Multiobjective Optimization of Water Distribution Networks using Metaheuristic Algorithms

THESIS

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CERTIFICATE

This is to certify that the thesis titled **Multiobjective Optimization of Water Distribution Networks using Metaheuristic Algorithms** submitted by **MADDUKURI NAVEEN NAIDU** ID No **2017PHXF009H** for award of Ph.D. of the Institute embodies original work done by him under our supervision.

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DECLARATION

This is to certify that the thesis titled "**Multiobjective Optimization of Water Distribution Networks using Metaheuristic Algorithms**" is based on my own research work and has been carried out under the guidance and supervision of Prof. A. Vasan, and co-supervision of Prof. Murari R R Varma, Dept. of Civil Engineering, BITS Pilani, Hyderabad Campus, Hyderabad, India.

The data and information which I have used from various sources have been duly acknowledged. I declare that this work has not been previously submitted by me to any other university/institute for the award of any other degree or diploma.

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(M Naveen Naidu)

ABSTRACT

Water Distribution Networks (WDNs) are like linchpin for any urban infrastructure system. As the installation and maintenance of these networks involves huge capital investment, the design of these systems is highly significant. The optimal design of these networks reduces initial capital investment without compromising on the demand requirements. The complexity of this optimization problem is due to the non-linear relationship between head losses and pipe discharges which leads to complex non-linear constraints. Mathematical models that imitate natural evolutionary processes have been gaining much importance for successfully optimizing engineering design problems. Most initial studies aimed to solve the design as a single objective, i.e., minimizing network cost. The challenge in optimization is associating other conflicting objectives with cost minimization and capturing the problem's true multiobjective nature. In most urban settings in India, the design of the WDNs assumes of continuous water supply. However, in most parts of the country, areas are supplied with water intermittently. This has resulted in challenges like pressure and demand losses at nodes in WDNs. Therefore, there is a need for new models that can accommodate these issues in the design of WDNs. Moreover, the operation and maintenance of WDNs are inherently complex tasks. One strategy to tackle these issues is the integration of district metered areas (DMAs) within WDNs. Present research work focuses on optimizing the design of WDNs and identifying optimal DMAs for a WDN in a multiobjective framework considering three scenarios.

In the last few decades, researchers working on multiobjective design of WDN have attempted to explore several new nature inspired optimization techniques to such complex problems as they are able to handle a discrete search space directly and are less likely to be trapped into the local optimal solutions. In the present study, three such optimization techniques [Multiobjective Particle Swarm Optimization Algorithm (MOPSOA) augmented with local search, Self-adaptive Multiobjective Cuckoo Search Algorithm (SAMOCSA) and NSGA-II algorithm augmented with a random multi-point crossover operator as well as local search (RLNSGA-II)] to solve multiobjective optimization models with some improvements in their working methodology have been implemented. Local search scheme has been augmented in two of the algorithms (MOPSOA and

RLNSGA-II) to effectively explore the least-crowded areas of the objective space to determine better pareto-optimal points.

The present study considers three scenarios. The first two scenarios determine the optimal WDN design based on different objectives for continuous and intermittent water supply. A simulation-optimization based program combining the water distribution network simulation software EPANET 2.2 and MATLAB is used for computation on a high performance computing cluster. In the first scenario, two objectives, namely, network cost and network resilience have been considered for continuous and intermittent water supply. The formulated mathematical model is applied to the three benchmark WDN problems (New York Tunnel WDN, Hanoi WDN and Balerma Irrigation Network) and later this is also applied to two real-life WDNs located in Telangana, India (Pamapur WDN and Vanasthalipuram WDN) to ensure practical relevance of the proposed methodology using MOPSOA, SAMOCSA and RLNSGA-II. The results of New York WDN, Hanoi WDN and Balerma Irrigation Network (BIN) for continuous water supply are compared with the solutions of Wang *et al.* (2015) to test the efficacy of the developed optimization algorithms. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable distribution of water. This expanded set of objectives is examined in the context of two real-life water distribution networks for intermittent water supply using RLNSGA-II algorithm. The third scenario focuses on determining the optimal design of DMAs considering three objectives for the optimization model. The initial clusters have been identified using Fast Newman algorithm. The objectives considered are minimizing network cost, maximizing network resilience and maximizing network equity. In this scenario, the proposed methodology has been applied on Pamapur WDN and Vanasthalipuram WDN to determine the optimal number of DMAs.

The results obtained from the first scenario are compared with the best-known algorithms available in the literature. The results have shown that the proposed algorithms have found better converged and distributed solutions for all three representative benchmark problems considered in the study consistently and evidently when compared with the best-known approximation of solutions published. Furthermore, as the complexity of the water distribution network increases, its advantages over other algorithms become more significant resulting in substantial cost savings.

Additionally, a comparison between continuous water supply and intermittent water supply is conducted within the framework of the first scenario. These comparative analyses reveal that velocity and pressure exhibit higher levels in intermittent water supply scenarios compared to continuous water supply scenarios. The findings from the second scenario indicate a notable enhancement in network equity for real-life water distribution networks, specifically Pamapur and Vanasthalipuram WDNs. It is observed that most of the non-dominated solutions on the pareto front on the upper middle portion for Vanasthalipuram WDN provide better network resilience for a lower network cost. Similarly, it is observed that all the points on the pareto front represent a better performance in terms of network equity for a lower cost when compared to the results obtained in scenario 1. In the third scenario, the results demonstrate the efficacy of the proposed methodology in effectively identifying DMAs. For Pampaur WDN, it can be observed that the network cost varies from Rs.9.55 lakhs to Rs.48.71 lakhs for DMAs that vary between 3 to 5. Five different combinations of DMAs have been found for 3 and 5 numbers of DMAs. The number of valves and flow meters varies from 12 to 21 and 6 to 10 respectively for the different DMAs obtained in the pareto front. The network resilience increases from 0.45 to 0.55 (around 22% increase) and network equity increases from 0.9150 to 0.9750 (around 7% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front. The average pressure in each DMA is slightly lower after partitioning for both the extreme points of the pareto front. The average pressure in DMA 3 is around 3% lower after partitioning for the leftmost point and it is around 3% lower in DMA 3 after partitioning for the rightmost point.

Similarly, for Vanasthalipuram WDN, it can be observed that the network cost varies from Rs.11.12 lakhs to Rs.55.08 lakhs for DMAs that vary between 3 to 7. Ten different combinations of DMAs have been found for 5 numbers of DMAs. The number of valves and flow meters varies from 23 to 45 and 7 to 15 respectively for the different DMAs obtained in the pareto front. The network resilience marginally increases (around 2% increase) and network equity also marginally increases (around 2% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front. The average pressure in each DMA is slightly lower (below 2%) after partitioning for both the extreme points. The average pressure in DMA 3 is around 1.75% lower after partitioning for the leftmost point and it is around 1.86% lower in DMA 3 after partitioning for the rightmost point.

This study presents a multiobjective design of water distribution networks considering three key objectives: minimizing Network Cost, maximizing Network Resilience and maximizing Network Equity. While similar multiobjective designs have been considered in other locations (very limited studies), our study uniquely applies these objectives to two specific and challenging locations, demonstrating the effectiveness and adaptability of our proposed techniques. Three optimization algorithms (MOPSOA, SAMOCSA and RLNSGA-II) used in this study have consistently outperformed, when compared with the best algorithms available in literature, yielding better converged and distributed solutions for the three benchmark problems (New York WDN, Hanoi WDN and Balerma Irrigation Network). These algorithms surpass the best-known approximation solutions published in the literature, showcasing their effectiveness and robustness. It is particularly noteworthy to mention their exploration and exploitation capabilities of large search spaces for finding better optimal solutions i.e., their ability to achieve substantial cost savings as network complexity increases. The proposed methodology demonstrated significant cost savings. The optimized designs achieved a balance between initial investment and long-term operational costs, making them economically viable for large-scale implementation. The optimized networks exhibited higher resilience, ensuring that the WDNs could better withstand disruptions and maintain service levels during adverse conditions. The methodology identified configurations that improved the system's ability to adapt to changes and recover from failures. The methodology also addressed the equity of water distribution which is a major concern in Indian conditions, ensuring a more uniform and fair distribution of water across different regions within the network. This helped in reducing disparities in water access and pressure, providing a more consistent service to all users. The conclusions emanated from the study show that the proposed methodology can effectively identify the optimal design of WDNs and identify DMAs while considering multiple objectives.

Keywords: Water Distribution Network; New York Tunnel WDN; Hanoi WDN; Balerma Irrigation Network; Pampaur WDN; Vanasthalipuram WDN; Multiobjective Particle Swarm Optimization Algorithm; Multiobjective Cuckoo Search Algorithm; NSGA-II; EPANET 2.2; District Metered Areas; Fast Newman Algorithm.

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List of ACRONYMS

AMS	Adaptive Metropolis Search
ASR	Average Supply Ratio
BIN	Balerma Irrigation Network
CSA	Cuckoo Search Algorithm
CWS	Continuous Water Supply
DE	Differential Evolution
DMAs	District Metered Areas
EPANET	Environmental Protection Agency Network Evaluation Tool
FNA	Fast Newman Algorithm
GALAXY	Genetically Adaptive Leaping Algorithm for Approximation and Diversity
HS	Harmony Search
IWS	Intermittent Water Supply
MCDM	Multi-Criteria Decision-Making
MOEA	Multiobjective Evolutionary Algorithms
MOPSOA	Multiobjective Particle Swarm Optimization Algorithm
ND	Non-dominated
NSDE	Nondominated Sorting Differential Evolution
NSGA-II	Non-dominated Sorting Genetic Algorithm -II
NYT	New York Tunnel
PSO	Particle Swarm Optimization
RLNSGA-II	Random multi-point crossover operator, Local search augmented with Non-dominated Sorting Genetic Algorithm - II
SAMOCSA	Self-Adaptive Multiobjective Cuckoo Search Algorithm
ULS	Unit Local Search

WDN	Water Distribution Network

List of SYMBOLS

A_{uw}	Adjacency matrix
ADEV	Deviation of the supply ratio of the node from the average supply ratio
C1	Cognitive learning factor
C2	Social learning factor
C_{iv}	Unit cost of isolation valve
C_{flwm}	Unit cost of flow meter
$C_{Hw}^{1.852}$	Hazen William Coefficient of the pipe
C_i	Cost per unit length of a given pipe diameter
D_i	Diameter of the pipe *i*
[D]	Set of commercially available diameters in the market
F_{ideal}	Fitness value of best nest
$F_{anti-ideal}$	Fitness value of worst nest
H_i	Head loss in the pipe *i*
H_i^{avl}	Head available at node *i*
H_i^{min}	Minimum head required at node *i*
H_r	Head of reservoir
L_i	Length of pipe *i*
MI	Modularity index
N_{pso}	Number of iterations in PSO
N_{iv}	Number of isolation valves
ND_n	Demand at node *n*
NL	Number of loops in the system
np	Number of pipes in the network
nn	Number of nodes
nor	Number of reservoirs
npu	Number of power units

P_{mut}	Mutation probability
p	Nodal pressure
p_{min}	Minimum pressure at node
p_{req}	Required pressure at node
P_a	Discovering probability parameter
P_p	Power generated by power unit p
q	Actual node outflow
q_{req}	Required demand at node
Q	Pipe flow
Q_i	Demand at node *i*
Q_r	Demand of reservoir
r1, r2	Random numbers between 0 and 1
r	Hydraulic resistance in the pipe
TCF	Total cost of DMAs
v_i	Velocity of the particle *i*
W	Inertia weight
x_{pbest}^{i}	Personal best position of the particle
x_{leader}	Position of the leader particle
x_i	Position of the particle i
α	Step size control parameter
β	Levy-flight parameter
γ	Efficiency of power unit
ΔE	Energy loss between two points of the known head
ΔH_i	Head loss in the pipe *i*

Chapter 1

Introduction

1.1. Background and Motivation

Water Distribution Networks (WDNs) are integral components of urban infrastructure, transporting water from its sources to domestic, commercial, and industrial users, thereby sustaining their daily functions. These WDNs are crucial in providing access to clean and safe water and supporting public health, sanitation and economic activities. However, the establishment and upkeep of WDNs necessitate substantial investments across the design, construction, operation, and maintenance phases. Due to the significant capital investment required, effective management practices, infrastructure investments, and technological advancements are crucial for maximizing performance, minimizing water loss, and securing the sustainability of water supply systems in the long term.

The design of the WDNs can be a challenging task due to various reasons like the non-linear relation between head loss and diameter, discrete pipe diameters being available in the market, non-deterministic polynomial hard problem, high-dimensional search space and being computationally intensive. Traditionally, the design of the WDN is dependent on engineers' knowledge and experience. However, this is not sufficient for the design of large WDNs. Initially, proposed solutions like linear programming had their limitations, as the distribution network design problem was non-linear by nature and failed to identify the optimal global solution. Non-linear programming approaches rely on the initial solution, but they do not guarantee global optimal solution. In addition, the use of discrete variables, viz. available market pipe sizes, reduces the quality of optimal solutions (Kidanu *et al.*, 2023; Parvaze *et al.*, 2023).

