Internship Report

on

Hydraulic and water quality modeling of water distribution systems using EPANET – an open-source package

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ABSTRACT

This report outlines the learning experiences during the internship at IIT Kanpur on the project titled "Hydraulic and water quality modelling of water distribution systems using EPANET- an open-source package". Water distribution systems (WDS) are critical to delivering clean water at the required quantities and qualities. They are interconnected assemblies of reservoirs, tanks, pipes, and hydraulic control elements and are considered the critical infrastructure of every modern community. Due to their complexity, computer-based tools adept at simulating hydraulic and water quality dynamics are integral in their design and operation. EPANET, an open-source package developed by the United States Environmental Protection Agency, is one of the most popular computed-based tools employed for WDS analysis. The work primarily involved using EPANET 2.2, the latest version, for hydraulic analysis (both single period and extended period) of continuously operating water distribution systems (WDS). Additionally, the focus was on modelling intermittent WDS using EPANET, which is a significant research problem due to its relevance to how consumers adapt to intermittent water supply practices. This adaptation was simulated using the EPANET 2.2 engine and its open-source Python-based extension, EPANET-IWS. Simulations were performed on two networks, a benchmark WDS and a real world rural WDS from South India. The results were analyzed to calculate the mean volume deficit at different consumer nodes across three different operating scenarios, allowing for a comparative analysis. This analysis is crucial for developing strategies to optimize water distribution and improve consumer satisfaction in regions with unreliable water supply. The project also included quality analysis of the network, focusing on chlorine dosing at the source.

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1.INTRODUCTION

1.1 Importance and Challenges in Water Distribution System

Water is an essential resource for sustaining life, and its efficient distribution is crucial for the health and well-being of communities. Modern water distribution systems (WDS) are intricate networks of reservoirs, tanks, pipes, pumps and valves designed to deliver water from sources to consumers at the required quality and quantity. WDS are vital for delivering clean, safe water to communities, but they face numerous challenges, particularly in regions experiencing rapid urbanization and resource constraints. These systems are foundational to the infrastructure of every urban and rural community. Many regions, especially rural areas, face issues with IWS where water is available only for certain periods of the day. The IWS not only affects the daily lives of residents but also poses significant public health risks due to the potential for contamination when pipes are not continuously filled.

1.2 Intermittent Water Supply

The IWS is a prevalent issue in many developing regions, including rural and urban areas of India. This practice, where water is provided to consumers only at specific times, is often a result of inadequate infrastructure, limited water resources, and high demand. Some particular challenges associated with IWS include:

- Public Health Risks: When pipes are empty, contaminants can enter through leaks and cracks. When the supply resumes, these contaminants can be carried into households, posing health risks.
- Consumer Adaptation: Households often adapt by storing water in various containers, which may not be sanitized properly, leading to secondary contamination.
- Operational Complexity: Managing an IWS system requires precise control and monitoring to ensure equitable distribution, which can be technologically and logistically challenging.

1.3 Role of Hydraulic and Water Quality Modeling

Due to the complexity of WDS, computer-based tools adept at simulating the hydraulic and the water quality dynamics are integral in their design, operation, and optimization. Hydraulic modeling helps in understanding how water flows through the system, the pressure in the nodes, pipes, and head loss. It ensures the operation of pumps and valves to reduce energy consumption and operational costs. It identifies and manages leaks in the system by analyzing pressure drops and flow variations. It also simulates different scenarios such as fire flow conditions, peak demand periods, and systems failures to ensure the network can handle emergencies. Water quality modeling focuses on the chemical and biological characteristics of the water as it travels through the distribution system. It ensures that disinfectant levels (chlorine) are maintained throughout the system to prevent microbial growth and contamination. It analyses the mixing behavior in storage tanks and the age of water in the system to prevent stagnation and degradation of water quality. It helps in understanding how different source waters blend and affect overall water quality in the distribution system. Modeling IWS systems using tools like EPANET is crucial for understanding these dynamics and developing strategies to mitigate the negative impacts.

1.4 Scope and Objectives of the Project

The adoption of the EPANET 2.2 and the EPANET-Python (EPyT) toolkit for hydraulic and water quality analysis of intermittent and continuous WDS is discussed in this report. Two networks (widely used EPANET 3, i.e., Net3 network and Suvarnadhara network, a real-world WDS) were used in the study. The benchmark network, Net3, is an altered rendition of North Marin, California, USA's original WDS. The Suvarnadhara is a recently designed rural WDS in Kerela, India. The emphasis was on using EPANET to model intermittent operation of WDS, an important research subject since it involves several complexities, especially pertaining to how customers adjust to IWS practices. The project also includes a quality modeling component with an emphasis on chlorine decay. The primary objectives of this study were:

- To perform hydraulic analysis (both single period and extended period) of continuously operating water distribution systems using EPANET 2.2.
- To model intermittent water distribution systems using the EPANET engine via the EPyT tool-kit.
- To simulate real-world scenarios and analyze the mean volume deficit at different consumer nodes.
- To conduct water quality analysis, focusing on chlorine decay modeling.

2. LITERATURE REVIEW

2.1 EPANET

EPANET (Environmental Protection Agency Network Evaluation Tool), developed by the United States Environmental Protection Agency, is a widely-used open-source software that performs extended period simulation of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves, and storage tanks or reservoirs. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age, and source tracing can also be simulated. It is designed to be a research tool for improving our understanding of the movement and fate of drinking water constituents within WDS. It can be used for many kinds of applications in WDS analysis, sampling program design, hydraulic model calibration, chlorine residual analysis, and consumer exposure assessment, etc. For advanced study and versatile network customization, the EPANET Python toolkit, EPyT, offers powerful tools and capabilities. In India, the problem of intermittent water supply affects many rural and urban areas. EPANET models the physical objects that constitute a distribution system as well as its operational parameters. It models a water distribution system as a collection of links connected to nodes. The links represent pipes, pumps, and control valves. The nodes represent junctions, tanks, and reservoirs. Fig 3.2.1 below is prime example which illustrates how these objects can be connected to one another to form a network.

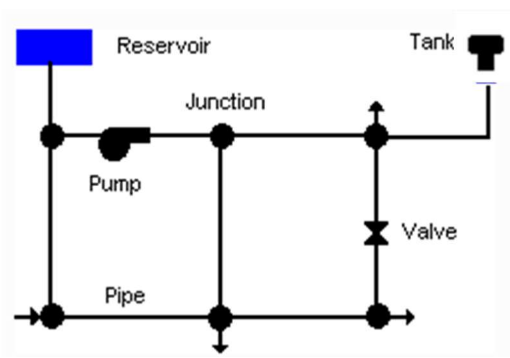

Figure 1: Physical Components in WDS

2.2 Hydraulic Modeling of WDS

EPANET's hydraulic simulation model computes hydraulic heads at junctions and flow rates through links for a fixed set of reservoir levels, tank levels, and water demands over a succession of points in time. From one time step to the next reservoir levels and junction demands are updated according to their prescribed time patterns while tank levels are updated using the current flow solution. The solution for heads and flows at a particular point in time involves solving simultaneously the conservation of flow equation for each junction and the head loss relationship across each link in the network. This process, known as hydraulically balancing the network, requires using an iterative technique to solve the nonlinear equations involved. EPANET employs the Global Gradient Algorithm for this purpose. It allows for two different ways of modeling water demands (i.e. consumption) at network junction nodes. Demand Driven Analysis requires that demands at each point in time are fixed values that must be delivered no matter what nodal pressures and link flows are produced by a hydraulic solution. This has been the classical approach used to model demands, but it can result in situations where required demands are satisfied at nodes with negative pressures - a physical impossibility. An alternative approach, known as Pressure Driven Analysis (PDA), allows the actual demand delivered at a node to depend on the node's pressure. Below some minimum pressure demand is zero, above some service pressure the full required demand is supplied and in between demand varies as a power law function of pressure. Using PDA is one way to avoid having positive demands at nodes with negative pressures. EPANET's Hydraulic Analysis Options are used to select a choice of demand model and to supply the parameters used by PDA.

2.3 Water Quality Modeling of WDS

EPANET's water quality simulator employs a Lagrangian time-step approach to monitor the movement and interaction of distinct water parcels within the network. This method tracks the parcels as they traverse through pipes and blend at junctions, all within set time intervals. These water quality time steps are typically much shorter than hydraulic time step (e.g., minutes rather than hours) to accommodate the short times of travel that can occur within pipes. It can track the growth or decay of a substance by reaction as it travels through a distribution system. In order to do this, it needs to know the rate at which the substance reacts and how this rate might depend on substance concentration. Reactions can occur both within the bulk flow and with material along the pipe wall. This is illustrated in Figure 1. In this example free chlorine (HOCl) is shown reacting with natural organic matter (NOM) in the bulk phase and is also transported through a boundary layer at the pipe wall to oxidize iron (Fe) released from the pipe wall. Bulk fluid reactions can also occur within tanks. EPANET allows a modeler to treat these two reaction zones separately.

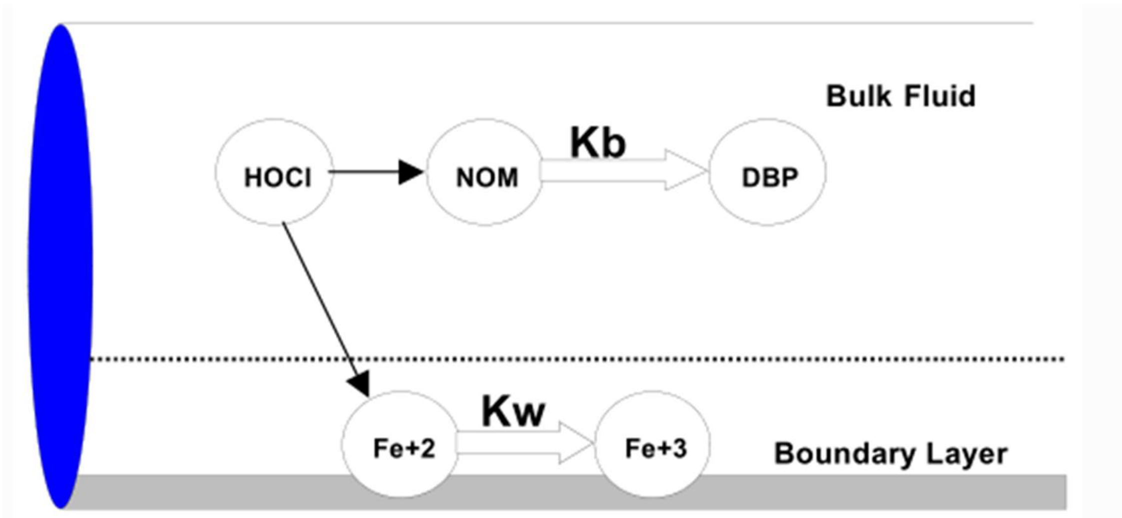

Figure 2: Reaction Zones within a pipe

2.4 Recent Advances in IWS Modeling Research

IWS systems are prevalent in regions with limited water resources and aging infrastructure. Understanding consumer behavior in these systems is crucial for optimizing water distribution and ensuring public health. Studies by Abhijith et al. (2023) highlight key coping strategies such as water storage practices, demand adjustment, clock time of water availability in IWS systems which can significantly influence consumers' ability to fill their storage tanks and meet water demands. Their study also highlighted that the positioning of consumers relative to the source tank is an essential factor in controlling their ability to withdraw, store, and use water during IWS practice.

Hydraulic and water quality modeling play a vital role in managing IWS systems. Abhijith et al. (2023) developed the EPyT-IWS tool kit to simulate IWS systems' dynamics. A modified version of the same, EPANET-IWS, is adopted in this study. This tool allows for the simulation of hydraulic behavior and water quality parameters, such as residual chlorine level. The parameters for water quality analysis, such as the bulk coefficient and wall coefficient, were derived from the work of Abhijith and S. Mohan (2020), aiding in the accurate modeling of chlorine decay and distribution within the network.

In conclusion, integrating consumer behavior insights and advanced modeling techniques is essential for developing effective and equitable water distribution strategies. The present study, leveraging the recent advancements in modeling (EPANET-IWS) and informed by key literature, aims to provide a detailed analysis of hydraulic and water quality dynamics in IWS systems.

