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# Surge Analysis and Protection for Water Distribution Networks

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**Abstract** In this paper, Bentley HAMMER software was employed to simulate, analyze, and protect the water distribution network of Assiut city in Egypt having two pump stations against a pump power failure for the current and future conditions.

Three scenarios were investigated; the current demand, 25% increased demand, and 50% increased demand. Each scenario included three cases; failure of PMP-1, failure of PMP-2, and failure of PMP-1 and PMP-2 together. Each case was studied without and with protection.

From the obtained results, case 3 was the worst-case followed by case 2, and finally, case 1.

For the current demand, the min pressures were -10.0 m and 30.7 m without and with protection. The protection devices were hydropneumatic tanks for cases 1 and 3, while an air valve was used with hydropneumatic tanks for case 2.

For the 25% increased demand, representing required demand 15 years later, the min pressures were -10.0 m and 31.1 m without and with protection. The protection devices had the same volume of hydropneumatic tanks for cases 1 and 3, while for case 2, the same air valve was employed with increased volume of hydropneumatic tanks by 50%.

For the 50% increased demand, representing required demand 25 years later, the min pressures were -3.9 m and 30.5 m without and with protection. The protection devices had the same volume of hydropneumatic tanks for case 1, increased volume of hydropneumatic tanks by 43% for case 3, while for case 2, a larger air valve by 33% was employed with increased volume of hydropneumatic tanks by 100%.

**Keywords** Water hammer, transient flow, hydropneumatic tank, Assiut city water distribution network

## 1. Introduction

The hydraulic transient phenomenon always exists, but it is just not obvious most of the time. Studying the nature and causes of transient phenomena, where the velocity and pressure can change suddenly, in the pipelines and distribution networks will permit facilities to avoid its destructive forces.

The common events that typically produce large changes in pressure are pump startup, pump power failure, valve opening, and closing operations. Also, improper operation of surge protection devices could be additional reasons causing the water hammer, which is a form of transient flow.

Several methods have been introduced and used to analyze water hammer problems such as the energy, arithmetic, graphical, characteristics, algebraic, implicit, and linear analyzing methods, Euler and Lagrangian based method, and decoupled hybrid methods, [1].

This paper employed the method of characteristics to construct models using the Bentley HAMMER Software V8.0 Edition to calculate, simulate, and protect against transients in a water supply system.

M. Kandil et al., [2], presented a water hammer as a transient flow in pipes due to a quick change in speed in pipes. The novelty of this study showed how the materials with less elastic modulus were less likely to occur in the water hammer than the high elastic modulus for the same operating conditions.

El-Hazek, [3], investigated the impact of different protection devices to assure surge protection for a pipeline system via Bentley HAMMER V8.0. Using five air vessels with a vacuum breaker valve as surge protection proved to be more effective and economical against pump power failure. Equations were obtained to predict the pressures according to the inlet pipe diameter, the area of the surge tank, and the pipe diameter. Also, it was found that cast iron pipes proved to be the best pipe material when using the air vessel as protection devices.

Emami et al, [4], observed that, in the same conditions, the effect of GRP pipe in reducing the maximum rate of water hammer was 25% less than the steel pipe. Wuyi Wan et al., [5], introduced a kind of intelligent self-controlled surge tank (IST), which proved to have advantages in pressure control and applicability compared to normal surge tanks. Kamil Urbanowicz, [6], showed that simple effective two-terms weighting functions were able to accurately model the analyzed transients.

Desmukh and Sadanand, [7], presented a case study where the manual analysis was done without surge protection devices. Also, the transient analysis of the pipeline was performed using Bentley Hammer V8i software without surge protection devices. The results obtained matched well with the manual results for the same case. Thus, the location for surge protection could be found out.

Abuiziah et al., [8], presented the influence of using the protection devices to control the adverse effects due to excessive and low pressure that occurred in the transient flow. Ali EL-Turki, [9], simulated a field case study to investigate a pipe burst that occurred on a pipeline system in the Man-Made River in Libya employing the Bentley HAMMER V8i software. The results showed that the transient pressures in the pipeline exceeded the bar rating of the pipe. Elsaeed et al., [10], investigated the unsteady flow in irrigation pipeline networks due to pump power failure. The study was applied using Water Hammer Software Wanda V 3.03.

El-Hazek, [11], employed the Bentley HAMMER model to simulate and analyze steady-state and transients in the irrigation pipeline systems. A hydropneumatic tank was employed as a protection device against power failure. It was concluded that by decreasing the tank diameter to 1/6 times the pipeline diameter, the max pressure decreased. More decreasing the diameter, the max pressure increased. A design chart and design equations were obtained, which accomplished savings of 55% in the diameter and 51% in liquid and hydropneumatic tank volumes.

Giuseppe Frega et al., [12], have proved that minimizing water hammer by the uniform valve closure in the first part of an urban water distribution network was not true based on the theoretical and experimental results obtained in their paper. Polanco et al, [13], showed that the systems operated in a fragile environment, as in cold regions, concern about the consequences of leakage increased due to the variation of physical properties of the fluid and the pipe material as a function of the temperature.

Skulovich et al., [14], introduced a new function fitting model that was integrated with mixed-integer programming to optimally place and size surge tanks for transient control for water distribution systems. The closed surge tank was optimal protection against transient events. Mehdi, [15], showed that the compressibility of the liquid and the elasticity of the pipeline caused a transient pressure wave to propagate throughout the hydraulic systems. Hassan et al., [16], discussed that frequent pump shut-off could be a quite serious threat to the stability of the newly installed network if adequate protection measures were not taken. Hassan and Gamal, [17], employed EPANET software to perform hydraulic and water quality analysis for the city of Assiut water supply network. The failure of some pipes in the networks changed the flow directions in some pipes through the network. Closing a pipeline increased pressure in a region and decreased it at another affecting the chlorine distribution through the network.

In this paper, surge analysis and protection for water distribution networks will be investigated employing Bentley HAMMER (V8.0 SELECT-series 5) software. The model is applied to a case study (Assiut city water distribution network, Egypt) to simulate, analyze, and protect the network against transient flow due to pump failure.

## 2. Materials and Method

Hydraulic models are important for the simulation, analysis, and design of water distribution networks. Bentley HAMMER (V8.0 SELECT-series 5) software is a widely used computer model that can be used to perform extended period simulation of hydraulic and water quality behavior within pressurized pipe networks and steady-state conditions. It is a very efficient and powerful tool for simulating hydraulic transients in pipelines and networks using the method of characteristics to solve differential equations of transient flow, [18].

