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# PERFORMANCE EVALUATION OF WATER DISTRIBUTION NETWORK USING COMPUTER MODEL SIMULATION

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## ABSTRACT

The paper describes the water supply system in Doha. It discusses the methodology used in estimating the water demand for each node of the water distribution network in the Garrafa District of Doha. A computer model of the network was built based on the available data and field observations. The applications of the model are to study the effect of water demands at the existing development level on the system pressure and the ability of the system to provide satisfactory pressure after full development. The network model was verified and analyzed for various modes of operation using computer model simulation.

The model was calibrated in a stepwise manner. For calibration flow and pressure measurements were made at critical points in the distribution network. These values were compared with the values obtained by analyzing the computer model using WATNET 3 software package developed by Water Research Center, U.K. The analysis indicated deficiencies in some locations in the network but the pressure of the water in the network no where fell below an acceptable minimum distribution pressure of 10m set by the water department.

## INTRODUCTION

The main source of potable water supply in Doha is the desalinated water. Large ground storage tanks are built at the Desalination Plant. Water from these storage tanks is pumped through transmission lines to the water works located in various districts of the city and stored in the ground storage tanks for distribution. The water works in each district consists of ground storage tanks, pumps and pumping mains connected to the storage tanks for supplying water to the water towers (elevated tanks) and a tanker filling station (1). The water is supplied for about 13 hours every day. The volume of water stored in the tanks represents about three day supply at the peak rate of demand. In case of any emergency e.g. fire or breakdown, the water demand is expected to be met form this storage and therefore no special provision for the fire demand has been made in the design of the water distribution system.

Some of the properties in the Garrafa district are not connected to the distribution system. These properties are supplied with water by tanker trucks which collect water at the tanker filling station (TFS) near the water tower located at the water works (Fig. 1). Every property has a surface water tank, which is either connected to the distribution system or is filled with water on alternate days by tanker trucks. In each property water is pumped from the surface tank to the roof tank which distributes the water within the property. The properties with gardens use drinking water for irrigation. The city has a tertiary treated sewage effluent system which meets the irrigation requirements of landscaping.

The water distribution network in the Garrafa district of Doha (Fig. 2) was selected for computer model simulation. The water demand for each node of the distribution network was estimated. The demand used in the analysis for various application is presented in Table 1. For the anlaysis and calibration the actual demand at the time of flow and pressure measurements, which was at 12 hrs were used. A computer model was set up to analyze the water distribution network. The model was calibrated in stepwise manner.

**Table 1. Water Demand Used in the Network Analysis**

| Application | Demand (L/s) | | Total Demand (L/s.) |
|---|---|---|---|
| | Distribution Network | Tanker Filling Station | |
| Model Verification (Tables - 3 & 4) | 169.62 | - | 169.62 |
| Model Analysis (Table 5) | 114.77 | 106.14 | 220.91 |
| Model Calibration by Activating Throttle Valve (Tables 7 & 8) | 114.77 | 106.14 | 220.91 |
| Final Calibration of model (Tables 9 & 10) by activating THV, correcting GL of nodes and adjusting values of C | 114.77 | 106.14 | 220.91 |
| Analysis of Calibrated Model for future development | 169.62 | 106.14 | 275.76 |
| Average demand | 172 L/s. | | |

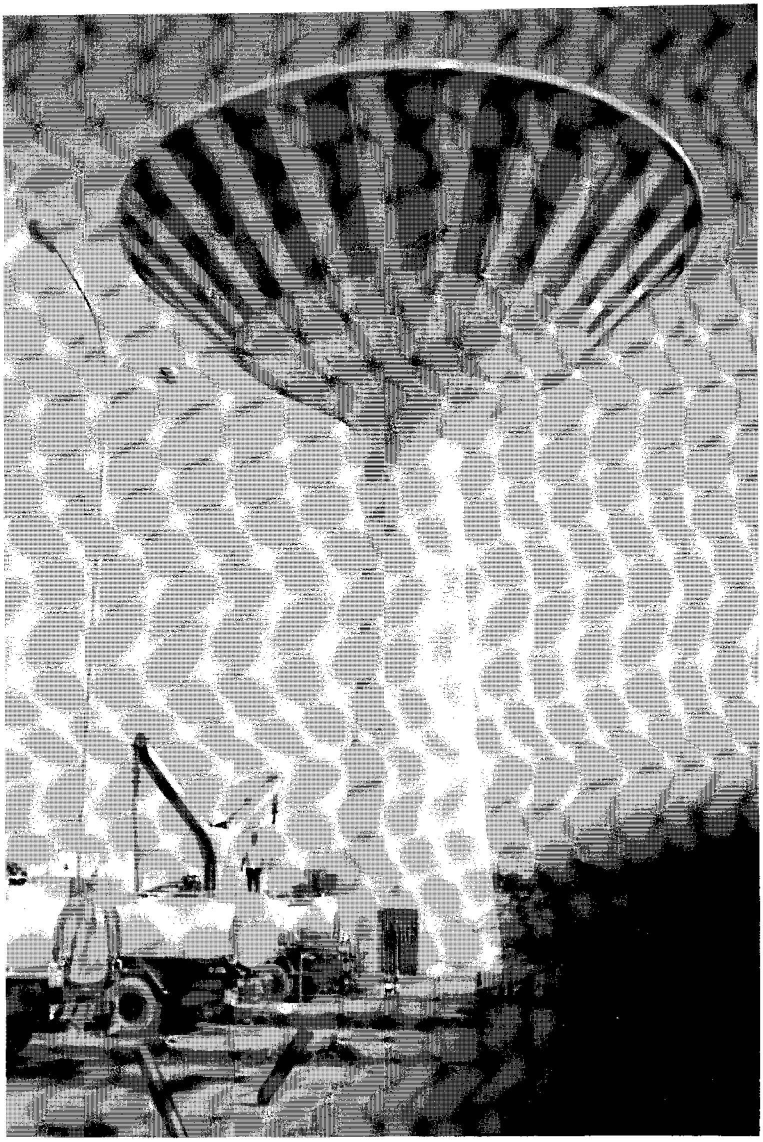

**Fig. 1: A view of water tower (WT20) with tanker filling station (TFS)**

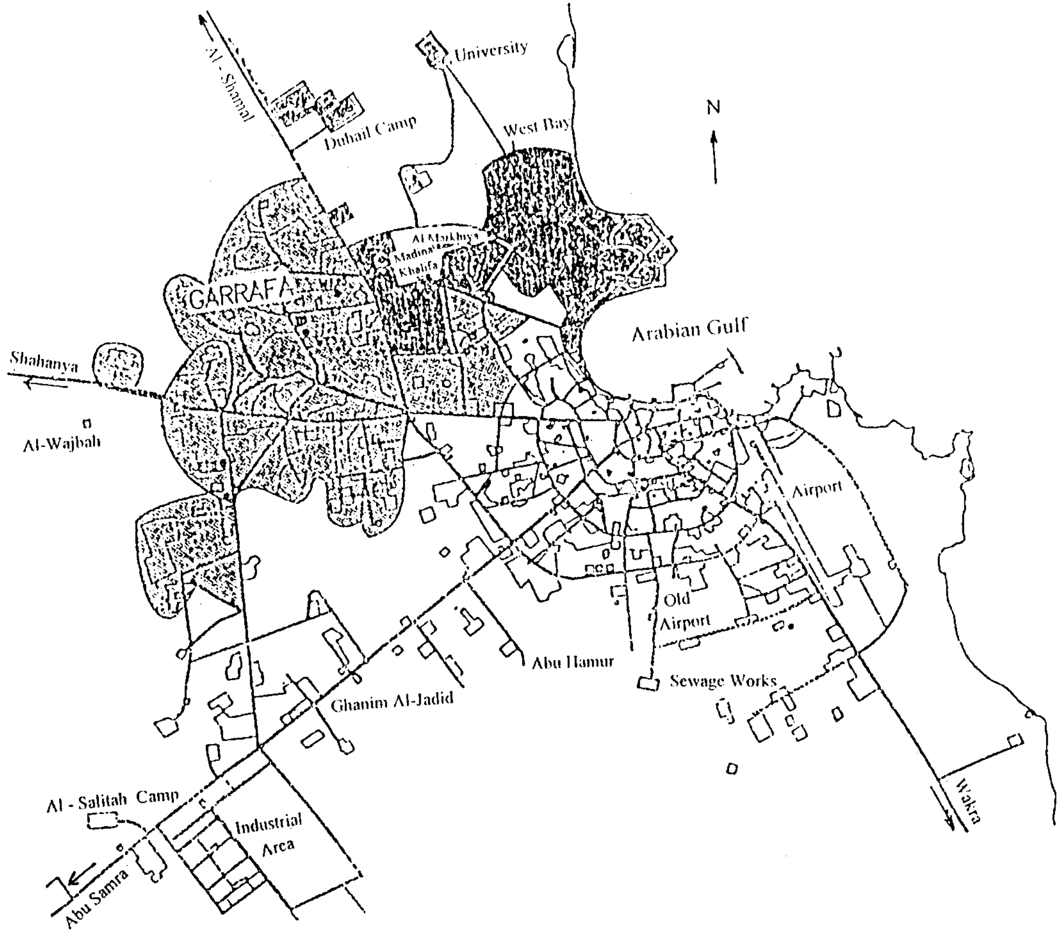


**Fig. 2: Map of Doha city showing Garrafa district**

The computer model was first verified to check initial data and find any anamolies such as high headlosses and negative pressure at any node. It was then analyzed for the following modes of operation for performance evaluation:

a) With Tanker filling station (TFS)
b) With Throttle valve (THV) added to the outlet main of the water tower (WT)
c) Future development

The applications of the model are to study the effect of water demands at the existing development level on the system pressure and the ability of the system to provide satisfactory pressure after full development.

Watnet 3 computer programme developed by Water Research Center U.K. was used in computer modeling (3). The computer programme was validated by comparing programme outputs with manually determined results and results obtained from other software packages (4,5)

The criteria for the selection of the Garrafa district was that it has multiple types of water usage, e.g. residential (palaces, villas, apartments, labors camps etc.), commercial, public and light industries (car washing garages, ice factory, petrol station, bakery etc). Further this district has a combination of old and new construction.