Enumeration of all the possible solutions and selecting the best is the direct approach to solving such a problem. However, due to the exponential growth of possible solutions with increased variables, namely the number of pipes, such a rapid approach is practically infeasible. In addition, the optimization of WDNs has a significant number of local optima, which makes it a combinatorial problem.

Mathematical models that imitate natural evolutionary processes have recently gained much importance for successfully optimizing engineering design problems. Several studies have used nature-inspired algorithms like Genetic Algorithm, Particle Swarm Optimization, Cuckoo Search Algorithm, Shuffled Frog Leaping Algorithm, Differential Evolution Algorithm, etc. and their variants to design water distribution networks. Most initial studies aimed to solve the design as a single objective, i.e., minimization of network cost. The above algorithms have shown significant efficiency in obtaining optimal solutions. The challenge in optimization is associating other conflicting objectives with cost minimization and capturing the problem's true multiobjective nature (Walski, 2001). Towards this direction, studies have attempted two-objective optimization, i.e. minimization of network cost and maximization of network resilience. Various evolutionary algorithms have been utilized towards this. However, there is no consensus on a commonly accepted optimization tool in WDN, as improved algorithms can still obtain better solutions.

In most urban settings in India, the design of the WDNs is based on the assumption of continuous water supply. However, more often than not urban, almost all peri-urban and rural areas are supplied water intermittently. This has resulted in challenges like pressure and demand losses at nodes in WDNs. Therefore, there is a need for new models that can accommodate these issues in the design of WDNs. Pressure-driven demand (Gupta and Bhave, 1996) offers promising solutions to address these challenges in the design of intermittent water supply.

In addition to improvements in the network design, efficient operation design during the life of the WDN can improve service and reliability. Implementing District Metered Areas (DMAs) has significantly enhanced the efficiency of water distribution systems by enabling WDNs to monitor better, manage, and detect leaks within the WDNs. DMAs are specific sections or zones within a WDN that are isolated and equipped with flow metres to monitor and measure water flow in and out of the area. The optimal design of DMAs in WDNs is critical for operation and maintenance in WDNs. Efficient DMA design is paramount for achieving optimal water distribution, minimizing losses, and enhancing system resilience. Engineers can determine the most effective placement and sizing of DMAs through advanced optimization techniques, such as metaheuristic algorithms.

In this study, three distinct scenarios have been considered. The first two scenarios determine the optimal WDN design based on different objectives for continuous and intermittent water supply. An optimization-simulation model is developed to obtain an optimal design for water distribution systems. This model integrates the developed multiobjective optimization algorithm and the water distribution system simulation software EPANET 2.2 (Environmental Protection Agency Network Evaluation Tool). In the first scenario, two objectives are considered: network cost and network resilience. The formulated optimization-simulation model is applied to the three benchmark WDN problems, and later, this is also applied to two real-life WDNs located in Telangana, India, to ensure the practical relevance of the proposed methodology in the first scenario. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable water distribution. This expanded set of objectives is examined in the context of two real-life water distribution networks. In the third scenario, the optimal design of DMAs has been considered with three objectives: minimization of network cost, maximization of network resilience and maximization of network equity for two real-life water distribution networks, Pamapur and Vanasthalipuram water distribution networks.

1.2. Layout of Thesis

Chapter 2 provides a detailed literature review on the optimal design of WDNs, covering various aspects such as single objective optimization, multiobjective optimization, and methodology employed. In addition, the chapter also reviews the studies that have described the optimal configuration of DMAs within the WDNs. Subsequently, gaps found in the literature review and the objectives of the study have been described.

Chapter 3 elaborates on WDN modelling, encompassing key components like pumps, tanks, pipes, and more, while also exploring fundamental hydraulic modelling principles such as the conservation of mass and energy laws. In addition, the chapter delves into specific methodologies like pressure-driven demand and demand-driven analysis, highlighting their applications and significance in modelling complex WDNs. Furthermore, it discusses the capabilities of the hydraulic simulation tool, EPANET 2.2, offering an understanding of its features and functionalities for accurate modelling and analysis of WDNs.

Chapter 4 describes the five WDNs that have been chosen to validate the proposed methodology. Three benchmark problems, representing two medium WDNs (New York Tunnel WDN and Hanoi WDN) and one large WDN (Balerma Irrigation Network) has been considered. The proposed methodology has also been tested on two real-life WDNs from Telangana, namely, Pamapur WDN and Vanasthalipuram WDN.

Chapter 5 describes the mathematical model for the optimal design of WDNs, which includes problem formulation of various objectives like minimization of network cost, network resilience and network equity and constraints like conservation of mass, energy, minimum pressure and discrete diameter as well as a mathematical model for the optimal design of DMAs in a WDN. The detailed working methodology of three optimization techniques [Multiobjective Particle Swarm Optimization Algorithm (MOPSOA) augmented with local search, Self-adaptive Multiobjective Cuckoo Search Algorithm (SAMOCSA) and NSGA-II algorithm augmented with a random multi-point crossover operator as well as local search (RLNSGA-II)] to solve multiobjective optimization models, and Fast Newman Algorithm that has been used to identify the clusters while identifying the DMAs in a WDN has also been explained in this chapter.

Chapter 6 describes the results and discussion, which includes three different scenarios. In the first scenario, two objectives, namely, network cost and network resilience have been considered. In this scenario, the results from the three optimization techniques (MOPSOA, SAMOCSA and RLNSGA-II) for continuous and intermittent water supply for the five WDNs have been analyzed and discussed. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable distribution of water services while reducing disparities. This expanded set of objectives is applied on the two real-life water distribution networks. The third scenario discusses the results of determining the optimal design of DMAs in detail.

Chapter 7 describes the summary and conclusions of this study.

Contributions from the study, scope for further work, publications from the research and references are included in the thesis.

The next chapter presents the literature review on the optimal design of WDNs and optimal design of DMAs in a WDN, as well as the gaps and objectives of the research work.

Chapter 2

Literature Review

2.1. General

WDNs are critical infrastructure systems that provide access to clean water to communities. The optimal design of these networks is essential for ensuring efficient water supply, minimizing costs, and reducing energy consumption. Additionally, the provision of DMAs plays a vital role in improving network performance by enabling better leak detection, pressure control, and overall management. This literature review aims to provide insights into the state-of-the-art techniques in the optimal design of WDNs and the design of DMAs while highlighting the objectives of this PhD thesis.

2.2. Optimal Design of Water Distribution Networks

The design of WDNs is challenging for engineers around the globe for various reasons. They include non-linear relationships between pipe discharges and head losses, introducing complex non-linear constraints and the discrete pipe diameters leading to a combinatorial optimization problem, among others. Sufficient literature is available on the optimization of WDN design focusing on cost minimization using linear programming (Alperovits and Shamir, 1977; Quindry *et al.*, 1981; Morgan and Goulter, 1985; Fujiwara *et al.*, 1987; Kessler and Shamir, 1989; Fujiwara and Khang, 1990; Sonak and Bhave, 1993). Similarly, the literature using non-linear programming includes Shamir (1974), El-Bahrawy and Smith (1987), Su *et al.* (1987), Lansey and Mays (1989), Duan *et al.* (1990), Bhave and Sonak (1992), Gupta et al. (1993, 1999), Varma *et al.* (1997) and many more. Continuous diameters and split pipes are frequently used in linear and non-linear programming optimization models. After optimization, the practice is to replace the value of the diameters (solved as a continuous variable) with the nearest commercial size, making the optimal solution a non-optimal solution. Also, using a link or split-pipe length with varying diameters is uncommon. Moreover, these methods depend on the initial solution in the search process to find the optimal solution.

Enumeration of all the possible solutions and selecting the best of them is the direct approach to solving such a problem. However, such an approach is practically infeasible due to the exponential growth of possible solutions with increased variables. In addition, optimization problems in WDNs have a significant number of local optima, which is a combinatorial problem. Mathematical models that imitate natural evolutionary processes have successfully been tested in optimizing engineering design problems.

Towards this, several researchers optimized the design of the WDN as a single objective, mainly cost minimization, using various evolutionary algorithms like Genetic Algorithm (Savic and Walters, 1997; Reca and Martínez, 2006; Kadu *et al.*, 2008), Simulated Annealing (Cunha and Sousa, 1999), Ant-colony Optimization (Maier *et al.*, 2003), Shuffled Frog Leaping Algorithm (Eusuff and Lansey, 2003), Differential Evolution (Suribabu, 2009; Vasan and Simonovic, 2010), Improved Crow Search Algorithm (Fallah *et al.*, 2019), Whale Optimization Algorithm (Ezzeldin and Djebedjian, 2020), Gravitational Search Algorithm (Fallah *et al.,* 2021) and many more. These techniques have efficiently provided the least cost solutions, with the number of function evaluations less than those compared to complete enumeration for benchmark problems.

Walski (2001) emphasized the need for new models to consider multiple objectives in the design of WDN. The biggest hurdle in WDN design is predicting future demand. A designer would like to provide excess head (beyond the required minimum head) at each node to overcome increased head losses under unexpected high demand or failure conditions. He also advocates using models that generate more reliable loops and avoid loops with pipes of widely different diameters. Prasad and Park (2004) presented a multiobjective genetic algorithm approach to design a WDN. They improved the resilience index developed by Todini (2000) while considering some of the practical suggestions by Walski (2001). Similarly, Ostfeld *et al.* (2014) successfully demonstrated a methodology for multiobjective optimization for the least cost design and resiliency of water distribution systems.

Similarly, several researchers have tried various approaches like Wang *et al.* (2015) obtained the best-known approximation of the true Pareto front for twelve benchmark problems by considering multiobjective optimization with two conflicting objectives, namely minimization of network cost and maximization of network resilience using five standard multiobjective evolutionary algorithms (MOEAs): Non-dominated Sorting Genetic Algorithm -II (NSGA-II), epsilon-NSGA-II, epsilon-MOEA, AMALGAM (a modified multialgorithm, genetically adaptive multiobjective) and Borg. AMALGAM is a hybrid optimization framework that combines four algorithms: NSGA-II, Adaptive Metropolis Search (AMS), Particle Swarm Optimization and Differential Evolution. The twelve benchmark problems tested had small, medium, intermediate, and large WDNs. To form the best-known true Pareto front, such non-dominated solutions were combined, and dominated solutions were eliminated. The complementarity of the five MOEAs across different problems suggests that no single method exhibited complete superiority over the others. Nonetheless, with minimal parameter tuning, the NSGA-II algorithm consistently outperformed the alternatives across all problems, making it a favourable choice. Furthermore, employing a small population size suffices for small and medium networks. However, to ensure the best-known approximation of the Pareto front for intermediate and large problems, it is advisable to utilize varying population sizes and random seeds. Siew *et al.* (2016) developed and applied a new multiobjective evolutionary optimization approach to design and upgrade WDNs with multiple pumps and service reservoirs. Sheikholeslami and Talatahari (2016) proposed a novel swarm-based optimization algorithm named Direct Search Optimization which integrates the Accelerated Particle Swarm Optimization with the Big-Bang Crunch Algorithm to optimize the design of WDNs. This approach obtained the optimal solution for three benchmark problems at a relatively low computational cost. Moosavian and Lence (2017) used Nondominated Sorting Differential Evolution (NSDE) for the multiobjective design of WDNs on three benchmarks problems (Two loop, Hanoi and Farhadgerd network). Two objectives have been considered in this study, namely minimization of network cost and maximization of network resilience. The results demonstrated NSDE's superiority over the AMALGAM algorithm, highlighting its effectiveness in generating pareto optimal solutions. Yazdi *et al.* (2017) developed a hybrid algorithm combining differential evolution (DE) and harmony search (HS) for multiobjective design of WDNs. This study was tested on Two loop, Hanoi, Fossolo and Balerma irrigation network with two conflicting objectives, minimization of network cost and maximization of network resilience. The results have shown that the proposed hybrid method provided better optimal solutions and outperformed the other algorithms considered in this study. Wang *et al.* (2017) introduced a new hybrid algorithm namely, GALAXY (Genetically Adaptive Leaping Algorithm for Approximation and Diversity) for multiobjective optimization of WDNs. The objectives considered in this study are minimization of network cost and maximization of network resilience. The proposed methodology has been tested on five benchmark problems (BakRyan, Hanoi, Pescara, Modena and Balerma WDNs). The results have shown that GALAXY demonstrates superior capability in efficiently and consistently identifying better converged and distributed boundary solutions.