Bentley HAMMER is based on technology first created by GENIVAR (Formerly Environmental

Hydraulics Group Inc.). However, it is a graphical interface software that makes it easy to quickly layout the schematic of a complex network of pipes, tanks, pumps, and surge control devices. Steady-state models from other software such as WaterCad or WaterGEMS can be directly used in Bentley HAMMER saving time and eliminating transcription errors, [8].

In this paper, Bentley HAMMER software is employed to simulate, analyze, and protect the water distribution network of Assiut city in Egypt for the current and future conditions.

**3. Case Study: Assiut City Water Distribution Network in Egypt**

The analysis of transient flow was performed for the Assiut city water supply network. Assiut city is a city in the Upper Egypt region that is located 400 km southern Cairo, as shown in Fig. 1, [19]. The network is fed by two sources of water, which are R-1(El-Helaly plant) and R-2 (Nazlet Abdellah plant), [20 – 21], as shown in Fig. 2. All the network 26 junctions lie at the same level (elevation = zero). The distribution network is composed of35 Cast Iron pipes with different lengths and diameters as illustrated in Table1. Two pumping stations labeled PMP-1 and PMP-2pump the water supplied from the two reservoirs into the distribution network.


*Figure 1: Assiut City, Egypt, [19]*

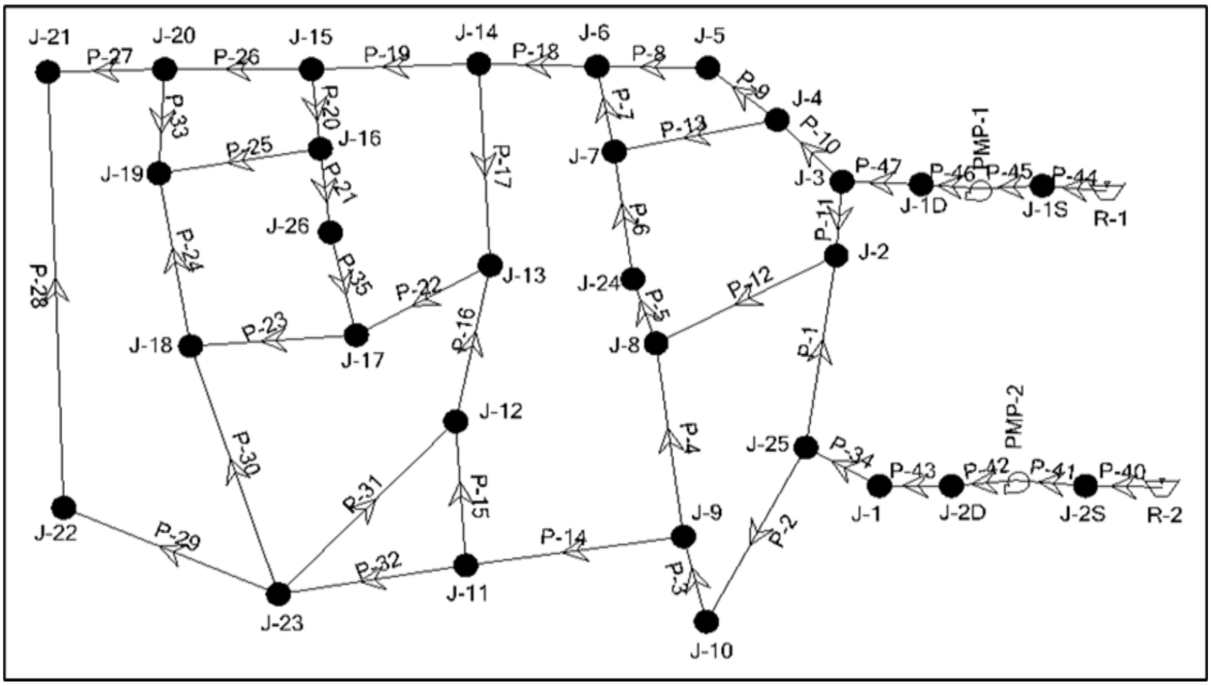



*Figure 2: Assiut City Water Distribution Network*

**Table 1:** Lengths and Diameters of the Network Pipes

| Pipe number | Length (m) | Diameter (mm) | Pipe number | Length (m) | Diameter (mm) | Pipe number | Length (m) | Diameter (mm) |
|---|---|---|---|---|---|---|---|---|
| **P1** | 1600 | 800 | **P13** | 1100 | 500 | **P25** | 950 | 300 |
| **P2** | 300 | 1000 | **P14** | 500 | 1000 | **P26** | 1200 | 600 |
| **P3** | 600 | 1000 | **P15** | 750 | 500 | **P27** | 400 | 600 |
| **P4** | 900 | 500 | **P16** | 850 | 500 | **P28** | 2650 | 600 |
| **P5** | 200 | 500 | **P17** | 1000 | 500 | **P29** | 2100 | 600 |
| **P6** | 300 | 500 | **P18** | 100 | 800 | **P30** | 1500 | 400 |
| **P7** | 1400 | 500 | **P19** | 300 | 600 | **P31** | 1600 | 400 |
| **P8** | 1100 | 800 | **P20** | 600 | 400 | **P32** | 1500 | 800 |
| **P9** | 500 | 800 | **P21** | 300 | 500 | **P33** | 700 | 400 |
| **P10** | 800 | 800 | **P22** | 600 | 400 | **P34** | 500 | 1200 |
| **P11** | 150 | 800 | **P23** | 600 | 400 | **P35** | 150 | 500 |
| **P12** | 850 | 500 | **P24** | 950 | 400 | | | |

**4. Results and Discussion**

Three main scenarios were performed to simulate, analyze, and protect the Assiut city water distribution network in Egypt employing Bentley HAMMER software for the current and future conditions. These investigated scenarios concerned the current demand, 25% increased demand, and 50% increased demand.

Each scenario included three cases, which were the failure of PMP-1 only, failure of PMP-2 only, and failure of PMP-1 and PMP-2 together. Each case was studied without and with protection. Also, for each case, simulation and studying via the Bentley Hammer model were performed for three profiles at different locations of the distribution network to investigate the max and min pressures. The first profile included junctions 1, 25, 10, 9, 8, and 2 that presented the near part of the distribution network to the pump stations. The second profile included junctions 3, 4, 5, 6, 14, 13, and 17 presenting the middle part of the network. The third profile included junctions 20, 21, 22, and 23 presenting the far part of the network to the pump stations.

**4.1. First Scenario: The Current Demand**

Assiut city water distribution network consists of 26 junctions that are illustrated in Table 2 for the current demand. The first scenario, current demand, included three studied cases without protection and with protection for each case as mentioned previously. The obtained results are tabulated in Table 3.