3. METHODOLOGY

3.1 Data Collection

In this study, two networks were used. The first one is EPANET Network 3 or Net3. This network is a benchmark network which is modified version of the original WDS of North, California, USA. There are total of 97 nodes, two reservoirs, three tanks, 117 link pipes and two pumps. Figure 3 shows the layout of Net3. The head present in the River and Lake are 220 ft. and 167 ft. respectively. The three tanks are at an elevation of 131.9 ft, 116.5 ft and 129 ft with diameter 85 ft, 50 ft and 164 ft, respectively. In this network, there involves five demand patterns. These patterns help to study the behavior of consumers. The two pumps are connected to both reservoirs. The pump connected to Lake reservoir is Link 10 and pump connected to River reservoir is Link 335. Link 10 is opened at 1 A.M in the morning and closed at 3 P.M in the afternoon on a day-to-day manner. The Link 335, on the other hand, is controlled by level in Tank 1. When the pump is closed, the bypass pipe is opened. Link 335 is open if level in Tank 1 is below 17.1 ft and closed if it is above 19.1 ft.

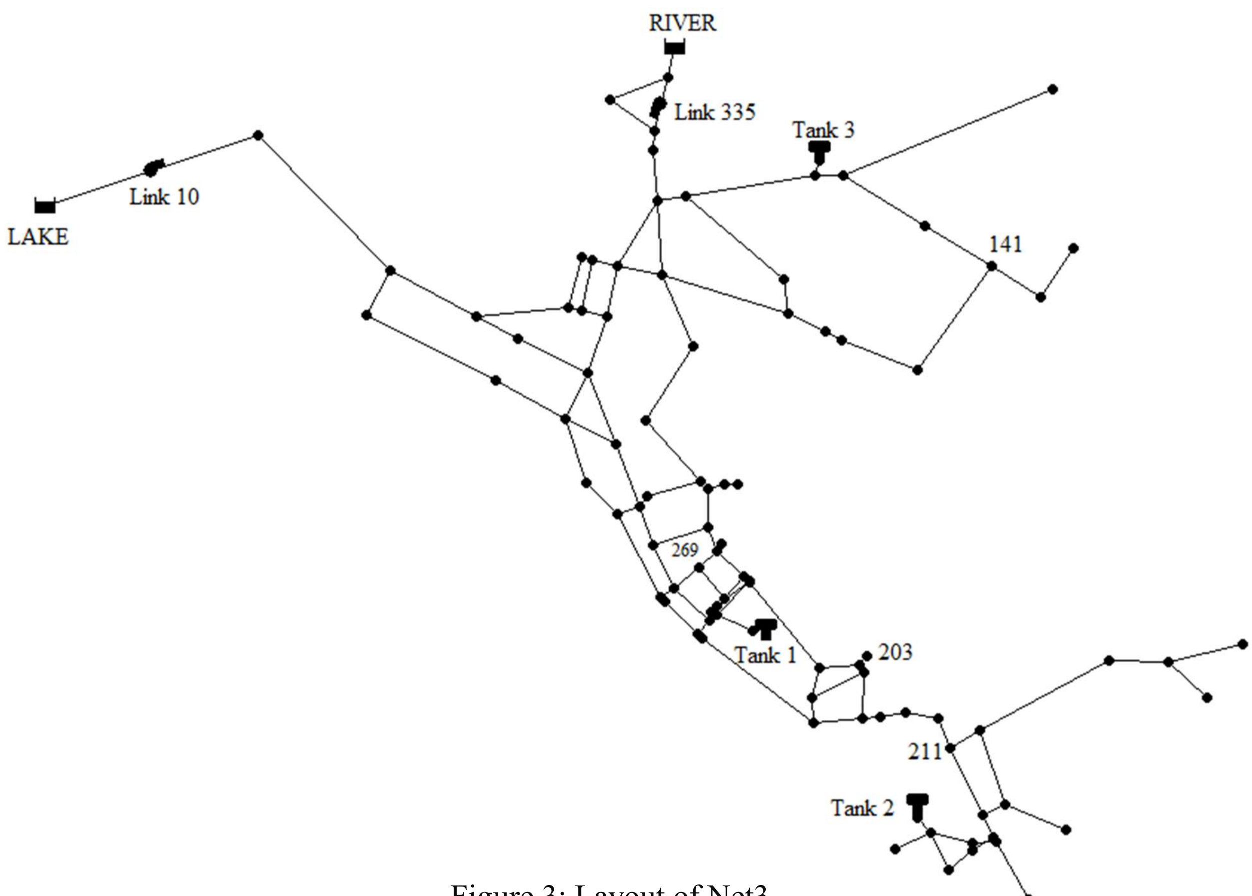

Figure 3: Layout of Net3

The second network used in this study is the Suvarnadhara network, a newly designed rural WDS in Kerela, India. Figure 6 shows the layout of Suvarnadhara network. The features of this network are as follows:

- ✓ It serves 1500 consumers (it is assumed that there are 4 members in each of the 375 houses served).
- ✓ Each consumer is to be supplied with 60 liters of water per day.
- ✓ Source of water is a protected open well (6 m diameter x 6.1 m depth) with a limited recuperation ability.
- ✓ The recommended yield of the well is 90,000 liters/day. The pumping can only be carried for 2.5 h on a continuous manner. A minimum of 8 h gap must be maintained between two pumping operations.
- ✓ Existing pump can only withdraw water at the rate of 300 L/min

Time Period (hr)	1	2	3	4	5	6	7	8	9	10	11	12
Multiplier	0.08	0.08	0.09	0.09	0.1	0.1	1.96	1.98	1.98	1.96	2.22	2.24
Time Period (hr)	13	14	15	16	17	18	19	20	21	22	23	24
Multiplier	0.75	0.75	0.65	0.7	0.8	0.92	2.66	2.56	0.57	0.29	0.26	0.21

Table 1: Pattern 1 for 24 h

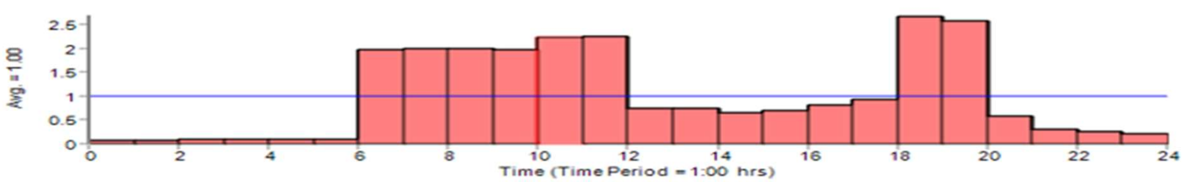

Figure 4: Bar graph for Pattern 1

Time Period (hr)	1	2	3	4	5	6	7	8	9	10	11	12
Multiplier	0	0	0	0	0	1	1	0.5	0	0	0	0
Time Period (hr)	13	14	15	16	17	18	19	20	21	22	23	24
Multiplier	0	0	1	1	0.5	0	0	0	0	0	0	0

Table 2: Pattern 2 for 24-h

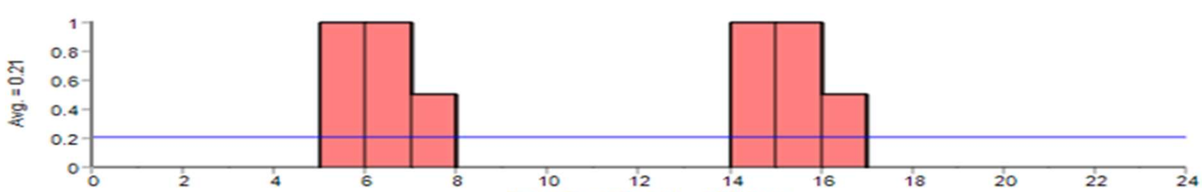

Figure 5: Bar graph for Pattern 2

This network contains 31 nodes, one tank, one open well connected to the main tank, and 35 pipes. The elevation and diameter of tank are 180 m and 6 m, respectively. There are two demand patterns. Pattern 1 is applied for all nodes and Pattern 2 is applied for source well. The pump is initially started at 6 am and runs until 8:30 am, as explained in Pattern 2. It begins, once more, at 3 pm and ends at 5:30 pm. There is an 8-hour break for groundwater recharging.

3.2 Single and Extended Period Analysis

This is performed using the EPANET engine after the input of required information of nodes, pipes, tanks and reservoirs. The single period analysis will give us the node pressure without any time stamp. To have a realistic analysis of an extended period of operation, we create a time pattern that alters demands at nodes vary in a periodic way over the course of day. For this study, we have used extended period analysis.

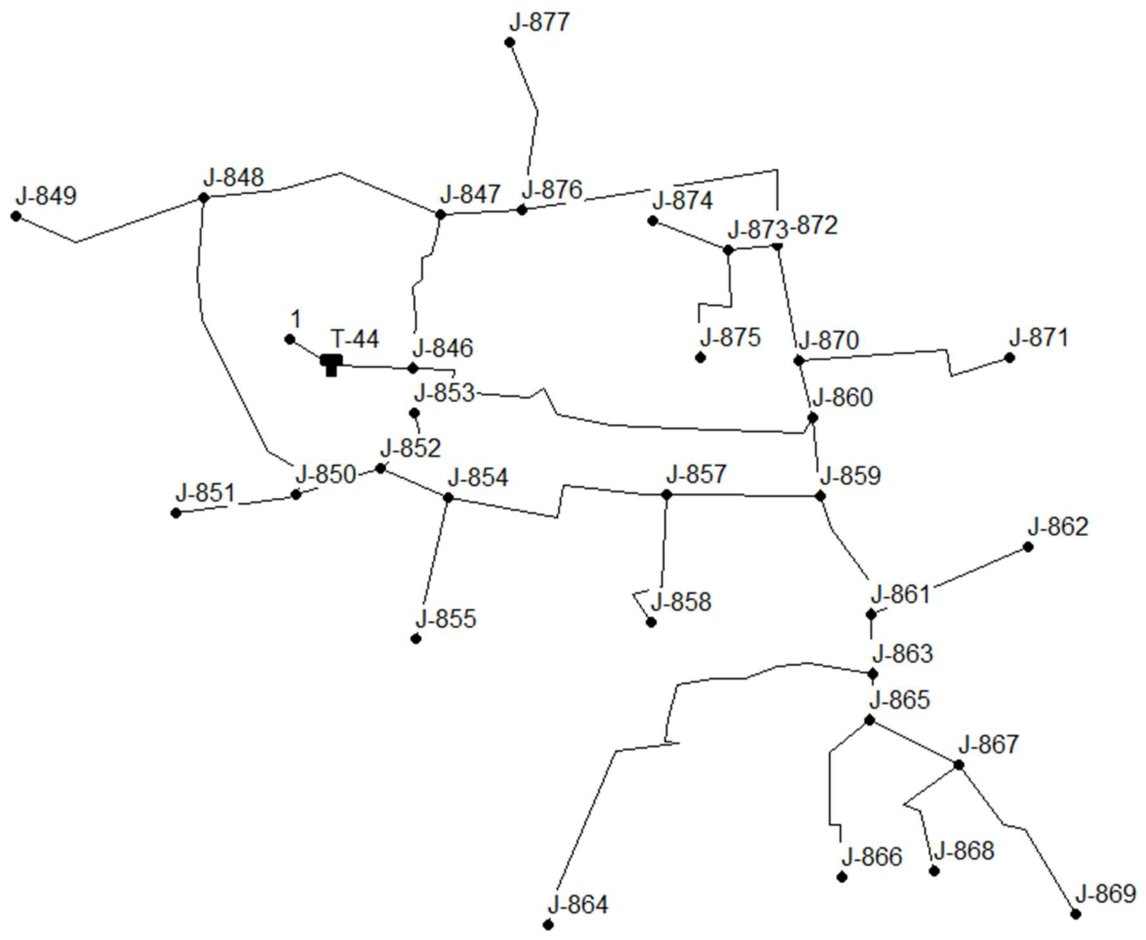

Figure 6: Layout of Suvarnadhara

3.3 Hydraulic Analysis

Hydraulic analysis was conducted on the Suvarnadhara network and Net3 network using EPANET-IWS to understand the performance of the system. For Suvarnadhara network, the network introduced several modifications, including the addition of two artificial pseudo nodes for connecting flow control valves, artificial overhead tanks at each original node, artificial consumer nodes representing original water consumption points, and artificial pseudo pipes connecting ferrule points, pseudo nodes, overhead tanks, and consumer nodes. This analysis focused on evaluating the demand deficit at various nodes over an extended simulation period. To assess the hydraulic performance of the Suvarnadhara network, demand deficit tables were obtained after running simulations using EPANET-IWS. These tables provided insight into how well the network met the water demand at different nodes under various scenarios. The demand deficit data, initially obtained in a specific file format, was converted into CSV file for ease of analysis. This conversion facilitated the processing and statistical analysis of the data. The following steps were undertaken:

1. File Conversion
    - Converted the demand deficit data from its original file format to CSV. (Refer Annexure)
2. Statistical Analysis
    - Read CSV File: Imported the CSV file containing demand deficit values for 31 nodes.
    - Calculated Statistics: Computed the mean, 25th percentile,75th percentile, and mode for the demand deficit values at each node.
    - Daily Means: Calculated the daily mean demand deficit for each node over the 120-day simulation period.
3. Scenario Comparison:
    - Analyzed the demand deficit under three different scenarios to compare the network's performance.

