling the highest pressures but still is controllable due to the surge protection with tanks. On the other hand, L_1 has the lowest pressures in the case of sudden shutdown without protection tanks. This illustrates the exposure of systems to hydraulic transient flow risks if adequate protection steps are not taken. This demonstrates, that there is an urgent and constant need for a correct design that takes into account all the conditions of the hydraulic system to avoid failures such as pipe explosions at high pressures and their collapse and blockage at low or negative pressures.

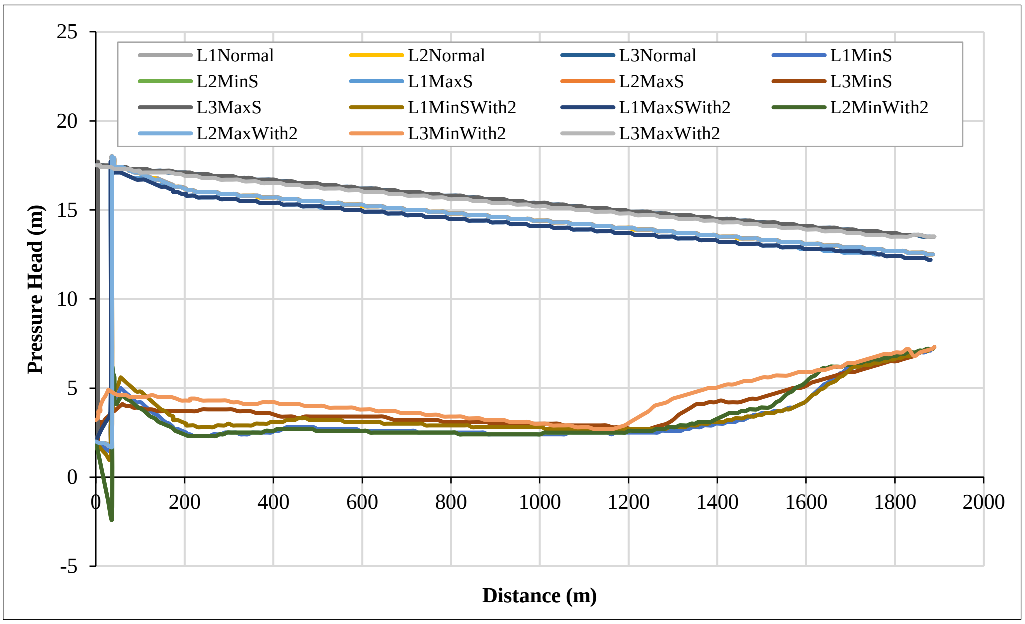

Figure 6. Pressure variations along the main pipes under normal operation, sudden shutdown and operation with two protection tanks

Figure 7 shows the pressure variation along the main pipes under normal operation conditions, sudden shutdown without tanks, operation with two tanks, and operation with three tanks. During operation, line L_3 was exposed to the maximum pressure with three tanks protection, which reflects the efficiency of the surge protection system in the network. The lowest pressure value occurred in line L1 without a protection tank during the MinS shutdown case, clearly emphasizing the system's exposure to hydraulic transients when tank protection is not sufficiently implemented. This comparison, therefore, draws attention to the necessity of employing surge protection measures to preserve pressure patterns in water supply systems. As is known, in hydraulic systems, when a sudden shutdown occurs in the pumps, negative pressures are formed immediately after the pumps, which may lead to the collapse and blockage of the pipes and air vapor origination, which leads to the failure of the entire system. Therefore, the good applications in this study are to explore the volume of the occurred air vapor after the pumps as a result of these negative pressures with and without protection tanks, as shown in Figure 8. In the current case, Figure 8 shows the occurred air vapor volume along the main pipes values under sudden shutdown without protection tank, and with two tanks.

