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Research Paper

Elevated tanks effect on transient pressures: case study

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ABSTRACT

Elevated tanks are an integral part of the water supply networks. This paper highlights the effect of elevated tanks' location and size on the transient pressures resulting from the sudden failure of pumps. A comparison between the impact of elevated tanks and air vessels on the water hammer was also performed. The Bentley HAMMER model was first validated then applied to analyze the unsteady flow within an actual distribution network. The results display that the elevated tanks have a considerable effect on the surge pressures, where they improve the extreme pressures effectively at and around them, but they cannot fully protect the system from the water hammer risks, as there are still relatively large negative pressures at some distant junctions. Besides, as the tank capacity increases, the surge pressures increase slightly. In our case study, the best location of the elevated tank is at the network extremity and then at the pumping stations, since the minimum pressures improve by 67 and 54%, respectively. Although the present case study may differ from other supply systems, the obtained results can provide an indication of the elevated tanks' role in alleviating undesirable water hammer effects.

Key words: elevated tanks, pressure transients, pumps, water distribution network, water hammer

HIGHLIGHTS

- This paper highlights the effect of elevated tanks' location and size on the water hammer pressures.
- A comparison between the impact of elevated tanks and air vessels was also performed.
- The Bentley HAMMER model was validated and then applied to analyze the unsteady flow within an actual distribution network.
- The gained results can give an indication about the effect of elevated tanks on the transient pressures.

INTRODUCTION

An instantaneous change in the outflow or inflow of an engineering system may result in initiating of transient conditions, including demand changes and sudden pump or valve operations in piping systems (Chaudhry 2014). These actions can lead to a series of negative and positive surge waves that travel along a pipe. These waves could collapse the piping system and its components, beside the possibility of water-column separation and contaminants ingress that adversely impacts water quality (Darweesh 2018; Yuce & Omer 2019), and even seriously influence the users' safety (Triki 2018). Numerous protection methods can inhibit or attenuate pressure oscillations during the water hammer events, among them, inserting a flexible tube into the pipe (Kubrak & Kodura 2020), flywheels, soft start/stop, air vessels, surge tanks, air valves, and pressure-relief valves (Martin 1999; Boulos *et al.* 2005; Jung & Karney 2009; Wan *et al.* 2019).

Elevated storage tanks, also known as demand balancing tanks, not only regulate the system operating pressure but also have adequate water volume for handling fluctuations in water consumption, beside supplying water during emergency events, such as firefighting and power failure (WHO 2014). Also, they allow the pumping stations to run regularly, safely, and economically (Fenkell 1928).

This paper discusses the impact of elevated tanks on transient pressures resulting from the abrupt power outage to the operating pumps of a real water distribution network. The elevated tank location and size were investigated. Bentley HAMMER software was applied in the analysis.

THEORETICAL BASIS FOR UNSTEADY PIPE FLOW

Numerous approaches were used to solve mass and momentum equations, and Bentley HAMMER (2018) utilizes the method of characteristics (MOC) to convert Equations (1) and (2) into two pairs of ordinary differential equations. Further information related to MOC is given in Wylie & Streeter (1993), Larock *et al.* (2000), and Thorley (2004):

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \tag{1}$$

$$\frac{\partial V}{\partial t}+g\frac{\partial H}{\partial x}+\frac{fV|V|}{2D}=0 \tag{2}$$

where D, f, g, H, t, V, and x are the pipe inside diameter, the pipe friction factor, the acceleration of gravity, the head, the time, the fluid velocity, and the distance along the pipe, respectively; and a denotes the pressure wave speed and is equal to $\sqrt{K/\rho}/\sqrt{1+(K/E)(D/e)}$ (Korteweg 1878); K is the fluid modulus of elasticity; ρ is the fluid density; E is the elastic modulus of the pipe material; and e is the conduit wall thickness.

METHODOLOGY

Although Bentley HAMMER is commercial software, it enables design engineers and utility managers to understand the water hammer phenomenon within pressurized conduits, judge and evaluate the simulation outputs, and identify alternative solutions. Moreover, it can be employed for conducting research studies (El-Turki 2013). In a hydraulic transient analysis, the pressure is not the only parameter, but also the most important one (Pothof & Karney 2012). First, Bentley HAMMER was validated against a previous study reported in the literature, then a model of the studied network was developed. In this research, Bentley HAMMER CONNECT Edition V10.01 was applied to investigate the influence of both elevated tanks' location and size on the transient pressures resulting from the sudden power failure of the operating pumps in an actual hydraulic system. Furthermore, the obtained results were compared with those of using air vessels rather than elevated tanks.