To effectively communicate the results of the hydraulic analysis, the mean volume deficit for all three scenarios was plotted on a single graph. The three scenarios are being:

a) **Scenario 1**: The pump was started at 12 midnight and will run for two and half hours until 2:30 am. Then there was a break of 8 hours and it started again at 12 noon and will continue until 2:30 pm. Figure 7 shows the pumping pattern for scenario 1.

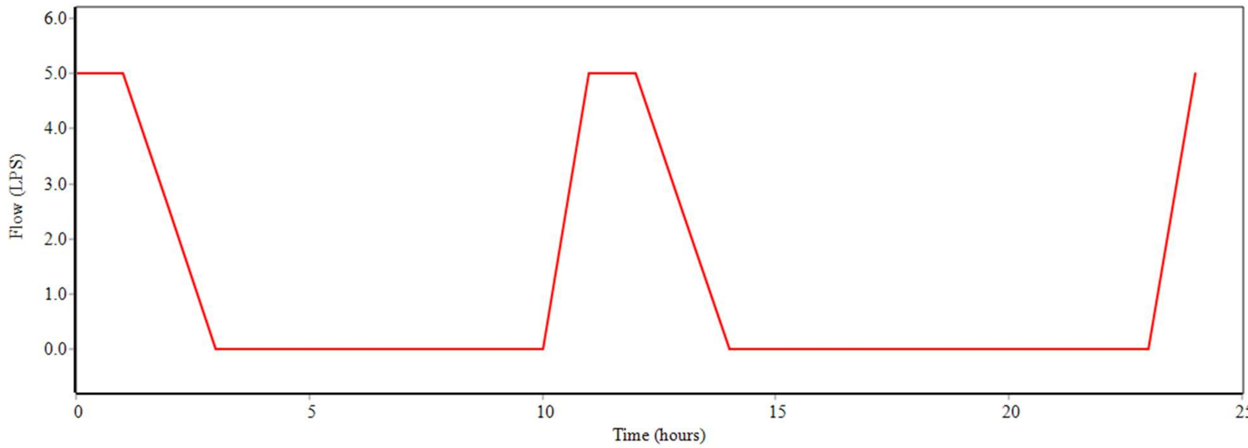

Figure 7: Pumping pattern for Scenario 1

b) **Scenario 2**: Scenario 2 happens just like scenario 1, but starts at 2 am instead of 12 midnight. Figure 8 shows pumping pattern for scenario 2.

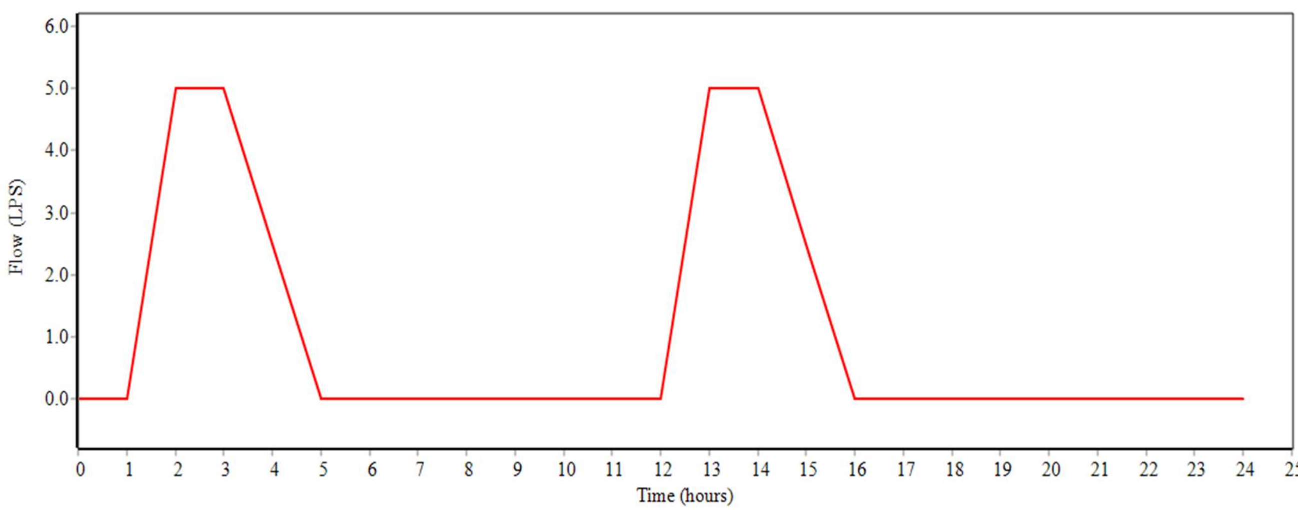

Figure 8: Pumping pattern for Scenario 2

c) Scenario 3: It also happens just like other two mentioned above scenario, but starts at 4:00 am. Figure 9 shows pumping pattern for scenario 3.

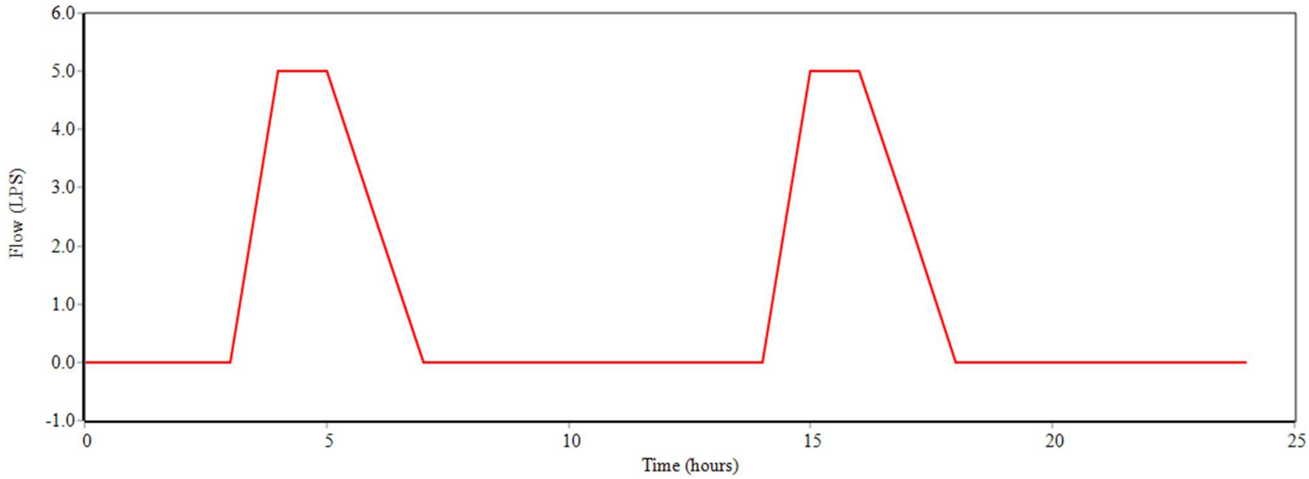

Figure 9: Pumping pattern for Scenario 3

The plot of mean volume deficit provided a clear comparison of how the network performed under each scenario and highlighted the difference in demand fulfillment across the nodes.

3.4 Quality Analysis

3.4.1 Net3 Network Quality Analysis

The Net3 network was analyzed under three distinct scenarios to study the behavior of chlorine concentration with different initial conditions. In Scenario 1, the chlorine concentration in the Lake Reservoir was set at 1 mg/L and in the river at 0 mg/L. In Scenario 2, the concentrations were reversed, with the Lake Reservoir at 0 mg/L and the river at 1 mg/L. Scenario 3 set both reservoirs at 0.5 mg/L. The parameters for these simulations included a bulk coefficient of -0.72 per day, a wall coefficient of -0.209 meter/day, a simulation time of 10 days, a hydraulic time step of 1 hour, and a quality time step of 5 minutes. The analysis focused on nodes 141, 203, 211, and 269, as well as Tanks 1, 2, and 3. Chlorine concentration simulations were conducted for each scenario, and the results were visualized by plotting chlorine concentration versus time for the selected nodes and tanks. Additionally, trace analyses were performed for these nodes and tanks, with the Lake and River as trace nodes.

3.4.2 Suvarnadhara Network Quality Analysis

For the Suvarnadhara network, the quality type was set to chlorine with a concentration of 1 mg/L at the open well source. The analysis incorporated 20 different bulk coefficients, specifically: -

0.188, -0.211, -0.318, -0.376, -0.595, -0.656, -0.709, -1.068, -1.094, -1.288, -1.87, -1.961, -2.026, -2.075, -2.084, -2.225, -2.528, -2.548, -2.649, and -2.697 (per day). The wall coefficient was fixed at 0.209 m/d (meter/day). Chlorine concentration simulations were conducted using this modified network, and the computed hydraulic and quality time series were obtained. Tank volume versus time plots were generated for the original tank (T-44) and all artificial overhead tanks. Subsequently, quality simulations for all 20 bulk coefficient values were performed, and chlorine concentration versus time plots were created for the original tank and all artificial overhead tanks.

4. RESULTS AND DISCUSSION

4.1 Overview

The results of this study provide critical insights into the hydraulic and water quality performance of the Suvarnadhara and Net3 water distribution networks under various operational scenarios. In the hydraulic analysis, demand deficit values were calculated for three different scenarios mentioned above, revealing significant differences in water availability at consumer nodes. The water quality analysis, conducted using chlorine concentration simulations, highlighted the impact of varying initial conditions and bulk coefficients on disinfectant levels. These findings offer valuable guidance for optimizing water distribution systems, particularly in regions with intermittent supply, and underscore the importance of precise modeling in ensuring safe and reliable water delivery.

4.2 Hydraulic Analysis Results

The hydraulic analysis of the Net3 network was conducted as part of a training exercise to assess various parameters critical to the efficient operation of the water distribution system. The analysis successfully traced the volume of water supplied from both the river and the lake to each node within the network. Additionally, pressure levels at each node were monitored, and the flow rates through the pipes were accurately measured. At every household connection, the demand was quantified, and the corresponding head loss was calculated. This comprehensive analysis provided valuable insights into the performance and functionality of the water distribution system.

The Suvarnadhara network was simulated using EPANET-IWS, and a demand deficit file was obtained. This file was then converted into a CSV format. Using this CSV file, the daily means for the 31 nodes were calculated over a simulation period of 120 days. The mean volume deficit for all nodes was then plotted to illustrate the variations and trends in water distribution across different scenarios. The three different scenarios are mentioned in Figure 7, 8 and 9. The mean volume deficit for the all 31 nodes in the network are show in Figure 10. The nodes which exhibit higher volume deficit are 2, 7, 19, 21, and 28. In the figure 6, these nodes are J-847, J-852, J-865, J-867 and J-874. For example, for node id 21, value of mean volume deficit for scenario 1 is 50%, whereas for scenario 2 and 3 it is 58% and 60% respectively. Similarly, for node id 28, values are 42%, 46% and 50% respectively. So, we can observe that, mean volume deficits are lower for the scenario 1. This means, if the pump operation is started at midnight, the consumers are likely to get more water than other scenarios. The reason behind the larger difference between other nodes and these given five nodes might be because these five nodes are at greater distance from the tank (T-44).