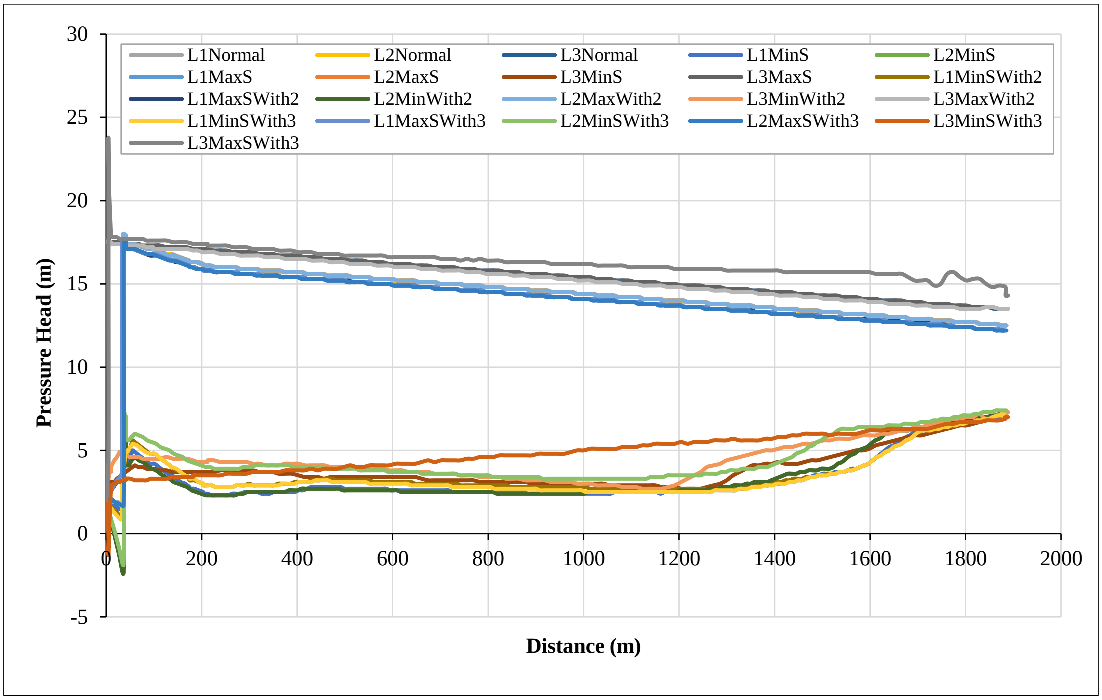

Figure 7. Pressure head variation along the main pipes under normal operation conditions, sudden shutdown without tanks, operation with two and three tanks

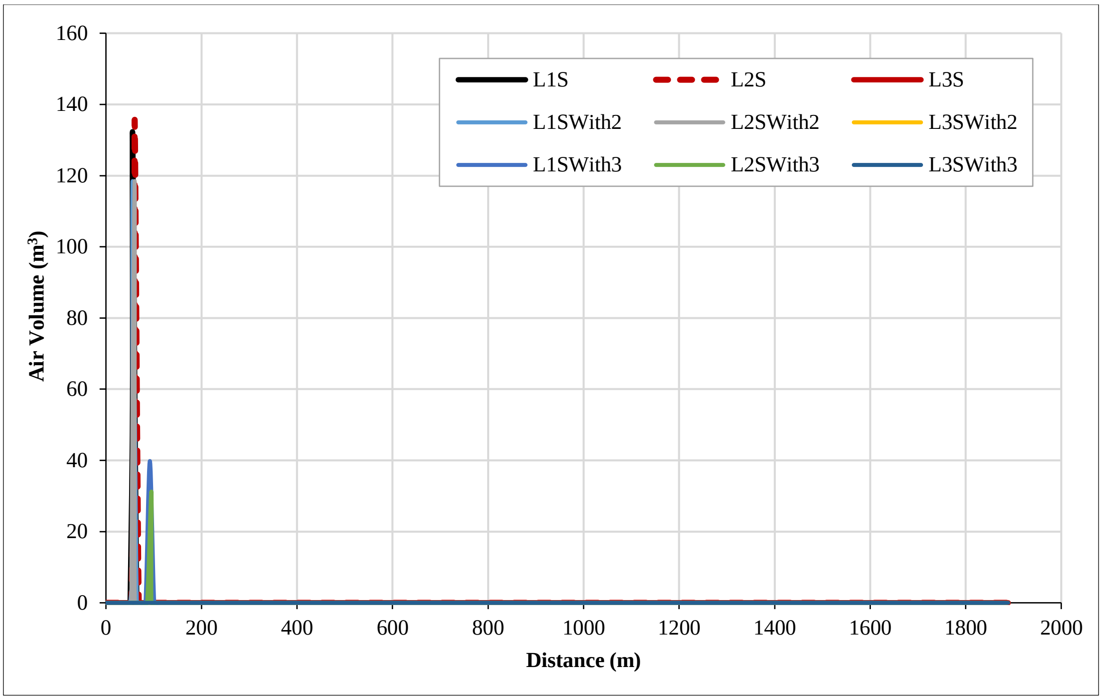

Figure 8. Air vapor volume occurrence along the main pipes under sudden shutdown with two and without protection tanks