The water tower supplies water to the distribution network by gravity. All the pipes in the network are interconnected representing a grid pattern. In such a system water can reach a given point of withdrawal from several directions. Additional loops can be added to improve the distribution of water. Loops are added to serve business districts and other high risk areas e.g. palaces and large villas. A schematic layout of the network is shown in Fig. 3.

The network consists of cement lined ductile iron pipes of 400 mm diameter trunk lines connected to the water tower, 300 mm diameter mains for major peripheral components, 200 mm, 150 mm and 100 mm submains serving the extended detailed grids of the network. Houses and other properties are connected by 32 mm and 64 mm diameter pipes. Gate valves are located at all crosses and tees for control and operation.

The existing ground level of the area, location of water mains, submains, nodes, pipelengths, diameter and valves were obtained from the map of the area and available drawings. The area, type and number of property supplied by various nodes were determined with the help of aerial photographs and field observations.

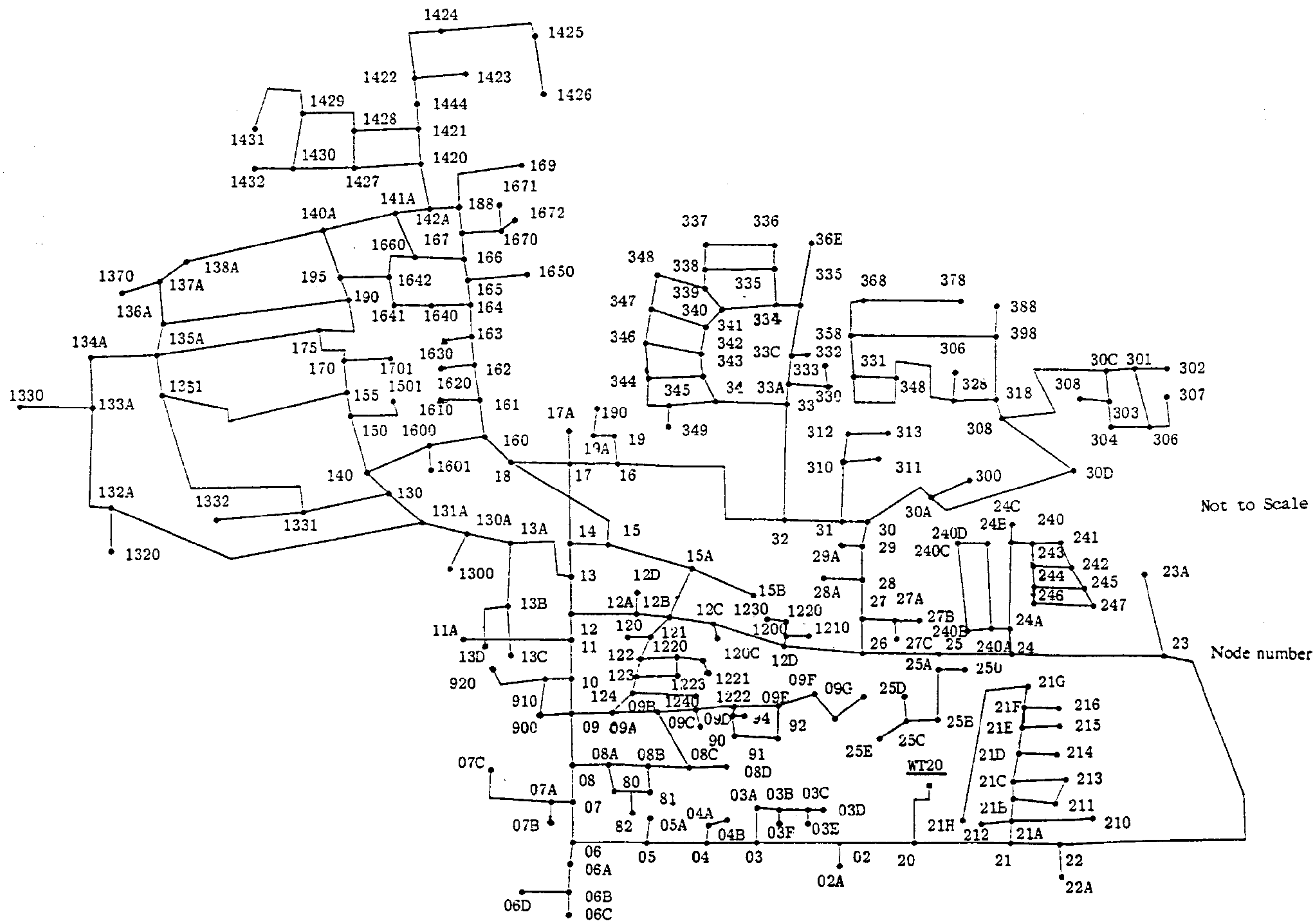


**Fig. 3: Schematic layout of water distribution network**

Flow and pressure measurements in the pumping main to the water tower inlet tanker filling station, and the water distribution network were made during the day. The above mentioned information is used to create the computer model of the water distribution network.

## NETWORK ANALYSIS AND SIMULATION

Network analysis is a means of investigating the complex relationships between a specified network consumption, pressure and flows (6,7). Network simulation is an extension of network analysis which models the operation of the distribution network over a simulated period of time. Such an analysis takes into consideration changing demands, pumps on line and its effect on tank levels. A typical duration is 24 hours but network simulation can be used over shorter and longer time scales.

Essentially the simulation consists of a series of steady state network analysis throughout the simulated time period (3,8). The result of a simulation can give snapshot view of pressures and flows for the network at any required time during the simulated period which was the case in this study. The simulation can also provide a profile of the performance of an individual network feature i.e. reservoir level, or node pressure during the whole or part of time simulated period.

The network simulation can model the effect of proposed changes in operation (2,7). Thus it is possible to analyse the effect of different pumping regimes, assess the performance of reservoirs and expansion in the network. The diurnal effects of different patterns of demand can also be assessed.

## NETWORK CALIBRATION

The results of the analysis of the computer model are compared with the actual field condition i.e. the measured flow and pressure at various points in the network. The comparison may show wide difference between the results obtained by analysis and the measured values which means the computer model must be calibrated. Calibration is the process of fine tuning the model until it simulates actual field conditions (9). It is the process of adjusting the input data of a water distribution system model to improve agreement between the modeled or predicted pressures and flows and the actual values as observed in the distribution system (10). In this study the model was calibrated by (a) setting the throttle valve to the outlet main of the water tower (b) using the actual levels of nodes, and (c) adjusting the value of Hazen-William Coefficient.

For a snapshot calibration which was used in this study, the acceptable performance criteria against which modeled flows and pressures should agree with recorded fields data are given below as the guideline.

a) Pipe flows where flow is more than 10% of total demand ± 5% of measured flow.
b) Node pressure = ± 0.5 m of measured pressure.

## ESTIMATION OF WATER DEMAND

An extensive property counting and categorization exercise has been carried out for the area covered by this model. The number of various categories of properties are given in Table 2.

**Table 2: Number of Various Categories of Properties**

| Public | | Commercial | | Residential | |
|---|---|---|---|---|---|
| Mosques | 10 | Petrol station, Car washing and servicing, Tea shop | 4 | Palaces, Villas, Apartments | 1340 |
| Schools | 4 | Ice factory | 2 | Labour camps | 5 |
| Health center | 1 | Bakery | 2 | | |
| Immigration office | 1 | | | | |
| Municipal office | 1 | | | | |
| Garden/nursery | 2 | | | | |
| Football ground | 1 | | | | |
| Electrical | 1 | | | | |
| substation | 1 | | | | |
| Cemetery | | | | | |
| Total | 22 | | 8 | | 1345 |
| Grand Total | | | | | 1375 |

Using the 1988/89 series of aerial photographs obtained from the Ministry of Municipal Affairs and Agriculture, small numbers of properties were grouped together into "BLOCKS'. Each block was referenced and the number and type of property within each block was counted and entered into a database system (1).

A consumer metering study was carried out to identify the average water consumption for each category of domestic property.

For non-domestic property, the Water Consumer Number of each property was obtained by a visit to each property. This number enabled access to the consumer meter records for each individual non-domestic property. Analysis of these gave the average water consumption for each individual property. Where these records were unavailable for an individual property, the average water consumption for a non domestic property of that type was used instead.

Each block is then allocated to a particular node within the network model. This is achieved by comparing the aerial photographs with the detailed plan of the water distribution network. Using the database system, it was then possible to obtain for each node a total estimate of nodal demand including metered non-domestic demand, and unmetered non-domestic demand.

The total demand estimate for the model is then compared with the total daily supply to the zone on the day that field data for model calibration was obtained. The difference between the two figures gives the unaccounted for water estimate for the zone. The model demand assigned to the model can thus be divided into four components:

1. unmetered domestic demand
2. unmetered non-domestic demand
3. metered domestic demand
4. Unaccounted for water

## SIMPLIFIED WATER DISTRIBUTION NETWORK

The water distribution network consisted of 298 pipes and 263 nodes with a total length of 34.476 km (Fig. 3). For the analysis, the water distribution network was therefore, simplified (Fig. 4) by considering pipes laid along the main roads. The pipes leading to individual areas were neglected and the flow to the area was aggregated and assumed to be drawn from the corresponding node. This procedure reduced the number of pipes to 77 and nodes to 70 and simplified the analysis and calibration of the network.