For case3concerningthe failure of PMP-1 and PMP-2 together, the three studied profiles are shown without protection in Figures 3, 4, and 5 and with protection in Figures 6, 7, and 8.

For the same case 3 concerning the failure of PMP-1 and PMP-2 together, the max pressure for all the distribution networks is shown in Figure 9. Also, the min pressure for all the distribution networks is shown in Figure 10 without protection (A) and with protection (B).

As an example, at Junction 10, the pressure, discharge, and air volume are illustrated in Figure 11 without protection (A) and with protection (B) for case 3 concerning the failure of PMP-1 and PMP-2 together.

**Table 2:** Current Demand for the Network Junctions

| **Node Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Demand (Lit/s)** | 0 | 61 | 0 | 61 | 34 | 40 | 61 | 52 | 30 | 30 | 54 | 81 | 61 |
| **Node Number** | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| **Demand (Lit/s)** | 40 | 16 | 32 | 61 | 87 | 61 | 41 | 78 | 78 | 101 | 0 | 40 | 0 |

**Table 3:** Max and Min Pressure Head for Cases of First Scenario, Current Demand

| **Junction** | **Max Head, m** | **Min Head, m** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Failure PMP-1 Only** | | **Failure PMP-2 Only** | | **Failure PMP-1 and PMP-2** | |
| | | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** |
| Profile-1 | | | | | | | |
| J-1 | 62.1 | 45.4 | 45.6 | 6.2 | 31.3 | 0.2 | 37.3 |
| J-25 | 61.9 | 45.0 | 45.3 | 10.7 | 31.3 | -0.7 | 37.3 |
| J-10 | 61.8 | 45.0 | 45.0 | 11.6 | 31.3 | -0.8 | 37.3 |
| J-9 | 61.5 | 44.7 | 44.4 | 14.2 | 31.2 | -0.2 | 37.3 |
| J-8 | 61.3 | 36.3 | 43.8 | 23.7 | 31.4 | 0.7 | 37.4 |
| J-2 | 61.7 | 27.4 | 44.1 | 25.4 | 32.0 | 0.7 | 37.8 |
| Profile-2 | | | | | | | |
| J-3 | 61.7 | 26.2 | 43.7 | 26.8 | 32.0 | 0.7 | 37.9 |
| J-4 | 61.1 | 29.6 | 43.6 | 26.0 | 31.6 | 0.6 | 37.5 |
| J-5 | 60.9 | 32.0 | 43.2 | 24.5 | 31.4 | -1.2 | 37.4 |
| J-6 | 60.6 | 32.6 | 42.2 | 22.0 | 31.1 | -0.2 | 37.1 |
| J-14 | 60.5 | 33.4 | 42.1 | 19.7 | 31.1 | -1.6 | 37.1 |
| J-13 | 60.4 | 34.9 | 42.1 | 21.7 | 30.9 | 0.0 | 36.9 |
| J-17 | 59.9 | 35.3 | 41.2 | 20.0 | 30.7 | 0.0 | 36.7 |
| Profile-3 | | | | | | | |
| J-20 | 60.0 | 39.2 | 41.6 | 6.3 | 30.8 | -8.3 | 36.8 |
| J-21 | 60.0 | 36.1 | 41.6 | 4.2 | 30.8 | -9.5 | 36.8 |
| J-22 | 60.1 | 26.9 | 41.7 | 10.1 | 30.7 | -10.0 | 36.8 |
| J-23 | 60.7 | 40.3 | 42.8 | 16.1 | 30.9 | -3.3 | 37.0 |

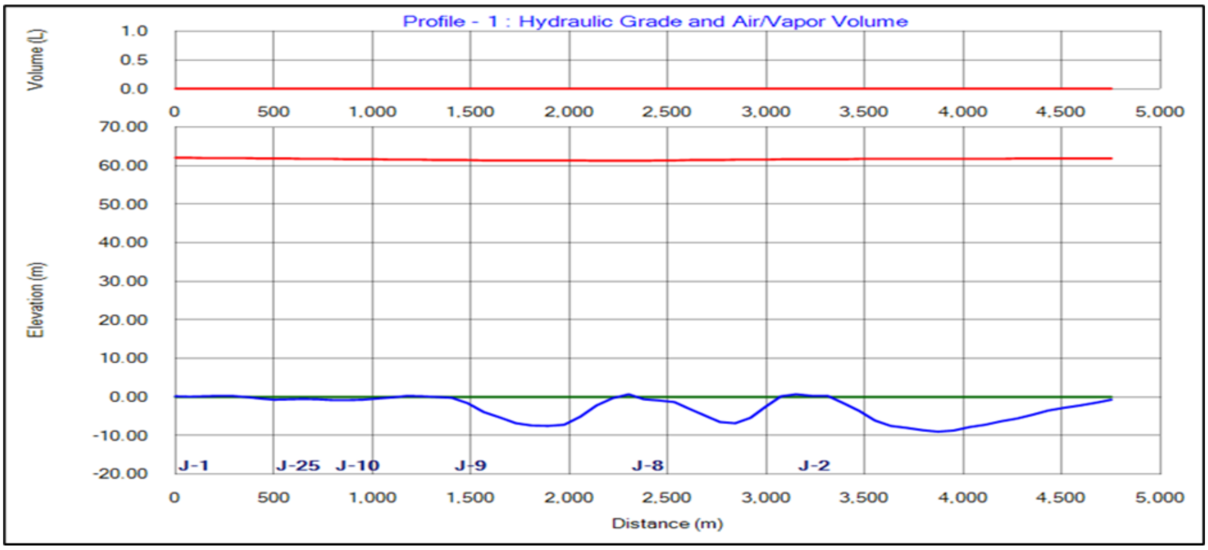



*Figure 3: Pressures and Air Volume, First Scenario, Case 3, Profile 1 without Protection*