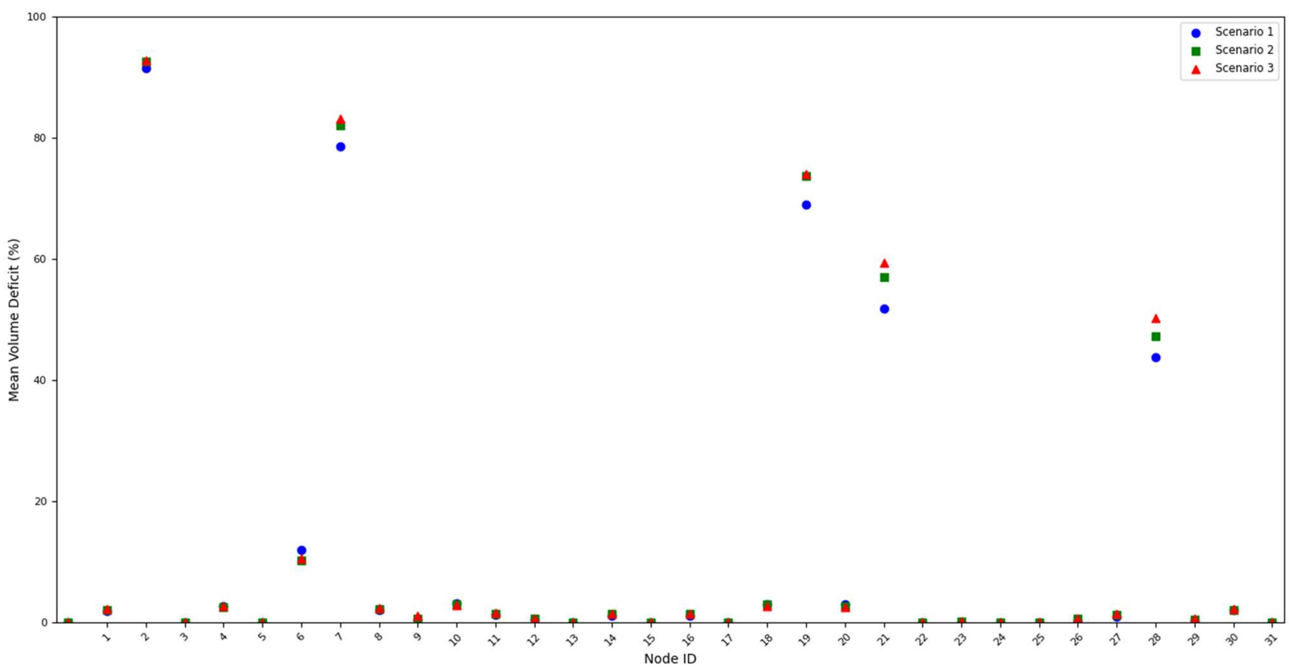

Figure 10: Mean Volume Deficit of 31 nodes (Suvarnadhara)

4.3 Water Quality Analysis Results

4.3.1 Net3 Network Results

Effective water quality management is critical for ensuring the safety and reliability of urban water distribution systems. In the analysis of the Net3 network, this study examines chlorine concentration dynamics across three scenarios with varying initial concentrations between the Lake Reservoir and the river. The study is simulated for 10 days (240 h). The findings presented here focus on chlorine concentration values obtained at nodes 203 and 269. These nodes serve as strategic points within the network, providing insights into how different chlorine levels influence disinfection efficacy and overall water quality. The subsequent discussion explores observed chlorine dispersion and decay patterns, offering a comprehensive assessment of the network's response to different operational conditions. The analysis also gives us the plot of trace node as Lake and River for both two nodes.

Trace Lake and River

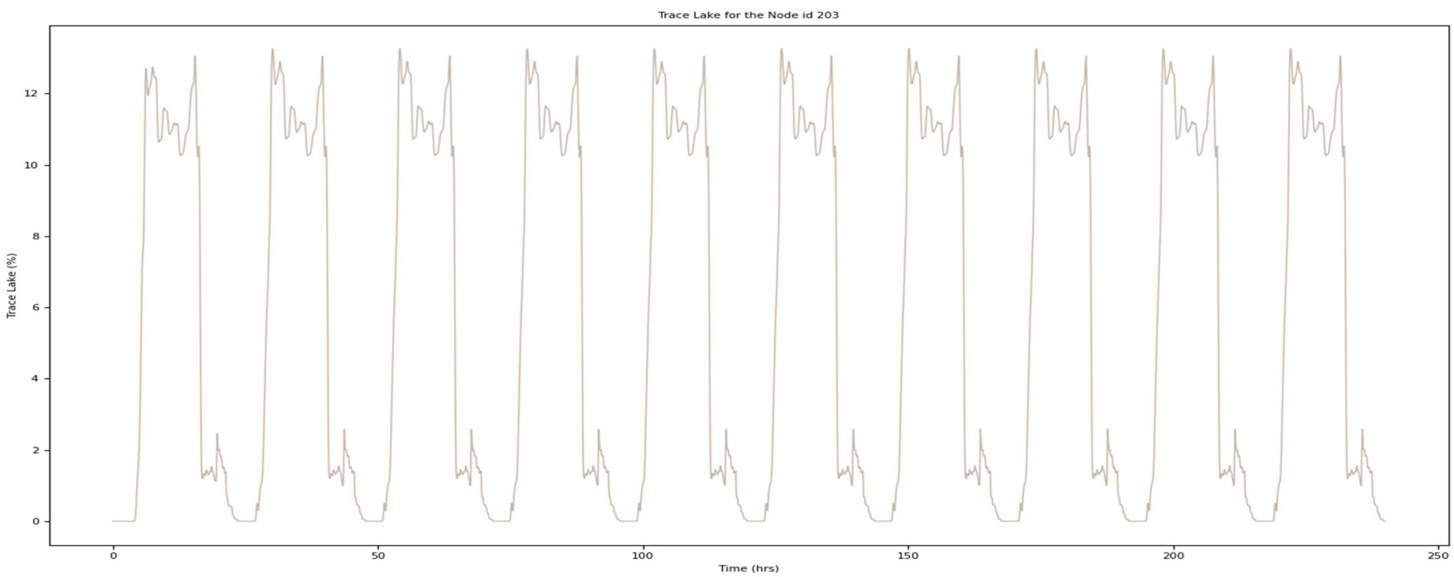

Figure 11: Trace Lake for Node 203

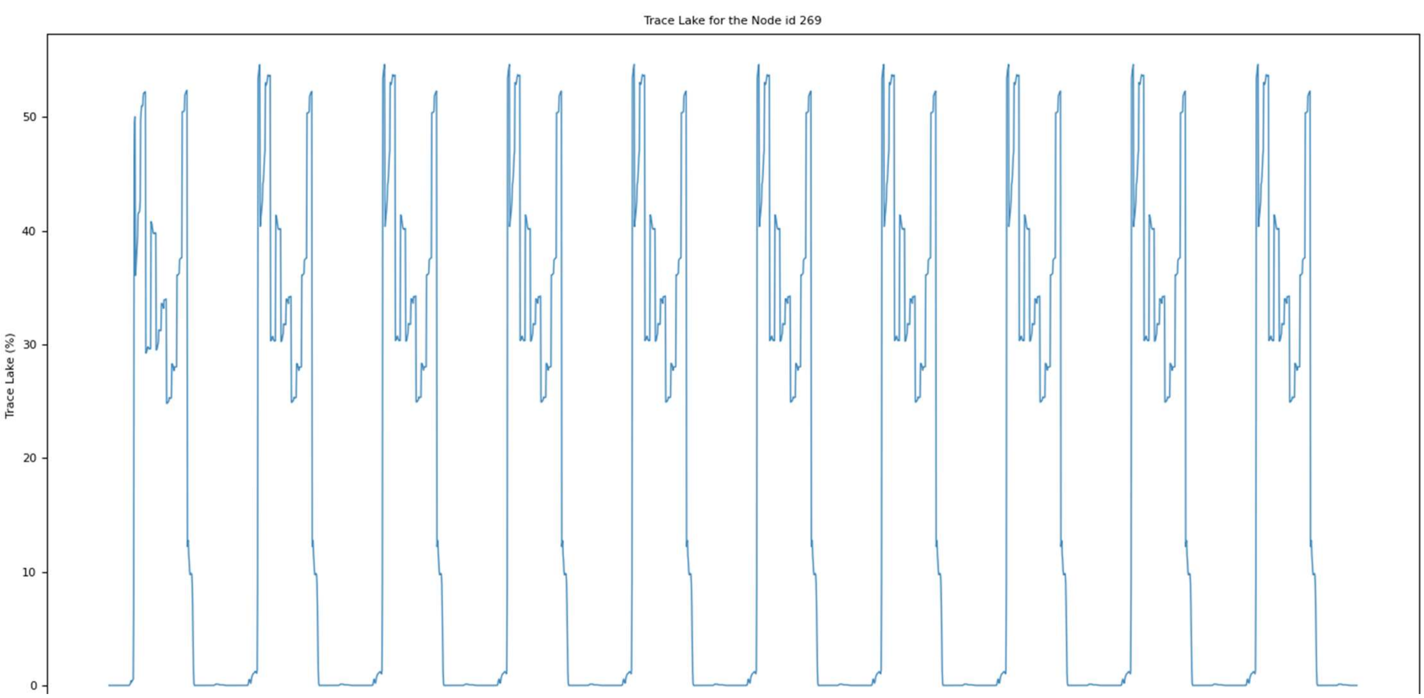

Figure 12: Trace Lake for Node 269

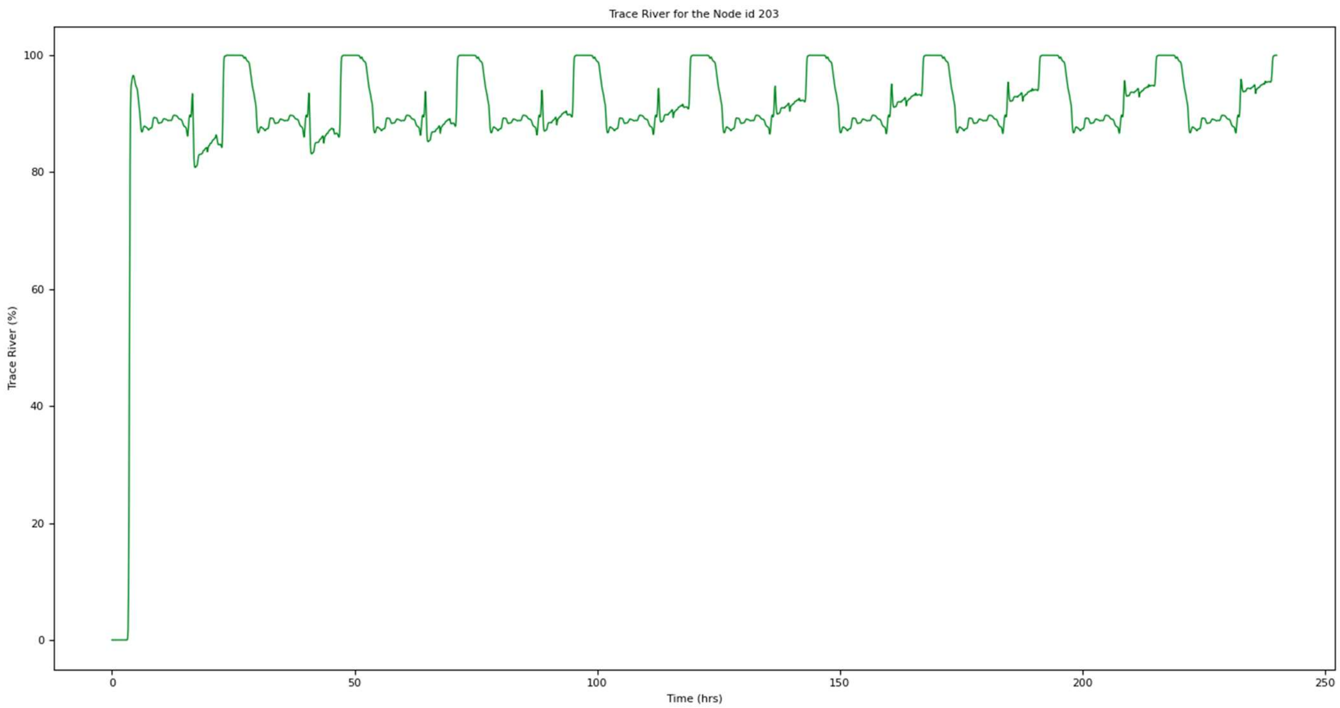

Figure 13: Trace River for Node 203

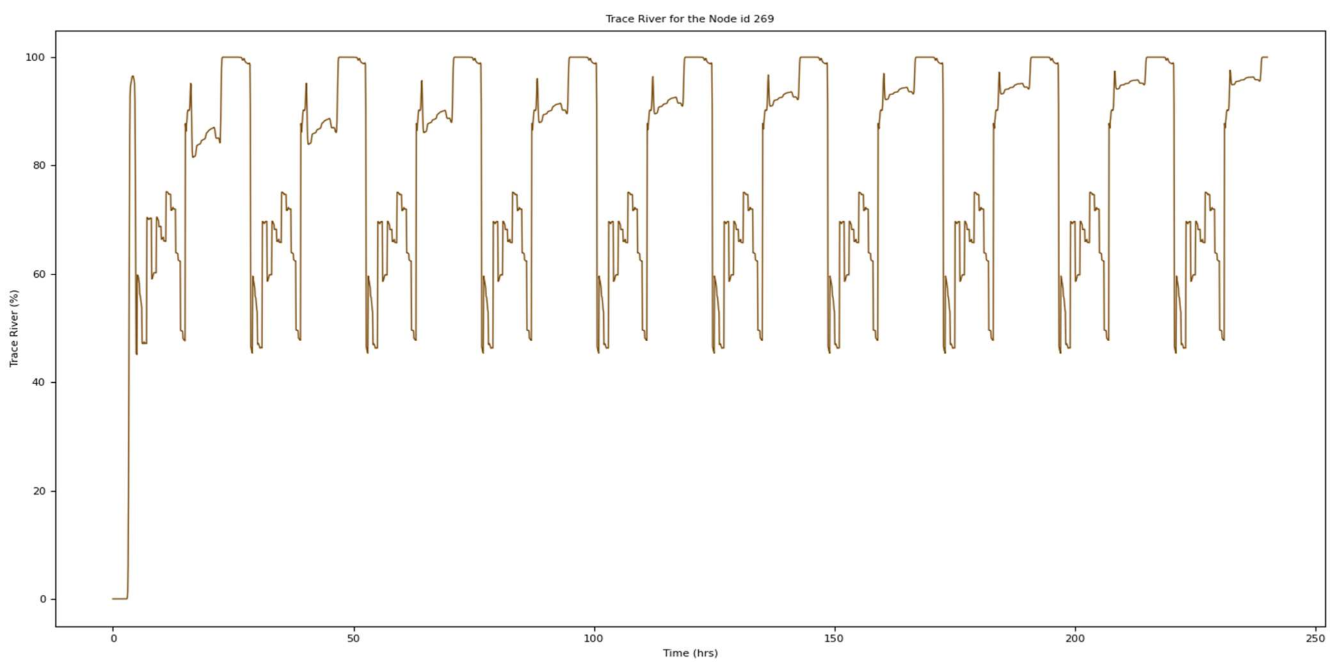

Figure 14: Trace River for Node 269

The figure 11 and 12 convey that at Nodes 203 and 269, the proportion of water flowing from the lake is around 13% and 55%, respectively. Similar to this, the figure 13 and 14 show that nodes