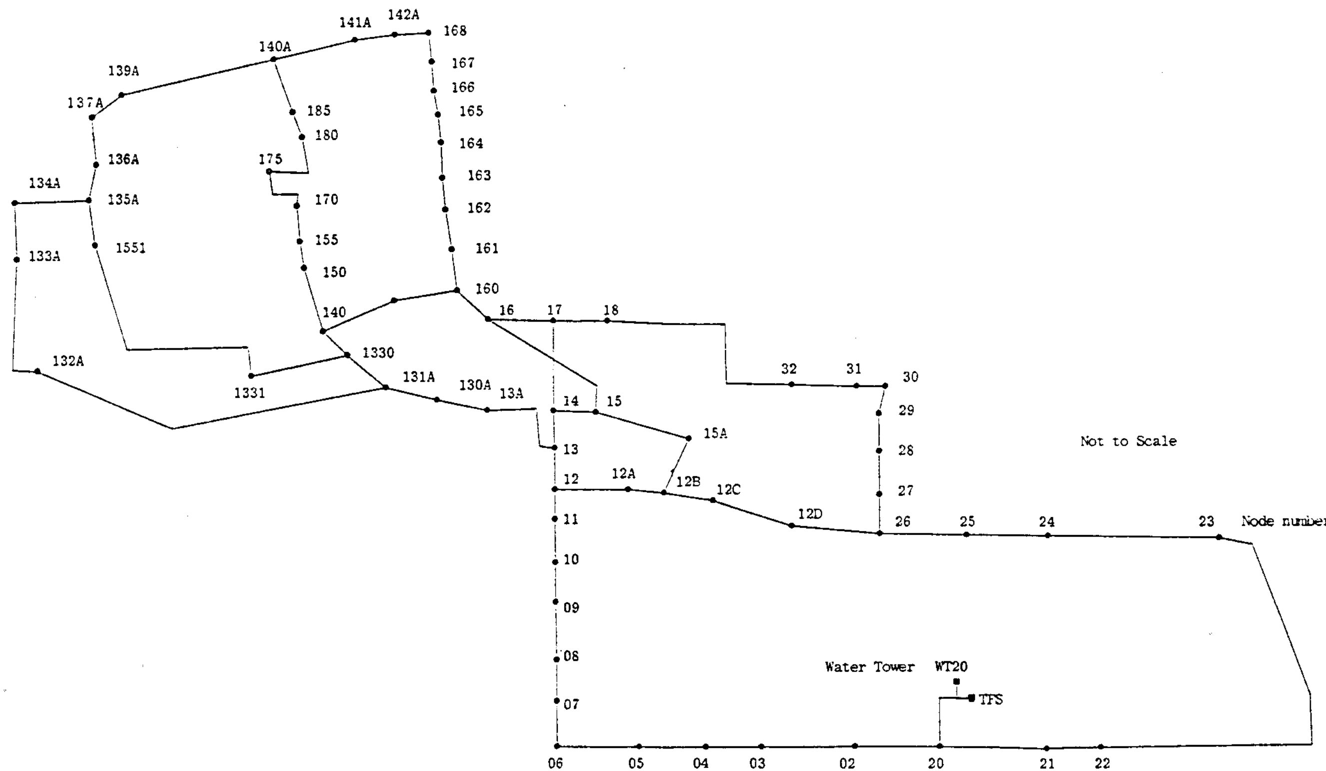


**Fig. 4: Simplified layout of water distribution network**

# VERIFICATION OF COMPUTER MODEL

The initial estimate of water demand including future demand based on property counting and property categories as discussed earlier was used for analyzing the network. The demand for the tanker filling station (TFS) was set at zero. The head of water in the tower was set at the maximum water level in the tower and assumed to be fixed. The total demand used in the verification of the model is given Table 1. This model was used to check initial data entered and to find if there are any anomalies, such as high headlosses along any pipeline, and negative pressures at any node.

The pipe flows and the available head at various nodes are given in Tables 3 and 4. The available head in the system varies between 26.79 m and 33.53 m. The maximum velocity of flow in the pipe between the water tower and node 20 is 1.35 m/s, which is the main supplying the entire distribution network (Table 4). However, the maximum velocity is 0.73 m/s, which is within the suggested value of velocity i.e. about 1 m/s. (4).

The maximum hydraulic gradient in the main supplying the entire distribution network is 3.2 m/km. This is understandable because of the high velocity in the pipeline. The maximum headloss in the network is 4 m/km between the nodes 180 and 185. The diameter of the pipe between the nodes 180 and 185 is 100 mm, whereas the pipe on either ends are 200 mm diameter. This is undesirable and should be changed to 200 mm diameter. Otherwise the maximum hydraulic gradient in the network is 1.2 m/km which is within the suggested value i.e. 3m/km

The analysis indicates that the headlosses are in general within the tolerable limits and none of the nodes has a negative pressure.

## Network Analysis with Tankers Filling Station (TFS)

The demand for the TFS was included in the computer model for the network (Table 5). A factor has been applied to the initial demand to ensure that the total demand matches the measured demand in pipes 20 - 2 and 20 - 21. These pipes were selected as they are very close to the supply source i.e. the water tower.

The fixed head source, was set at the actual water level in the water tower at the time of the collection of field data. In the field test, the available pressure at nodes 29 and 139A were also measured. For pressure measurements node 29 and

**Table 3: Total Demand and Available Head for Verification of Water Network Model**

| Node | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 02 | | 0.00 | 12.9 | 43.58 | 30.68 | |
| 03 | | 1.74 | 15.5 | 43.16 | 27.66 | |
| 04 | | 0.00 | 15.6 | 43.00 | 27.40 | |
| 05 | | 1.39 | 14.3 | 42.69 | 28.39 | |
| 06 | | 0.23 | 9.6 | 42.32 | 32.72 | |
| 07 | | 0.77 | 8.5 | 42.03 | 33.53 | |
| 08 | | 1.26 | 9.0 | 41.96 | 32.96 | |
| 09 | | 70.55 | 9.5 | 41.77 | 32.27 | |
| 10 | | 0.71 | 9.5 | 41.77 | 32.27 | |
| 11 | | 0.00 | 8.6 | 41.76 | 33.16 | |
| 12 | | 0.00 | 8.7 | 41.75 | 33.05 | |
| 12A | | 0.00 | 9.2 | 41.78 | 32.58 | |
| 12B | | 4.82 | 10.1 | 41.78 | 31.68 | |
| 12C | | 0.00 | 9.8 | 41.90 | 32.10 | |
| 12D | | 2.28 | 9.8 | 41.92 | 32.12 | |
| 13 | | 0.00 | 8.6 | 41.74 | 33.14 | |
| 130 | | 0.00 | 9.3 | 41.62 | 32.32 | |
| 130A | | 0.79 | 8.9 | 41.68 | 32.78 | |
| 131A | | 0.39 | 9.4 | 41.63 | 32.23 | |
| 132A | | 1.02 | 10.7 | 41.53 | 30.83 | |
| 1331 | | 0.04 | 11.6 | 41.56 | 29.96 | |
| 133A | | 17.40 | 10.6 | 41.49 | 30.89 | |
| 134A | | 0.00 | 11.7 | 41.49 | 29.79 | |

**Table 3: (Contd.)**

| Node | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 135A | | 0.69 | 10.9 | 41.49 | 30.59 | |
| 136A | | 0.00 | 11.2 | 41.49 | 30.29 | |
| 137A | | 2.08 | 11.2 | 41.49 | 30.29 | |
| 139A | | 0.00 | 11.2 | 41.49 | 30.29 | |
| 13A | | 2.08 | 8.6 | 41.73 | 33.13 | |
| 14 | | 0.00 | 8.8 | 4.74 | 32.94 | |
| 140 | | 0.20 | 9.2 | 41.61 | 32.41 | |
| 140A | | 0.05 | 10.3 | 41.48 | 31.18 | |
| 141A | | 0.37 | 10.3 | 41.48 | 31.18 | |
| 142A | | 8.04 | 10.4 | 41.48 | 31.08 | |
| 15 | | 0.00 | 10.3 | 41.74 | 31.44 | |
| 150 | | 0.78 | 10.0 | 41.60 | 31.60 | |
| 155 | | 0.00 | 9.8 | 41.60 | 31.80 | |
| 1551 | | 0.69 | 11.7 | 41.50 | 29.80 | |
| 16 | | 0.00 | 9.3 | 41.74 | 32.44 | |
| 160 | | 0.00 | 9.5 | 41.67 | 32.17 | |
| 1600 | | 0.87 | 10.6 | 41.62 | 31.02 | |
| 161 | | 0.04 | 9.6 | 41.64 | 32.04 | |
| 162 | | 0.69 | 9.9 | 41.61 | 31.71 | |
| 163 | | 0.87 | 9.8 | 41.59 | 31.79 | |
| 164 | | 0.00 | 9.8 | 41.56 | 31.76 | |
| 165 | | 0.15 | 10.0 | 41.53 | 31.53 | |
| 166 | | 0.00 | 10.1 | 41.50 | 31.40 | |

**Table 3: (Contd.)**

| Node | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 167 | | 0.39 | 10.2 | 41.49 | 31.29 | |
| 168 | | 3.82 | 10.4 | 41.48 | 31.08 | |
| 170 | | 0.00 | 9.2 | 41.59 | 32.39 | |
| 175 | | 0.00 | 10.1 | 41.58 | 31.48 | |
| 18 | | 5.56 | 10.8 | 41.74 | 30.94 | |
| 180 | | 0.00 | 10.4 | 41.57 | 31.17 | |
| 185 | | 0.00 | 10.4 | 41.49 | 31.09 | |
| 20 | | 0.00 | 10.6 | 43.75 | 33.10 | |
| 21 | | 4.57 | 11.4 | 43.48 | 32.08 | |
| 22 | | 0.00 | 11.6 | 43.46 | 31.86 | |
| 23 | | 1.55 | 17.2 | 42.72 | 25.52 | |
| 24 | | 4.87 | 15.6 | 42.39 | 26.79 | |
| 25 | | 2.17 | 13.8 | 42.29 | 28.49 | |
| 26 | | 0.00 | 12.6 | 42.16 | 29.56 | |
| 27 | | 2.08 | 14.0 | 42.13 | 28.13 | |
| 28 | | 0.69 | 14.0 | 42.13 | 28.13 | |
| 29 | | 0.00 | 13.3 | 42.11 | 28.81 | |
| 30 | | 11.48 | 13.3 | 42.10 | 28.80 | |
| 31 | | 0.44 | 12.8 | 42.10 | 29.30 | |
| 32 | | 10.94 | 11.6 | 42.09 | 30.49 | |
| TFS | | 0.00 | 17.5 | 44.94 | 27.44 | |
| Water Tower | RESR | 0.00 | 17.5 | 45.00 | 27.50 | |
| WT20 | | | | | | 169.62 |