VALIDATION OF BENTLEY HAMMER RESULTS

The computed results by Bentley HAMMER were compared with those calculated by Chaudhry (2014). He developed a computer program in FORTRAN language based on MOC to analyze and solve the transient conditions induced by the sudden shutdown of the operating pumps in a pressurized pipeline. Figure 1 shows the transient results of Chaudhry (2014) versus those of Bentley HAMMER. It is seen from Figure 1(a)–1(d) that the comparison gives a good agreement with correlation coefficients (R^2) ranging from 98.9 to 99.8%. Once Bentley HAMMER results were validated, then they can be utilized to simulate the transient behavior in Assiut water supply network with different elevated tank scenarios.

STUDY AREA DESCRIPTION

This study was carried out on the Assiut drinking water system. Assiut city is the capital of Upper Egypt, and its area is nearly 10 km^2. The model of Assiut city water network was obtained as an EPANET file, then it was exported to an acceptable water hammer format file (*.inp). Furthermore, the network data are available in Mohamed & Abozeid (2011). According to Figure 2(a), there are two feeding water sources (R_{27} and R_{28}), from which the water is pumped into the network with an average base demand of 1.256 m^3/s through two pumping stations (PU_{36} and PU_{37}). Both pumping units have the same characteristics, but the capacity of PU_{37} is twice that of PU_{36}, i.e., PU_{37} has a rating curve with heads of 70, 65, 60 m that correspond to flow rates of 0, 0.6, and 0.8 m^3/s, whereas PU_{36} has the same heads with flow rates of 0, 0.3, and 0.4 m^3/s. The system composites of 10 loops, 26 junctions labeled with J_i, 35 pipes labeled with P_i, and ranging in diameter from 300 to 1,200 mm with a total length of 30 km. All pipes were made of cast iron, and the average calculated pressure wave speed (Korteweg 1878) is 1,000 m/s. The difference in elevation of the network junctions is small, so it was considered a flat surface (equal elevation). Based on studies of Mohamed & Abozeid (2011) and Mohamed & Gad (2011), a daily water demand pattern (Figure 2(b)) was used to describe medium town requirements (AWWA 1989) throughout 24 h. The peak (critical) consumption hour considered in this study is also presented in the figure. The diurnal demand factors vary from 0.35 to 1.60, and those values have been multiplied by the average daily water consumption for all the network junctions.