203 and 269 have nearly 100% of their water coming from rivers. This affects the amount of chlorine present in the corresponding nodes.

Scenario 1: Initial chlorine dosage in Lake (1 mg/L) and River (0 mg/L)

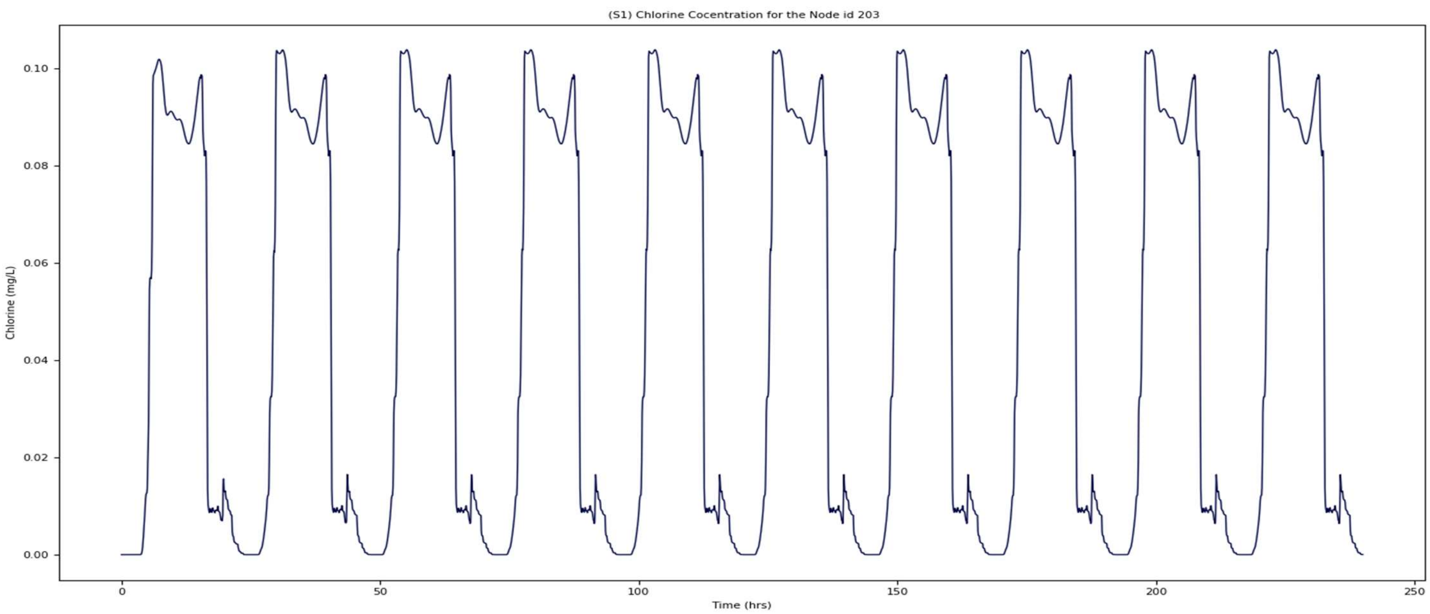

Figure 15: Chlorine Concentration for Node 203 (Scenario 1)

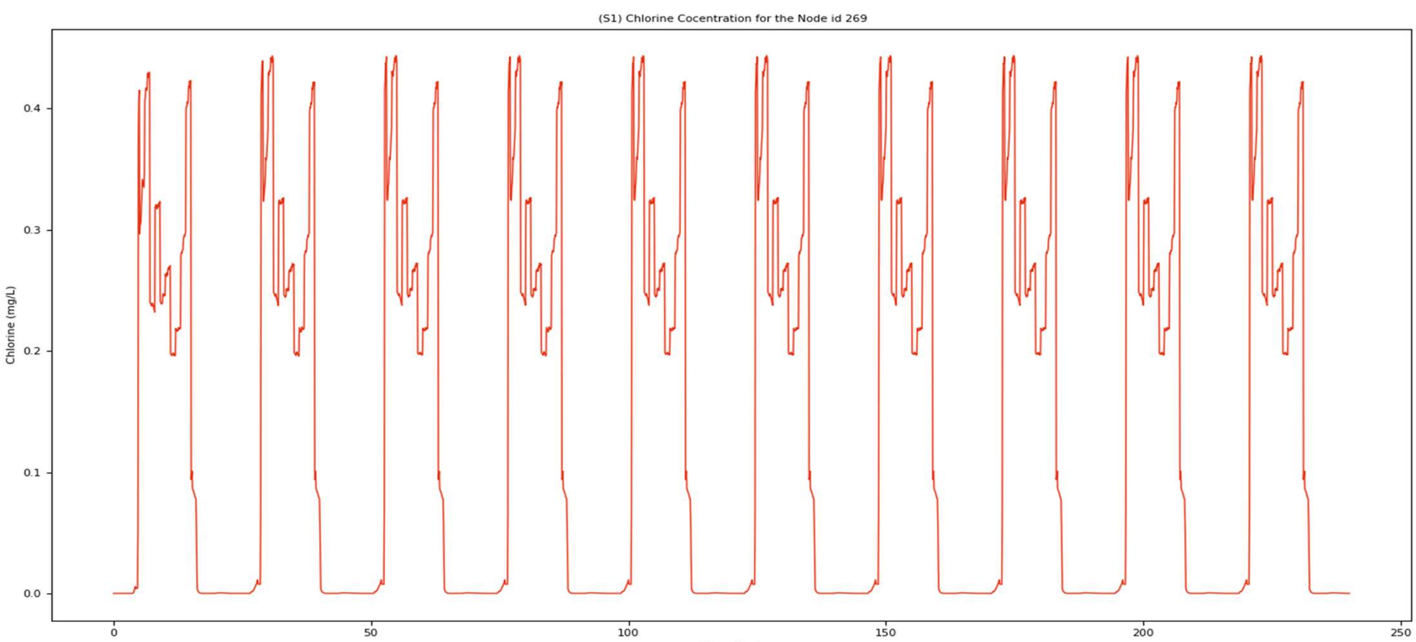

Figure 16: Chlorine Concentration for Node 269 (Scenario 1)

In figure 15 and 16, we can observe that the chlorine concentration for Node 203 is reaching 0.1 mg/L and for Node 269, it is about 0.5 mg/L. The reason behind this is due to the amount of water coming from Lake to this particular node. As we know, the amount of lake water reaching node 203 is 13% and for node 269 it is 55%. As there is 1 mg/L chlorine dosage in lake reservoir, the concentration in nodes is depended on the amount of water coming from the reservoir.

Scenario 2: Initial chlorine dosage in Lake (0 mg/L) and River (1 mg/L)

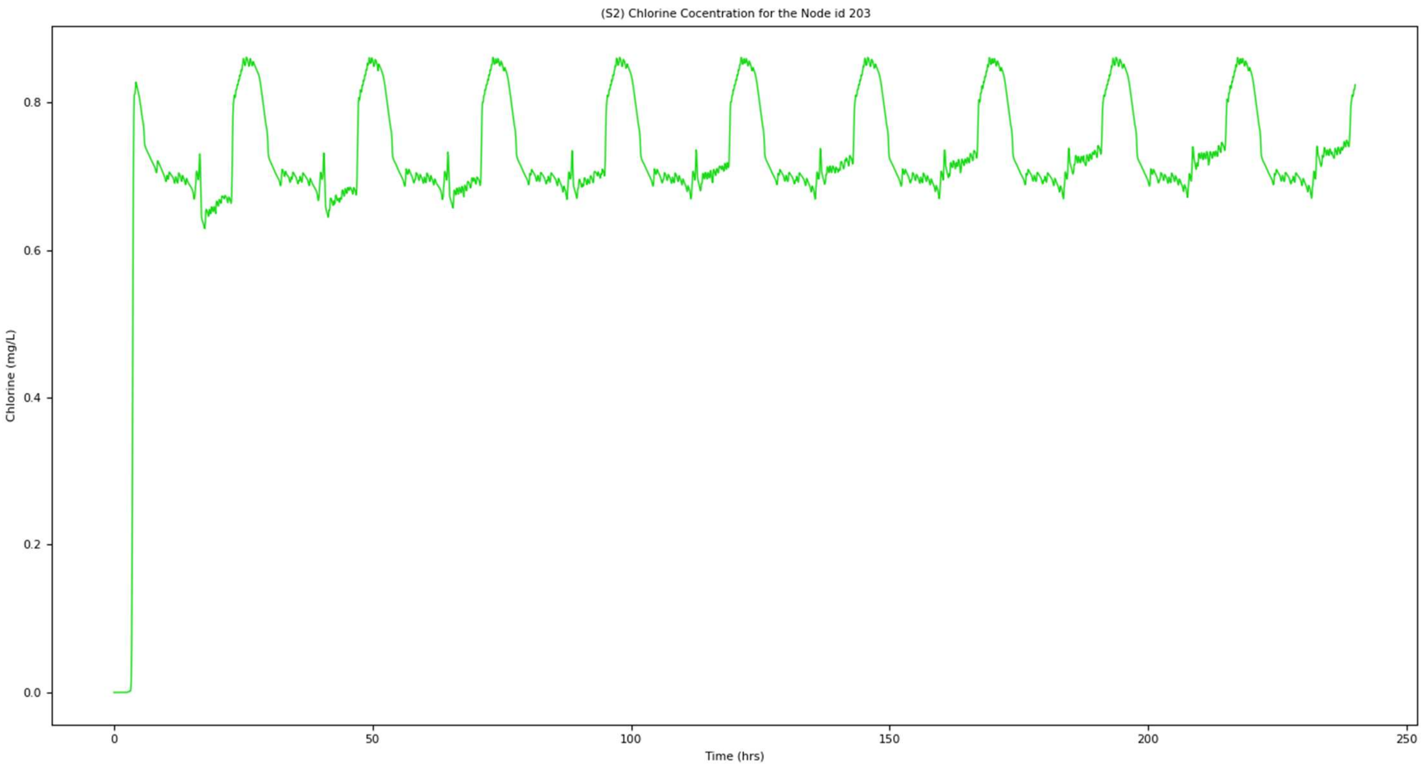

Figure 17: Chlorine Concentration for Node 203 (Scenario 2)

In figure 17 and 18, it gives us the idea of chlorine concentration in the nodes when there is 1 mg/L chlorine dosage in the river reservoir. We know in node 203 and 269, the maximum water comes from river (almost 100%). So, we can observe that the chlorine concentration for both nodes are around 0.9 mg/L.