## Table 4: Results of Analysis of Water Distribution Network Model Used for Verification

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity m/s | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 02 | 03 | 400 | 405 | 151 | 91.96 | 0.73 | 0.41 | 1.0 |
| 02 | 20 | 400 | 170 | 151 | -91.96 | -0.73 | -0.17 | -1.0 |
| 03 | 04 | 400 | 170 | 151 | 90.22 | 0.72 | 0.17 | 1.0 |
| 04 | 05 | 400 | 305 | 151 | 90.22 | 0.72 | 0.30 | 1.0 |
| 05 | 06 | 400 | 395 | 151 | 88.83 | 0.71 | 0.38 | 1.0 |
| 06 | 07 | 400 | 305 | 151 | 88.60 | 0.70 | 0.29 | 1.0 |
| 07 | 08 | 400 | 75 | 151 | 87.83 | 0.70 | 0.07 | 0.9 |
| 08 | 09 | 400 | 200 | 151 | 86.57 | 0.69 | 0.18 | 0.9 |
| 09 | 10 | 400 | 125 | 151 | 16.02 | 0.13 | 0.01 | 0.0 |
| 10 | 11 | 400 | 294 | 151 | 15.31 | 0.12 | 0.01 | 0.0 |
| 11 | 12 | 400 | 160 | 151 | 15.31 | 0.12 | 0.01 | 0.0 |
| 12 | 12A | 300 | 180 | 150 | -15.58 | -0.22 | -0.03 | -0.2 |
| 12 | 13 | 400 | 55 | 151 | 30.89 | 0.25 | 0.01 | 0.1 |
| 12A | 12B | 300 | 30 | 150 | -26.56 | -0.38 | -0.12 | -0.2 |
| 12B | 12C | 300 | 285 | 150 | -26.56 | -0.38 | -0.12 | -0.4 |
| 12B | 15A | 150 | 45 | 149 | 6.17 | 0.35 | 0.04 | 0.8 |
| 12C | 12D | 300 | 25 | 150 | -26.56 | -0.38 | -0.01 | -0.4 |
| 12D | 26 | 300 | 500 | 150 | -28.84 | -0.41 | -0.25 | -0.5 |
| 13 | 13A | 400 | 70 | 151 | 33.94 | 0.27 | 0.01 | 0.2 |
| 13 | 14 | 400 | 25 | 151 | -3.06 | -0.02 | 0.00 | 0.0 |
| 130 | 131A | 200 | 40 | 150 | -8.28 | -0.26 | -0.01 | -0.3 |
| 130 | 1331 | 100 | 125 | 148 | 1.52 | 0.19 | 0.06 | 0.4 |
| 130 | 140 | 200 | 25 | 150 | 6.76 | 0.22 | 0.00 | 0.2 |
| 130A | 131A | 300 | 95 | 150 | 31.07 | 0.44 | 0.05 | 0.6 |
| 130A | 13A | 300 | 90 | 150 | -31.86 | -0.45 | -0.05 | -0.6 |
| 131A | 132A | 300 | 330 | 150 | 22.40 | 0.32 | 0.10 | 0.3 |
| 132A | 133A | 300 | 145 | 150 | 21.38 | 0.30 | 0.04 | 0.3 |
| 1331 | 1551 | 100 | 140 | 148 | 1.48 | 0.19 | 0.06 | 0.4 |
| 133A | 134A | 300 | 100 | 150 | 3.98 | 0.06 | 0.00 | 0.0 |

**Table 4: (Contd.)**

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity m/s | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 134A | 135A | 300 | 185 | 150 | 3.98 | 0.06 | 0.00 | 0.0 |
| 135A | 136A | 300 | 55 | 150 | 4.07 | 0.06 | 0.00 | 0.0 |
| 135A | 1551 | 100 | 105 | 148 | -0.78 | -0.10 | -0.01 | -0.1 |
| 136A | 137A | 300 | 20 | 150 | 4.07 | 0.06 | 0.00 | 0.0 |
| 137A | 139A | 300 | 70 | 150 | 1.98 | 0.03 | 0.00 | 0.0 |
| 139A | 140A | 300 | 125 | 150 | 1.98 | 0.03 | 0.00 | 0.0 |
| 14 | 15 | 400 | 45 | 151 | -2.23 | -0.02 | 0.00 | 0.0 |
| 14 | 17 | 400 | 160 | 151 | -0.83 | -0.01 | 0.00 | 0.0 |
| 140 | 150 | 200 | 35 | 150 | 7.07 | 0.22 | 0.01 | 0.2 |
| 140 | 1600 | 100 | 85 | 148 | -0.50 | -0.06 | 0.00 | -0.1 |
| 140A | 141A | 300 | 85 | 150 | 8.22 | 0.12 | 0.00 | 0.0 |
| 140A | 185 | 200 | 80 | 150 | -6.29 | -0.20 | -0.01 | -0.1 |
| 141A | 142A | 300 | 55 | 150 | 7.85 | 0.11 | 0.00 | 0.0 |
| 142A | 168 | 300 | 30 | 150 | -0.19 | 0.00 | 0.00 | 0.0 |
| 15 | 15A | 300 | 160 | 150 | -6.12 | -0.09 | 0.00 | 0.0 |
| 15 | 16 | 400 | 180 | 151 | 3.89 | 0.03 | 0.00 | 0.0 |
| 150 | 155 | 200 | 15 | 150 | 6.29 | 0.20 | 0.00 | 0.1 |
| 155 | 170 | 200 | 65 | 150 | 6.29 | 0.20 | 0.01 | 0.1 |
| 16 | 160 | 150 | 60 | 149 | 7.52 | 0.43 | 0.07 | 1.2 |
| 16 | 17 | 400 | 45 | 151 | -3.63 | -0.03 | 0.00 | 0.0 |
| 160 | 1600 | 100 | 155 | 148 | 1.37 | 0.17 | 0.06 | 0.4 |
| 160 | 161 | 150 | 40 | 149 | 6.15 | 0.35 | 0.03 | 0.8 |
| 161 | 162 | 150 | 45 | 149 | 6.11 | 0.35 | 0.04 | 0.8 |
| 162 | 163 | 150 | 35 | 149 | 5.42 | 0.31 | 0.02 | 0.6 |
| 163 | 164 | 150 | 70 | 149 | 4.54 | 0.26 | 0.03 | 0.4 |
| 164 | 165 | 150 | 65 | 149 | 4.54 | 0.26 | 0.03 | 0.4 |
| 165 | 166 | 150 | 65 | 149 | 4.40 | 0.25 | 0.03 | 0.4 |
| 166 | 167 | 150 | 33 | 149 | 4.40 | 0.25 | 0.01 | 0.4 |
| 167 | 168 | 150 | 35 | 149 | 4.01 | 0.23 | 0.01 | 0.3 |
| 17 | 18 | 400 | 115 | 151 | -4.46 | -0.04 | 0.00 | 0.0 |
| 170 | 175 | 200 | 80 | 150 | 6.29 | 0.20 | 0.01 | 0.1 |
| 175 | 180 | 200 | 85 | 150 | 6.29 | 0.20 | 0.01 | 0.1 |

## Table 4: (Contd.)

| From Node | To Node | Diam. (mm)) | Length (m) | Frict. | Flow (L/s) | Velocity m/s | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 18 | 32 | 200 | 695 | 150 | -10.02 | -0.32 | -0.35 | -0.5 |
| 180 | 185 | 100 | 20 | 148 | 6.29 | 0.80 | 0.08 | 4.0 |
| 20 | 21 | 400 | 355 | 151 | 77.66 | 0.62 | 0.26 | 0.7 |
| 20 | TFS | 400 | 375 | 151 | -169.62 | -1.35 | -1.19 | -0.2 |
| 21 | 22 | 400 | 40 | 151 | 73.09 | 0.58 | 0.03 | 0.7 |
| 22 | 23 | 400 | 1110 | 151 | 73.09 | 0.58 | 0.74 | 0.7 |
| 23 | 24 | 400 | 515 | 151 | 71.54 | 0.57 | 0.33 | 0.6 |
| 24 | 25 | 400 | 17 | 151 | 66.67 | 0.53 | 0.10 | 0.6 |
| 25 | 26 | 400 | 245 | 151 | 64.49 | 0.51 | 0.13 | 0.5 |
| 26 | 27 | 400 | 180 | 151 | 35.66 | 0.28 | 0.03 | 0.2 |
| 27 | 28 | 400 | 10 | 151 | 33.57 | 0.27 | 0.00 | 0.2 |
| 28 | 29 | 400 | 105 | 151 | 32.88 | 0.26 | 0.02 | 0.2 |
| 29 | 30 | 400 | 65 | 151 | 32.88 | 0.26 | 0.01 | 0.2 |
| 30 | 31 | 400 | 20 | 151 | 21.40 | 0.17 | 0.00 | 0.1 |
| 31 | 32 | 400 | 125 | 151 | 20.96 | 0.17 | 0.01 | 0.1 |
| TFS | WT20 | 400 | 20 | 151 | -169.62 | -1.35 | -0.06 | -3.2 |

**Table 5: Total Demand and Available Head for Water Distribution Network Model with Tanker Filling Station (TFS)**

| Node No. | Total Demand (L/s) | Ground (Level) (m) | Total Head (m) | Available (m) | Supply (L/s) |
|---|---|---|---|---|---|
| 02 | 0.00 | 12.9 | 40.24 | 27.34 | |
| 03 | 1.17 | 15.5 | 40.04 | 24.54 | |
| 04 | 0.00 | 15.6 | 39.95 | 24.35 | |
| 05 | 0.94 | 14.3 | 39.81 | 25.51 | |
| 06 | 0.16 | 9.6 | 39.62 | 30.02 | |
| 07 | 0.52 | 8.5 | 39.48 | 30.98 | |
| 08 | 0.85 | 9.0 | 39.45 | 30.45 | |
| 09 | 47.74 | 9.5 | 39.36 | 29.86 | |
| 10 | 0.48 | 9.5 | 39.36 | 29.86 | |
| 11 | 0.00 | 8.6 | 39.35 | 30.75 | |
| 12 | 0.00 | 8.7 | 39.35 | 30.65 | |
| 12A | 0.00 | 9.2 | 39.36 | 30.16 | |
| 12B | 3.26 | 10.1 | 39.37 | 29.27 | |
| 12C | 0.00 | 9.8 | 39.42 | 29.62 | |
| 12D | 1.54 | 9.8 | 39.43 | 29.63 | |
| 13 | 0.00 | 8.6 | 39.35 | 30.75 | |
| 130 | 0.00 | 9.3 | 39.28 | 29.98 | |
| 130A | 0.54 | 8.9 | 39.32 | 30.42 | |
| 131A | 0.26 | 9.4 | 39.29 | 29.89 | |
| 132A | 0.69 | 10.7 | 39.24 | 28.54 | |
| 1331 | 0.03 | 11.6 | 39.26 | 27.66 | |
| 133A | 11.77 | 10.6 | 39.22 | 28.62 | |
| 134A | 0.00 | 11.7 | 39.22 | 27.52 | |
| 135A | 0.47 | 10.9 | 39.22 | 28.32 | |
| 136A | 0.00 | 11.2 | 39.22 | 28.02 | |