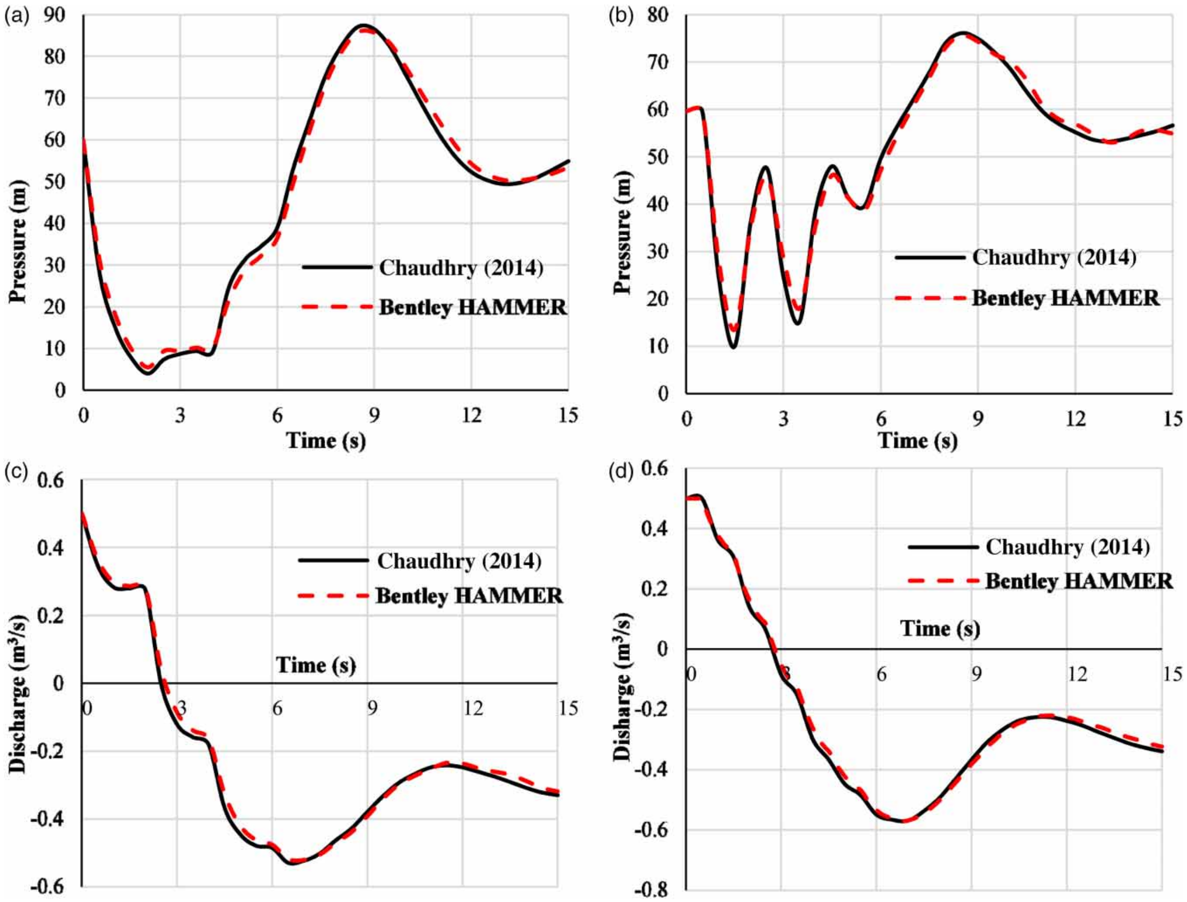

Figure 1 | Transient pressures at: (a) pump extremity; (b) junction of the two pipes, and temporal variations of discharge at (c) pump extremity; and (d) downstream reservoir.

HYDRAULIC TRANSIENT SIMULATIONS

The hydraulic transient situation within the pressurized system (Figure 2(a)) was first simulated and analyzed without an elevated tank and then by integrating an elevated tank at diverse locations in the system. In all simulations, the surge analysis was performed due to the sudden failure of all operating pumps during the peak hour, as it is the worst scenario as reported by Tullis (1989) and Carmona-Paredes *et al.* (2019). The tank was modeled according to the continuity equation, and its site was identified arbitrarily; close to the pumping plants (J_1 and J_3), in the middle (J_{13} and J_{17}), and at the boundary of the network (J_{21} and J_{22}). According to HBRC (2017), it is proposed that the network requires an elevated tank with a size of 10,000 m^3 to assure a balance between the consumed and supplied water. To examine the effect of tank's size on the maximum and minimum pressures (will be denoted as P_{max} and P_{min}) enveloped at every junction in the network, three storage sizes (having the same height of 10.0 m, but differing in the horizontal section area) were suggested: 5,000, 7,500, and 10,000 m^3. The elevation data are an important parameter, as the extreme pressures generally happen at the highest and lowest locations in a water supply system. In our situation, all nodes have the same level, arbitrary junctions were selected to represent various locations in the system; J_1 and J_3 being at the nearest points from the pumping stations, J_{21} and J_{22} lying at the network extremity, and J_{13} and J_{17} being in the middle. To obtain a reasonable accuracy, the surge analysis was done with a time step of 0.01 s and for a duration of 300 s.

RESULTS AND DISCUSSION

Effect of elevated tank's location on transient pressures

The extreme pressures enveloped in meters of water at the network junctions are shown in Figure 3. Some statistical measures: maximum and minimum pressures (P_{max} and P_{min}), standard deviation 'STDEV' and standard error 'SE' were