Cunha and Marques (2020) developed a multiobjective simulated annealing algorithm and tested on 12 benchmark WDNs. Two objectives, minimization of network cost and maximization of network resilience have been considered in this study. The proposed algorithms showed very good performance and converged to better pareto fronts. Yazdi and Taji Elyatoo (2022) investigated different reliability indices of a WDN and compared their performance for designing a WDN for three benchmark WDNs (Hanoi, Pescara and Modena) using NSGA-II. The results showed that network resilience index proposed by Prasad and Park (2004) outperforms other metrics. Palod *et al.* (2022) developed multiobjective Jaya Algorithm and applied it on two benchmark networks using three different reliability indices. It was found that the network resilience index proposed by Prasad and Park (2004) is better for Two Loop network and for the Hanoi network, modified resilience index performs better. Bi *et al.* (2022) formulated a multiobjective model with six objectives focusing on economic, structural and functional aspects in the operation and management of the WDN and solved by Borg, which is one state-of-the-art multi-objective evolutionary algorithm. A real-world case study with 1278 decision variables is used to demonstrate the effectiveness of the proposed framework. The results showed that the complex trade-offs among these six different objectives gave practical insights while designing large real-world WDN problems. Parvaze *et al.* (2023) reviewed the developments in the optimization of WDNs using genetic algorithms. The review concluded that in spite of so many published work on design optimization of WDNs over the past three decades, there is still a lack of consensus among researchers and practitioners regarding the best way to construct a WDN design optimization model or using the most suitable optimization algorithm to solve the multiobjective model. Kidanu *et al.* (2023) proposed an improved version of NSGA-II and tested on five benchmark WDNs of different sizes for a two objective model (minimization of network cost and maximization of network resilience). The results showed that the proposed algorithm outperformed the original NSGA II.

In many Indian cities, WDNs are designed assuming continuous water supply. However, in practice the water is supplied intermittently, the duration ranging from 1 to 4 hours daily. Due to this, there are pressure and discharge fluctuations at every node in WDNs. Understanding the system behavior through hydraulic model simulations is crucial to propose solutions for these problems. Therefore, several researchers (Bhave, 1981; Germanopoulos, 1985; Wagner *et al.*, 1988; Chandapillai, 1991; Tanyimboh *et al.*, 2001; Tanyimboh and Templeman, 2010) have attempted to establish equations relating pressure and flow at nodes in WDNs . Few studies (Gupta and Bhave, 1996; Shirzad *et al.*, 2013) compared various methods for predicting these equations with experimental work and found equations proposed by Wagner *et al.* (1988) to be the most effective. Vairavamoorthy *et al.* (2007) in his study has attempted to design two networks in Bangalore, India as intermittent water supply. Mohapatra *et al.* (2014) designed an intermittent water supply for the city of Nagpur, Maharashtra, India. There are very few reported studies with regards to design of intermittent water supply in the Indian context and there isn't any research in the literature for Hyderabad, India.

Nyahora *et al.* (2020) has used genetic algorithm for enhancing intermittent water supply (IWS) systems by integrating cost-effective interventions such as pipe replacement, booster pump, and elevated tank installation. This approach maximizes equity and reliability while minimizing costs, facilitating the transition towards continuous water supply. The proposed methodology has been applied to Hanoi WDN and another real-life WDN namely Milagro (located in Ecuador). The results have shown importance of equity and reliability in decision-making for IWS systems. Ramani *et al.* (2023) has used NSGA-II algorithm for design of intermittent WDN for multiobjective optimization (maximization of network resilience and maximization of network equity). The proposed algorithm was successfully tested on two small benchmark problems.

2.3. Optimal Design of District Metered Areas in a Water Distribution Network

Introducing DMAs within WDNs can make the operations and maintenance of WDN efficient and reliable. DMAs are distinct zones that enable utilities to monitor and manage water flow, detect leaks, and optimize network performance. The optimal design of DMAs is a complex, multiobjective optimization problem and traditional approaches often face challenges in handling the network's complexity. Therefore, several researchers have tried multi-phase procedures to enhance the efficiency and effectiveness of the design of DMAs. The multi-phase procedure is a comprehensive methodology comprising several steps, each contributing to the optimal design of DMAs. The main phases involved are node clustering and optimization. Among these, the Fast Newman Algorithm (FNA), originally proposed by Clauset *et al.* (2004) is the most widely adopted clustering algorithm. Optimization has been done using evolutionary algorithms like genetic algorithm, particle swarm optimization, etc. A brief description of the design of DMAs in the literature has been included below.

Diao *et al.* (2013) has proposed an automated approach for creating boundaries for DMAs based on the community structure of water distribution systems. Community structure involves grouping vertices into communities with denser connections within them than between them, a common characteristic in complex systems. The method was tested on a real-world distribution system and compared to a manually designed DMA layout. While further refinements are needed, the achieved community structure closely aligns with the real zoning plan, making this approach a valuable addition to automated methods that aim to enhance or replace the traditional trial-and-error approach. Campbell *et al.* (2015) introduced an innovative method for partitioning water supply networks. The approach draws inspiration from social network theory and graph theory, specifically community detection and shortest path concepts and employs a multiobjective optimization procedure via Agent Swarm Optimization. It optimizes a range of criteria, including energy efficiency, operational performance and economic considerations. The approach's feasibility was demonstrated by generating four viable solutions on a segment of real WDNs.

Laucelli *et al.* (2017) proposed a two-step strategy for planning DMAs within WDNs. In the first step, an optimal segmentation design was achieved by maximizing the modularity index specifically tailored for WDNs while minimizing the number of conceptual cuts (without considering devices like flow meters). The second step involves the actual optimal DMA design, which determines the positions of flow meters and closed valves at these conceptual cuts. This optimal DMA design is accomplished through a three-objective optimization process to minimize the number of flow meters, total unsupplied customer demand, and background leakages. The study demonstrates the procedure's effectiveness and flexibility using real-life networks. Han and Liu (2017) has introduced a novel methodology for designing DMAs in WDNs. This methodology treats the WDN as an undirected graph represented by a weighted topology matrix. Nontrivial eigenvectors are calculated using the normalized Laplacian matrix. Clusters are determined using a combination of k-means and genetic algorithms to minimize the squared distance error between nodes and their centroids in Euclidean space. The feasibility of this methodology is demonstrated through testing on a real WDN.

Rahmani *et al.* (2018) has introduced a new method to optimize WDNs by configuring DMAs using graph theory. It aims to enhance DMA efficiency in monitoring and controlling water networks, offering insights into improved system management. Pesantez *et al.* (2019) has introduced an automated approach to design DMAs in WDNs. The goal is to enhance the efficiency of water management by creating well-structured control zones. The approach combines graph theory, optimization and heuristics to design DMAs that minimize the variation in demand similarity among them. The proposed methodology has been applied to four water networks, demonstrating its effectiveness in improving demand similarity among DMAs. Bui *et al.* (2021) presented a method for optimal DMA design using a Self-Organizing Map (SOM) and a Community Structure Algorithm. It begins with SOM-based clustering and then employs the algorithm to refine DMA layouts. The approach was tested on hypothetical and real networks, demonstrating its ability to adapt to changing water demand efficiently. Yu *et al.* (2022) introduced a two-step process for DMA partitioning: clustering and dividing. The first step involves clustering nodes through an improved METIS graph partitioning method. In the second step, feasible solutions for optimizing the location of flowmeters and gate valves on boundary pipes are obtained using improved particle swarm optimization.

Sharma *et al.* (2022) proposed a multi-step approach for DMA identification. In the first step, a community detection algorithm was applied to identify DMAs. The second step involves optimization using the genetic algorithm by simultaneously taking multiple objectives such as economic criteria, water quality, resilience, and network pressure, resulting in a Pareto optimal solution. In the final step, a multi-criteria decision-making (MCDM) tool is utilized to determine a unique solution based on user-defined weightings for various objectives. The methodology was tested on a medium-sized water network, demonstrating its ability to effectively identify optimal DMA partitions. Sharma *et al.* (2023) applied NSGA-III algorithm for multiobjective design of DMAs in WDN. Five objectives considered in this study are design cost, operational cost, Resilience Index, average pressure and water age. The proposed methodology has been applied to two benchmark problems, demonstrating its capability to identify optimal DMAs. Kakeshpour *et al.* (2024) used NSGA-II algorithm for multiobjective design of DMAs in WDN. The two objectives considered in their study are minimization of total cost and minimization of average pressure in high pressure zones. The proposed methodology has been applied to two benchmark problems. The results have shown that the proposed methodology has significantly reduced average pressure in high pressure zones.

2.4. Gaps found in Literature Review

Based on the literature review, the following gaps have been identified:

- Despite the potential effectiveness of metaheuristic algorithms in solving multiobjective optimization problems, there is a gap in their application to multiobjective WDN design under intermittent water supply system. This gap limits the exploration of diverse optimization techniques that could enhance the efficiency and effectiveness of generating design solutions of WDNs.
- Existing literature lacks comprehensive formulation of multiobjective WDN design models that effectively consider multiple objectives for complex real-life case studies. While some studies address single objectives, such as minimizing cost or maximizing resilience, there is a notable absence of models that simultaneously account for multiple objectives, hindering the development of holistic solutions.
- Many researchers have limited their testing to small and medium benchmark problems, neglecting the examination of large, real-life, complex problems. This gap highlights the necessity of conducting experiments on such larger-scale, practical scenarios to better understand the applicability and effectiveness of proposed methodologies in real-world contexts.
- While the identification of DMAs is crucial for effective WDN management, literature lacks a multiphase procedure that leverages metaheuristic algorithms for this purpose.

Existing methods often rely on manual or heuristic approaches, which may not fully exploit the potential for optimization and automation offered by metaheuristic algorithms. Thus, there is a gap in the literature concerning the development of systematic, algorithm-based approaches for identifying DMAs in WDNs.

- Research efforts focusing on case studies from Telangana, India, are notably scarce, indicating a gap in the existing literature. This lack of attention to a significant urban area suggests an opportunity for further exploration and analysis of WDN design, management and optimization specific to Telangana's unique characteristics and challenges.

2.5. Objectives of the Study

The following objectives have been derived based on the literature review conducted above.

1. To formulate of multiobjective WDN design model, considering network cost, network resilience and network equity for a complex real-life case study in continuous and intermittent water supply system
2. To solve the proposed multiobjective model using three metaheuristic optimization algorithms (particle swarm optimization, cuckoo search algorithm and genetic algorithm) to generate pareto optimal solutions that represents the optimal WDN design
3. To formulate a two-step procedure for identifying the optimal design of DMAs in a WDN using a metaheuristic optimization algorithm

The next chapter details the WDN modelling and discusses the capabilities of the hydraulic simulation tool, EPANET 2.2, offering an understanding of its features and functionalities for accurate modelling and analysis of WDNs.

Chapter 3

Water Distribution Network Modeling

3.1. General

Water distribution network modeling involves the creation of mathematical representations and simulations to analyse the behavior and performance of a system that delivers water from its source to consumers. These models typically include components such as pipes, pumps, valves, storage tanks, and demand nodes, along with parameters such as pipe diameter, material properties, elevation, and water demand. Hydraulic equations, conservation of mass, and energy principles are applied to simulate the flow of water through the network under various operating conditions. Modeling tools range from demand-driven analysis and pressure-driven demand that consider factors like pressure variations, water quality, and demand fluctuations. The modeling in this study was carried out using the United States Environmental Protection Agency's (EPA) EPANET software (Rossman, 2000). A brief description of the model's capabilities and design principles is given in this chapter.

3.2. EPANET 2.2 – Hydraulic Simulation Tool

EPANET 2.2 or the "EPA's Water Distribution System Analysis Program," is a renowned and widely used software tool developed by the United States Environmental Protection Agency (Rossman, 2000). It is a robust and versatile hydraulic and water quality modeling solution for analyzing water distribution networks. EPANET 2.2 assists engineers and water utility professionals in evaluating the performance of water supply systems. It enables users to simulate water flow, pressure, water quality, and contaminant transport. With a user-friendly graphical interface, EPANET 2.2 is an invaluable tool for designing and optimizing distribution networks, assessing water quality and ensuring the safe and efficient delivery of clean drinking water to consumers, making it an essential resource in water infrastructure management. EPANET 2.2 works on a global gradient algorithm for hydraulic analysis of WDNs. The global gradient algorithm determines the flows and pressure at each node by solving the hydraulic equations(conservation of mass and conservation of energy) simultaneously.

3.3. Water Distribution Network Components

The WDN contains components like pumps, tanks, reservoirs, pipes and valves. Pipes are links that convey water from one point in the network to another. Reservoirs are nodes that represent an infinite external source or sink of water to the network. They could represent water storage structures or sources such as lakes, rivers, groundwater aquifers, etc. Reservoirs can also serve as water quality source points. Tanks are nodes with storage capacity, where the volume of stored water can vary with time during a simulation. The primary input properties for tanks are bottom elevation (where the water level is zero), diameter (or shape dimensions, if non-cylindrical), initial, minimum, and maximum water levels and initial water quality. Pumps are links that impart energy to the fluid, thereby raising its hydraulic head. The principal input parameters for a pump are its start node, end node, and pump curve (the combination of heads and flows that the pump can produce). Instead of a pump curve, the pump could be represented as a constant energy device that supplies a constant amount of energy to the fluid for all combinations of flow and head. Valves are links that limit the pressure or flow at a specific point in the network (Bhave and Gupta, 2017).