**Table 5: (Contd)**

| Node No. | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|
| 137A | 1.41 | 11.2 | 39.22 | 28.02 | |
| 139A | 0.00 | 11.2 | 39.22 | 28.02 | |
| 13A | 1.41 | 8.6 | 39.34 | 30.74 | |
| 14 | 0.00 | 8.8 | 39.35 | 30.55 | |
| 140 | 0.14 | 9.2 | 39.28 | 30.08 | |
| 140A | 0.03 | 10.3 | 39.22 | 28.92 | |
| 141A | 0.25 | 10.3 | 39.22 | 28.92 | |
| 142A | 5.44 | 10.4 | 39.22 | 28.82 | |
| 15 | 0.00 | 10.3 | 39.35 | 29.05 | |
| 150 | 0.53 | 10.0 | 39.28 | 29.28 | |
| 155 | 0.00 | 9.8 | 39.28 | 29.48 | |
| 1551 | 0.47 | 11.7 | 39.23 | 27.53 | |
| 15A | 0.03 | 10.5 | 39.35 | 28.85 | |
| 16 | 0.00 | 9.3 | 39.35 | 30.05 | |
| 160 | 0.00 | 9.5 | 39.31 | 29.81 | |
| 1600 | 0.59 | 10.6 | 39.28 | 28.68 | |
| 161 | 0.03 | 9.6 | 39.30 | 29.70 | |
| 162 | 0.47 | 9.9 | 39.28 | 29.38 | |
| 163 | 0.59 | 9.8 | 39.27 | 29.47 | |
| 164 | 0.00 | 9.8 | 39.26 | 29.46 | |
| 165 | 0.10 | 10.0 | 39.24 | 29.24 | |
| 166 | 0.00 | 10.1 | 39.23 | 29.13 | |
| 167 | 0.26 | 10.2 | 39.22 | 29.02 | |
| 168 | 2.58 | 10.4 | 39.22 | 28.82 | |
| 17 | 0.00 | 9.3 | 39.35 | 30.05 | |
| 170 | 0.00 | 9.2 | 39.27 | 30.07 | |
| 175 | 0.00 | 10.1 | 39.27 | 29.17 | |
| 18 | 3.76 | 10.8 | 39.35 | 28.55 | |
| 180 | 0.00 | 10.4 | 39.26 | 28.86 | |
| 185 | 0.00 | 10.4 | 39.22 | 28.82 | |

**Table 5: (Contd.)**

| Node No. | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|
| 20 | 0.00 | 10.6 | 40.32 | 29.67 | |
| 21 | 3.09 | 11.4 | 40.19 | 28.79 | |
| 22 | 0.00 | 11.6 | 40.18 | 28.58 | |
| 23 | 1.05 | 17.2 | 39.82 | 22.62 | |
| 24 | 3.30 | 15.6 | 39.66 | 24.06 | |
| 25 | 1.47 | 13.8 | 39.61 | 25.81 | |
| 26 | 0.00 | 12.6 | 39.55 | 26.95 | |
| 27 | 1.41 | 14.0 | 39.53 | 25.53 | |
| 28 | 0.47 | 14.0 | 39.53 | 25.53 | |
| 29 | 0.00 | 13.3 | 39.53 | 26.23 | |
| 30 | 7.77 | 13.3 | 39.52 | 26.22 | |
| 31 | 0.30 | 12.8 | 39.52 | 26.72 | |
| 32 | 7.40 | 11.6 | 39.52 | 27.92 | |
| TFS | 106.14 | 17.5 | 40.90 | 23.40 | |
| WT20 | 0.00 | 17.5 | 41.00 | 23.50 | 220.91 |

139A were selected as node 29 lies near the middle of the network and node 139A at the far end of the distribution network.

This model was calibrated so that the flow along pipes 20 - 02 and 20 - 21 and pressure at nodes 20 and 139A match the measured values, obtained during the field test.

A comparison between the modeled flows and pressure and the recorded field data is presented below so as to see whether the calibration of the model meets the earlier mentioned performance criteria.

**Pipe 20 - 02**

| | | |
|---|---|---|
| Actual measured flow | = | 57.438 L/s |
| Allowable range | = | ± 5% |
| Max. Allowable | = | 60.310 L/s |
| Min. Allowable | = | 54.566 L/s |
| Modeled flow | = | 62.22 L/s. |

*This is outside the allowable range

**Pipe 20 - 21**

| | | |
|---|---|---|
| Actual measured flow | = | 57.333 L/s |
| Allowable range | = | ± 5% |
| Max. Allowable | = | 60.199 L/s |
| Min. Allowable | = | 54.466 L/s |
| Modeled flow | = | 52.22 L/s. |

* This is outside the allowable range

**Node 29**

| | | |
|---|---|---|
| Actual measured pressure | = | 22.5 m |
| Allowable range | = | ± 0.5 m |
| Max. Allowable | = | 28.0 m |
| Min. Allowable | = | 23.0 m |
| Modeled pressure | = | 26.2 m |

* This is within the allowable range.

**Node 139A**

| | | |
|---|---|---|
| Actual measured pressure | = | 22.7 m |
| Allowable range | = | ± 0.5 m |
| Max. Allowable | = | 23.2 m |
| Min. Allowable | = | 22.2 m |
| Modeled pressure | = | 28.0 m |

* This is outside the allowable range.

**Node 20**

| | | |
|---|---|---|
| Actual measured pressure | = | 25.1 m |
| Allowable range | = | ± 0.5 m |
| Max. Allowable | = | 25.6 m |
| Min. Allowable | = | 24.6 m |
| Modeled pressure | = | 29.7 m |

* This is outside the allowable range.

**Model Calibration with Throttle Valve (THV) Added to the Outlet Main of Water Tower**

Most of the value of the modeled flows and pressures obtained after analysis given earlier are outside the range of the allowable values. Therefore the valve controlling flow to the distribution system was partly closed to reduce the pressure (and flow) to the distribution system and sustain slightly higher pressure for the tanker filling station.

At node 20 the modeled pressure is 29.7 m whereas the measured pressure is 25.1 m indicating a difference of 4.6 m. To match the modeled and measured pressures, the Throttled Valve was set, according to the following calculations (3).

$$D_p = 132.15\ Q2^2\ Kv^2$$
$$4.6 = 132.15 \times (114.77)^2 \times Kv^2$$
$$Kv = 615$$

Where :

$D_p$ : drop in pressure (m)
Q : flow ($m^3$/h)
throttling factor

Therefore for calibration the throttling valve was set at 615 (Table 6).

**Table 6: Throttle Valve Data in Network**

| Inlet Node | Outlet Node | Valve Type | Setting | Inlet Head (m) | Outlet Head (m) | Flow (L/s) | Status |
|---|---|---|---|---|---|---|---|
| TFS | 01 | THV | 615.00 | 40.90 | 36.29 | 114.77 | Active |

The ground levels corresponding to nodes 29 and 139A (Table 7) were used in the analysis in the beginning (Table 8). For calibration the actual levels above datum of these nodes, where pressures were measured were used in the analysis.

Node 29 = actual level is 12.476 m above National Datum
Node 139A = actual level is 11.296 m above National Datum

The model was analyzed after making these modifications i.e. setting of throttled valve and correcting the levels of nodes.

The results indicate that the modeled pressure at nodes 20 and 29 lies within the allowable range satisfying the calibration criteria i.e. ± 0.5 m expect node 139A.

Node - 139A = Actual measured pressure = 22.7 m
= Actual measured pressure = 23.3 m

which is slightly out of the range. This discrepancy was removed by adjusting the value of "C" which is discussed below.

**Model Calibration by Adjusting Hazen-William Coefficient "C"**

To remove the difference between the modeled and measured pressure, the value of Hazen-William Coefficient C was altered from 151 to 139 in stepwise manner (Table 10) in pipes between nodes 20-2-11 (Fig. 4). This section of the network was selected because the flow in this part is relatively large and lies outside the allowable range. The data and the results of analysis for network are presented in Tables 9 and 10 respectively. Due to the change in C-value the modeled flow came within the allowable range. This also brought the modeled pressure at node 139A within the allowable range. (Table 11).

This model is now a calibrated model because the modeled flows and pressures are within the allowable range set by the acceptable performance criteria mentioned earlier.