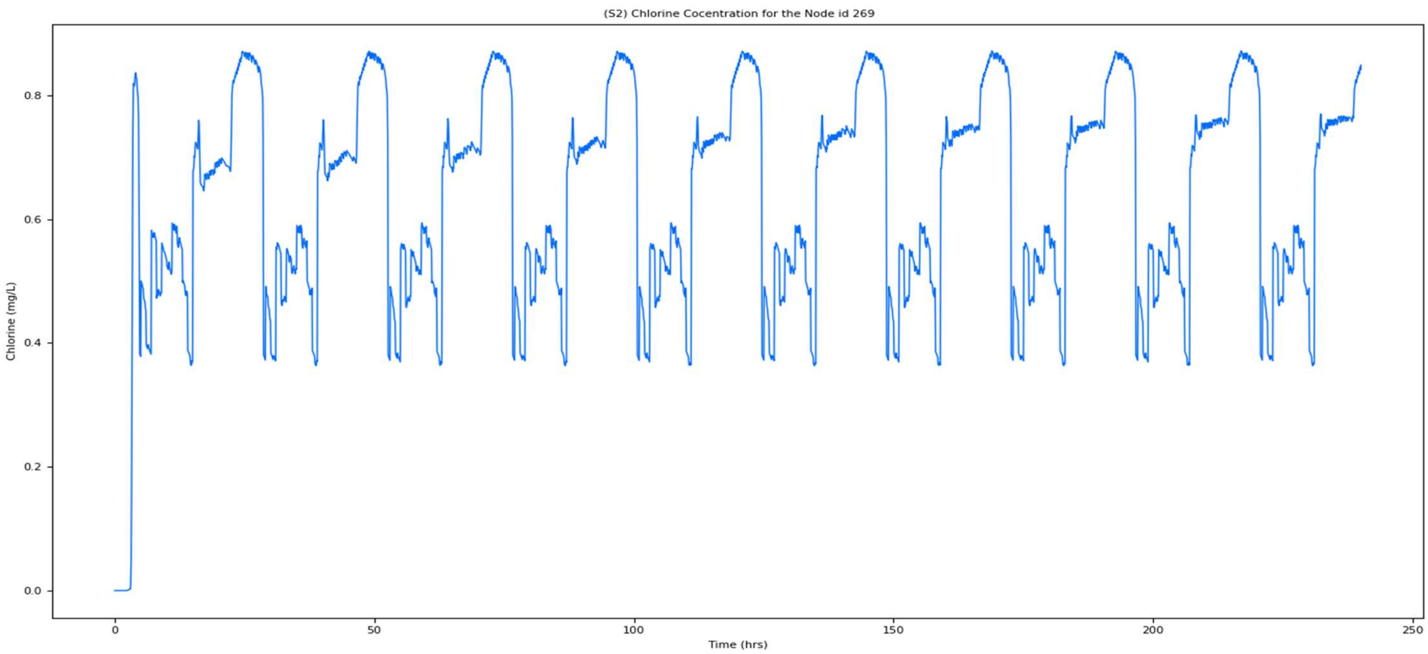

Figure 18: Chlorine Concentration for Node 269 (Scenario 2)

Scenario 3: Initial chlorine dosage in Lake (0.5 mg/L) and River (0.5 mg/L)

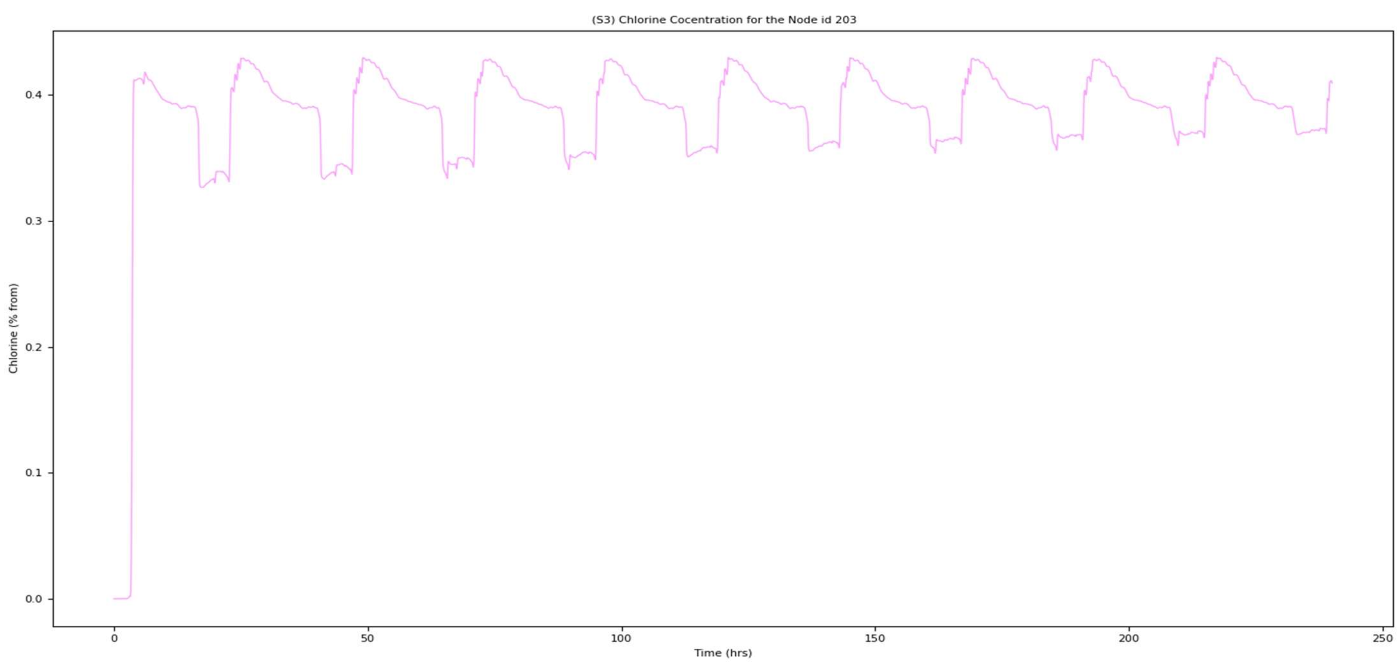

Figure 19: Chlorine Concentration for Node 203 (Scenario 3)

Similarly, Figure 19 and 20 exhibit the chlorine concentration in nodes 203 and 269 when the chlorine dosage is 0.5 mg/L in both lake reservoir and river reservoir. Since the majority of the water are coming from the river, the chlorine concentration in the nodes is less affected by the lake reservoir. We can observe, the chlorine concentration in the both nodes are 0.45 mg/L (around 0.5 mg/L).

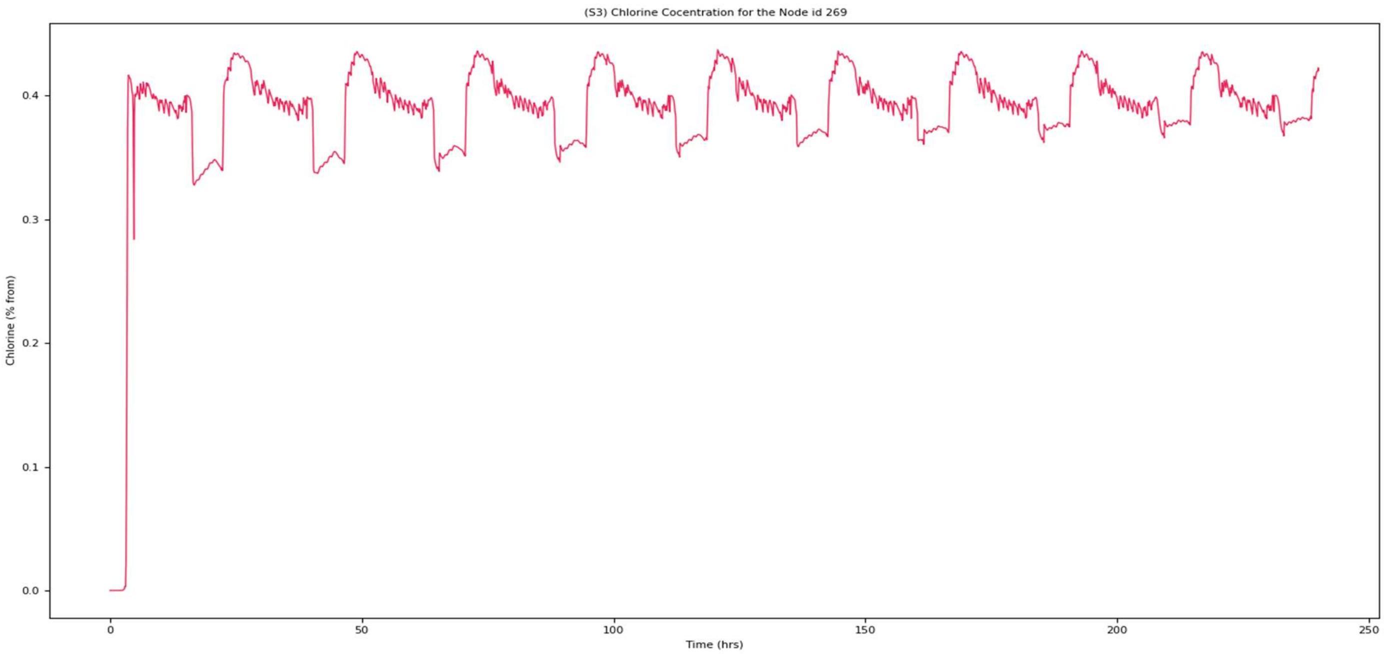

Figure 20: Chlorine Concentration for Node 269 (Scenario 3)

4.3.2. Suvarnadhara Network Results

In the analysis of this network, the value of wall coefficient is kept fixed at -0.209 m/d but the value of bulk coefficient is changed from the range of -0.188 /day to -2.697 /day to take into

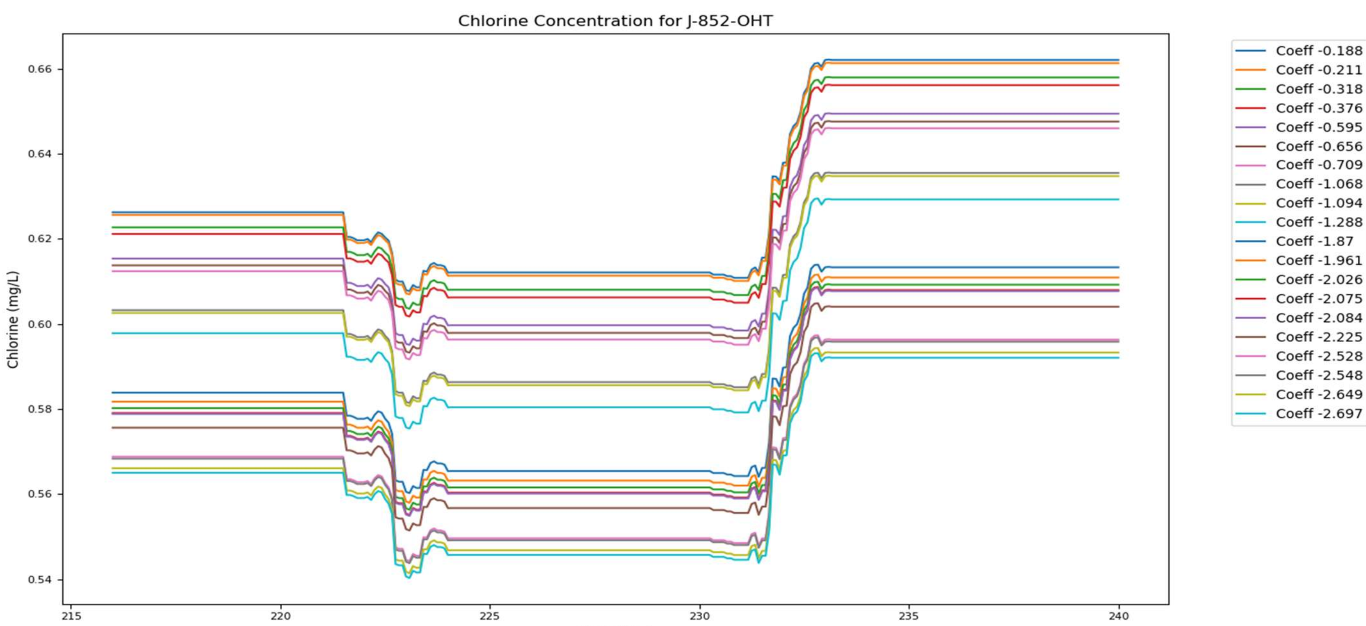

Figure 21: Chlorine Concentration for J-852-OHT

account of the lack of knowledge on the exact rate at which chlorine decays in the WDS under consideration. The chlorine concentration at open source well is kept at 1 mg/L (chlorine addition is the only treatment undertaken). After analysis, chlorine concentration volume of tank at original tank (T-44) and artificial overhead tanks were obtained. For study, node id J-852, J-867 and J-875 are taken (Refer to Figure 6).