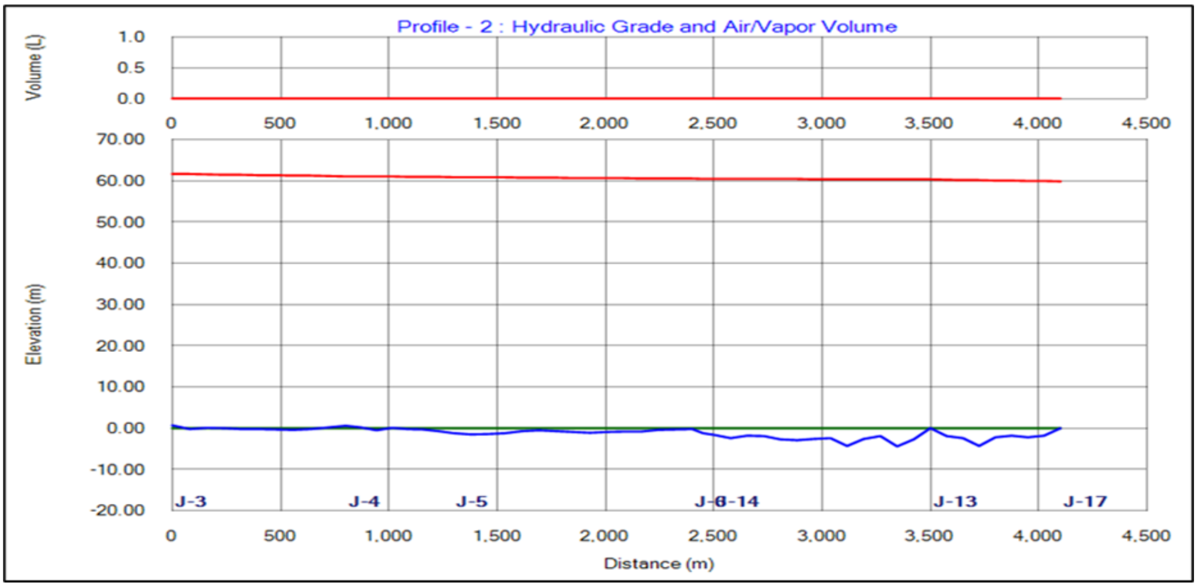



*Figure 4: Pressures and Air Volume, First Scenario, Case 3, Profile 2 without Protection*

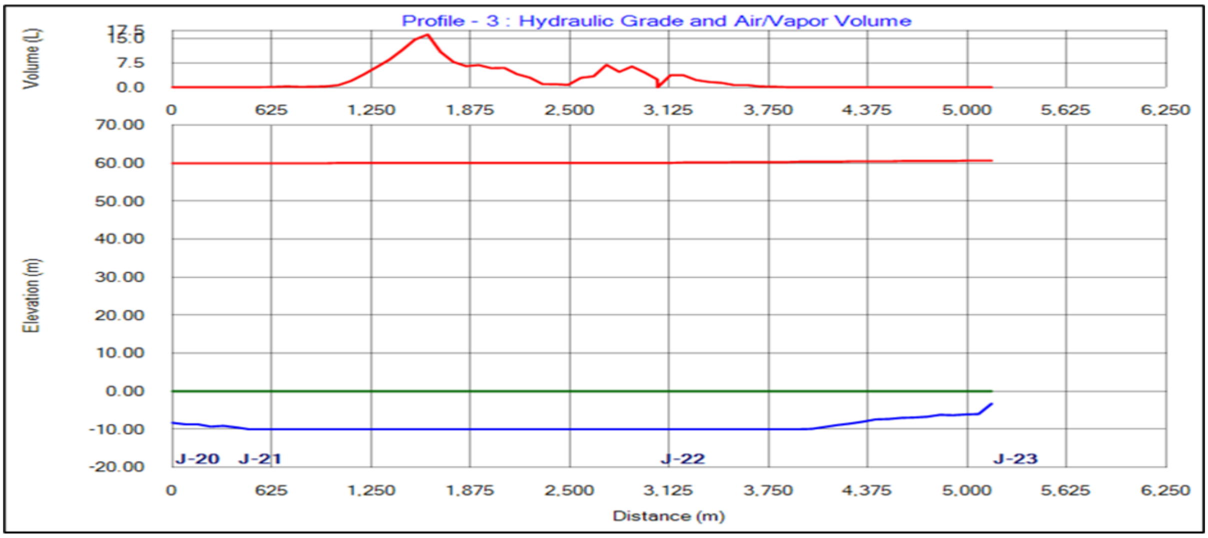



*Figure 5: Pressures and Air Volume, First Scenario, Case 3, Profile 3 without Protection*

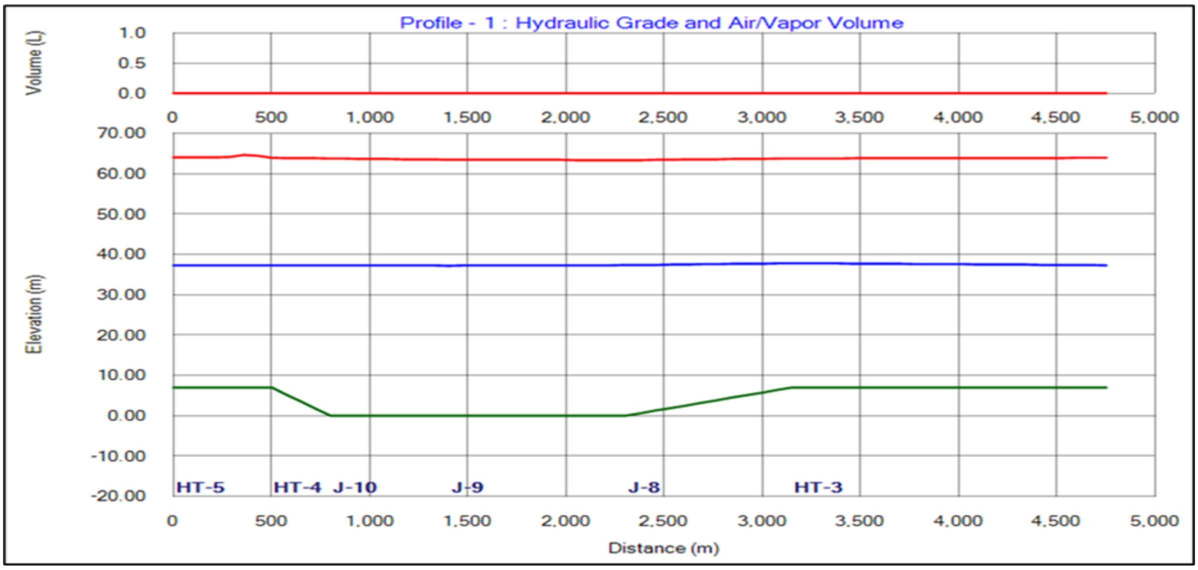



*Figure 6: Pressures and Air Volume, First Scenario, Case 3, Profile 1 with Protection*