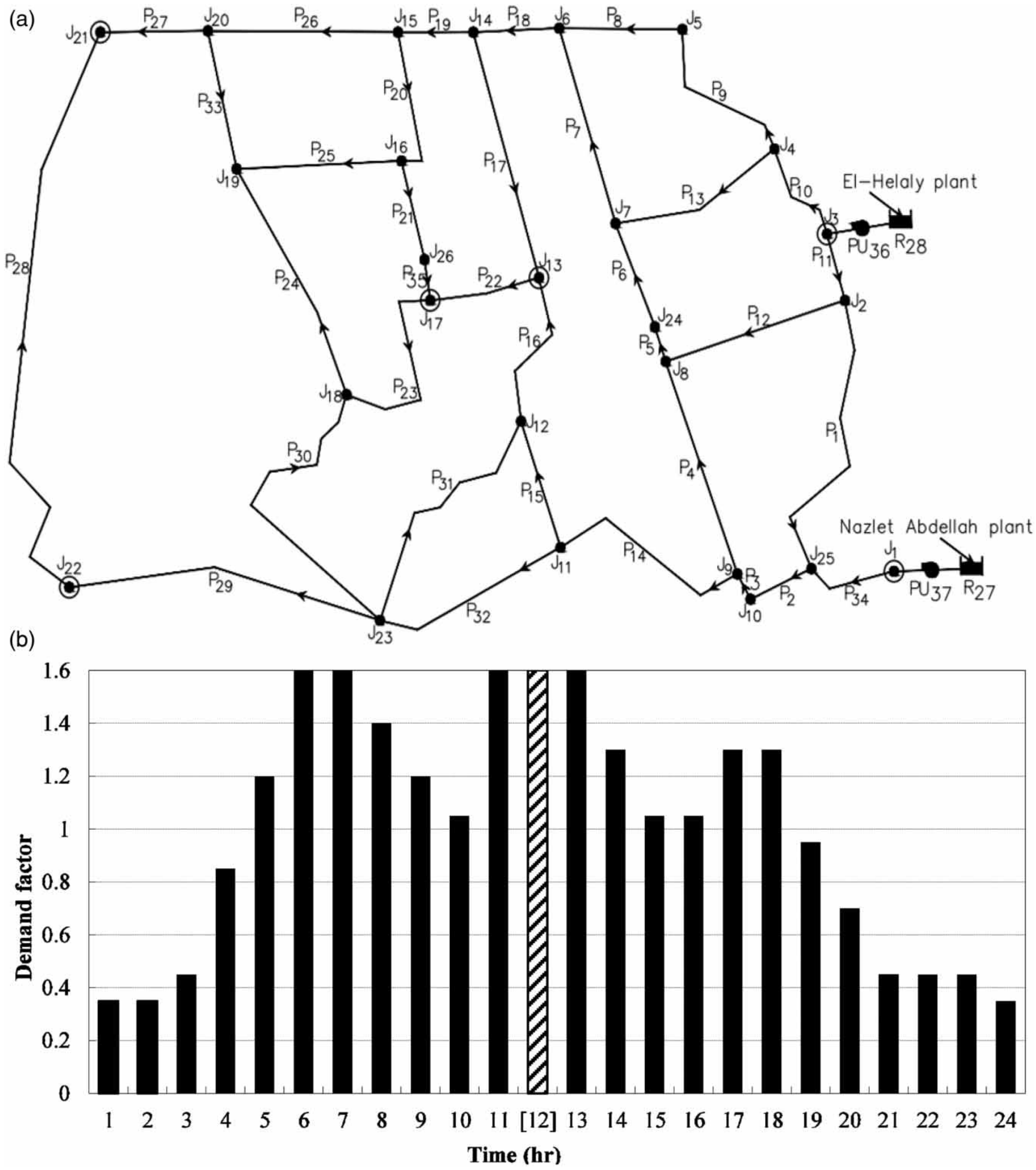

Figure 2 | (a) Schematic of Assiut city water distribution network including the studied nodes and the elevated tank locations (black circle); (b) water demand pattern.

used to compare the studied network performance under different scenarios of the elevated tank location (Table 1). The average maximum and minimum pressures for the network without an elevated tank were 32.8 and −9.0 m, respectively, whereas $P_{\max}$ and $P_{\min}$ were 35.6 and −10.0 m, respectively, and the vapor pressure has been reached at the majority of nodes (Figure 3(a)). On the other side, for using an elevated tank with a size of 10,000 m^3 at J$_1$ (Figure 3(b)), the average maximum and minimum heads were 39.9 and 4.8 m, respectively, and the minimum pressure improved (by 54%) to −4.6 m; moreover, the maximum pressure increased (by 20%) to 42.7 m. While for using the same storage capacity at J$_{13}$ (Figure 3(c)), all tank parameters remain constant except its location, the average maximum and minimum pressures were 42.0 and 2.8 m, respectively, the minimum pressure was −10.0 m, and the maximum pressure increased (24%) to 44.2 m. For the case of using the