## Table 7: Total Demand and Available Head for Water Distribution Network After Activating Throttled Valve

| Node No. | Node Type | Total Demand (L/S) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/S)) |
|---|---|---|---|---|---|---|
| 01 | THV | 0.00 | 17.5 | 36.29 | 18.79 | |
| 02 | | 0.00 | 12.9 | 35.63 | 22.73 | |
| 03 | | 1.17 | 15.5 | 35.43 | 19.93 | |
| 04 | | 0.00 | 15.6 | 35.35 | 19.75 | |
| 05 | | 0.94 | 14.3 | 35.21 | 20.91 | |
| 06 | | 0.16 | 9.6 | 35.02 | 25.42 | |
| 07 | | 0.52 | 8.5 | 34.88 | 26.38 | |
| 08 | | 0.85 | 9.0 | 34.85 | 25.85 | |
| 09 | | 47.74 | 9.5 | 34.76 | 25.26 | |
| 10 | | 0.48 | 9.5 | 34.76 | 25.26 | |
| 11 | | 0.00 | 8.6 | 34.75 | 26.15 | |
| 12 | | 0.00 | 8.7 | 34.75 | 26.05 | |
| 12A | | 0.00 | 9.2 | 34.76 | 25.56 | |
| 12B | | 3.26 | 10.1 | 34.76 | 24.66 | |
| 12C | | 0.00 | 9.8 | 34.82 | 25.02 | |
| 12D | | 1.54 | 9.8 | 34.83 | 25.03 | |
| 13 | | 0.00 | 8.6 | 34.74 | 26.14 | |
| 130 | | 0.00 | 9.3 | 34.68 | 25.38 | |
| 130A | | 0.54 | 8.9 | 34.71 | 25.81 | |
| 131A | | 0.26 | 9.4 | 34.69 | 25.29 | |
| 132A | | 0.69 | 10.7 | 34.64 | 23.94 | |
| 1331 | | 0.03 | 11.6 | 34.65 | 23.05 | |
| 133A | | 11.77 | 10.6 | 34.62 | 24.02 | |
| 134A | | 0.00 | 11.7 | 34.62 | 22.92 | |
| 135A | | 0.47 | 10.9 | 34.62 | 23.72 | |
| 136A | | 0.00 | 11.2 | 34.62 | 23.42 | |

**Table 7: (Contd.)**

| Node No. | Node Type | Total Demand (L/S) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/S) |
|---|---|---|---|---|---|---|
| 137A | | 1.41 | 11.2 | 34.62 | 23.42 | |
| 139A | | 0.00 | 11.3 | 34.62 | 23.32 | |
| 13A | | 1.41 | 8.6 | 34.74 | 26.14 | |
| 14 | | 0.00 | 8.8 | 34.74 | 25.94 | |
| 140 | | 0.14 | 9.2 | 34.68 | 25.48 | |
| 140A | | 0.03 | 10.3 | 34.62 | 24.32 | |
| 141A | | 0.25 | 10.3 | 34.62 | 24.32 | |
| 142A | | 5.44 | 10.4 | 34.61 | 24.21 | |
| 15 | | 0.00 | 10.3 | 34.74 | 24.44 | |
| 150 | | 0.53 | 10.0 | 34.68 | 24.68 | |
| 155 | | 0.00 | 9.8 | 34.68 | 24.68 | |
| 1551 | | 0.47 | 11.7 | 34.63 | 22.93 | |
| 15A | | 0.03 | 10.5 | 34.75 | 24.25 | |
| 16 | | 0.00 | 9.3 | 34.74 | 25.44 | |
| 160 | | 0.00 | 9.5 | 34.71 | 25.21 | |
| 1600 | | 0.59 | 10.6 | 34.68 | 24.08 | |
| 161 | | 0.03 | 9.6 | 34.70 | 25.10 | |
| 162 | | 0.47 | 9.9 | 34.68 | 24.78 | |
| 163 | | 0.59 | 9.8 | 34.67 | 24.87 | |
| 164 | | 0.00 | 9.8 | 34.65 | 24.85 | |
| 165 | | 0.10 | 10.0 | 34.64 | 24.64 | |
| 166 | | 0.00 | 10.1 | 34.63 | 24.53 | |
| 167 | | 0.26 | 10.2 | 34.62 | 24.42 | |
| 168 | | 2.58 | 10.4 | 34.61 | 24.21 | |
| 17 | | 0.00 | 9.3 | 34.74 | 25.44 | |
| 170 | | 0.00 | 9.2 | 34.67 | 25.47 | |
| 175 | | 0.00 | 10.1 | 34.67 | 24.57 | |
| 18 | | 3.76 | 10.8 | 34.74 | 23.94 | |
| 180 | | 0.00 | 10.4 | 34.66 | 24.26 | |

**Table 7: (Contd.)**

| Node | Node Type | Total Demand (L/S) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/S) |
|---|---|---|---|---|---|---|
| 185 | | 0.00 | 10.4 | 34.62 | 24.22 | |
| 20 | | 0.00 | 10.6 | 35.72 | 25.07 | |
| 21 | | 3.09 | 11.4 | 35.59 | 24.19 | |
| 22 | | 0.00 | 11.6 | 35.58 | 23.98 | |
| 23 | | 1.05 | 17.2 | 35.22 | 18.02 | |
| 24 | | 3.30 | 15.6 | 35.06 | 19.46 | |
| 25 | | 1.47 | 13.8 | 35.01 | 21.21 | |
| 26 | | 0.00 | 12.6 | 34.95 | 22.35 | |
| 27 | | 1.41 | 14.0 | 34.93 | 20.93 | |
| 28 | | 0.47 | 14.0 | 34.93 | 20.93 | |
| 29 | | 0.00 | 12.5 | 34.92 | 22.45 | |
| 30 | | 7.77 | 13.3 | 34.92 | 21.62 | |
| 31 | | 0.30 | 12.8 | 34.92 | 22.12 | |
| 32 | | 7.40 | 11.6 | 34.91 | 23.31 | |
| TFS | THV | 106.14 | 17.5 | 40.90 | 23.40 | |
| WT20 | RESR | 0.00 | 17.5 | 41.00 | 23.50 | 220.91 |

## Table 8: Results of Analysis for Water Distribution Network After Activating Throttled Valve

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 01 | 20 | 400 | 375 | 151 | 114.77 | 0.91 | 0.58 | 1.5 |
| 02 | 03 | 400 | 405 | 139 | 60.22 | 0.48 | 0.22 | 0.5 |
| 02 | 20 | 400 | 170 | 139 | -60.22 | -0.48 | -0.09 | -0.5 |
| 03 | 04 | 400 | 170 | 139 | 59.05 | 0.47 | 0.09 | 0.5 |
| 04 | 05 | 400 | 305 | 139 | 59.05 | 0.47 | 0.16 | 0.5 |
| 05 | 06 | 400 | 395 | 139 | 58.11 | 0.46 | 0.20 | 0.5 |
| 06 | 07 | 400 | 305 | 139 | 57.95 | 0.46 | 0.15 | 0.5 |
| 07 | 08 | 400 | 75 | 139 | 57.43 | 0.46 | 0.04 | 0.5 |
| 08 | 09 | 400 | 200 | 139 | 56.58 | 0.45 | 0.10 | 0.5 |
| 09 | 10 | 400 | 125 | 139 | 8.84 | 0.07 | 0.00 | 0.0 |
| 10 | 11 | 400 | 294 | 139 | 8.36 | 0.07 | 0.00 | 0.0 |
| 11 | 12 | 400 | 160 | 151 | 8.36 | 0.07 | 0.00 | 0.0 |
| 12 | 12A | 300 | 180 | 150 | -11.68 | -0.17 | -0.02 | -0.1 |
| 12 | 13 | 400 | 55 | 151 | 20.04 | 0.16 | 0.00 | 0.1 |
| 12A | 12B | 300 | 30 | 150 | -11.68 | -0.17 | 0.00 | -0.1 |
| 12B | 12C | 300 | 285 | 150 | -17.97 | -0.25 | -0.06 | -0.2 |
| 12B | 15A | 150 | 45 | 149 | 4.45 | 0.25 | 0.02 | 0.4 |
| 12C | 12D | 300 | 25 | 150 | -19.40 | -0.27 | -0.01 | -0.2 |
| 12D | 26 | 300 | 500 | 150 | -20.94 | -0.30 | -0.14 | -0.3 |
| 13 | 13A | 400 | 70 | 151 | 22.97 | 0.18 | 0.01 | 0.1 |
| 13 | 14 | 400 | 25 | 151 | -2.93 | -0.02 | 0.00 | 0.0 |
| 130 | 131A | 200 | 40 | 150 | -5.60 | -0.18 | -0.01 | -0.1 |
| 130 | 1331 | 100 | 125 | 148 | 1.03 | 0.13 | 0.03 | 0.2 |
| 130 | 140 | 200 | 25 | 150 | 4.57 | 0.15 | 0.00 | 0.1 |
| 130A | 131A | 300 | 95 | 150 | 21.02 | 0.30 | 0.03 | 0.3 |
| 130A | 13A | 300 | 90 | 150 | -21.56 | -0.30 | -0.03 | -0.3 |

**Table 8: (Contd.)**

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 131A | 132A | 300 | 330 | 150 | 15.16 | -0.21 | -0.03 | -0.1 |
| 132A | 133A | 300 | 145 | 150 | 14.47 | 0.20 | 0.02 | 0.1 |
| 1331 | 1551 | 100 | 140 | 148 | 1.00 | 0.13 | 0.03 | 0.2 |
| 133A | 134A | 300 | 100 | 150 | 2.70 | 0.04 | 0.00 | 0.0 |
| 134A | 135A | 300 | 185 | 150 | 2.70 | 0.04 | 0.00 | 0.0 |
| 135A | 136A | 300 | 55 | 150 | 2.76 | 0.04 | 0.00 | 0.0 |
| 135A | 1551 | 100 | 105 | 148 | -0.53 | -0.07 | -0.01 | -0.1 |
| 136A | 137A | 300 | 20 | 150 | 2.76 | 0.04 | 0.00 | 0.0 |
| 137A | 139A | 300 | 70 | 150 | 1.35 | 0.02 | 0.00 | 0.0 |
| 139A | 140A | 300 | 125 | 150 | 1.35 | 0.02 | 0.00 | 0.0 |
| 14 | 15 | 400 | 45 | 151 | -1.86 | -0.01 | 0.00 | 0.0 |
| 14 | 17 | 400 | 160 | 151 | -1.07 | 0.01 | 0.00 | 0.0 |
| 140 | 150 | 200 | 35 | 150 | 4.78 | 0.15 | 0.00 | 0.1 |
| 140 | 1600 | 100 | 85 | 148 | -0.34 | -0.04 | 0.00 | 0.0 |
| 140A | 141A | 300 | 85 | 150 | 5.56 | 0.08 | 0.00 | 0.0 |
| 140A | 185 | 200 | 80 | 150 | -4.25 | -0.14 | -0.01 | -0.1 |
| 141A | 142A | 300 | 55 | 150 | 5.31 | 0.08 | 0.00 | 0.0 |
| 142A | 168 | 300 | 30 | 150 | -0.13 | 0.00 | 0.00 | 0.0 |
| 15 | 15A | 300 | 160 | 150 | -4.43 | -0.06 | 0.00 | 0.0 |
| 15 | 16 | 400 | 180 | 151 | 2.57 | 0.02 | 0.00 | 0.0 |
| 150 | 155 | 200 | 15 | 150 | 4.25 | 0.14 | 0.00 | 0.1 |
| 155 | 170 | 200 | 65 | 150 | 4.25 | 0.14 | 0.00 | 0.1 |
| 16 | 160 | 150 | 60 | 149 | 5.09 | 0.29 | 0.03 | 0.6 |
| 16 | 17 | 400 | 45 | 151 | -2.52 | -0.02 | 0.00 | 0.0 |
| 160 | 1600 | 100 | 155 | 148 | 0.93 | 0.12 | 0.03 | 0.2 |