Figure 8 shows the air vapor volume distribution along the main pipelines occurred during the sudden shutdown of the pumps. It is observed that the occurred air vapors are not originated after a distance beyond 85m away from the pumps. In addition, the occurred air vapor volumes are exaggerated to value of 135 m^3 when the hydraulic system is not equipped with the protection tanks; inversely the main pipelines endure no excessive rise in air vapor volume when equipped with protection tanks as presented in Figure 8.

It is both important and concerning to compare the hydraulic pressures in the pipes before and after the pumps under different scenarios, as illustrated in Figures 9 to11. The hydraulic transient analysis for the water distribution network is detailed in these figures. Figure 9 provides a thorough comparison of pressure variations in the L1P-3-1-CV-3 pipeline under three distinct scenarios: a sudden shutdown without tank protection, and shutdowns with two and three protection tanks. The data illustrates that, during the sudden shutdown without a protection tank, the pressure head drops from

17.95 m, 17.95 m, and 17.63 m to 7.8 m, 7.04 m, and 5.51 m after 60 seconds for the L1P-3-1-CV-3S pipeline, with the varying outcomes based on the number of protection tanks. This indicates that the system faces significant exposure to hydraulic transients, which can potentially damage equipment and reduce operational efficiency. When two protection tanks are introduced, the pressure profile becomes less unstable, and the overall pressure remains comparatively higher at different stages. In the case of three protection tanks, although the same drop in pressure head occurs, it is more uniform, demonstrating the efficiency of these protective measures in mitigating the issues caused by water hammers. These results highlight the importance of using pressure booster tanks to maintain pressure within the water distribution network, thereby enhancing operational reliability and preventing infrastructure failures.