3.4. Hydraulic Modeling

Hydraulic modeling is a fundamental aspect of network modeling, focusing on the flow of water through pipes and other network components. It calculates flow rates, pressures, and velocities, enabling engineers and water utility managers to understand how water moves throughout the network (Bhave and Gupta, 2017). The following fundamental assumptions have made:

- ✓ Steady-State Flow: The equations assume that flow parameters such as velocity, pressure, and density remain constant with time at every point in the flow field. This steady-state condition implies that the flow does not vary over time.

- ✓ Incompressible Flow: The continuity equation assumes that the fluid density is constant and does not change significantly within the flow field. This assumption is applicable to liquids and certain low-speed gases where density changes are negligible.
- ✓ Irrorational Flow: The assumption of Irrorational flow simplifies the conservation of energy equation, assuming that there is no vorticity or rotational motion of fluid particles about their own axes. This assumption is particularly relevant for deriving Bernoulli's equation.
- ✓ Inviscid Flow: In the derivation of Euler's equation, it is assumed that the flow is inviscid, meaning that there are no viscous effects or frictional forces present in the flow.

EPANET 2.2 follows the conservation of mass and conservation of energy in the design of the network. A brief description of the design procedure is given in the following passages.

3.4.1. Conservation of Mass

The continuity equation must be satisfied at each node of the network as shown below.

$$\sum_{i\in in,n} Q_i = \sum_{j\in out,n} Q_j + ND_n \ \forall n \in nn \qquad (3.1)$$

where Q = pipe flow; ND_n = demand at node *n*; *in,n* = set of pipes entering to the node *n*; *out,n* = set of pipes emerging from the node *n*; *nn* = number of nodes.

3.4.2. Conservation of Energy

The energy balance constraint expresses the energy conservation law between the initial and final points of the known heads. These initial and final points can be the same physical point, resulting in a closed loop. The energy balance constraint can be expressed mathematically for each loop as

$$\sum_a r_a Q^b = 0 \qquad (3.2)$$

where 'a' represents the link pipe in the loop; r represents hydraulic resistance in the link pipe in the loop; b is the exponent, and Q is the flow in the link pipe in the loop.

The above equation for two points of the known head can be written as

$$\sum_a r_a Q^b = \Delta E \tag{3.3}$$

where ΔE is the energy loss between two points of the known head.

Hydraulic resistance 'r' can be calculated from the Hazen Williams head loss equation (Bhave and Gupta, 2017).

$$r = \frac{\alpha L}{C_{Hw}^{1.852} D^{4.87}} \tag{3.4}$$

where L is the pipe length, α is a constant, D is the pipe diameter and C_{Hw}^{p} represents Hazen William Coefficient of the pipe.

3.4.3. *Pressure-Driven Analysis*

Pressure-driven analysis is a fundamental aspect of hydraulic modeling in water distribution networks (Gupta and Bhave, 1996). It involves the study of how water pressure affects the flow and distribution of water within the network. By simulating pressure changes, engineers and water utility managers can assess the system's behavior, identify potential issues and ensure adequate pressure is maintained to meet consumer needs. Pressure-driven analysis is crucial for optimizing the layout of pipes, selecting pump and valve settings, and designing pressure control strategies. It helps maintain water quality, reduces leakage and ensures that water reaches consumers' taps at sufficient pressure levels, making it a key component in the efficient and reliable operation of water distribution systems. In pressure-driven demand other than conservation of mass and energy, the pressure-driven demand relationship has been included, elaborated below.

Pressure demand relationship.

$$q = q_{req}, \;\; if\ p > p_{req}\ (required\ outflow) \tag{3.5}$$

$$q = q_{req}\ (\frac{p - p_{min}}{p_{req} - p_{min}})^{0.5}, \;\; if\ \ p_{min} \le p\ \le\ p_{req}\ (partial\ outflow) \tag{3.6}$$

$$q = 0, \;\; if\ p < p_{min}\ \ (zero\ outflow) \tag{3.7}$$

where q is the actual node outflow, q_{req} is the demand; p is the nodal pressure, p_{min} is the minimum pressure, p_{req} is the required pressure.

3.4.4. Demand-Driven Analysis

Demand-driven analysis is a vital aspect of water distribution network modeling, focusing on understanding and simulating the impacts of varying water demands within the system (Gupta and Bhave, 1996). By considering factors such as consumer usage patterns, population growth, and industrial requirements, demand-driven analysis helps assess how different areas of the network experience changes in flow rates and pressure levels. This analysis aids in the design of appropriately sized pipes, pumps and storage facilities to meet the fluctuating demand. It ensures the network can efficiently supply water even during peak usage periods, improving water quality, system resilience, and overall customer satisfaction while optimizing resource utilization. In demand-driven analysis conservation of mass and conservation of energy has been used in the design of the water distribution network which has been elaborated from equations 3.1 to 3.7 above.

The next chapter provides a detailed description of five WDNs considered to validate the proposed methodology. These five WDNs include three benchmark WDNs and two real-life WDNs.

Chapter 4

Description of the Chosen Case Studies

4.1. General

In this study, the five WDNs have been chosen to validate the proposed methodology. Three benchmark problems, representing two medium WDNs (number of pipes between 21-50; New York WDN as branched and Hanoi WDN as looped) and one large WDN (number of pipes greater than 100; Balerma Irrigation Network). Additionally, the proposed methodology has also been tested on two real-life WDNs from Telangana, namely, Pamapur WDN and Vanasthalipuram WDN. The details of the chosen five WDNs are stated below.

4.2. Benchmark Problems

4.2.1. *New York Tunnel Water Distribution Network*

The New York Tunnel (NYT) WDN consists of 20 nodes, 21 pipes and one loop. It is fed by gravity from a reservoir with a fixed head of 91.44 m. All the existing pipes are considered for duplication in order to meet the projected future demand. The Hazen-Williams roughness coefficient for both new and existing pipes is 100. The minimum nodal pressure requirement for all nodes, except 16 and 17, is 77.72 m and for nodes 16 and 17 it is 79.25 m and 83.15 m, respectively. There are 16 possible decisions for each pipe as there are 15 market pipe diameter sizes available for each pipe in the network. The “do nothing” option is considered as the 16th. Considering all 21 pipes for possible duplication, the search space for the optimal solution equals to 16^{21} possible network design configurations. The relevant network data for this WDN is provided in the Tables 4.1, 4.2 and the network layout is shown in Fig. 4.1 (Schaake and Lai, 1969).

Table 4.1 Pipe Diameters Available in the Market for New York WDN with Corresponding Costs

S. No.	Diameter (m)	Unit Cost ($)	S. No.	Diameter (m)	Unit Cost ($)
1	0	0	9	3.05	416.46
2	0.91	93.59	10	3.35	468.71
3	1.22	133.70	11	3.66	522.11
4	1.52	176.32	12	3.96	576.59
5	1.83	221.05	13	4.27	632.09
6	2.13	267.61	14	4.57	688.54
7	2.44	315.80	15	4.88	745.91
8	2.74	365.46	16	5.18	804.14

Table 4.2 Hydraulic Details of New York WDN

Node Data			Pipe Data		
Node	Demand (m^3/s)	Minimum Head (m)	Pipe	Length (m)	Diameter (m)
1	-57.13	91.44	1	3535.68	4.57
2	2.62	77.72	2	6035.04	4.57
3	2.62	77.72	3	2225.04	4.57
4	2.50	77.72	4	2529.84	4.57
5	2.50	77.72	5	2621.28	4.57
6	2.50	77.72	6	5821.68	4.57
7	2.50	77.72	7	2926.08	3.35
8	2.50	77.72	8	3810.00	3.35
9	4.81	77.72	9	2926.08	4.57
10	0.03	77.72	10	3413.76	5.18
11	4.81	77.72	11	4419.60	5.18
12	3.32	77.72	12	3718.56	5.18
13	3.32	77.72	13	7345.68	5.18
14	2.62	77.72	14	6431.28	5.18
15	2.62	77.72	15	4724.40	5.18

Node Data			**Pipe Data**		
Node	**Demand (m^3/s)**	**Minimum Head (m)**	**Pipe**	**Length (m)**	**Diameter (m)**
16	4.81	79.25	16	8046.72	1.83
17	1.63	83.15	17	9509.76	1.83
18	3.32	77.72	18	7315.20	1.52
19	3.32	77.72	19	4389.12	1.52
20	4.81	77.72	20	11704.32	1.52
			21	8046.72	1.83

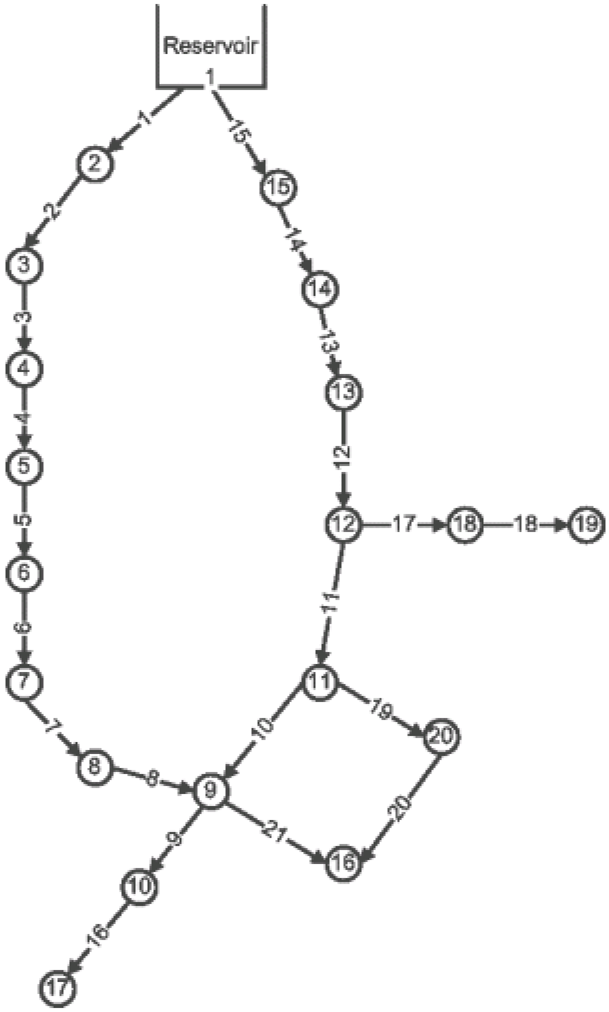

Figure 4.1 Layout of New York WDN

4.2.2. Hanoi Water Distribution Network

Hanoi WDN consists of 32 nodes and 34 pipes connecting them, organized in three loops fed by gravity from a single source with a 100 m fixed head. The pipe lengths vary from 100 to 3500 m, with a Hazen-Williams coefficient of 130 and the minimum pressure head required at each node is 30 m above the ground level. There are six commercially available pipes to be considered for 34 pipes making the total search space as 6^{34}. The relevant network data for this WDN is provided in the Tables 4.3, 4.4 and the network layout is shown in Fig. 4.2 (Savic and Walters, 1997).