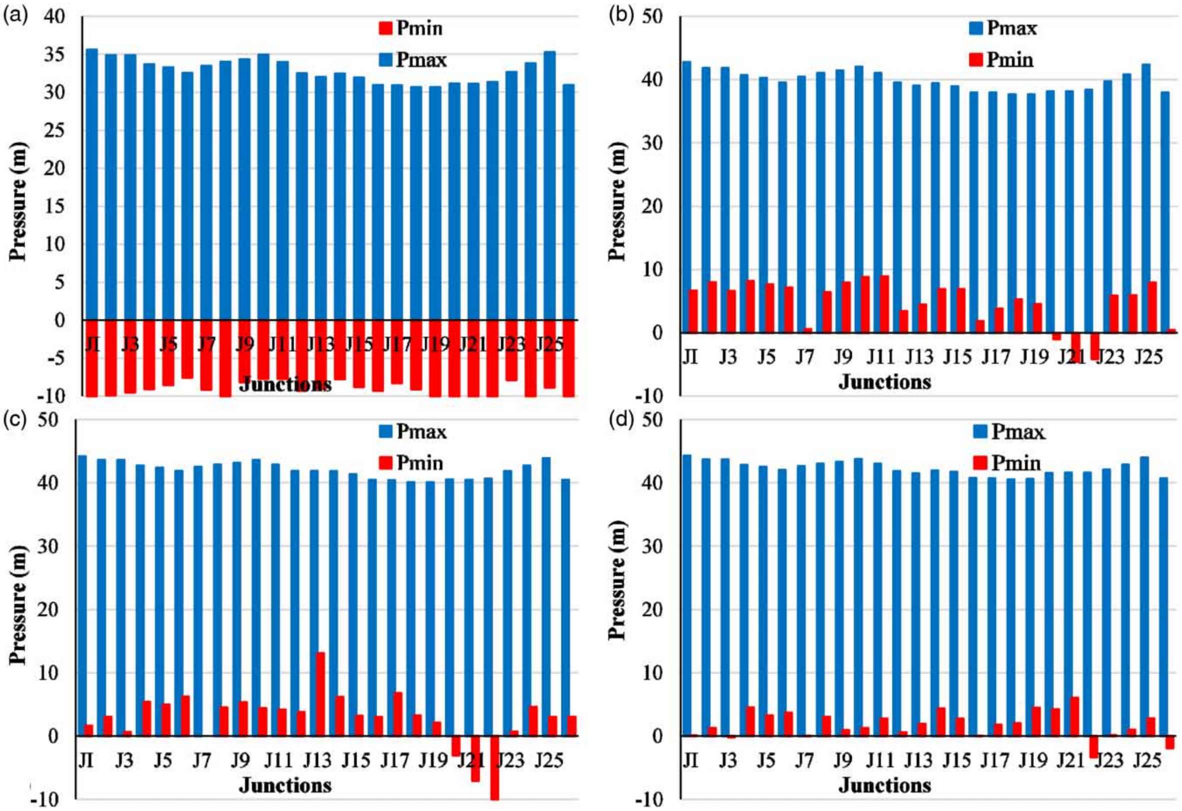

Figure 3 | Transient pressures for different elevated tank locations: (a) without elevated tank; (b) elevated tank at J_1; (c) elevated tank at J_{13}; and (d) elevated tank at J_{21}.

Table 1 | Statistical comparisons among different elevated tank locations

10,000 m^3	**Without elevated tank**	**Elevated tank at J_1**	**Elevated tank at J_3**	**Elevated tank at J_{13}**	**Elevated tank at J_{17}**	**Elevated tank at J_{21}**	**Elevated tank at J_{22}**	**Air vessel**
$P_{\max}$ (m)	35.6	42.7	43.0	44.2	44.2	44.3	44.0	35.6
$P_{\min}$ (m)	−10.0	−4.6	−7.3	−10.0	−10.0	−3.3	−6.1	−0.8
Avg. $P_{\max}$ (m)	32.8	39.9	40.4	42.0	42.3	42.2	41.9	32.6
Avg. $P_{\min}$ (m)	−9.0	4.8	4.1	2.8	2.9	1.8	1.0	0.2
STDEV ($P_{\max}$) (m)	1.6	3.8	1.6	1.3	1.1	1.1	1.2	1.5
STDEV ($P_{\min}$) (m)	0.9	3.1	4.3	4.4	4.7	2.1	3.6	0.4
SE ($P_{\max}$) (m)	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.3
SE ($P_{\min}$) (m)	0.2	0.7	0.8	0.9	0.9	0.4	0.7	0.1

same tank size at J_{21} (Figure 3(d)), the average minimum and maximum pressures were 42.2 and 1.8 m, respectively, the minimum pressure improved (67%) to −3.3 m, and the maximum pressure increased (24.5%) to 44.3 m. Results of the hydraulic transient simulation for the whole network junctions are presented in Supplementary Material, Appendix A.