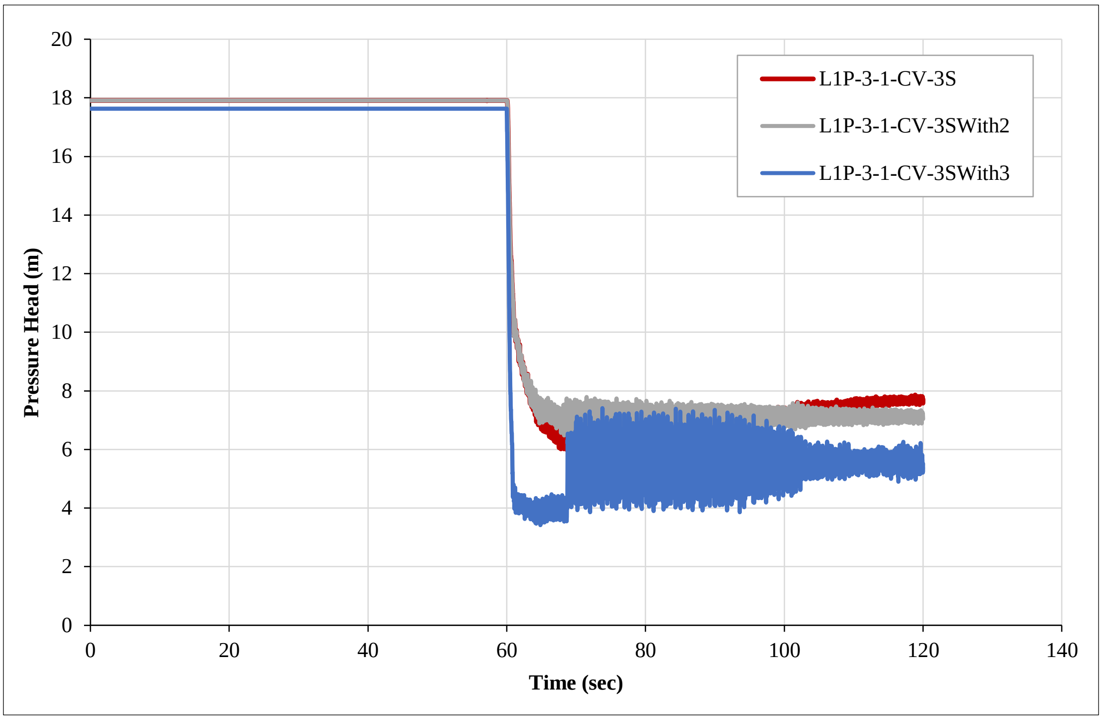

Figure 9. Pressure head variations versus time of L1P-3-1-CV-3 under sudden shutdown without protection tanks, with two and three protection tanks

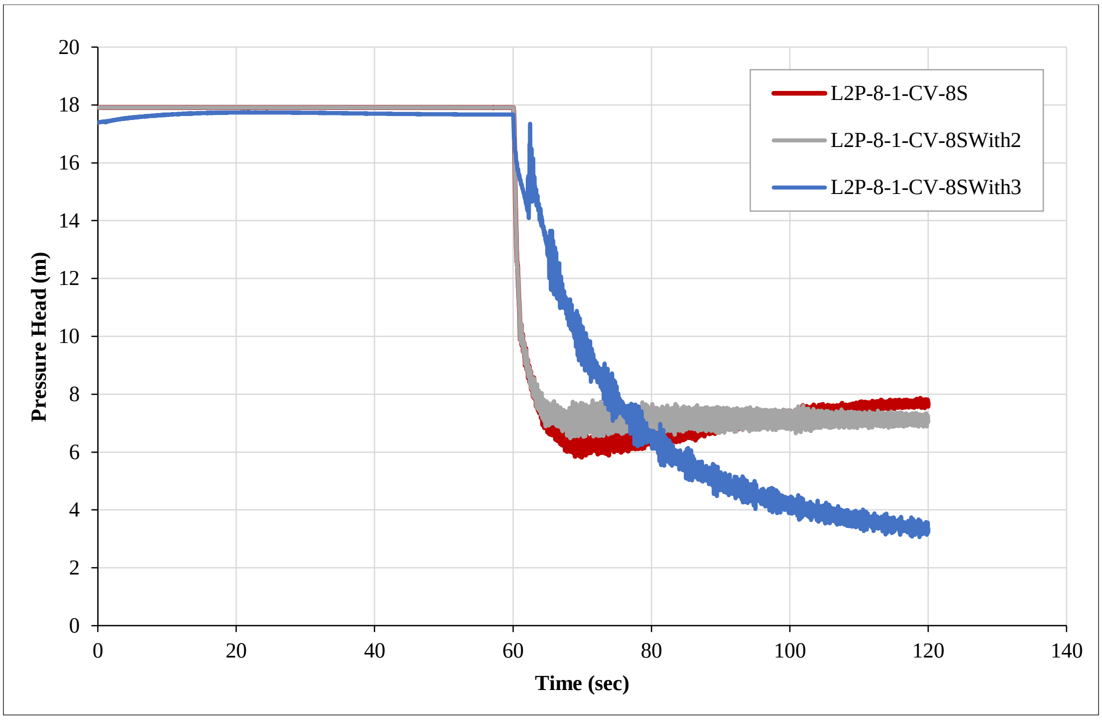

Figure 10. pressure head variations of L2P-8-1-CV-8 under sudden shutdown without tank protection, with two and three protection tanks