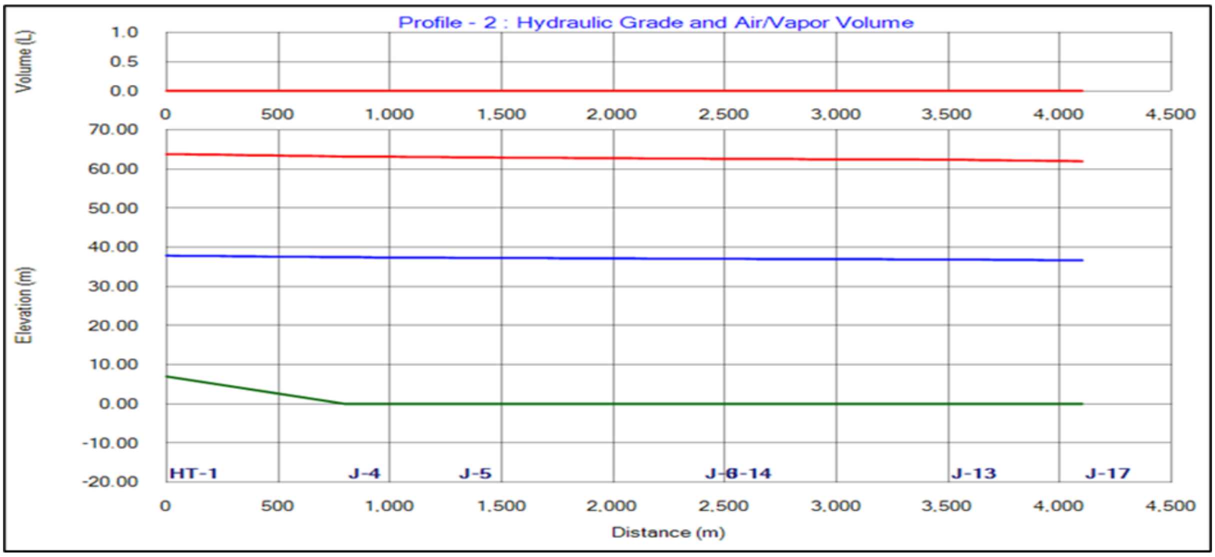



*Figure 7: Pressures and Air Volume, First Scenario, Case 3, Profile 2 with Protection*

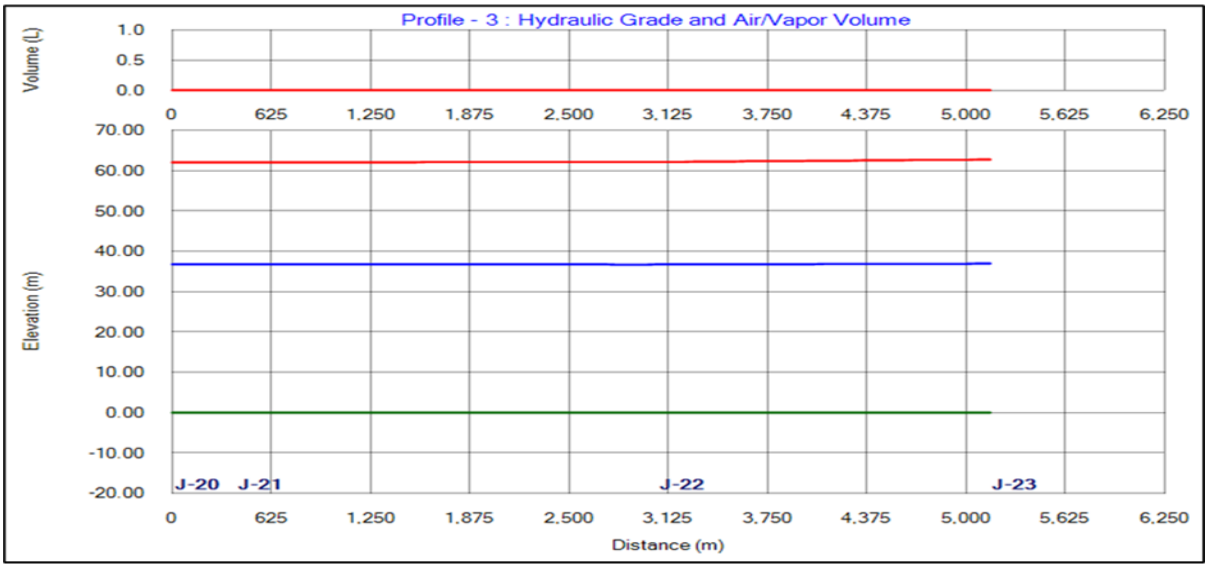
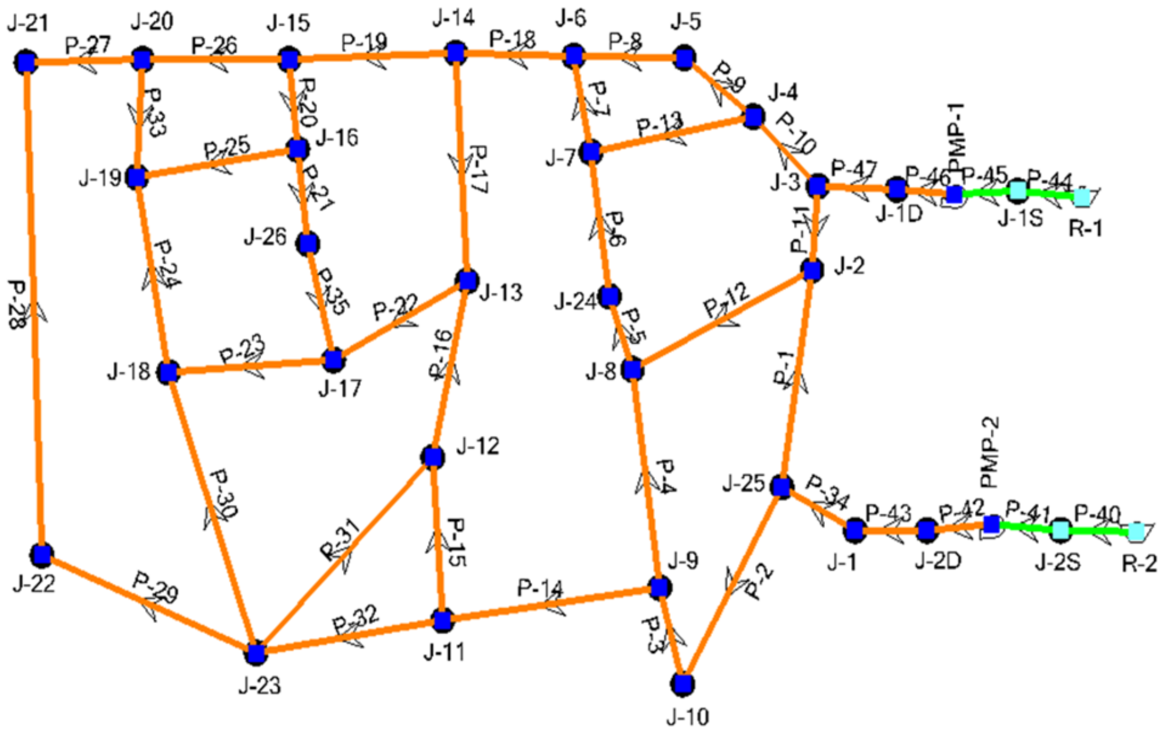