It is seen from the table and the previous discussion that the best place for the high tank is at junction J_{21} (at the extremity of the network), as it has the highest minimum pressure and the smallest standard error: −3.3 and 0.4 m, respectively, followed by at J_1 (close to the pumping station PU_{37}), where $P_{\min}$ and SE were −4.6 and 0.7 m, respectively. This is most likely resulting from the fact that node J_{21} lies in a large demand area, not the highest consumption rate one. There are some individual junctions in different locations in the system, which have a higher consumption rate than at the network extremity; however, the elevated tank does not perform as efficiently as at the network extremity. Also, J_1 is marked by its closeness to the highest capacity pumping station (PU_{37}). Interestingly, these findings are consistent with those of Mays (2000) and Batchabani & Fuamba (2012), who stated that the best place of water towers is near high consumption areas (i.e., not exactly the highest consumption rate points).

The changes of pressure with time at different points in the pipe network, without/with an elevated tank of size 10,000 m^3 at various sites, are shown in Figure 4(a)–4(c). It is evident from the figure that the case of no elevated tank has the largest pressure oscillations and these oscillations continue for a long time compared with the other cases. Also, the pressure fluctuations are small at the elevated tank and its surrounding pipes and increase at the furthest ones.

In summary, the elevated tank plays an important role in safeguarding the water pipes from the transient pressures, while it cannot provide full protection for the network against the water hammer. It can be seen from Table 1 and Figure 3 that the minimum pressures were improved at the majority of network nodes, in different proportions, but the network still contains a significant negative pressure at some nodes. These improvements are higher at and around the tank location, and they decrease as we move away from the tank. Also, the elevated tank performance is better as it approaches the pumping station and at the network edge than in the middle, as the negative pressures in the network have been greatly improved, while the positive pressures were relatively increased. This could be attributed to during the downsurge period the elevated tank provides the generality of the network pipes with water that can prevent water-column separation and very low pressures. Whereas during the upsurge period, the positive pressure wave directs water toward the tank, since this tank is not sealed, i.e., it does not contain any volume of trapped air in its upper portion that can accommodate water from the system or absorb the pressure fluctuations, which in turn increases the positive pressure throughout the system compared with no tank.

Effect of elevated tank's size on transient pressures

To study the effect of elevated tank's capacity on the transient pressures, three different sizes (5,000, 7,500, and 10,000 m^3) were suggested, while the other parameters kept constant. Figure 5 elucidates the surge pressures at some selected nodes for