Table 4.3 Pipe Diameters Available in the Market for Hanoi WDN with Corresponding Costs

S. No.	1	2	3	4	5	6
Diameter (m)	304.8	406.4	508	609.6	762	1016
Unit Cost ($)	45.73	70.40	98.38	129.33	180.75	278.28

Table 4.4 Hydraulic details of Hanoi WDN

Node Data				**Pipe Data**			
Node	**Demand (m^3/s)**	**Node**	**Demand (m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
1	-5.54	17	0.24	1	100	18	800
2	0.25	18	0.37	2	1350	19	400
3	0.24	19	0.02	3	900	20	2200
4	0.04	20	0.35	4	1150	21	1500
5	0.20	21	0.26	5	1450	22	500
6	0.28	22	0.13	6	450	23	2650
7	0.38	23	0.29	7	850	24	1230
8	0.15	24	0.23	8	850	25	1300
9	0.15	25	0.05	9	800	26	850
10	0.15	26	0.25	10	950	27	300
11	0.14	27	0.10	11	1200	28	750
12	0.16	28	0.08	12	3500	29	1500
13	0.26	29	0.10	13	800	30	2000
14	0.17	30	0.10	14	500	31	1600
15	0.08	31	0.03	15	550	32	150
16	0.09	32	0.22	16	2730	33	860
-	-	-	-	17	1750	34	950

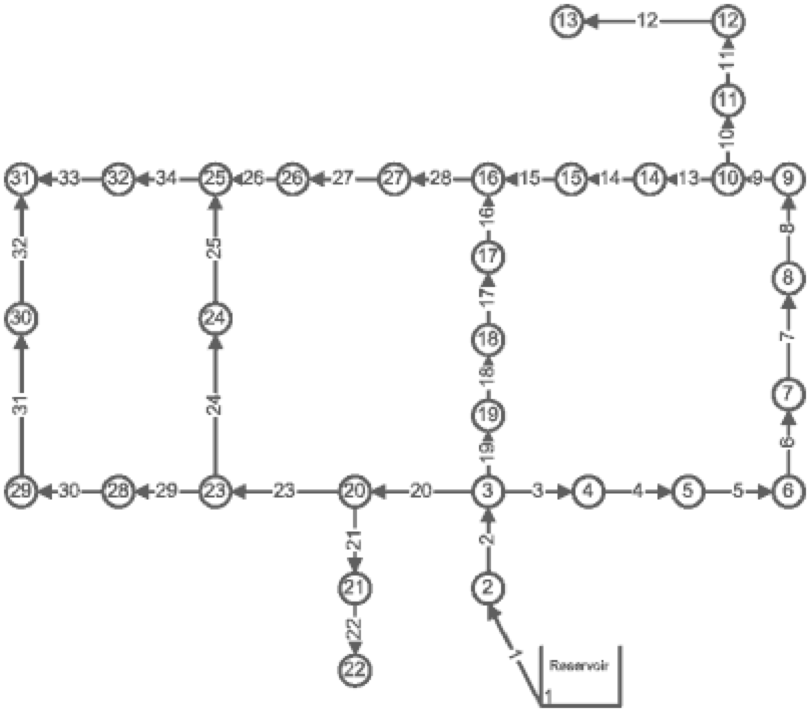

Figure 4.2 Layout of Hanoi water distribution network

4.2.3. Balerma Irrigation Network

Balerma Irrigation network (BIN) has 454 pipes, 443 demand nodes, 8 loops and fed by 4 source nodes with constant head between 112 m and 127 m. The minimum pressure head required at each demand node is 20 m. The material of pipes is polyvinyl chloride (PVC). Head-losses are calculated using the Darcy–Weisbach equation with an absolute pipe roughness of k = 0.0025 mm (Bhave and Gupta, 2017). There are 10 different commercially available diameters in the market. Therefore, the total search space is 10^{454}. The relevant network data for this WDN is provided in Tables 4.5, 4.6 and the network layout is shown in Fig.4.3 (Reca, 2006).

Table 4.5 Pipe Diameters Available in the Market for BIN with Corresponding Costs

Diameter (10^{-3} m)	**Unit Cost (€)**	**Diameter (10^{-3} m)**	**Unit Cost (€)**
2870.2	7.22	5745.48	28.6
3215.64	9.1	7239	45.39
3672.84	11.92	9189.72	76.32
4135.12	14.84	11485.88	124.64
4592.32	18.38	14777.72	215.85

Table 4.6 Hydraulic details of BIN

Pipe	**Length (m)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
1	65	115	246	229	182	343	90
2	260	116	100	230	93	344	286
3	164	117	750	231	151	345	146
4	250	118	250	232	85	346	170
5	100	119	250	233	300	347	222
6	68	120	200	234	250	348	31
7	164	121	273	235	132	349	69
8	164	122	205	236	211	350	297
9	65	123	200	237	69	351	83
10	98	124	312	238	400	352	77
11	145	125	308	239	259	353	130
12	96	126	40	240	155	354	257
13	181	127	346	241	187	355	720
14	92	128	334	242	222	356	351
15	100	129	73	243	82	357	188
16	177	130	114	244	220	358	159
17	159	131	93	245	300	359	189
18	155	132	161	246	270	360	83
19	168	133	221	247	78	361	200
20	103	134	150	248	90	362	94
21	113	135	254	249	123	363	128
22	850	136	160	250	86	364	67

Pipe	**Length (m)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
23	149	137	400	251	81	365	170
24	175	138	66	252	51	366	176
25	500	139	127	253	212	367	105
26	134	140	105	254	400	368	136
27	164	141	187	255	218	369	128
28	137	142	86	256	109	370	40
29	223	143	126	257	55	371	65
30	394	144	250	258	214	372	83
31	191	145	116	259	145	373	257
32	440	146	269	260	329	374	85
33	459	147	42	261	372	375	151
34	184	148	329	262	368	376	326
35	300	149	145	263	96	377	135
36	116	150	56	264	79	378	222
37	198	151	171	265	181	379	225
38	510	152	236	266	320	380	101
39	127	153	264	267	236	381	101
40	189	154	108	268	63	382	149
41	95	155	125	269	164	383	218
42	250	156	190	270	280	384	569
43	375	157	269	271	103	385	816
44	100	158	227	272	150	386	320
45	231	159	110	273	46	387	74
46	61	160	110	274	314	388	150
47	282	161	140	275	264	389	317
48	88	162	284	276	229	390	262
49	134	163	298	277	265	391	314
50	40	164	200	278	51	392	419
51	189	165	150	279	87	393	345
52	225	166	193	280	363	394	671
53	201	167	73	281	163	395	421
54	66	168	156	282	136	396	700
55	78	169	132	283	200	397	603
56	197	170	106	284	59	398	477
57	197	171	160	285	59	399	380
58	177	172	225	286	81	400	206
59	85	173	93	287	142	401	616

Pipe	Length (m)	Pipe	Length (m)	Pipe	Length (m)	Pipe	Length (m)
60	222	174	325	288	248	402	347
61	288	175	106	289	110	403	249
62	130	176	194	290	66	404	184
63	127	177	103	291	99	405	141
64	96	178	149	292	415	406	75
65	110	179	138	293	1450	407	227
66	205	180	146	294	350	408	397
67	176	181	147	295	400	409	162
68	300	182	398	296	68	410	177
69	500	183	131	297	459	411	70
70	119	184	38	298	310	412	350
71	228	185	78	299	169	413	350
72	295	186	287	300	176	414	820
73	191	187	253	301	392	415	175
74	129	188	215	302	246	416	169
75	152	189	170	303	87	417	135
76	115	190	135	304	64	418	213
77	444	191	145	305	233	419	474
78	580	192	254	306	90	420	280
79	350	193	103	307	174	421	1800
80	209	194	85	308	51	422	611
81	212	195	600	309	108	423	354
82	455	196	300	310	190	424	209
83	250	197	100	311	293	425	500
84	168	198	306	312	168	426	400
85	145	199	256	313	317	427	44
86	172	200	239	314	342	428	300
87	110	201	450	315	415	429	800
88	250	202	130	316	142	430	345
89	148	203	268	317	183	431	750
90	123	204	70	318	131	432	103.6
91	139	205	471	319	75	433	219
92	210	206	176	320	362	434	214
93	159	207	190	321	392	435	80
94	144	208	158	322	236	436	23
95	148	209	206	323	168	437	121
96	161	210	83	324	263	438	100

Pipe	Length (m)	Pipe	Length (m)	Pipe	Length (m)	Pipe	Length (m)
97	267	211	165	325	84	439	102
98	320	212	69	326	50	440	52
99	444	213	200	327	182	441	116
100	184	214	90	328	158	442	79
101	322	215	137	329	102	443	82
102	228	216	58	330	69	444	157
103	129	217	107	331	121	445	381
104	254	218	118	332	81	446	363
105	224	219	177	333	96	447	2500
106	202	220	153	334	87	448	752
107	162	221	133	335	195	449	100
108	435	222	170	336	209	450	177
109	488	223	210	337	67	451	500
110	179	224	165	338	55	452	100
111	137	225	115	339	167	453	500
112	160	226	163	340	81	454	200
113	168	227	100	341	225	-	-
114	350	228	110	342	44	-	-

Figure 4.3 Layout of Balerma Irrigation Network

4.3. Real Life Case Studies

4.3.1. *Pamapur Water Distribution Network*

Pamapur WDN is located in Kothakota mandal, Wanaparthy district, Telangana state, India. The Pamapur water distribution network comprises of 122 pipes, 102 demand nodes, and three tanks. All the pipes are made of polyvinyl chloride. A uniform Hazen-Williams roughness coefficient of 130 is applied to all pipes. The minimum pressure of all demand nodes is fixed at 6 m except for node 22, which is 5.75 m respectively. There are 13 different commercially available diameters in the market. The total search space for this WDN is 13^{122}. The relevant network data for this WDN is provided in Tables 4.7, 4.8 and the network layout is shown in Fig. 4.4 (Pankaj *et al.*, 2020).

Table 4.7 Pipe Diameters Available in the Market for Pamapur WDN with Corresponding Costs

S. No	**Diameter (10^{-3} m)**	**Unit Cost (Rs.)**
1	44.4	65
2	56.2	98
3	66.8	138
4	80.4	197
5	98.6	296
6	112	378
7	125.4	474
8	143.4	621
9	161.4	780
10	179.4	964
11	201.8	1245
12	224.4	1532
13	251.4	1921

Table 4.8 Hydraulic details of Pamapur WDN

Node Data				**Pipe Data**			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
1	0.57	62	1.88	1	101.43	62	30.82
2	3.20	63	0.72	2	106.69	63	30.79
3	3.57	64	2.07	3	97.34	64	30.65
4	1.22	65	1.50	4	91.62	65	29.35
5	0.63	66	2.35	5	106.7	66	30.52
6	0.62	67	2.22	6	115.77	67	29.44
7	0.88	68	3.53	7	83.93	68	27.24
8	0.92	69	1.03	8	79.96	69	27.64
9	0.25	70	1.13	9	75.74	70	26.85
10	0.42	71	4.08	10	76.06	71	25.62
11	0.52	72	3.17	11	82.05	72	25.81
12	0.52	73	0.25	12	95.6	73	25.63
13	0.30	74	3.28	13	71.64	74	23.91
14	2.63	75	2.33	14	70.02	75	23.59
15	1.15	76	1.57	15	70.04	76	23.13
16	0.85	77	0.45	16	69.95	77	24.54
17	0.97	78	1.62	17	69.35	78	21.68
18	0.77	79	1.00	18	67.41	79	21.48
19	1.02	80	0.80	19	66.46	80	21.39
20	2.07	81	1.10	20	65.09	81	20.58
21	0.47	82	1.30	21	63.06	82	20.54
22	0.62	83	0.75	22	62.34	83	18.15
23	2.50	84	0.27	23	60.88	84	17.45
24	0.93	85	1.52	24	60.45	85	15.47
25	0.23	86	1.57	25	59.15	86	13.26
26	1.65	87	2.35	26	56.44	87	12.57
27	0.98	88	1.35	27	53.19	88	12.5
28	1.28	89	1.02	28	55.44	89	10.65
29	1.47	90	0.28	29	65.65	90	10.2
30	0.58	91	0.98	30	54.67	91	44
31	0.35	92	1.50	31	54.13	92	19.03
32	0.97	93	1.70	32	51.55	93	86.92
33	0.85	94	2.03	33	52.06	94	44.92
34	0.58	95	0.77	34	47.41	95	24.24
35	0.25	96	1.48	35	47.87	96	24.35
36	0.83	97	0.92	36	66.1	97	38.15
37	0.20	98	0.53	37	47.27	98	118.12
38	1.40	99	1.50	38	46.38	99	66.2

Node Data				Pipe Data			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
39	2.53	100	1.35	39	45.24	100	40.96
40	2.28	101	1.22	40	46.34	101	50.1
41	3.58	102	0.17	41	45.94	102	72.69
42	1.22	-	-	42	45.32	103	81.81
43	0.95	-	-	43	45.88	104	55.73
44	1.42	-	-	44	44.95	105	16.29
45	2.73	-	-	45	43.68	106	92.34
46	2.60	-	-	46	41.5	107	211.45
47	1.73	-	-	47	40.57	108	202.66
48	0.57	-	-	48	39.99	109	171.95
49	0.45	-	-	49	39.1	110	172.12
50	2.33	-	-	50	39.98	111	158.85
51	2.38	-	-	51	38.55	112	158.93
52	0.20	-	-	52	37.72	113	150.65
53	3.03	-	-	53	34.76	114	131.64
54	0.22	-	-	54	33.97	115	126.81
55	1.25	-	-	55	33.56	116	128.19
56	2.10	-	-	56	34.2	117	120.36
57	1.32	-	-	57	32.58	118	125.91
58	1.02	-	-	58	31.53	119	120.53
59	0.75	-	-	59	31.63	120	108.46
60	2.37	-	-	60	32.55	121	105.57
61	0.57	-	-	61	31.22	122	40