*Figure 8: Pressures and Air Volume, First Scenario, Case 3, Profile 3 with Protection*



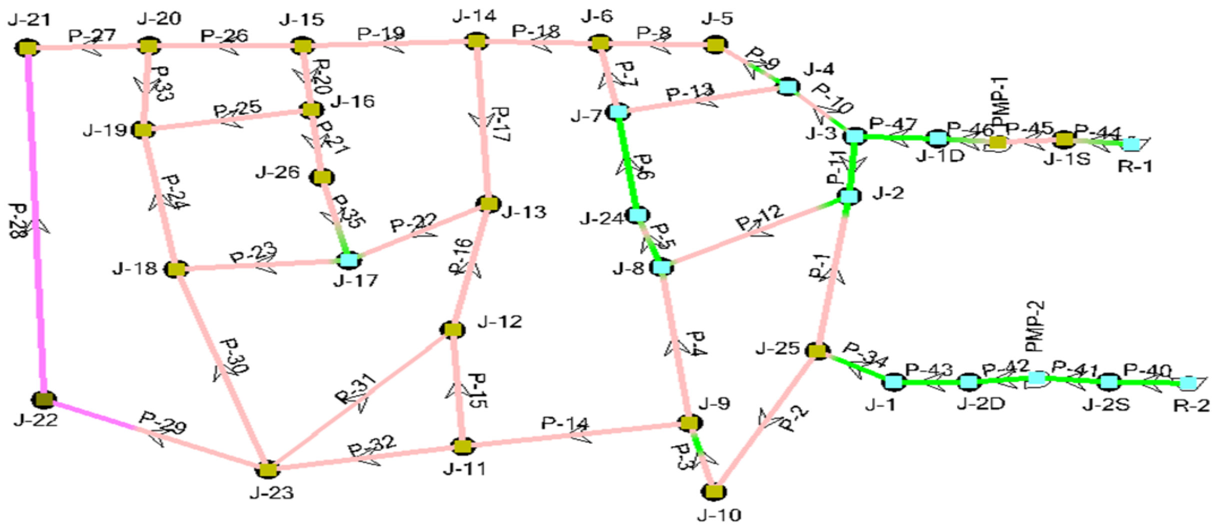

| Value <= (m) | Color |
|---|---|
| 30.00 | 0, 255, 0 |
| 50.00 | 127, 191, 0 |
| 70.00 | 255, 128, 0 |

Pipes

| Value <= (m) | Color |
|---|---|
| 30.00 | 128, 255,... |
| 50.00 | 0, 192, 192 |
| 70.00 | 0, 0, 255 |

Nodes

***Figure 9:*** *Max Pressure, First Scenario, Case 3*



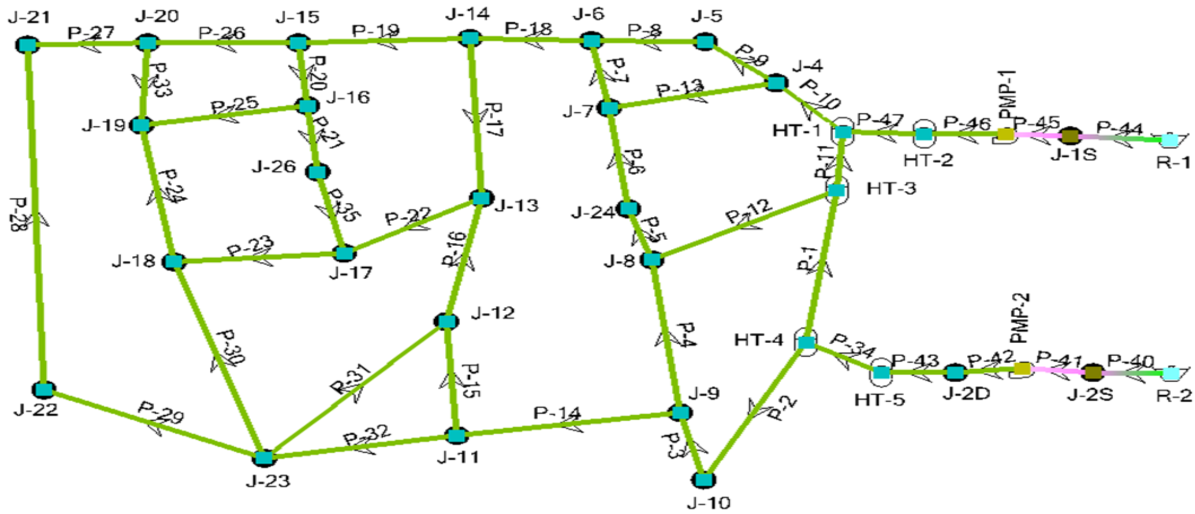

**(A)**

**Pipes**

| Value <= (m) | Color |
|---|---|
| -10.00 | 255, 128,... |
| 0.00 | 255, 192,... |
| 30.00 | 0, 255, 0 |

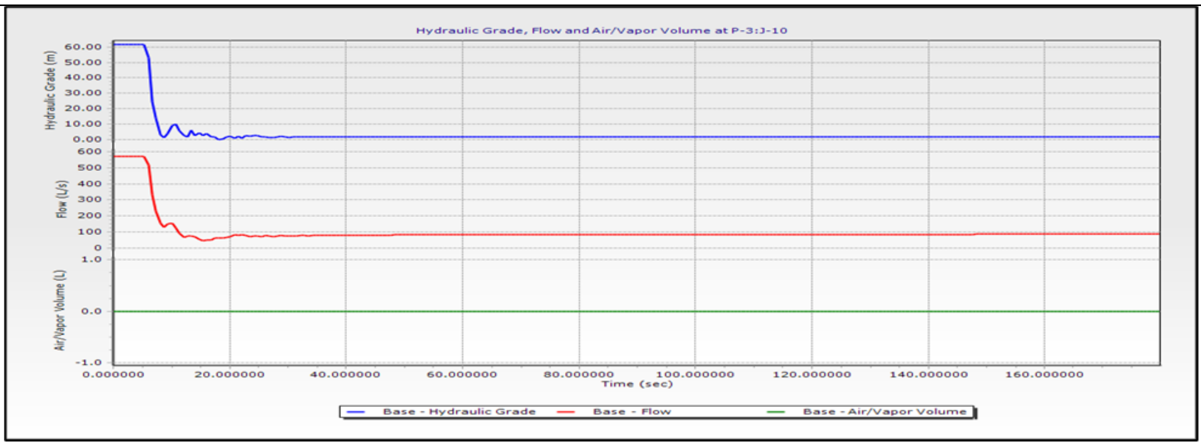
**Nodes**

| Value <= (m) | Color |
|---|---|
| -10.00 | 128, 128, 0 |
| 0.00 | 192, 192, 0 |
| 30.00 | 128, 255,... |