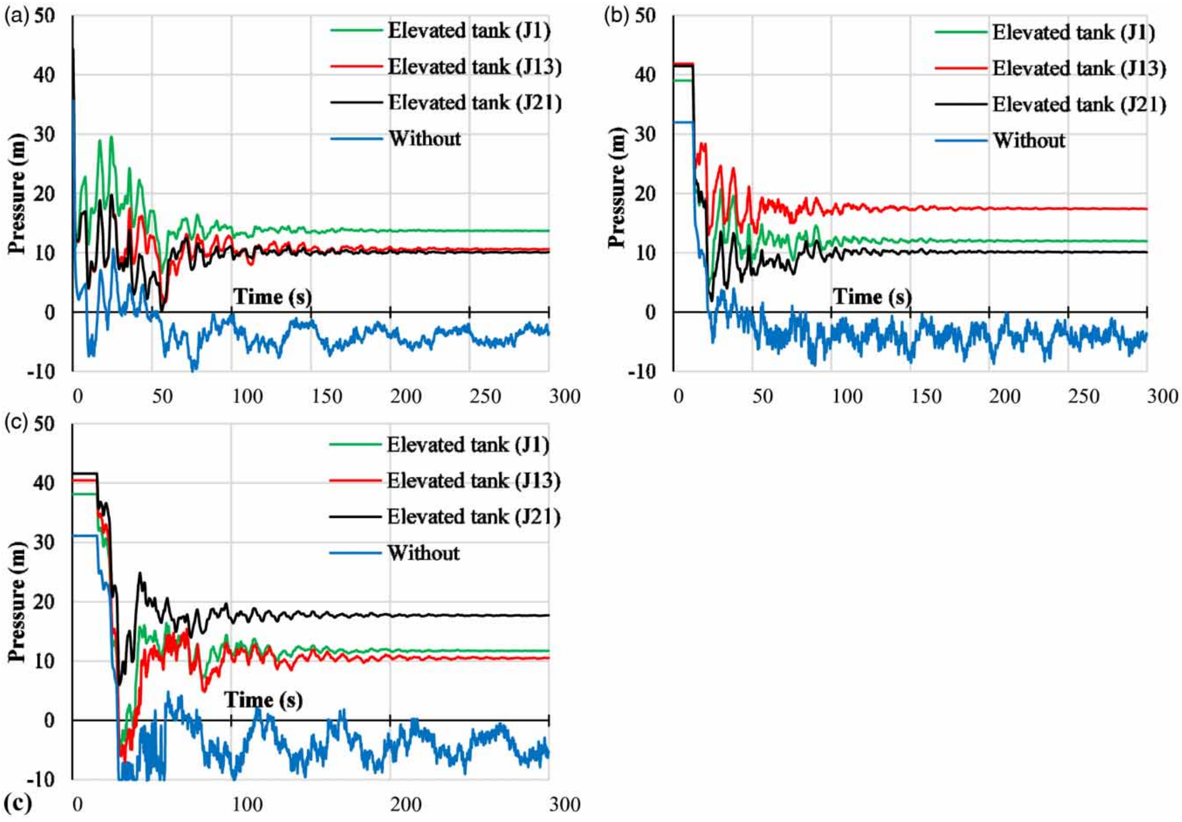

Figure 4 | Variations of transient pressure with time at various junctions: (a) J_1; (b) J_{13}; and (c) J_{21} for different elevated tank locations.