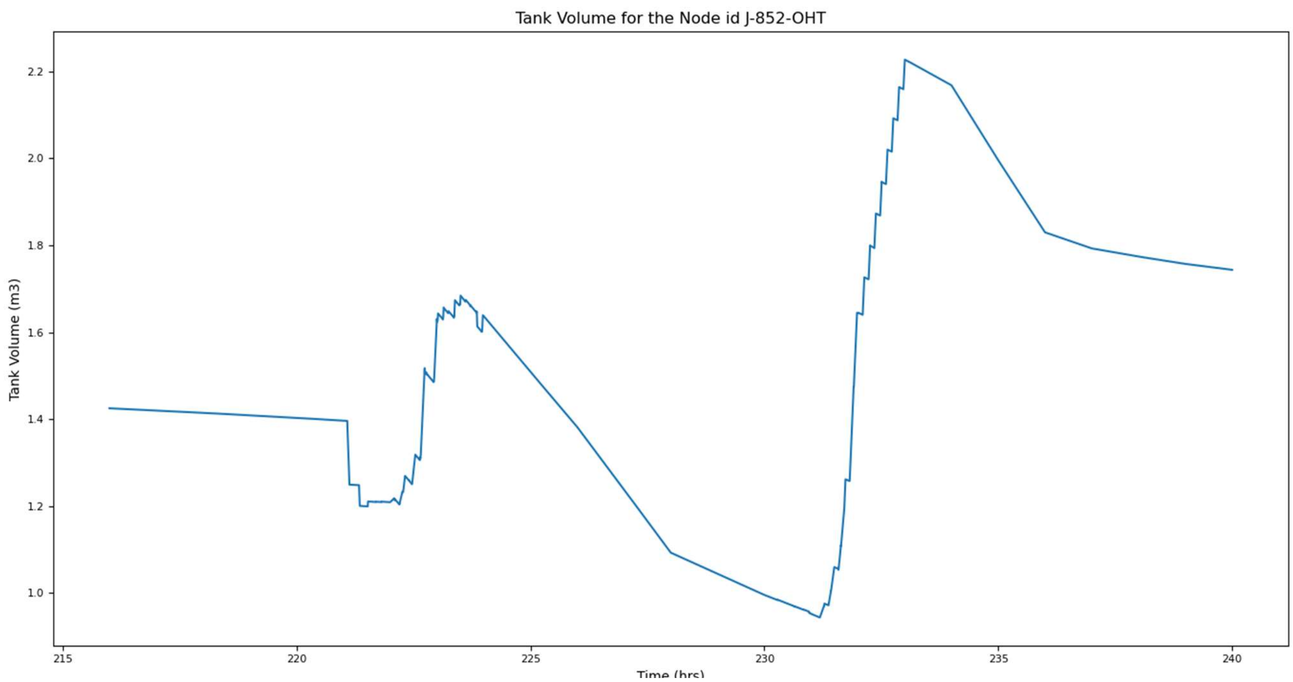

Figure 22: Tank Volume for J-852-OHT

The simulation was done for 10 days (240 hours). For detailed study, the data of last 24 hours were plotted. It is evident from the numbers that there is a spike in the tank volume and chlorine concentration after 222 hours. This is as a result of the pump being turned on at 6:00 am and running for 2.5 hours. The pump is resumed for 2.5 hours again at 3:00 pm, which is why there is another surge in the concentration values after 231 hours. This study demonstrates that the concentration of chlorine varies as the water fills the tank. Additionally, from figure 21, 23 and 25 we may infer that the chlorine levels in the overhead tank at consumer nodes varies within certain ranges for a 1 mg/L chlorine dose in the source well.

Figure 21 shows chlorine concentration variation across different value of bulk coefficient. The concentration values are varying between 0.54 mg/l to 0.66 mg/L. Figure 22 exhibits the tank volume along the day. We can see that at 222 hours the volume suddenly drops initially, but gradually increases. This is because, consumers in J-852 might use more water in 6 AM in the morning. Hence, it can be inferred that as the amount of water entering the tank and leaving the tank varies, the chlorine levels also vary in the tank.

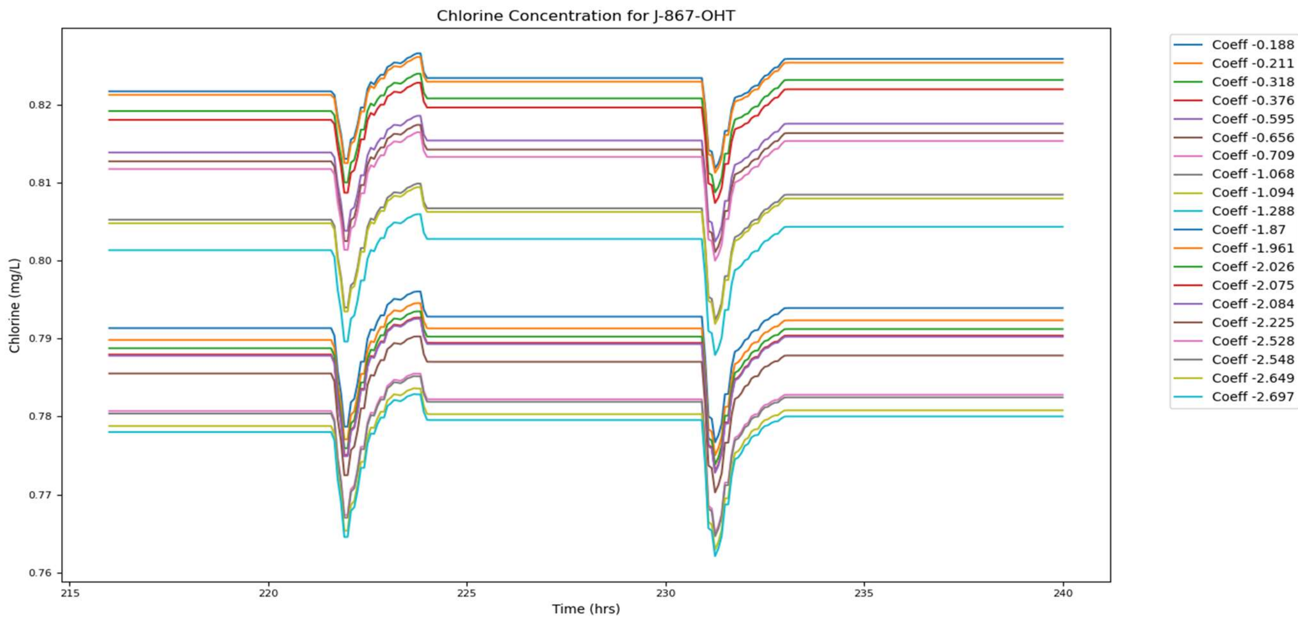

Figure 23: Chlorine Concentration for J-867-OHT

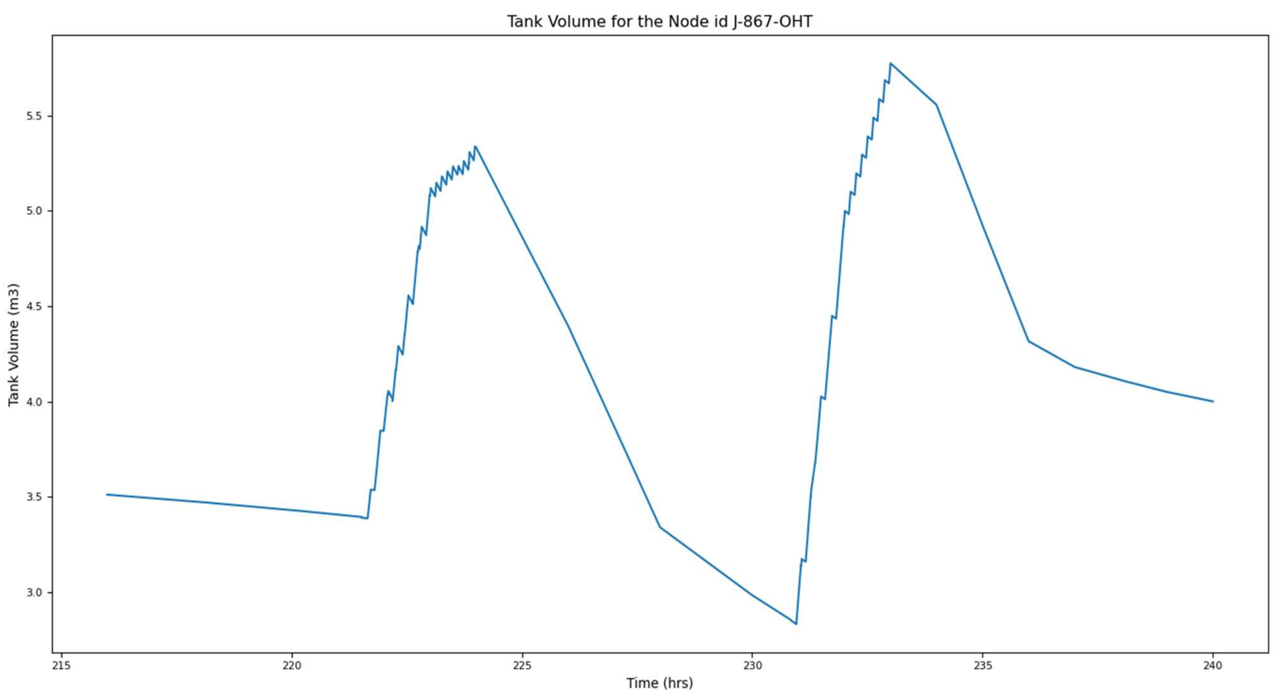

Figure 24: Tank Volume for J-867-OHT

Figure 23 exhibits the chlorine concentration for Node J-867 across different value of bulk coefficient. We can observe the chlorine concentration is varying from 0.761 mg/L to 0.828 mg/L. In figure 24, we see the increase in tank volume at 222 hours as the pump is starting to draw the water from the well. After two and half hours, as the consumers start using the water the volume tank slowly decreases and at 231 hours, the pump is started and tank is filled up again.