**Table 8: (Contd.)**

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 160 | 161 | 150 | 40 | 149 | 4.16 | 0.24 | 0.02 | 0.4 |
| 161 | 162 | 150 | 45 | 149 | 4.14 | 0.23 | 0.02 | 0.4 |
| 162 | 163 | 150 | 35 | 149 | 3.67 | 0.21 | 0.01 | 0.3 |
| 163 | 164 | 150 | 70 | 149 | 3.07 | 0.17 | 0.1 | 0.2 |
| 164 | 165 | 150 | 65 | 149 | 3.07 | 0.17 | 0.01 | 0.2 |
| 165 | 166 | 150 | 65 | 149 | 2.98 | 0.17 | 0.01 | 0.2 |
| 166 | 167 | 150 | 33 | 149 | 2.98 | 0.17 | 0.01 | 0.2 |
| 167 | 168 | 150 | 35 | 149 | 2.71 | 0.15 | 0.01 | 0.2 |
| 17 | 18 | 400 | 115 | 151 | -3.60 | -0.03 | 0.00 | 0.0 |
| 170 | 175 | 200 | 80 | 150 | 4.25 | 0.14 | 0.01 | 0.1 |
| 175 | 180 | 200 | 85 | 150 | 4.25 | 0.14 | 0.01 | 0.1 |
| 18 | 32 | 200 | 695 | 150 | -7.36 | -0.23 | -0.20 | -0.3 |
| 180 | 185 | 100 | 20 | 148 | 4.25 | 0.54 | 0.04 | 1.9 |
| 20 | 21 | 400 | 355 | 151 | 54.55 | 0.43 | 0.14 | 0.4 |
| 21 | 22 | 400 | 40 | 151 | 51.46 | 0.41 | 0.01 | 0.3 |
| 22 | 23 | 400 | 1110 | 151 | 51.46 | 0.41 | 0.39 | 0.3 |
| 23 | 24 | 400 | 515 | 151 | 50.41 | 0.40 | 0.17 | 0.3 |
| 24 | 25 | 400 | 172 | 151 | 47.11 | 0.37 | 0.05 | 0.3 |
| 25 | 26 | 400 | 245 | 151 | 45.64 | 0.36 | 0.07 | 0.3 |
| 26 | 27 | 400 | 180 | 151 | 24.71 | 0.20 | 0.02 | 0.1 |
| 27 | 28 | 400 | 10 | 151 | 23.30 | 0.19 | 0.00 | 0.1 |
| 28 | 29 | 400 | 105 | 151 | 22.83 | 0.18 | 0.01 | 0.1 |
| 29 | 30 | 400 | 65 | 151 | 22.83 | 0.18 | 0.01 | 0.1 |
| 30 | 31 | 400 | 20 | 151 | 15.06 | 0.12 | 0.00 | 0.0 |
| 31 | 32 | 400 | 125 | 151 | 14.76 | 0.12 | 0.00 | 0.0 |
| TFS | WT20 | 400 | 20 | 151 | -220.91 | -1.76 | -0.10 | -5.2 |

**Table 9: Total Demand and Available Head for Calibrated Model**

| Node No. | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 01 | THV | 0.00 | 17.5 | 36.29 | 18.79 | |
| 02 | | 0.00 | 12.9 | 35.63 | 22.73 | |
| 03 | | 1.17 | 15.5 | 35.41 | 19.91 | |
| 04 | | 0.00 | 15.6 | 35.32 | 19.72 | |
| 05 | | 0.94 | 14.3 | 35.16 | 20.86 | |
| 06 | | 0.16 | 9.6 | 34.96 | 25.36 | |
| 07 | | 0.52 | 8.5 | 34.80 | 26.30 | |
| 08 | | 0.85 | 9.0 | 34.76 | 25.76 | |
| 09 | | 47.74 | 9.5 | 34.67 | 25.17 | |
| 10 | | 0.48 | 9.5 | 34.67 | 25.17 | |
| 11 | | 0.00 | 8.6 | 34.66 | 26.06 | |
| 12 | | 0.00 | 8.7 | 34.66 | 25.96 | |
| 12A | | 0.00 | 9.2 | 34.68 | 25.48 | |
| 12B | | 3.26 | 10.1 | 34.68 | 24.58 | |
| 12C | | 0.00 | 9.8 | 34.75 | 24.95 | |
| 12D | | 1.54 | 9.8 | 34.75 | 24.95 | |
| 13 | | 0.00 | 8.6 | 34.66 | 26.06 | |
| 130 | | 0.00 | 9.3 | 34.59 | 25.29 | |
| 130A | | 0.54 | 8.9 | 34.62 | 25.72 | |
| 131A | | 0.26 | 9.4 | 34.60 | 25.20 | |
| 132A | | 0.69 | 10.7 | 34.55 | 23.85 | |
| 1331 | | 0.03 | 11.6 | 34.57 | 22.97 | |
| 133A | | 11.77 | 10.6 | 34.53 | 23.93 | |
| 134A | | 0.00 | 11.7 | 34.53 | 22.83 | |
| 135A | | 0.47 | 10.9 | 34.53 | 23.63 | |

**Table 9: (Contd.)**

| Node No. | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 136A | | 0.00 | 11.2 | 34.53 | 23.33 | |
| 137A | | 1.41 | 11.2 | 34.53 | 23.33 | |
| 139A | | 0.00 | 11.3 | 34.53 | 23.23 | |
| 13A | | 1.41 | 8.6 | 34.65 | 26.05 | |
| 14 | | 0.00 | 8.8 | 34.66 | 25.86 | |
| 140 | | 0.14 | 9.2 | 34.59 | 25.39 | |
| 140A | | 0.03 | 10.3 | 34.53 | 24.23 | |
| 141A | | 0.25 | 10.3 | 34.53 | 24.23 | |
| 142A | | 5.44 | 10.4 | 34.53 | 24.13 | |
| 15 | | 0.00 | 10.3 | 34.66 | 24.36 | |
| 150 | | 0.53 | 10.0 | 34.59 | 24.59 | |
| 155 | | 0.00 | 9.8 | 34.59 | 24.79 | |
| 1551 | | 0.47 | 11.7 | 34.54 | 22.84 | |
| 15A | | 0.03 | 10.5 | 34.66 | 24.16 | |
| 16 | | 0.00 | 9.3 | 34.66 | 25.36 | |
| 160 | | 0.00 | 9.5 | 34.62 | 15.12 | |
| 1600 | | 0.59 | 10.6 | 34.59 | 23.99 | |
| 161 | | 0.03 | 9.6 | 34.61 | 25.01 | |
| 162 | | 0.47 | 9.9 | 34.59 | 24.69 | |
| 163 | | 0.59 | 9.8 | 34.58 | 24.78 | |
| 164 | | 0.00 | 9.8 | 34.56 | 24.76 | |
| 165 | | 0.10 | 10.0 | 34.55 | 24.55 | |
| 166 | | 0.00 | 10.1 | 34.54 | 24.44 | |
| 167 | | 0.26 | 10.2 | 34.53 | 24.33 | |
| 168 | | 2.58 | 10.4 | 34.53 | 24.13 | |
| 17 | | 0.00 | 9.3 | 34.66 | 25.36 | |
| 170 | | 0.00 | 9.2 | 34.58 | 25.38 | |
| 175 | | 0.00 | 10.1 | 34.58 | 24.48 | |
| 18 | | 3.76 | 10.8 | 34.66 | 23.86 | |
| 180 | | 0.00 | 10.4 | 34.57 | 24.17 | |

**Table 9: (Contd.)**

| Node No. | Node Type | Total Demand (L/s) | Ground Level (m) | Total Head (m) | Available Head (m) | Supply (L/s) |
|---|---|---|---|---|---|---|
| 185 | | 0.00 | 10.4 | 34.53 | 24.13 | |
| 20 | | 0.00 | 10.6 | 35.72 | 25.07 | |
| 21 | | 3.09 | 11.4 | 35.58 | 24.18 | |
| 22 | | 0.00 | 11.6 | 35.57 | 23.97 | |
| 23 | | 1.05 | 17.2 | 35.18 | 17.98 | |
| 24 | | 3.30 | 15.6 | 35.01 | 19.41 | |
| 25 | | 1.47 | 13.8 | 34.96 | 21.16 | |
| 26 | | 0.00 | 12.6 | 34.89 | 22.29 | |
| 27 | | 1.41 | 14.0 | 34.87 | 20.87 | |
| 28 | | 0.47 | 14.0 | 34.87 | 20.87 | |
| 29 | | 0.00 | 12.5 | 34.86 | 22.39 | |
| 30 | | 7.77 | 13.3 | 34.86 | 21.56 | |
| 31 | | 0.30 | 12.8 | 34.86 | 22.06 | |
| 32 | | 7.40 | 11.6 | 34.85 | 23.25 | |
| TFS | THV | 106.14 | 17.2 | 40.90 | 23.40 | |
| WT20 | RESR | 0.00 | 17.5 | 41.00 | 23.50 | 220.91 |