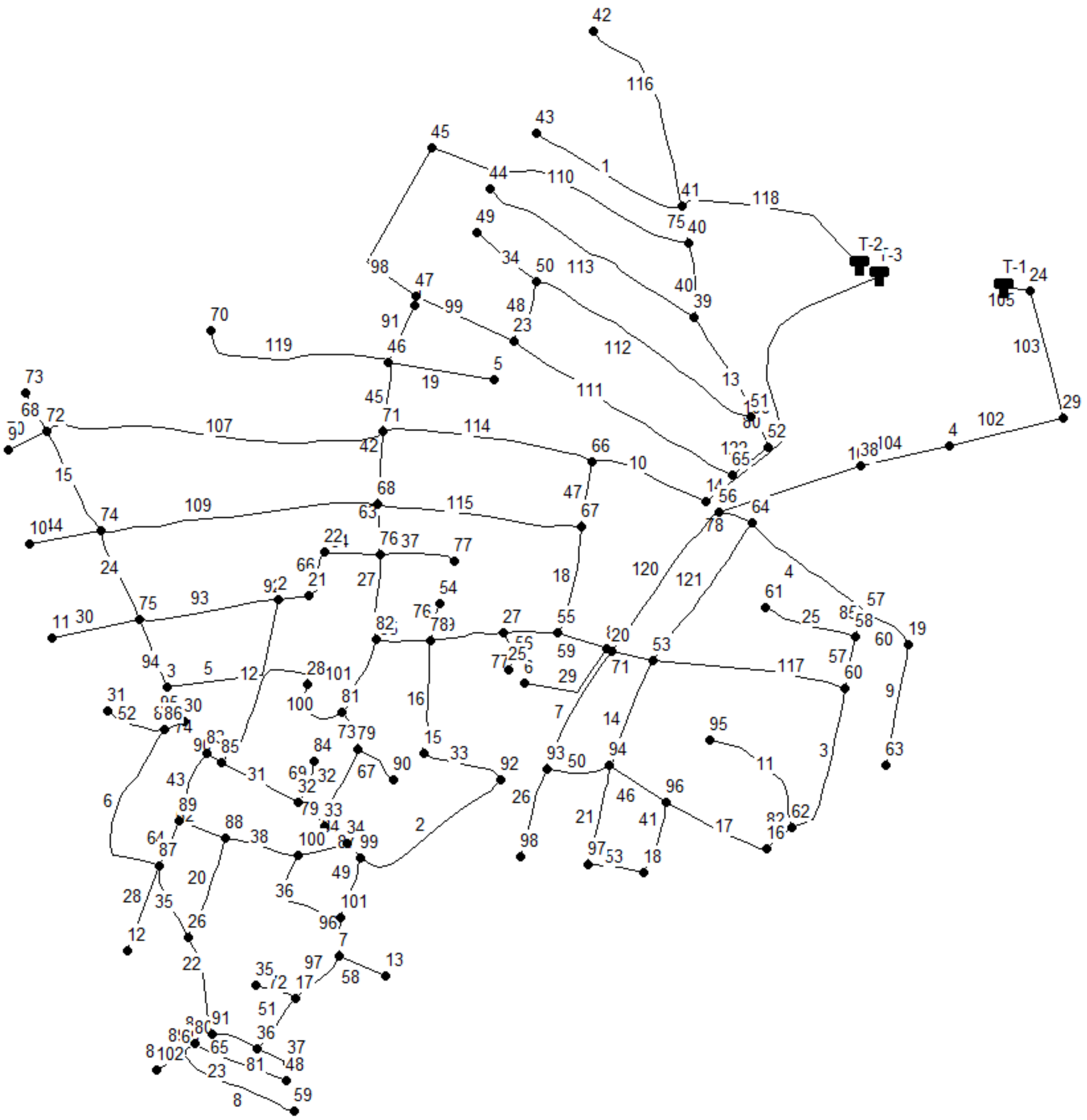

Figure 4.4 Layout of Pamapur WDN

4.3.2. *Vanasthalipuram Water Distribution Network*

Vanasthalipuram is located in Hyderabad, Telangana State, India. Vanasthalipuram WDN comprises of 301 pipes, 211 demand nodes, and one tank. All the pipes are made of polyvinyl chloride. A uniform Hazen-Williams roughness coefficient of 130 is applied to all pipes. The minimum pressure of all demand nodes is fixed at 6 m. There are 13 different commercially available diameters in the market. The total search space for this WDN is 13^{301}. The relevant network data for this WDN is provided in Tables 4.9, 4.10 and the network layout is shown in Fig. 4.5.

Table 4.9 Pipe Diameters Available in the Market for Vanasthalipuram WDN with Corresponding Costs

S. No	**Diameter (10^{-3} m)**	**Unit Cost (Rs.)**
1	44.4	65
2	56.2	98
3	66.8	138
4	80.4	197
5	98.6	296
6	112	378
7	125.4	474
8	143.4	621
9	161.4	780
10	179.4	964
11	201.8	1245
12	224.4	1532
13	251.4	1921

Table 4.10 Hydraulic details of Pamapur WDN

Node Data				**Pipe Data**			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
1	1.74	152	1.74	1	1.73	152	47.62
2	0.87	153	1.74	2	2.69	153	47.64
3	10.24	154	8.51	3	2.83	154	48.57
4	5.21	155	3.47	4	2.80	155	48.62
5	16.49	156	6.95	5	2.88	156	48.64
6	0.00	157	4.34	6	3.74	157	48.66
7	6.25	158	6.42	7	4.01	158	48.68

Node Data				Pipe Data			
Node	Demand (10^{-4} m^3/s)	Node	Demand (10^{-4} m^3/s)	Pipe	Length (m)	Pipe	Length (m)
8	3.47	159	5.21	8	9.35	159	48.72
9	3.47	160	14.58	9	10.10	160	48.82
10	6.77	161	6.95	10	10.57	161	49.06
11	2.34	162	6.95	11	11.48	162	49.75
12	1.91	163	3.65	12	11.84	163	50.50
13	0.87	164	3.65	13	12.41	164	50.91
14	1.22	165	0.87	14	13.07	165	50.95
15	7.29	166	3.82	15	13.27	166	51.22
16	0.00	167	3.82	16	13.71	167	51.04
17	10.94	168	1.04	17	15.19	168	51.15
18	15.45	169	1.04	18	18.88	169	51.30
19	1.74	170	2.34	19	19.81	170	51.89
20	2.43	171	4.34	20	20.75	171	51.93
21	5.21	172	8.51	21	21.29	172	51.93
22	3.82	173	10.76	22	21.83	173	52.08
23	13.72	174	5.73	23	21.98	174	52.14
24	3.47	175	7.64	24	22.55	175	52.23
25	4.51	176	2.26	25	22.92	176	52.66
26	0.87	177	4.51	26	23.35	177	52.81
27	6.60	178	12.50	27	23.78	178	52.86
28	6.08	179	4.86	28	23.91	179	53.09
29	4.51	180	6.25	29	24.57	180	53.72
30	0.00	181	8.16	30	24.79	181	54.23
31	3.73	182	7.29	31	25.01	182	53.91
32	3.65	183	5.21	32	25.13	183	53.92
33	5.56	184	5.21	33	25.51	184	54.82
34	3.30	185	3.47	34	25.68	185	54.91
35	3.82	186	1.04	35	25.76	186	55.29
36	3.47	187	2.17	36	25.78	187	55.33
37	3.47	188	7.81	37	25.87	188	55.68
38	3.30	189	6.77	38	25.96	189	55.72
39	1.56	190	6.08	39	26.15	190	56.78
40	2.61	191	3.65	40	26.37	191	57.49
41	2.78	192	7.81	41	26.41	192	57.57
42	1.91	193	14.93	42	27.96	193	57.77
43	7.29	194	8.68	43	28.02	194	57.79

Node Data				**Pipe Data**			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
44	1.74	195	3.82	44	28.12	195	57.80
45	1.04	196	2.17	45	28.14	196	59.35
46	1.74	197	1.74	46	28.22	197	63.56
47	4.51	198	2.17	47	28.28	198	60.56
48	4.34	199	2.17	48	28.30	199	60.88
49	4.34	200	1.74	49	28.96	200	61.62
50	3.47	201	4.95	50	29.32	201	61.94
51	3.65	202	5.38	51	29.76	202	63.56
52	7.73	203	12.67	52	29.87	203	62.98
53	5.21	204	5.90	53	30.03	204	63.40
54	3.82	205	15.45	54	30.04	205	63.91
55	0.52	206	0.87	55	30.08	206	64.12
56	7.29	207	1.04	56	30.10	207	65.46
57	0.87	208	3.13	57	30.29	208	66.10
58	5.38	209	2.61	58	30.76	209	66.59
59	6.08	210	2.61	59	30.82	210	67.07
60	3.99	211	8.16	60	31.10	211	67.24
61	2.61	-	-	61	31.21	212	67.81
62	2.08	-	-	62	31.42	213	67.84
63	5.21	-	-	63	31.54	214	68.95
64	9.03	-	-	64	31.83	215	71.15
65	7.38	-	-	65	31.84	216	72.59
66	5.21	-	-	66	31.95	217	72.62
67	1.22	-	-	67	31.96	218	73.13
68	1.39	-	-	68	32.01	219	73.27
69	1.56	-	-	69	32.11	220	73.53
70	1.39	-	-	70	32.19	221	74.19
71	1.74	-	-	71	32.42	222	78.87
72	2.34	-	-	72	32.45	223	81.71
73	12.24	-	-	73	32.53	224	82.11
74	6.95	-	-	74	32.56	225	82.24
75	9.03	-	-	75	32.52	226	82.24
76	2.61	-	-	76	33.15	227	82.32
77	1.65	-	-	77	33.28	228	82.59
78	1.65	-	-	78	33.98	229	83.15
79	29.51	-	-	79	34.16	230	87.45

Node Data				**Pipe Data**			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
80	3.21	-	-	80	34.33	231	88.06
81	1.39	-	-	81	34.62	232	89.83
82	3.47	-	-	82	34.76	233	91.14
83	6.08	-	-	83	35.23	234	91.80
84	4.51	-	-	84	35.53	235	92.40
85	15.45	-	-	85	35.59	236	97.94
86	5.56	-	-	86	35.62	237	98.39
87	7.12	-	-	87	35.91	238	99.00
88	3.73	-	-	88	36.00	239	100.24
89	11.20	-	-	89	36.11	240	101.25
90	3.65	-	-	90	36.45	241	101.43
91	4.95	-	-	91	36.44	242	102.35
92	6.77	-	-	92	36.46	243	104.03
93	4.34	-	-	93	36.47	244	104.55
94	2.17	-	-	94	36.51	245	105.18
95	5.21	-	-	95	36.71	246	105.18
96	10.42	-	-	96	36.91	247	106.38
97	1.39	-	-	97	36.99	248	107.66
98	0.00	-	-	98	37.03	249	108.72
99	12.15	-	-	99	37.21	250	109.45
100	3.13	-	-	100	37.21	251	112.78
101	1.74	-	-	101	37.24	252	112.89
102	8.16	-	-	102	37.27	253	113.01
103	9.20	-	-	103	37.39	254	113.41
104	3.47	-	-	104	37.98	255	113.41
105	3.47	-	-	105	37.85	256	113.47
106	5.21	-	-	106	38.19	257	114.42
107	5.21	-	-	107	38.21	258	114.63
108	10.42	-	-	108	38.45	259	115.09
109	3.47	-	-	109	38.48	260	115.69
110	3.47	-	-	110	38.59	261	115.88
111	6.08	-	-	111	39.31	262	117.20
112	2.17	-	-	112	39.62	263	120.77
113	2.43	-	-	113	39.68	264	132.36
114	5.56	-	-	114	39.72	265	133.11
115	5.04	-	-	115	40.26	266	134.00

Node Data				**Pipe Data**			
Node	**Demand (10^{-4} m^3/s)**	**Node**	**Demand (10^{-4} m^3/s)**	**Pipe**	**Length (m)**	**Pipe**	**Length (m)**
116	5.04	-	-	116	40.49	267	136.91
117	1.74	-	-	117	40.73	268	137.00
118	2.87	-	-	118	41.02	269	137.27
119	2.87	-	-	119	41.09	270	137.38
120	3.13	-	-	120	41.14	271	138.66
121	3.30	-	-	121	41.28	272	139.13
122	1.74	-	-	122	41.42	273	139.20
123	3.30	-	-	123	42.00	274	142.33
124	3.65	-	-	124	42.51	275	145.99
125	1.74	-	-	125	42.60	276	169.81
126	3.13	-	-	126	42.77	277	170.02
127	3.13	-	-	127	43.27	278	176.65
128	14.76	-	-	128	43.45	279	32.87
129	2.61	-	-	129	43.76	280	78.95
130	7.12	-	-	130	43.89	281	46.26
131	2.43	-	-	131	43.97	282	101.49
132	6.95	-	-	132	44.20	283	11.62
133	9.38	-	-	133	44.55	284	150.00
134	1.74	-	-	134	44.97	285	90.08
135	3.65	-	-	135	45.03	286	150.00
136	3.47	-	-	136	45.21	287	81.46
137	1.74	-	-	137	45.26	288	150.00
138	7.99	-	-	138	45.43	289	53.04
139	13.72	-	-	139	45.57	290	150.00
140	10.24	-	-	140	45.64	291	40.91
141	3.82	-	-	141	45.72	292	150.00
142	16.15	-	-	142	45.76	293	35.46
143	5.21	-	-	143	45.80	294	150.00
144	12.33	-	-	144	46.24	295	10.80
145	5.21	-	-	145	46.35	296	44.54
146	6.77	-	-	146	46.35	297	65.03
147	9.90	-	-	147	46.48	298	22.07
148	5.21	-	-	148	46.63	299	58.77
149	8.51	-	-	149	46.81	300	50.78
150	5.21	-	-	150	47.05	301	99.22
151	8.16	-	-	151	64.02	-	-