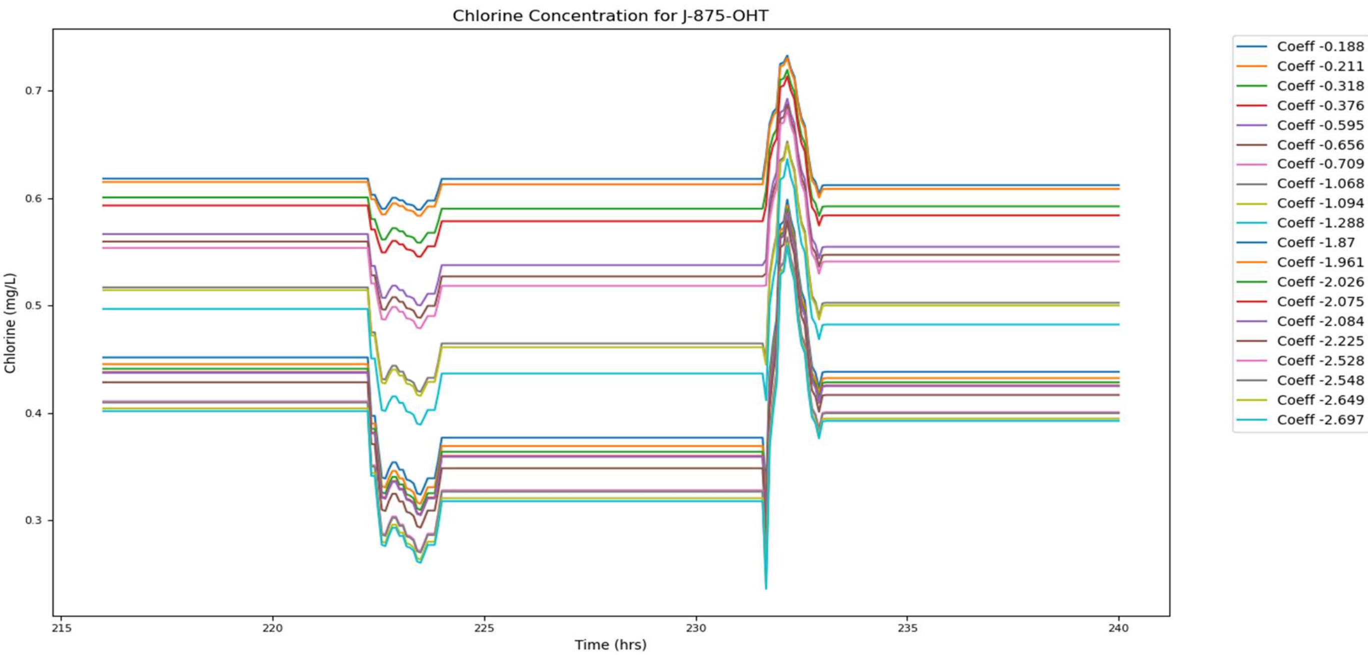

Figure 25: Chlorine Concentration for J-875-OHT

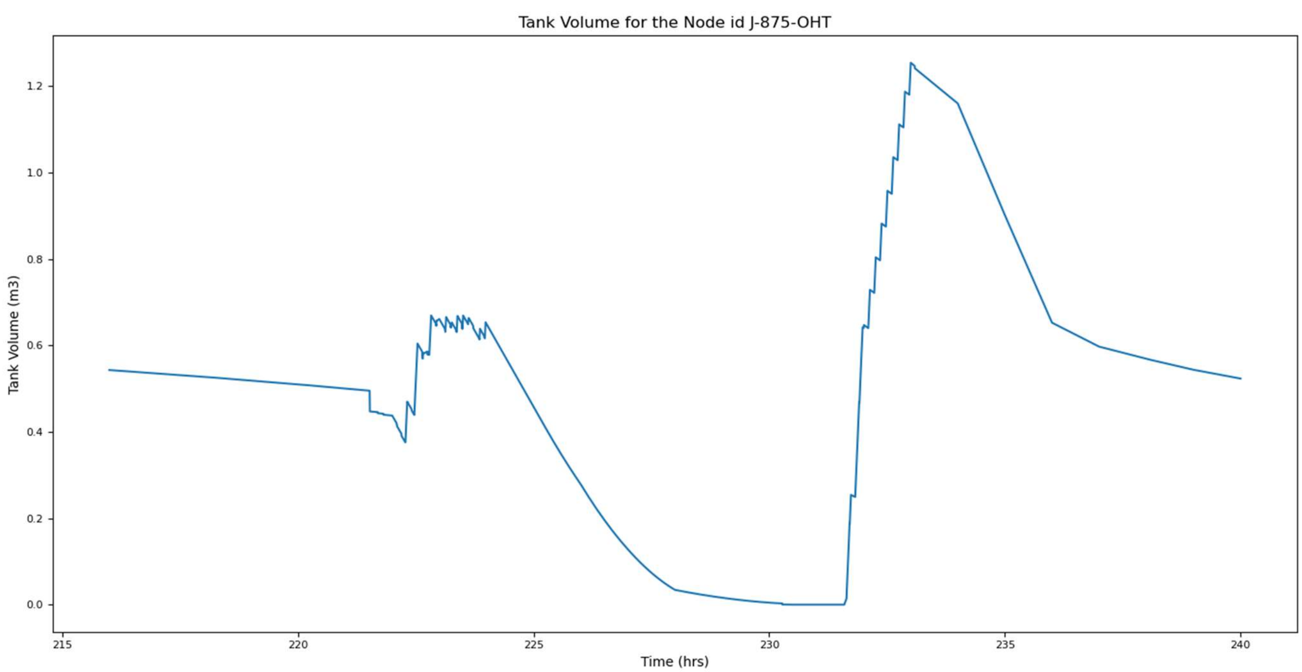

Figure 26: Tank Volume for J-875-OHT

We can see from figure 26 that there is less water enters the tank at 222 hours than there is at 231 hours. The user may be using more water at this hour, which might be the cause. However, at 231 hours, there isn't much water use, giving the tank an opportunity to fill.

5. CONCLUSION

This study conducted an extensive hydraulic and water quality analysis of the Suvarnadhara network, revealing critical insights into the performance and behavior of the system under various scenarios.

In the Suvarnadhara network, under IWS operation interesting dynamics were observed in the tank volume and chlorine concentration over time. This study illustrated the dynamic nature of chlorine concentration as water fills the tanks. The findings of this study underscore the importance of considering operational schedules and their impact on water quality when managing WDS.

6. REFERENCES

1) Abhijith, G. R., Naidu, M. N., Boindala, S. P., Vasana, A., & Ostfeld, A. (2023). Analyzing the role of consumer behavior in coping with intermittent supply in water distribution systems. *Journal of Hydroinformatics, 25*(5), 1766. https://doi.org/10.2166/hydro.2023.022
2) Abhijith, G. R., & Mohan, S. (2020). Random walk particle tracking embedded cellular automata model for predicting temporospatial variations of chlorine in water distribution systems. *Environmental Processes, 7*(1), 93-107. https://doi.org/10.1007/s40710-019-00406-6

7. ANNEXURE

7.1 Code for converting into csv file:

```
import pandas as pd

from os import getcwd

path = getcwd() + '\\Analysis_Results_Scenario-1-120\\'

Demand_deficit = pd.read_csv(path + 'Demand deficit').to_numpy()

#Save the NumPy array to a CSV file for further processing

df = pd.DataFrame(Demand_deficit)

csv_path = path + 'Demand_deficit.csv'

df.to_csv(csv_path, index=False)
```

7.2 Code for means, 25th percentile, 75th percentile and mode:

```
import pandas as pd

import numpy as np

from os import getcwd

#Define the path to the CSV file

path = getcwd() + '\\Analysis_Results_Scenario-1-120\\'

csv_path = path + 'Demand_deficit.csv'

#Read the data from the csv file into the Dataframe

data = pd.read_csv(csv_path)

#Skip the first row and the first column

data = data.iloc[1:,1:]

#Calculate the mean for each node (column)

node_means = data.mean(axis=0)
```

```
#Define the path to the output text file
    output_path = path + 'node_means.txt'
# Convert the list of node means to a DataFrame
    node_means_df = pd.DataFrame(node_means)
# Define the path to the output Excel file
    output_excel_path = path + 'node_means.xlsx'
# Save the node means to an Excel file
    node_means_df.to_excel(output_excel_path, index=False)
    print(f'Daily means of nodes saved to {output_excel_path}')
#Save the means to a text file
    with open(output_path, 'w') as file :
        file.write(node_means.to_string())
        print(f'Means of nodes saved to {output_path}')
#Print the results
    print('The mean for each node is given below:\n',node_means)
## Calculate the 25th percentile for each node (column)
    node_25th_percentile = data.quantile(0.25, axis=0)
# Define the path to the output text file
    output_path = path + 'node_25th_percentile.txt'
# Save the 25th percentiles to a text file
    with open(output_path, 'w') as file:
        file.write(node_25th_percentile.to_string())
```

```
    print(f'25th percentiles of nodes saved to {output_path}')
    print('The 25th percentile for each node is given below:\n',node_25th_percentile)
# Calculate the 75th percentile for each node (column)
    node_75th_percentile = data.quantile(0.75, axis=0)
# Define the path to the output text file
    output_path = path + 'node_75th_percentile.txt'
# Save the 75th percentiles to a text file
    with open(output_path, 'w') as file:
        file.write(node_75th_percentile.to_string()
          print(f'75th percentiles of nodes saved to {output_path}')
          print('The 75th percentile for each node is given below:\n',node_75th_percentile)
# Calculate the mode for each node (column)
    node_modes = data.mode(axis=0).iloc[0]  # Taking the first mode in case of multiple modes
# Define the path to the output text file
    output_path = path + 'node_modes.txt'
# Save the modes to a text file
    with open(output_path, 'w') as file:
        file.write(node_modes.to_string())
         print(f'Modes of nodes saved to {output_path}')
         print('The mode for each node is given below:\n',node_modes)
# Calculate the number of days
    num_days = data.shape[0] // 24
# Initialize a list to store daily means
```

```
    daily_means_list = []
# Loop over each day and calculate the mean for each node
    for day in range(num_days):
        # Get the data for the current day
        daily_data = data.iloc[day*24:(day+1)*24, :]
        # Calculate the mean for the current day
        daily_mean = daily_data.mean(axis=0)
        # Append the daily mean to the list
        daily_means_list.append(daily_mean)
# Convert the list of daily means to a DataFrame
    daily_means_df = pd.DataFrame(daily_means_list)
# Define the path to the output Excel file
    output_excel_path = path + 'daily_means_S1.xlsx'
# Save the daily means to an Excel file
    daily_means_df.to_excel(output_excel_path, index=False)
    print(f'Daily means of nodes saved to {output_excel_path}')
```

7.3 Code for Plotting mean volume deficit.

```
import pandas as pd
import matplotlib.pyplot as plt
from os import getcwd
# Define the path to the Excel file
path = getcwd() + '\\Analysis_Results_Scenario-1-120\\'
excel_path = path + 'node_means_S1.xlsx'
```

```
# Read the data for each scenario from separate sheets
scenario1_df = pd.read_excel(excel_path, sheet_name='Scenario 1')
scenario2_df = pd.read_excel(excel_path, sheet_name='Scenario 2')
scenario3_df = pd.read_excel(excel_path, sheet_name='Scenario 3')
# Plotting all scenarios in the same plot
plt.figure(figsize=(16, 12))  # Set the figure size
# Define a color palette and marker styles for differentiation
colors = ['b', 'g', 'r']
markers = ['o', 's', '^']
scenarios = [scenario1_df, scenario2_df, scenario3_df]
scenario_names = ['Scenario 1', 'Scenario 2', 'Scenario 3']
# Loop through each scenario and plot
for i, scenario_df in enumerate(scenarios):
    for column in scenario_df.columns:
        plt.scatter(scenario_df.index, scenario_df[column],
                    label=f'{scenario_names[i]}',
                    color=colors[i % len(colors)],
                    marker=markers[i % len(markers)])
# Adding labels and title
x_array = list(range(1,33))
plt.xlabel('Node ID')
plt.xticks(x_array, rotation= 90)
plt.margins(0.01)
```

```
plt.ylabel('Mean Volume Deficit (%)')

plt.ylim(0, 100)

plt.legend(title='', bbox_to_anchor=(1, 1), loc='best', fontsize='small')

plt.xticks(rotation=45)  # Rotate x-axis labels if needed for better readability

plt.tight_layout()  # Adjust layout to fit everything nicely

# Save the plot as an image file

plot_path = path + 'means_combined_plot.png'

plt.savefig(plot_path)

# Show the plot

plt.show()

print(f'Combined plot of mean values saved to {plot_path}')
```

7.4 Code for Plotting Chlorine concentration across different scenario

```
import subprocess

import sys

import numpy as np

subprocess.call([sys.executable, '-m', 'pip', 'install', 'epyt'])

from epyt import epanet

from os import getcwd

import pandas as pd

# Loading the network

file_name = 'Net3_Controls.inp'

d = epanet(getcwd()+'\\Net3\\' + file_name)
```

```
#Setting the quality type as Chlorine

d.setQualityType('chem', 'Chlorine')

#Setting source quality at the reservoir

reservoir_index_R = 93

reservoir_index_L = 94

source_strength_R = 0 #mg/l chlorine

source_strength_L = 1 #mg/l chlorine

d.setNodeSourceQuality(reservoir_index_R, source_strength_R)

d.setNodeSourceQuality(reservoir_index_L, source_strength_L)

"""Setting bulk and wall reaction coefficients"""

bulk_coefficient = d.getLinkBulkReactionCoeff()

bulk_coefficient_set = [-0.72 for i in bulk_coefficient]

d.setLinkBulkReactionCoeff(bulk_coefficient_set)

wall_coefficient = d.getLinkWallReactionCoeff()

wall_coefficient_set = [-0.209 for i in wall_coefficient]

d.setLinkWallReactionCoeff(wall_coefficient_set)

'''Setting the simulation duration and time steps'''

sim_time = 10 * 24 * 3600 # 10 days

d.setTimeSimulationDuration(sim_time)

h_step = 3600 # 1 hour

d.setTimeHydraulicStep(h_step)

q_step = 300 # 300 seconds

d.setTimeQualityStep(q_step)
```

```
"""Base scenario: Running hydraulic and water quality analysis"""

H1 = d.getComputedHydraulicTimeSeries()

Q1 = d.getComputedQualityTimeSeries()

print('Base scenario analysis completed.\n')

'''Node ID for Plotting'''

NodeIndex = d.getNodeIndex(['141','203','211','269'])

''''Converting seconds into hrs'''

hrs_time = Q1.Time /3600

'''plotting'''

nodeID = d.getNodeNameID()

d.getNodeIndex()

node_indices =  NodeIndex

for index in node_indices:

  d.plot_ts(X=hrs_time, Y=Q1.NodeQuality[:, index -1],

         title=f' (S1) Chlorine Cocentration for the Node id {d.getNodeNameID(index)}',

         xlabel='Time (hrs)', ylabel=f'Chlorine (mg/L)',

         marker=None)

      d.plot_show()
```