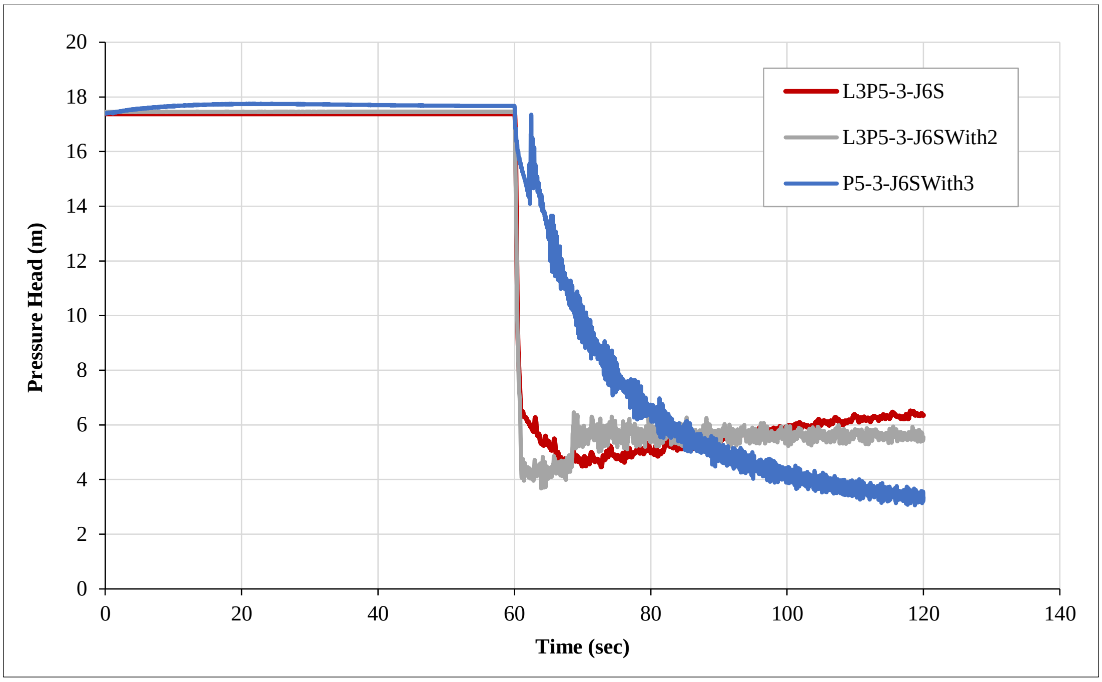

Figure 11. Pressure head variation of the pipeline L3P5-3-J-6 under sudden shutdown without tank protection, with two and three protection tanks

Similarly, Figure 10 displays the pressure head variations for the L2P-8-1-CV-8 pipeline under comparable scenarios. It is observed that the pressure fluctuates significantly without surge tanks, particularly when three tanks are present. The figure confirms that the pressure head drops after 60 seconds from 17.95 m, 17.95 m, and 17.63 m to 7.77 m, 7.28 m, and 3.23 m for the L1P-3-1-CV-3S pipeline during sudden shutdowns without protection tanks, and when equipped with two and three protection tanks, respectively. This emphasizes the acceptability and reliability of the hydraulic system when protection tanks are included. Figure 11 illustrates the pressure head variations over time for the L3P5-3-J-6 pipeline. Similar to the previous findings, the pressure heads drop after 60 seconds of operation, starting from 17.95 m, 17.95 m, and 17.63 m down to 6.35 m, 5.56 m, and 3.41 m during a sudden shutdown without protection tanks, and with two and three protection tanks, respectively.

By comparing the maximum and minimum pressure results shown in Figures 9, 10, and 11, it is apparent that the L1 pipeline exhibits the most significant pressure variations, particularly under the scenario of sudden shutdown without a protection tank. As demonstrated in Figure 6, pipeline L_1 has the lowest minimum pressure reading during this condition, proving how at risk it is to hydraulic transients. This vulnerability is severe since it leads to various problems, including backflow and, in the worst-case scenario, pipe collapse when the pressure is too low.

Figure 11 displays the L_3 pressure profile in the pipeline after the installation of surge tanks. When tanks are taken into account, the L_3 pipeline's fluctuation in these values is also characterized by higher pressure, which is evidence that surge tanks do reduce pressure build up during transient conditions. Surge tanks reduce hydraulic shocks and create a more consistent pressure range if they are positioned inside the L_3 pipeline. The location of the L_1 pipeline in the network and the lack of preventive measures make it more exposed to variations in flow conditions, which is the reason for the very high-pressure oscillations in this pipeline. In conclusion, the L_1 pipeline has the highest sensitivity to pressure fluctuations and the lowest pressure. The L_3 pipeline, on the other hand, provides the best results in terms of maximum pressure and system reliability because it has surge tank protection. Figures 12 and 13 show the discharge versus time under sudden shutdown without protection tanks, with two and three tanks of the pipes L3P5-7-J-8 and L1-P33-J18 respectively.