## Table 10: Results of Analysis for Calibrated Model

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 01 | 20 | 400 | 375 | 151 | 114.77 | 0.91 | 0.58 | 1.5 |
| 02 | 03 | 400 | 405 | 139 | 60.22 | 0.48 | 0.22 | 0.5 |
| 02 | 20 | 400 | 170 | 139 | -60.22 | -0.48 | -0.09 | -0.5 |
| 03 | 04 | 400 | 170 | 139 | 59.05 | 0.47 | 0.09 | 0.5 |
| 04 | 05 | 400 | 305 | 139 | 59.05 | 0.47 | 0.16 | 0.5 |
| 05 | 06 | 400 | 395 | 139 | 58.11 | 0.46 | 0.20 | 0.5 |
| 06 | 07 | 400 | 305 | 139 | 57.95 | 0.46 | 0.15 | 0.5 |
| 07 | 08 | 400 | 75 | 139 | 57.43 | 0.46 | 0.04 | 0.5 |
| 08 | 09 | 400 | 200 | 139 | 56.58 | 0.45 | 0.10 | 0.5 |
| 09 | 10 | 400 | 125 | 139 | 8.84 | 0.07 | 0.00 | 0.0 |
| 10 | 11 | 400 | 294 | 139 | 8.36 | 0.07 | 0.00 | 0.0 |
| 11 | 12 | 400 | 160 | 151 | 8.36 | 0.07 | 0.00 | 0.0 |
| 12 | 12A | 300 | 180 | 150 | -11.68 | -0.17 | -0.02 | -0.1 |
| 12 | 13 | 400 | 55 | 151 | 20.04 | 0.16 | 0.00 | 0.1 |
| 12A | 12B | 300 | 30 | 150 | -11.68 | -0.17 | 0.00 | -0.1 |
| 12B | 12C | 300 | 285 | 150 | -17.97 | -0.25 | -0.06 | -0.2 |
| 12B | 15A | 150 | 45 | 149 | 4.45 | 0.25 | 0.02 | 0.4 |
| 12C | 12D | 300 | 25 | 150 | -19.40 | -0.27 | -0.01 | -0.2 |
| 12D | 26 | 300 | 500 | 150 | -20.94 | -0.30 | -0.14 | -0.3 |
| 13 | 13A | 400 | 70 | 151 | 22.97 | 0.18 | 0.01 | 0.1 |
| 13 | 14 | 400 | 25 | 151 | -2.93 | -0.02 | 0.00 | 0.0 |
| 130 | 131A | 200 | 40 | 150 | -5.60 | -0.18 | -0.01 | -0.1 |
| 130 | 1331 | 100 | 125 | 148 | 1.03 | 0.13 | 0.03 | 0.2 |
| 130 | 140 | 200 | 25 | 150 | 4.57 | 0.15 | 0.00 | 0.1 |
| 130A | 131A | 300 | 95 | 150 | 21.02 | 0.30 | 0.03 | 0.3 |
| 130A | 13A | 300 | 90 | 150 | -21.56 | -0.30 | -0.03 | -0.3 |

**Table 10: (Contd.)**

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 131A | 132A | 300 | 330 | 150 | 15.16 | -0.21 | -0.03 | -0.1 |
| 132A | 133A | 300 | 145 | 150 | 14.47 | 0.20 | 0.02 | 0.1 |
| 1331 | 1551 | 100 | 140 | 148 | 1.00 | 0.13 | 0.03 | 0.2 |
| 133A | 134A | 300 | 100 | 150 | 2.70 | 0.04 | 0.00 | 0.0 |
| 134A | 135A | 300 | 185 | 150 | 2.70 | 0.04 | 0.00 | 0.0 |
| 135A | 136A | 300 | 55 | 150 | 2.76 | 0.04 | 0.00 | 0.0 |
| 135A | 1551 | 100 | 105 | 148 | -0.53 | -0.07 | -0.01 | -0.1 |
| 136A | 137A | 300 | 20 | 150 | 2.76 | 0.04 | 0.00 | 0.0 |
| 137A | 139A | 300 | 70 | 150 | 1.35 | 0.02 | 0.00 | 0.0 |
| 139A | 140A | 300 | 125 | 150 | 1.35 | 0.02 | 0.00 | 0.0 |
| 14 | 15 | 400 | 45 | 151 | -1.86 | -0.01 | 0.00 | 0.0 |
| 14 | 17 | 400 | 160 | 151 | -1.07 | 0.01 | 0.00 | 0.0 |
| 140 | 150 | 200 | 35 | 150 | 4.78 | 0.15 | 0.00 | 0.1 |
| 140 | 1600 | 100 | 85 | 148 | -0.34 | -0.04 | 0.00 | 0.0 |
| 140A | 141A | 300 | 85 | 150 | 5.56 | 0.08 | 0.00 | 0.0 |
| 140A | 185 | 200 | 80 | 150 | -4.25 | -0.14 | -0.01 | -0.1 |
| 141A | 142A | 300 | 55 | 150 | 5.31 | 0.08 | 0.00 | 0.0 |
| 142A | 168 | 300 | 30 | 150 | -0.13 | 0.00 | 0.00 | 0.0 |
| 15 | 15A | 300 | 160 | 150 | -4.43 | -0.06 | 0.00 | 0.0 |
| 15 | 16 | 400 | 180 | 151 | 2.57 | 0.02 | 0.00 | 0.0 |
| 150 | 155 | 200 | 15 | 150 | 4.25 | 0.14 | 0.00 | 0.1 |
| 155 | 170 | 200 | 65 | 150 | 4.25 | 0.14 | 0.00 | 0.1 |
| 16 | 160 | 150 | 60 | 149 | 5.09 | 0.29 | 0.03 | 0.6 |
| 16 | 17 | 400 | 45 | 151 | -2.52 | -0.02 | 0.00 | 0.0 |
| 160 | 1600 | 100 | 155 | 148 | 0.93 | 0.12 | 0.03 | 0.2 |

## Table 10: (Contd.)

| From Node | To Node | Diam. (mm) | Length (m) | Frict. | Flow (L/s) | Velocity (m/s) | Headloss (m) | Headloss Gradient (m/Km) |
|---|---|---|---|---|---|---|---|---|
| 160 | 161 | 150 | 40 | 149 | 4.16 | 0.24 | 0.02 | 0.4 |
| 161 | 162 | 150 | 45 | 149 | 4.14 | 0.23 | 0.02 | 0.4 |
| 162 | 163 | 150 | 35 | 149 | 3.67 | 0.21 | 0.01 | 0.3 |
| 163 | 164 | 150 | 70 | 149 | 3.07 | 0.17 | 0.1 | 0.2 |
| 164 | 165 | 150 | 65 | 149 | 3.07 | 0.17 | 0.01 | 0.2 |
| 165 | 166 | 150 | 65 | 149 | 2.98 | 0.17 | 0.01 | 0.2 |
| 166 | 167 | 150 | 33 | 149 | 2.98 | 0.17 | 0.01 | 0.2 |
| 167 | 168 | 150 | 35 | 149 | 2.71 | 0.15 | 0.01 | 0.2 |
| 17 | 18 | 400 | 115 | 151 | -3.60 | -0.03 | 0.00 | 0.0 |
| 170 | 175 | 200 | 80 | 150 | 4.25 | 0.14 | 0.01 | 0.1 |
| 175 | 180 | 200 | 85 | 150 | 4.25 | 0.14 | 0.01 | 0.1 |
| 18 | 32 | 200 | 695 | 150 | -7.36 | -0.23 | -0.20 | -0.3 |
| 180 | 185 | 100 | 20 | 148 | 4.25 | 0.54 | 0.04 | 1.9 |
| 20 | 21 | 400 | 355 | 151 | 54.55 | 0.43 | 0.14 | 0.4 |
| 21 | 22 | 400 | 40 | 151 | 51.46 | 0.41 | 0.01 | 0.3 |
| 22 | 23 | 400 | 1110 | 151 | 51.46 | 0.41 | 0.39 | 0.3 |
| 23 | 24 | 400 | 515 | 151 | 50.41 | 0.40 | 0.17 | 0.3 |
| 24 | 25 | 400 | 172 | 151 | 47.11 | 0.37 | 0.05 | 0.3 |
| 25 | 26 | 400 | 245 | 151 | 45.64 | 0.36 | 0.07 | 0.3 |
| 26 | 27 | 400 | 180 | 151 | 24.71 | 0.20 | 0.02 | 0.1 |
| 27 | 28 | 400 | 10 | 151 | 23.30 | 0.19 | 0.00 | 0.1 |
| 28 | 29 | 400 | 105 | 151 | 22.83 | 0.18 | 0.01 | 0.1 |
| 29 | 30 | 400 | 65 | 151 | 22.83 | 0.18 | 0.01 | 0.1 |
| 30 | 31 | 400 | 20 | 151 | 15.06 | 0.12 | 0.00 | 0.0 |
| 31 | 32 | 400 | 125 | 151 | 14.76 | 0.12 | 0.00 | 0.0 |
| TFS | WT20 | 400 | 20 | 151 | -220.91 | -1.76 | -0.10 | -5.2 |

**Table 11: Water Distribution System Simulation Model Calibration Results Garrafa District, Doha (from Tables 9 & 10)**

| Identification | Measured Values | | Modeled Values | |
|---|---|---|---|---|
| | Flow | Pressure $m^3/s$ | Pressure m | % Error |
| Pipe 20-02 | 57.438 | - | - | 4.84% |
| Pipe 20-21 | 57.333 | - | - | -5.03% |
| Node 20 | - | 25.1 | 25.07 | -0.12% |
| Node 29 | - | 22.5 | 22.39 | -0.50% |
| Node 139 A | - | 22.7 | 23.23 | -2.30% |

## Future Development

The effect of the future development on the number of consumers connected to the network and the consequent expansion of the distribution network was also studied as follows:

a) The demand at various nodes in the distribution system was increased to simulate increasing demand from existing consumers and additional demand from added consumers.

b) The demand at the tanker filling station was kept at the same level to simulate replacement of existing consumers who will receive water by tankers outside the distribution system.

After this modification the network was analyzed to find if the pressure of water at any node, falls below an acceptable level i.e. 10m, which is the acceptable minimum distribution pressure set by the Ministry of Electricity and Water. It was found that the pressure at none of the nodes falls below 10m. This pressure is sufficient to fill the ground storage tank in every property.

## CONCLUSION

The analysis indicates that the flow velocity in pipes and headlosses in general are within the allowable limits and none of the nodes has a negative pressure. The pressure at the nodes are sufficient to supply water to the ground storage tank in every property.

A comparison between the modeled flows and pressures and recorded field data indicates that the acceptable performance criteria was not met. However, the difference between the modeled and measured flows came within the allowable range after calibration thus satisfying the performance criteria.

After taking into account the increased number of consumers in future the analysis indicated that the pressure of water at none of the nodes falls below an acceptable level i.e. 10m, which is the acceptable minimum distribution pressure set by the Water Department.

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