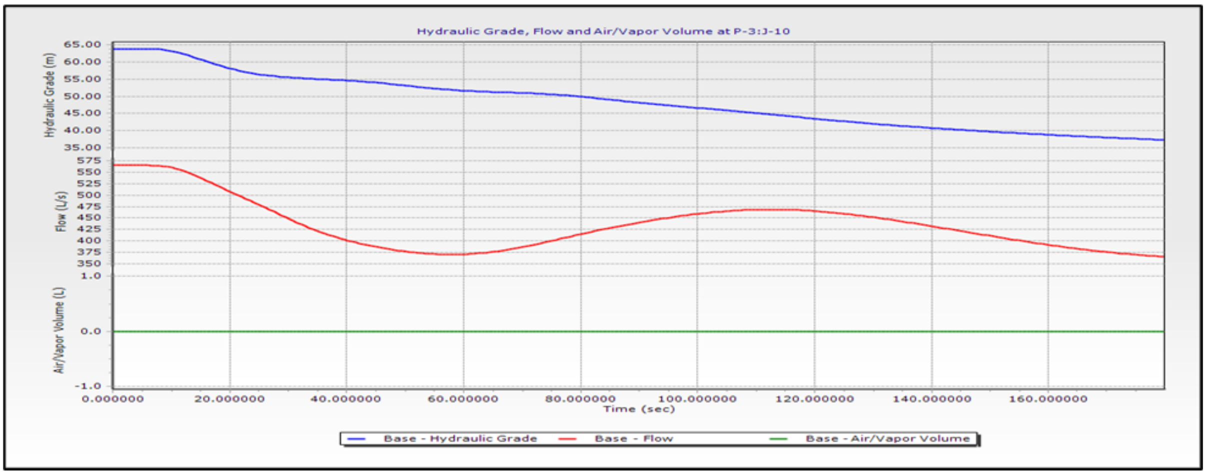



**(B)**

*Figure 10: Min Pressure without Protection (A) and with Protection (B), First Scenario, Case 3*




A




B

***Figure 11:*** *Pressure, Discharge, and Air Volume at Junction 10 without Protection (A) and with Protection (B), First Scenario, Case 3*

From the obtained results, case 3 concerning the failure of PMP-1 and PMP-2 together was the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1.

Without protection, the min pressures were in the range of -10.0 m to 45.4 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 30.7 m to 45.6 m. The protection devices were hydropneumatic tanks for all cases except case 2, where an air valve was used associated with hydropneumatic tanks.

### 4.2. Second Scenario: 25% Increased Demand

For future increasing population and consequently increasing water demand, a second scenario was investigated for 25% increased demand. This 25% increased demand for the Assiut city water distribution network is illustrated in Table 4.

According to the population governmental records and future interpretation according to the Egyptian Code, the 25% increased demand will be required 15 years later representing the demand in the Year 2035, [20].

The second scenario, 25% increased demand, included three studied cases without protection and with protection for each case as mentioned previously. The obtained results are shown in Table 5.

**Table 4:** 25% Increased Demand for the Network Junctions

| **Node Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Demand (Lit/s)** | 0 | 76 | 0 | 75 | 43 | 50 | 76 | 65 | 38 | 38 | 68 | 101 | 76 |
| **Node Number** | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| **Demand (Lit/s)** | 50 | 20 | 40 | 76 | 109 | 76 | 51 | 98 | 98 | 126 | 0 | 50 | 0 |

**Table 5:** Max and Min Pressure Head for Cases of Scenario 2, 25% Increased Demand

| **Junction** | **Max Head, m** | **Min Head, m** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Failure PMP-1 Only** | | **Failure PMP-2 Only** | | **Failure PMP-1 and PMP-2** | |
| | | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** |
| Profile-1 | | | | | | | |
| J-1 | 62.1 | 45.8 | 44.9 | 3.3 | 31.9 | -2.2 | 33.7 |
| J-25 | 61.9 | 45.3 | 44.3 | 7.5 | 32.0 | -3.2 | 33.8 |
| J-10 | 61.6 | 45.1 | 43.9 | 8.6 | 31.9 | -2.7 | 33.7 |
| J-9 | 61.2 | 43.1 | 43.1 | 11.7 | 31.8 | -1.0 | 33.7 |
| J-8 | 61.0 | 30.7 | 41.7 | 21.1 | 32.0 | 0.9 | 33.9 |
| J-2 | 61.6 | 22.0 | 41.0 | 27.0 | 33.0 | 0.5 | 34.5 |
| Profile-2 | | | | | | | |
| J-3 | 61.6 | 20.1 | 40.1 | 27.8 | 33.2 | 1.1 | 34.6 |
| J-4 | 60.7 | 23.6 | 40.6 | 26.5 | 32.4 | 1.0 | 34.0 |
| J-5 | 60.4 | 27.2 | 40.4 | 21.9 | 32.2 | 0.3 | 33.8 |
| J-6 | 59.8 | 29.1 | 39.9 | 19.0 | 31.7 | 1.3 | 33.5 |
| J-14 | 58.3 | 29.7 | 39.8 | 19.2 | 31.7 | 1.2 | 33.5 |
| J-13 | 58.0 | 31.9 | 40.1 | 22.5 | 31.4 | 1.5 | 33.2 |
| J-17 | 57.4 | 32.4 | 39.2 | 19.3 | 31.1 | 1.6 | 32.9 |
| Profile-3 | | | | | | | |
| J-20 | 57.6 | 36.2 | 39.4 | 10.2 | 31.2 | -3.9 | 33.1 |
| J-21 | 57.5 | 33.7 | 39.4 | 8.2 | 31.2 | -8.6 | 33.0 |
| J-22 | 57.7 | 25.3 | 40.0 | 10.5 | 31.1 | -10.0 | 33.0 |
| J-23 | 58.6 | 37.8 | 41.3 | 15.3 | 31.4 | 0.0 | 33.3 |

When the demand increased by 25%, case 3 concerning the failure of PMP-1 and PMP-2 together was also the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1.