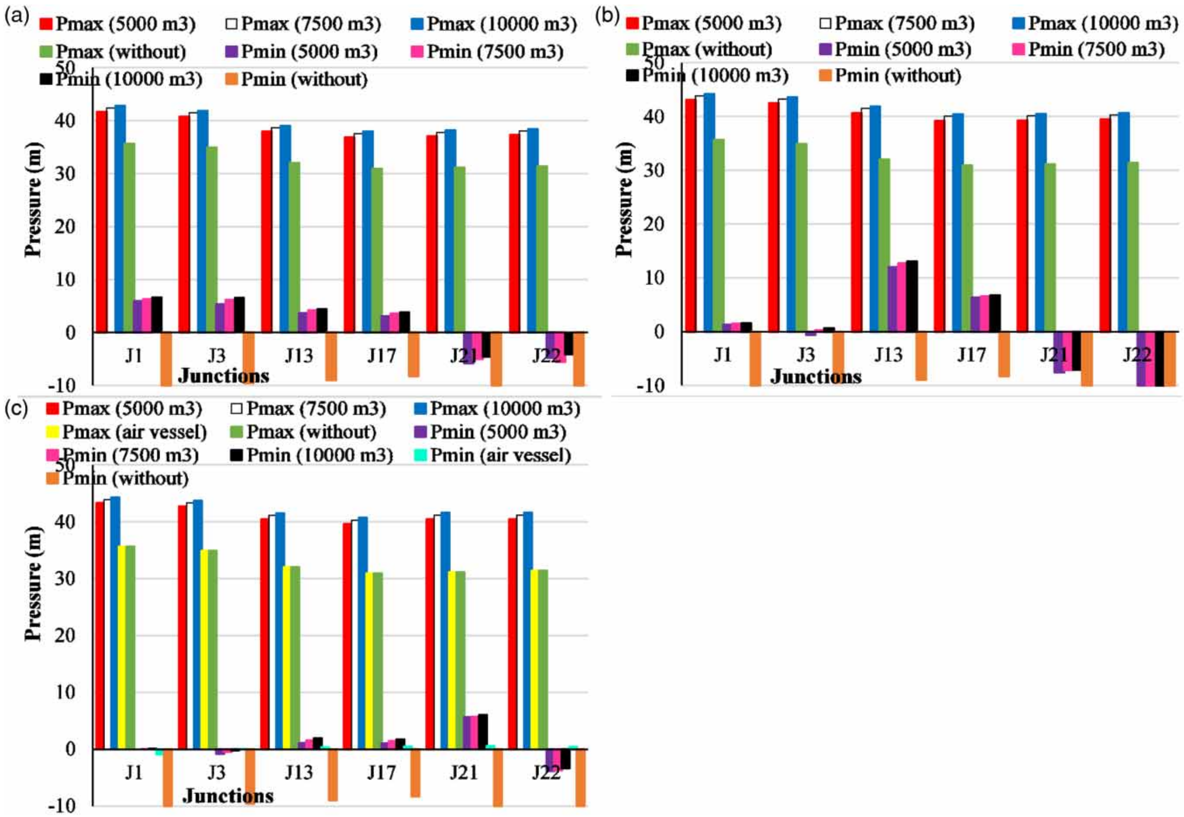

Figure 5 | Transient pressures for different elevated tank sizes: (a) elevated tank at J_1; (b) elevated tank at J_{13}; and (c) elevated tank at J_{21}.

the case of no elevated tank and the three cases of tank's volume. It is notable from Figure 5(a)–5(c) that, regardless of the tank location, the extreme pressures increase slightly as the tank capacity increases. For example, at using a storage tank with 5,000 m^3 at J_{13}, the maximum and minimum pressures were equal to 43.0 and 1.3 m at J_1, respectively, while they were 39.3 and -7.6 m at J_{21}, respectively. If the tank volume increases to 7,500 m^3 and it is located at the same node (J_{13}), the extreme pressures increased to 43.8 m (1.9%) and 1.5 m (15%) at J_1, whereas they were equal to 40.1 m (2%) and -7.1 m (6.6%) at J_{21}, respectively. Finally, if the tank capacity reaches 10,000 m^3, the surge pressures increased to 44.2 m (2.8%) and 1.6 m (23%) at J_1, respectively, while they were 40.5 m (3%) and -7.0 m (7.9%) at J_{21}, respectively. $P_{\max}$ and $P_{\min}$ for all network junctions with different tank capacities can be found in Supplementary Material, Appendices B and C.

To compare the influence of air vessels and elevated tanks on the surge pressures, the Assiut city drinking water system was investigated again by using air chambers only, as it is an effective way of protecting from water hammer risks. By using the trial and error method, two air vessels with a total capacity of 150 m^3 (75 m^3 each one), instead of storage tanks, located at the pumping stations (PU_{36} and PU_{37}) can alleviate effectively the extreme pressures within acceptable limits (minimum pressure of -0.8 m and the maximum pressure of $+35.6$ m). Figure 5(c) reveals the transient pressures for the cases of using air vessels and elevated tanks of different sizes. The compressed air tanks protected effectively the water pipes from the water hammer problem more than the elevated tanks, where the minimum pressure was improved by 90% and the maximum pressure was increased by 1% compared to without protection. While for using an elevated tank with a volume of 10,000 m^3 at J_{21}, the minimum pressure inside the network improved only by 67%, and the maximum pressure increased by 24% than the case of no elevated tanks. Hopefully, this research helps water utilities in addressing the serious water hammer issue through water supply systems.

It is worth noting that the effect of elevated tanks on the surge pressures may differ for another water supply system, according to its size, junction elevations, diurnal demand curve, number and positions of the water sources, design of the overhead storage, or even the water hammer causes.

CONCLUSIONS

In this article, the influence of elevated tanks' size and location on the water hammer due to the instant failure of pump power was studied. Also, a comparison between the impact of elevated tanks and air vessels on the extreme pressures was done. Bentley HAMMER software results were first validated by comparing its outputs against another study, then it was used to investigate the unsteady flow in the water supply system of Assiut city. The results indicate that elevated tanks can improve effectively the extreme pressures in and around the tank, but there are still some negative pressures at some remote points. Besides, as the elevated tank volume increases, the transient pressures improve relatively. In our case study, the most appropriate location for the elevated tank is at the network extremity, as the minimum pressure is −3.3 m (improved by 67% than without tank), while it equals −10.0 m (0%) and −4.6 m (54%) in the middle and at the pumping station, respectively. Further investigations are recommended to assess another parameter: the water level/volume in the storage tank at the moment of pump failure and to compare the present findings with *in situ* measurements. Moreover, machine learning algorithms could be incorporated into Bentley HAMMER simulator to identify the optimum location and size of the elevated tanks within a pipe network considering the water hammer.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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