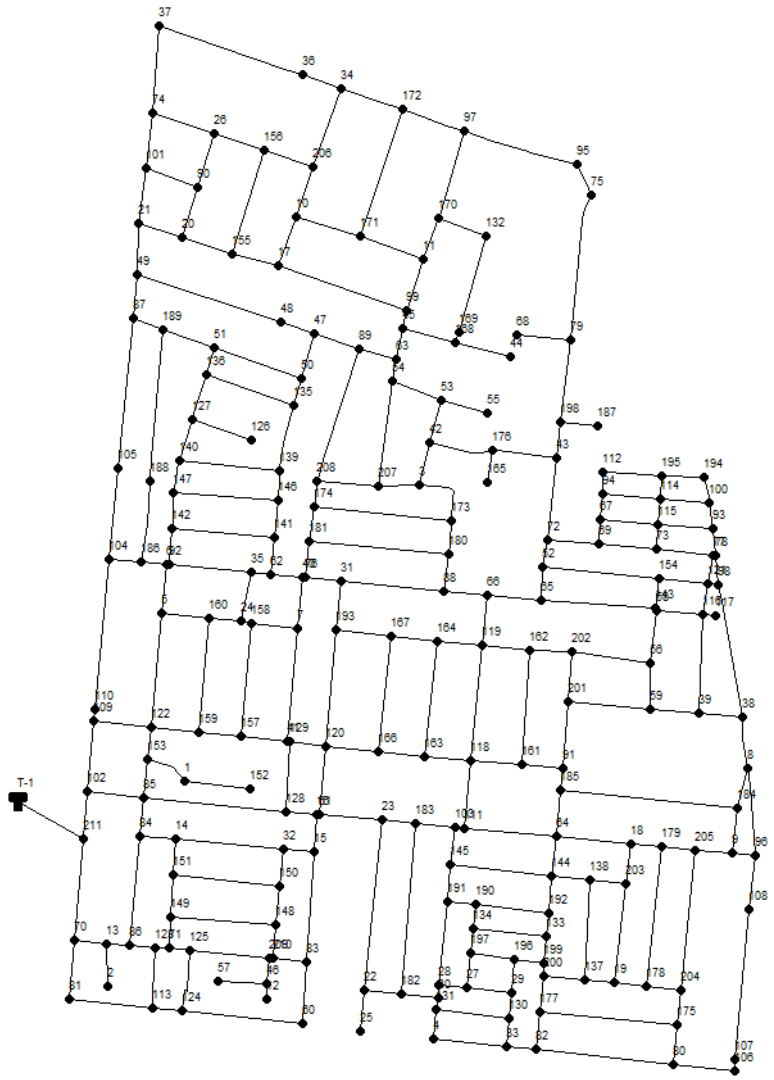

Figure 4.5 Layout of Vanasthalipuram WDN

Table 4.11 provides the unit cost of flow meters and valves adopted for various commercial sizes of pipes as obtained from the schedule of rates provided by the Government of Telangana for the year 2023-24.

Table 4.11 Commercial rates of flow meters and valves

Pipe Diameter (10^{-3} m)	**Unit Cost of Flow Meter (Rs.)**	**Unit Cost of Valve (Rs.)**
50	-	3,669
80	-	7,843
100	1,12,332	10,563
150	1,24,542	11,334
200	1,55,826	14,168
250	1,83,810	-

The next chapter describes about mathematical model formulation for optimal design of water distribution networks, explanation of the various nature inspired algorithms, fast newman algorithm and the different metrics used to compare the pareto optimal solutions obtained by optimization algorithms.

Chapter 5

Mathematical Modeling and Solution Techniques

5.1. General

Water distribution network design problem was historically formulated as least-cost optimization problem where the variables are standard pipe diameters available in the market. Network cost in water distribution is crucial for optimizing infrastructure expenses, ensuring efficient resource allocation, and maintaining affordable water services for consumers while supporting the sustainability of the system. The limitations of optimal design focusing on minimizing network cost alone have been criticized broadly (Engelhardt *et al.*, 2000; Walski, 2001) which led the researchers to transform the single objective model formulation to multi-objective models. The other objectives studied were reliability, resilience, leakage prevention, equity, carbon emissions etc. Among all the other objectives, network resilience and network equity of the network has been the prime consideration for the present study in addition to minimizing the network cost. Every network design should consider the possibility that a few components might be subjected to failure. The network needs to be designed such that even with the failure of a few components, the system should be able to satisfy at least the minimum requirements. The capacity of the network layout to overcome sudden failure is termed as the resilience of the network. Network resilience in water distribution ensures continuous water supply during disruptions, safeguarding public health and minimizing economic impacts by swiftly adapting to changing conditions. In developing countries, intermittent water supply is followed in which the water is supplied only for a fixed duration in a week. One of the major challenges associated with the intermittent water supply systems is maintaining equitable water distribution. Network equity in water distribution ensures fair and equal access to clean water for all communities, mitigating disparities and promoting social justice and inclusivity within society. Keeping the above-mentioned points in mind, three objectives namely Network Cost, Network Resilience and Network Equity have been considered in this study to determine the optimal design of WDNs.

WDNs are one of the major essential public infrastructures designed to meet the daily water requirements of a community. Dividing a water distribution network into subsystems named as district metered areas (DMAs) can improve the efficiency and ease of achieving management goals. Properly designed and maintained DMAs can help water utilities reduce water losses, improve system efficiency and enhance the overall reliability of their distribution networks. It is essential to prioritize the implementation of DMAs as part of a broader water management strategy. Determining the most suitable layout for DMAs of a water distribution network poses a complex challenge for engineers, as it consists simultaneous consideration of multiple interconnected factors. This research study introduces a methodology for achieving optimal DMAs design. The proposed methodology incorporates two key stages, including: (1) clustering to identify clusters using Fast Newman algorithm and (2) multiobjective optimization that provides optimal DMAs configurations. Three objectives considered in this study are minimizing the Network Cost, maximizing Network Resilience and maximizing the Network Equity.

5.2. Mathematical Model for Optimal Design of Water Distribution Networks

The mathematical model for minimization of network cost, maximizing of network resilience and maximization of network equity along with the constraints are detailed below. The optimal design for a network should satisfy the law of conservation of mass and energy as well as meet the demand needs at each node in the network.

5.2.1. Minimization of Network Cost

The diameter and the length of each pipe determine the cost of the network. The following equation 5.1 gives the mathematical representation of network cost:

$$Network\ Cost\ =\ \sum_{i=1}^{np} C_i\ (D_i) \times L_i \tag{5.1}$$

where C_i = Cost per unit length of a given pipe diameter, L_i = Length of pipe *i*, D_i = Diameter of the pipe *i* and np = Number of pipes in the network

5.2.2. Maximization of Network Resilience

A resilience index was initially developed by (Todini *et al.*, 2000) and improved upon by Prasad and Park (2004) called as network resilience which considers the uniformity of pipes around each demand node. The resilience index equation 5.2 is explained as:

$$Network\ Resilience = \frac{\sum_{i=1}^{nn} Q_i (H_i^{avl} - H_i^{min})}{\left(\sum_{r=1}^{nor} Q_r H_r + \sum_{p=1}^{npu} \frac{P_p}{\gamma}\right) - \sum_{i=1}^{nn} Q_i H_i^{min}} \tag{5.2}$$

where, Q_i = demand at node i (cuft/s), H_i^{avl} = Available head at node i, H_i^{min} = Minimum head required at node i, nn = number of nodes, nor = number of reservoirs, Q_r = Demand of reservoir, H_r = Head of reservoir, npu = number of power units, P_p = Power generated by power unit p, γ = efficiency of power unit.

Theoretically, network resilience lies between 0 and 1. However, part of the total energy supplied at the source is consumed to overcome the frictional losses in the water distribution network. The available energy at end nodes is always less than the initial energy supplied. Due to this reason, resilience never attains the value of 1.

5.2.3. Maximization of Network Equity

Network equity is defined to quantify the equity in distribution of water among the nodes in water distribution network. Gottipati and Nanduri (2014) proposed an index as shown in Eq. 5.3 to quantify the equity among the nodes in an intermittent water distribution system. It is based on the ratio of the actual quantity of water delivered at a node to the demand at the node is defined as the supply ratio of the node. The average supply ratio (ASR) is the mean of the supply ratios of all the nodes in the network. The deviation of the supply ratio of the node from the ASR is computed at each node, and the mean of these deviations is defined as ADEV.

$$Network\ Equity = 1 - \left(\frac{ADEV}{ASR}\right) \tag{5.3}$$

If the demand is exactly satisfied at all the nodes in the network, then the supply ratios at all the nodes will be one and hence the network equity would also be one. Network equity value would be less than one if the distribution of water among the nodes is not uniform.

5.2.4. Constraints

The constraints [Eq. (5.4), Eq. (5.5), Eq. (5.6) and Eq. (5.7)] to the optimization model for a water distribution network design are as follows:

(i) Continuity Constraint (Mass Conservation Law):

For each node other than source, the law of continuity (conservation of mass) should be satisfied

$$\sum_{i\in in,n} Q_i = \sum_{j\in out,n} Q_j + ND_n \ \forall n \in nn \qquad (5.4)$$

where Q = pipe flow; ND_n = demand at node *n*; *in,n* = set of pipes entering to the node *n*; *out,n* = set of pipes emerging from the node *n*; *nn* = number of nodes.

(ii) Energy Conservation Constraint (Energy Conservation Law):

The total loss of energy or head in a closed loop should be equal to zero

$$\sum_{i\epsilon l} \Delta H_i = 0; \ \forall l \in \mathrm{NL} \qquad (5.5)$$

where, ΔH_i = head loss in the pipe *i* at a loop *l*, *NL* = number of total loops in the system

(iii) Minimum Pressure Head Constraint at Nodes:

At every junction, the pressure head should be equal to or more than the minimum pressure head required

$$H_i^{avl} \geq H_i^{min} \ \ i = 1,2,3, \dots \dots nn \qquad (5.6)$$

(iv) Selection of diameters constraint

$$D_i \in [D] \qquad (5.7)$$

where, [D] = set of commercially available diameters in the market

5.3. Mathematical Model for Optimal Design of District Metered Areas in a Water Distribution Network

In this study, minimization of total cost, maximization of network resilience and maximization of network equity are the objectives considered for multiobjective optimization. The mathematical model for minimization of total cost has been given below. The mathematical model for maximizing the network resilience and maximization of network equity is the same as expressed in Eqs. 5.2 and 5.3.

5.3.1. Minimization of Total Cost

The total cost of implementation of DMAs depends on the number of isolation valves and flow meters. The following equation 5.8 gives the mathematical representation of total cost of implementation:

$$TCF = \sum_{i=1}^{N_{iv}} c_{iv} + \sum_{i=1}^{N_{flm}} c_{flwm} \tag{5.8}$$

where C_{iv} = unit cost of isolation valve; C_{flwm} = unit cost of flow meter; N_{iv} = number of isolation valves, N_{flm} = number of flow meters and *TCF* = Total Cost Function.

The formulated objective function is governed by the constraints, which includes flow continuity and energy conservation that must be satisfied across the water distribution network.

5.4. Solution Techniques Used in the Study

In the last few decades, researchers working on multiobjective design of WDN have attempted to explore several new metaheuristic optimization techniques to such complex problems as they are able to handle a discrete search space directly and are less likely to be trapped into the local optimal solutions (Yang, 2020). In the present study, three such optimization techniques [Multiobjective Particle Swarm Optimization Algorithm (MOPSOA) augmented with local search, Self-adaptive Multiobjective Cuckoo Search Algorithm (SAMOCSA) and NSGA-II algorithm augmented with a random multi-point crossover operator as well as local search (RLNSGA-II)] to solve multiobjective optimization models with some improvements in their working methodology have been implemented. Local search scheme has been augmented in two of the algorithms (MOPSOA and RLNSGA-II) to effectively explore the least-crowded areas of the objective space to determine better pareto-optimal points. Although these optimization algorithms work well for solving the problems, the robustness and efficiency of these algorithms are significantly dependent on certain control parameters specific to the working of the optimization algorithm. Appropriate values of these control parameters for obtaining near global optimal solution is not the same for every problem. Extensive sensitivity analysis studies need to be conducted for each problem which makes the process computationally expensive to determine the best suited parameter set accurately. To overcome this difficulty, studies have been done in developing algorithms to avoid pre-specifying the parameter values or algorithms which modify these parameters dynamically during the iterative process of the algorithm, based on the number of iterations or fitness value of the objective function. These algorithms are known as self-adaptive algorithms. The study focusses on developing a self-adaptive multiobjective cuckoo search algorithm for solving the design of WDNs. It is proposed to dynamically adjust the two parameters which largely govern the exploration and exploitation search strategies by the algorithm, i.e., step size control parameter 'α' and discovering probability parameter 'P_a'. These parameters are essential for enhancing the performance of the algorithm and the values of these parameters vary with the type of problem. This self-adaptation enables the algorithm to search in larger search space initially and as the iteration increases, the search space also decreases, enabling a better convergence rate as compared to original cuckoo search. Fast Newman Algorithm (FNA) has been used to identify the clusters while identifying the DMAs in a WDN. The description of the working of all these three optimization techniques and FNA is given in the following sections.