Without protection, the min pressures were in the range of -10.0 m to 45.8 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 31.1 m to 44.9 m. The protection devices had the same volume of hydropneumatic tanks for case 1 of PMP-1 failure and case 3 of PMP-1 and PMP-2 failure together. While for case 2 of PMP-2 failure, the same air valve was employed with increased volume of hydropneumatic tanks by 50%.

### 4.3. Third Scenario: 50% Increased Demand

For future increasing population and consequently increasing water demand, a third scenario was investigated for 50% increased demand. This 50% increased demand for the Assiut city water distribution network is illustrated in Table 6.

According to the population governmental records and future interpretation according to the Egyptian Code, the 50% increased demand will be required 25 years later representing the demand in the Year 2045, [20].

The third scenario, 50% increased demand, included three studied cases without protection and with protection for each case as mentioned previously. The obtained results are shown in Table 7.

When the demand increased by 50%, case 3 concerning the failure of PMP-1 and PMP-2 together was still the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1.

Without protection, the min pressures were in the range of -3.9 m to 46.3 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 30.5 m to 44.3 m. The protection devices had the same volume of hydropneumatic tanks for case 1 of PMP-1 failure and increased volume of hydropneumatic tanks by 43% for case 3 of PMP-1 and PMP-2 failure together. While for case 2 of PMP-2 failure, a larger air valve by 33% was employed with increased volume of hydropneumatic tanks by 100%.

**Table 6:** 50% Increased Demand for the Network Junctions

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Node Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| **Demand (Lit/s)** | 0 | 90 | 0 | 90 | 51 | 60 | 92 | 78 | 45 | 45 | 120 | 120 | 90 |
| **Node Number** | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| **Demand (Lit/s)** | 60 | 24 | 48 | 90 | 120 | 90 | 62 | 110 | 110 | 145 | 0 | 60 | 0 |

**Table 7:** Max and Min Pressure Head for Cases of Scenario 3, 50% Increased Demand

| **Junction** | **Max Head, m** | **Min Head, m** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Failure PMP-1 Only** | | **Failure PMP-2 Only** | | **Failure PMP-1 and PMP-2** | |
| | | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** | **Without Protection** | **With Protection** |
| Profile-1 | | | | | | | |
| J-1 | 62.2 | 46.3 | 44.3 | 1.9 | 31.6 | -3.4 | 36.5 |
| J-25 | 61.8 | 45.6 | 43.5 | 6.4 | 31.6 | -3.9 | 36.6 |
| J-10 | 61.5 | 45.0 | 42.9 | 8.2 | 31.6 | -2.5 | 36.5 |
| J-9 | 60.9 | 42.0 | 41.9 | 12.0 | 31.5 | 0.3 | 36.3 |
| J-8 | 60.6 | 27.6 | 39.6 | 19.8 | 31.8 | 1.3 | 36.6 |
| J-2 | 61.4 | 19.3 | 38.0 | 27.1 | 33.0 | -3.4 | 37.4 |
| Profile-2 | | | | | | | |
| J-3 | 61.4 | 16.3 | 36.9 | 28.9 | 33.4 | -1.1 | 37.5 |
| J-4 | 60.2 | 20.5 | 37.9 | 25.0 | 32.4 | 1.0 | 36.7 |
| J-5 | 59.8 | 22.9 | 37.9 | 20.1 | 32.0 | 0.7 | 36.4 |
| J-6 | 59.1 | 27.6 | 37.7 | 18.9 | 31.4 | 1.6 | 35.9 |
| J-14 | 59.0 | 28.7 | 37.8 | 19.7 | 31.3 | 1.6 | 35.9 |
| J-13 | 58.6 | 31.9 | 38.2 | 19.8 | 30.9 | 1.6 | 35.5 |
| J-17 | 57.8 | 31.3 | 37.5 | 18.5 | 30.5 | 1.5 | 35.1 |
| Profile-3 | | | | | | | |
| J-20 | 58.0 | 35.9 | 37.5 | 14.0 | 30.7 | 0.2 | 35.3 |
| J-21 | 58.0 | 33.1 | 37.5 | 12.4 | 30.6 | 0.0 | 35.3 |
| J-22 | 58.2 | 24.3 | 38.0 | 13.2 | 30.6 | -2.4 | 35.2 |
| J-23 | 59.3 | 37.8 | 39.7 | 16.6 | 30.9 | 1.1 | 35.7 |

### 5. Conclusions

In this paper, Bentley HAMMER software was employed to simulate, analyze, and protect the water distribution network of Assiut city in Egypt, which had two pump stations, against a pump power failure for the current and future conditions.

Three scenarios were investigated concerning the current demand, 25% increased demand, and 50% increased demand. Each scenario included three cases, which were the failure of PMP-1 only, failure of PMP-2 only, and failure of PMP-1 and PMP-2 together. Each case was studied without and with protection.

From the obtained results, for all scenarios, case 3 concerning the failure of PMP-1 and PMP-2 together was the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1.

For the current demand, without protection, the min pressures were in the range of -10.0 m to 45.4 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 30.7 m to 45.6 m. The protection devices were hydropneumatic tanks for cases 1 and 3, while an air valve was used associated with hydropneumatic tanks for case 2.

When the demand increased by 25%, case 3 concerning the failure of PMP-1 and PMP-2 together was also the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1. This scenario represented the required demand 15 years later, which would be the demand in the year 2035.

Without protection, the min pressures were in the range of -10.0 m to 45.8 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 31.1 m to 44.9 m. The protection devices had the same volume of hydropneumatic tanks for case 1 of PMP-1 failure and case 3 of PMP-1 and PMP-2 failure together. While for case 2 of PMP-2 failure, the same air valve was employed with increased volume of hydropneumatic tanks by 50%.

When the demand increased by 50%, case 3 concerning the failure of PMP-1 and PMP-2 together was still the worst-case followed by case 2 concerning the failure of PMP-2, and finally, case 1 concerning the failure of PMP-1.

Without protection, the min pressures were in the range of -3.9 m to 46.3 m for the studied cases, while employing protecting techniques achieved min pressures in the range of 30.5 m to 44.3 m. The protection devices had the same volume of hydropneumatic tanks for case 1 of PMP-1 failure and increased volume of hydropneumatic tanks by 43% for case 3 of PMP-1 and PMP-2 failure together. While for case 2 of PMP-2 failure, a larger air valve by 33% was employed with increased volume of hydropneumatic tanks by 100%.

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