The effect of surge tank operation on hydraulic performance is further demonstrated in the interaction of discharge and water head over time in Figures 12 and 13 for three operational scenarios of the L3P5-7-J-8 and L1-P33-J18 pipelines. This is evident by the graph indicating that discharge rates vary widely during transient conditions, especially where surge tank protection is applied. It is shown that in the absence of the surge tanks, the discharge has sharp fluctuations, telling exposure to up normal hydraulic impacts, which can result in energy losses and system damage. On the contrary, when surge tanks are combined into the system, the discharge pattern varies substantially, and there is a reduced fluctuation in pressure rates and variation between the minimum and maximum flow rates. This stability is important to maintain routine service and ensure that structures within the pipeline do not fail. Also, the dataset of operation showing daily average discharge included the pressure head, which demonstrates how the hydraulic head varies with flow parameters, thus emphasizing the efficiency of the surge tanks to increase the dependability of the operation. The "with3"—in this example, three surge tanks—is always the optimal configuration for the L3P5-7-J-8 pipeline system, as can be shown by comparing Figures 12 and 13.

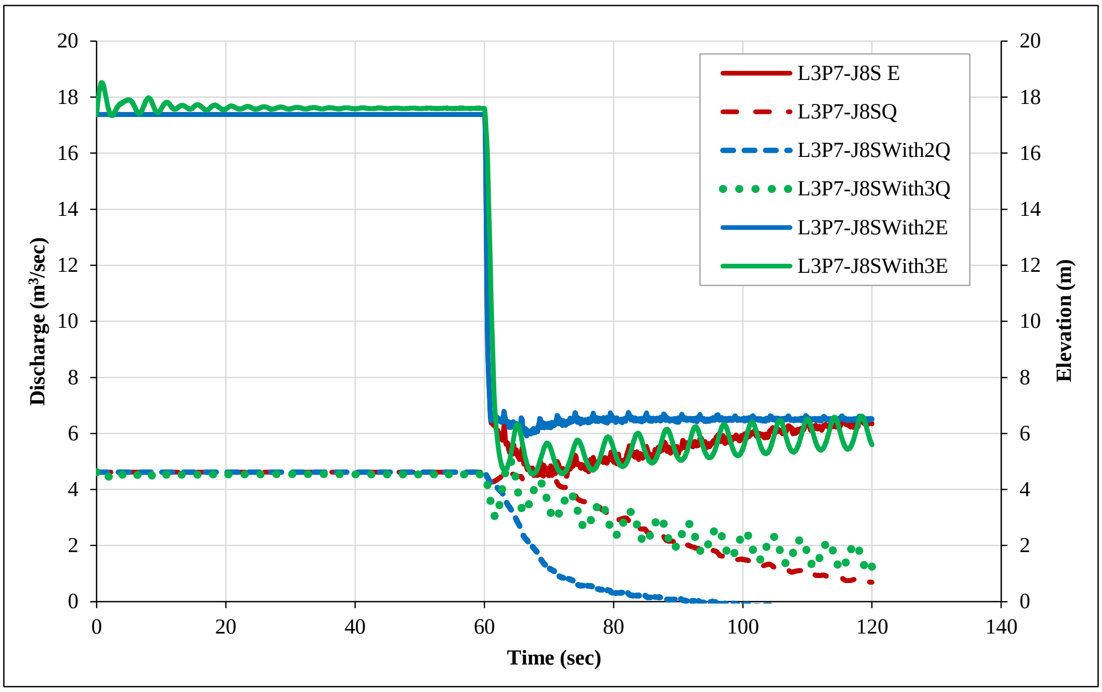

Figure 12. Variations of discharge versus time for L3P5-7-J-8 under sudden shutdown without protection tanks, with two and three tanks

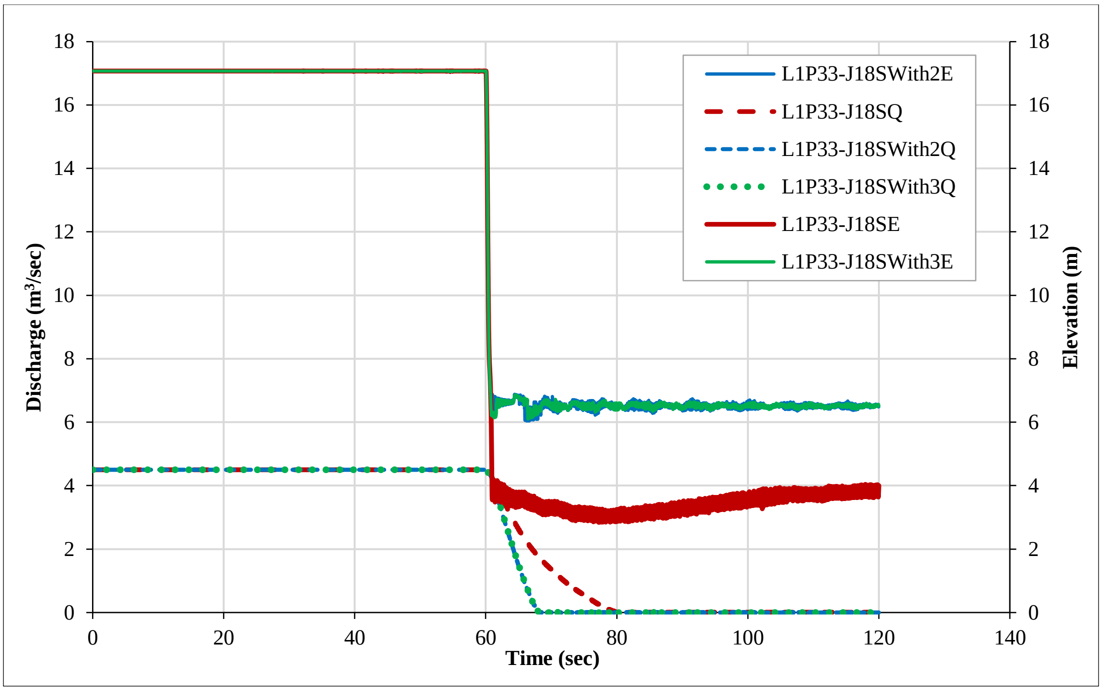

Figure 13. variations of discharge versus time for L1-P33-J18 under sudden shutdown without protection tanks, with two and three tanks

In contrast to the "without" and "with 2," the "with3" shows a high degree of stability of the elevation and discharge profiles, as shown in Figure 12, which will lessen the hydraulic transients and fluctuations. To prevent cavitation and backward flow, these components must remain stable. For this reason, operational reliability depends on this requirement. Better performance characterizations relating to pressure fluctuations and system stability would provide the "with3" scenario even more confidence if the same tendencies were seen in Figure 13. That's for this reason, in both figures, the "with3" scenario might be selected as the best choice. It makes it possible for water to be distributed smoothly while maintaining equal flow and pressure levels, which improves the WD system's stability and efficiency.

4. Conclusion

The pressure was comparatively steady during normal system and component operation, with recorded maximum pressures of 17.5 m. Using this scenario, a typical view of the system's operation was obtained, and it was observed that steady pressure was necessary to enable sufficient water delivery. The analysis of sudden shutdown scenarios revealed important weak points within the system. During these events, the minimum pressure dropped to 12.5 m, exposing the pipelines to hydraulic transients and increasing the risk of operational failures. According to the results, the absence of protective measures, including surge tanks, and serious pressure fluctuations may cause service disruptions and inefficiencies. The pressure control and the discharging rate were much more stable when surge tanks were installed. Consequently, the case of three surge tanks produced the most promising results in terms of pressure fluctuation minimization and the general improvement of the system's stability. It was discovered that using surge tanks improved network discharge rates and controlled pressure. The models that integrated surge tanks showed significantly less variation in both pressure and discharge, indicating that both factors are essential for managing transient flow.

5. Declarations

5.1. Author Contributions

Conceptualization, L.A. and K.S.; methodology, L.A.; software, K.S.; validation, N.M., F.L., and A.N.; formal analysis, N.M.; investigation, L.A.; resources, K.S.; data curation, M.S.A.; writing—original draft preparation, L.A.; writing—review and editing, A.N.; visualization, M.S.A.; supervision, K.S.; project administration, N.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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