5.4.1. Multiobjective Particle Swarm Optimization Algorithm (MOPSOA)

Particle Swarm Optimization (PSO) is a popular metaheuristic optimization algorithm inspired by the social and collective behavior of bird flocking (Kennedy and Eberhart, 1995). It is widely used to solve complex optimization problems across various fields, including engineering, economics, and data science. In PSO, the potential solutions, called particles, fly through the search space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space which are associated with the best solution it has achieved so far. PSO is known for its high convergence speed which makes it more suitable for solving multiobjective optimization problems (Coello *et al.*, 2004). Several variations of the MOPSO algorithm have been reported by Sierra and Ceollo(2005) and Parsopoulos and Vrahatis (2008). Here, it is proposed to use the MOPSO algorithm proposed by Coello et al. (2004) with some modifications.

The velocity update formula in MOPSOA is similar to that used in single-objective PSO, and is given below:

$$v_i(t) = wv_i(t-1) + C1 * r1\left(x^i_{pbest} - x_i(t)\right) + C2 * r2(x_{leader} - x_i(t)) \tag{5.9}$$

where t denotes the PSO iteration number, x_i and v_i are the position and velocity of the ith particle, respectively, and r1 and r2 are random numbers between 0 and 1. The algorithm parameters are W (inertia weight), C1 (cognitive learning factor), and C2 (social learning factor). It should be pointed out that, although the decision variables in the present research work considered here take on discrete values, they are treated as real numbers in the velocity and position update equations. In computing the particle fitness, each decision variable is converted to the nearest integer (which gives the pipe diameter index for the concerned pipe).

The MOPSOA algorithm differs from the single-objective PSO algorithm in the computation of x^i_{pbest} (the personal best position of the particle so far) and x_{leader} (the position of the leader). In Coello et al. (2004), x^i_{pbest} is updated in every iteration by comparing its current position with the previous value of x^i_{pbest}. If the current position dominates, it replaces x^i_{pbest}. If it is non-dominated with respect to x^i_{pbest}, then one of them is selected randomly as the next x^i_{pbest}.

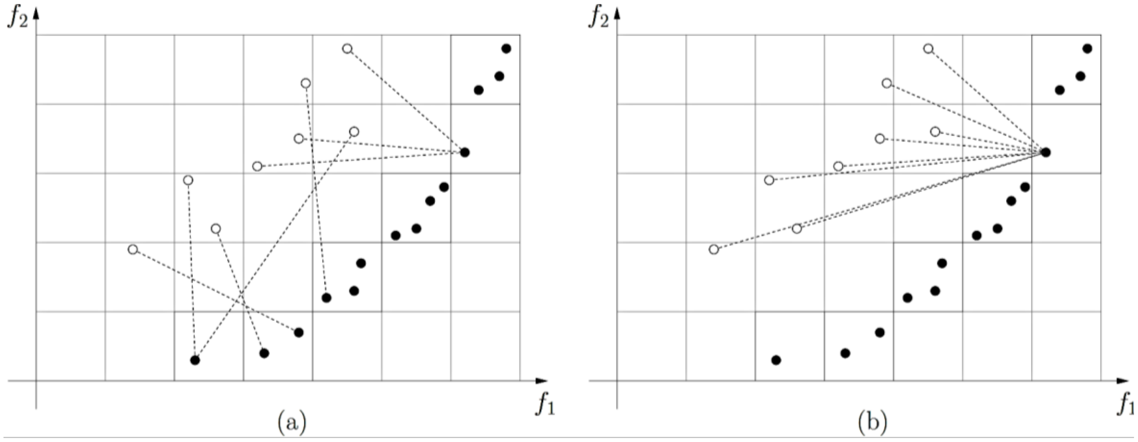

Figure 5.1 Illustration of leader selection procedure: (a) MOPSO algorithm used in Coello *et al.* (2004), (b) MOPSOA algorithm proposed in this work. Hollow circles: PSO particles, filled circles: current non-dominated solutions.

In MOPSOA, assignment of x_{leader} is made using the non-dominated (ND) set stored in an external archive (repository). The objective space is divided into hyper cubes, and each ND solution, depending on its position in the objective space, is assigned one of these hyper cubes. For each particle, in each PSO iteration, a leader is selected from the archive giving preference to ND solutions which occupy less-crowded hyper cubes. Roulette-wheel selection is used to first select a hypercube, and one of the ND solutions in that hypercube is picked randomly as the leader. This procedure helps to ensure that the ND solutions are well distributed in the objective space. In addition, a mutation operator is used in Coello *et al.* (2004) to enhance exploration of the search space in the beginning of the search. The mutation rate is made zero as the algorithm converges. With this background, the modifications made in the proposed MOPSOA algorithm are described below.

(a) Archive Manipulation: The hyper grid approach used in Coello *et al.* (2004) has been modified in Patil (2020) to avoid changing of grid boundaries and for more efficient use of memory. This new approach, which uses a hyper grid with a fixed cell size and does not involve grid boundaries, is used in the MOPSOA program.

(b) Leader Selection: The leader selection process in MOPSO used in Coello *et al.* (2004) is illustrated in Fig. 5.1 (a). In each PSO iteration, each particle is assigned one of the ND particles in the archive, preferring less crowded hyper cubes. In MOPSOA proposed in this work, we continue to use the roulette-wheel selection procedure of the

MOPSO algorithm. However, to intensify exploration of the less-crowded regions of the archive, we assign the same leader to all particles, as shown in Fig. 5.1 (b) and keep the same leader for N_{leader}^{const} iterations.

(c) Mutation: In PSO, when the velocity and position update steps fail to generate new ND solutions, mutation can be useful (Parsopoulos and Vrahatis, 2008). In the context of the WDN benchmark problems, it is observed that there is an initial phase of MOPSO in which the ND set is improved relatively rapidly. However, beyond a certain point, the rate of generation of new solutions drops significantly. For this reason, different mutation schemes have been implemented in MOPSOA as shown in Fig. 5.2. In the "constant" option, the mutation probability remains constant (a low value such as 0.01). In the "pulse" option, the probability is made non-zero only for N_{mut} iterations in the early stages and zero otherwise. In the "periodic" option, the probability is made non-zero for N_{mut} iterations in every N_{period} iterations, thus periodically encouraging enhanced exploration. The mutation process itself is common in the three cases and involves changing one of the decision variables of the particle randomly.

(d) Local Search: The local search operation procedure is done using the following procedure named as a "unit local search" (ULS) step. In MOPSOA, local search is implemented as follows.

  a. Choose a subset S of the current ND set.
  b. Select one individual from S for local improvement. Define a scalar fitness function with linear weighting where the weights are obtained using an estimate of the gradient of the pareto front. For the selected individual,
    i. Find the Hooke-Jeeves pattern search direction using the above scalar fitness function.
    ii. Perform the cultural learning step by applying the same pattern search direction to a group of individuals in the current ND set.
  c. Repeat (b) until a sufficient number of children are created.

As seen in the procedure above, a ULS step can lead to some improvement in the ND set. If it is applied again on the new ND set, further improvement is possible. For this purpose, MOPSOA allows the ULS to be repeated N_{LS}^{max} times at a given PSO iteration.

If, after some ULS steps, it is found that no further generation of new ND solutions is taking place, the local search step is discontinued.

(e) Local search is expensive, and it is not practical to perform it in every PSO iteration. In MOPSOA, therefore, local search is performed periodically instead of every iteration. Furthermore, it was observed in the context of the WDN problems that local search is more effective in the early stages. Based on this observation, a two-stage local search strategy is implemented. From iteration $N_{PSO}^{(1)}$ to $N_{PSO}^{(2)}$, local search is performed every T_1 iterations, and after $N_{PSO}^{(2)}$, it is performed every T_2 iterations.

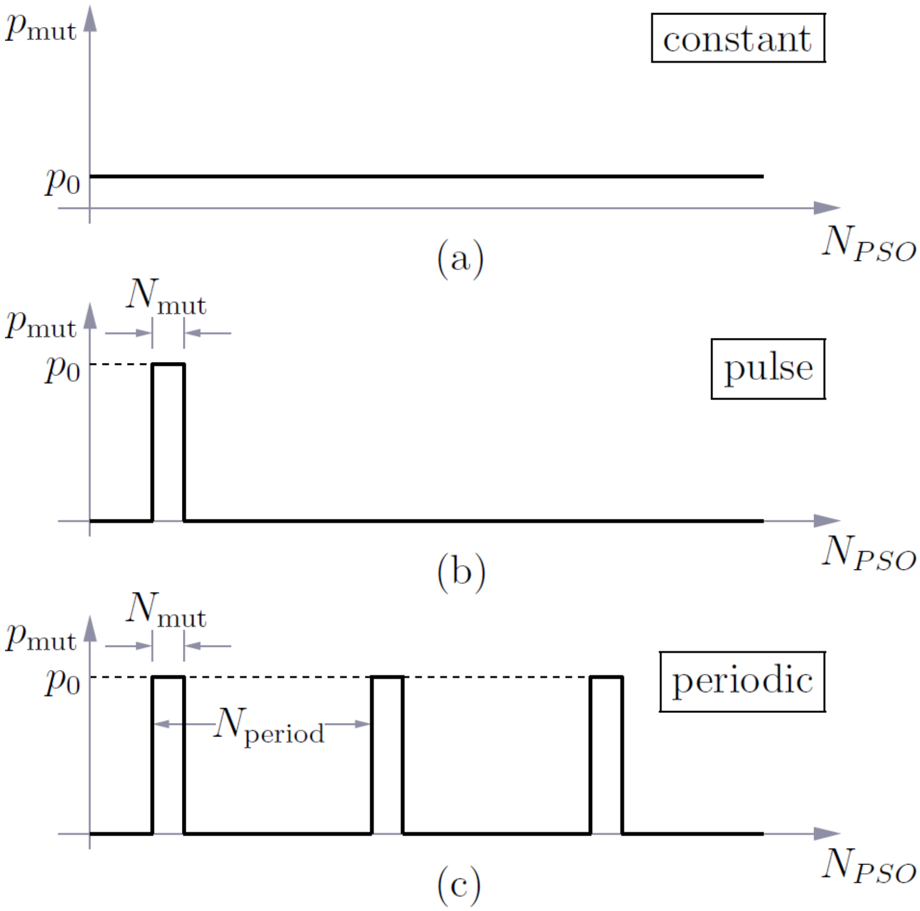

Figure 5.2 Mutation Probability versus PSO iteration number for different mutation schemes implemented in MOPSOA

5.4.2. *Self-Adaptive Multiobjective Cuckoo Search Algorithm (SAMOCSA)*

Cuckoo Search Algorithm (CSA) is a swarm intelligence based metaheuristic optimization algorithm developed by Yang and Deb (2009). CSA mimics the breeding behaviour of few cuckoo species and Levy flight behaviour of some birds and fruit flies. To trap the behaviour of cuckoos in nature and adapt it to be suitable for using as an algorithm, there are three basic rules:

(i) each cuckoo lays one egg at a time in a nest and dumps it in a randomly chosen nest

(ii) the best nests which resemble the closest to the host's eggs (high quality eggs) are carried to the further generations

(iii) the number of available host nests is fixed and any egg laid by a cuckoo may be discovered by the host bird with a probability $P_a \in [0,1]$.

The working of CSA is explained with the help of a flowchart as shown in Fig. 5.3. In the first step, parameters of CSA are set consisting of the number of nests, the step size control parameter 'α' and shifting parameter 'P_a'. Initial locations of the nests are determined by a randomly assigned set to each decision variable. As can be seen from the algorithm in the flowchart, new cuckoos are generated by Levy flights using the equations of local random walk Eq. 5.10 (intended primarily for exploitation of the current solutions) and global random walk Eq. 5.11 (intended primarily for exploration of the search space defined in the function).

Local random walk (Eq. 7) is performed using the P_a parameter is expressed as,

$$nest_i^{new} = nest_i^{cur} + \alpha \otimes H(Pa - rand) \otimes (nest_j^{cur} - nest_k^{cur}) \tag{5.10}$$

Global random walk (Eq. 8) is performed by using the α (step length) and the best nest using Levy-Flight

$$nest_i^{new} = nest_i^{cur} + \alpha * f(best, \beta) \tag{5.11}$$

Here *f* is a function of current best nest and levy-flight parameter β.

The generating new cuckoos and discovering alien eggs steps are alternately performed until the termination criteria (i.e., till the algorithm reaches the maximum function evaluations [FEval]) is satisfied (Yang and Deb, 2009). The performance of this algorithm is sensitive to two main parameters, i.e. step size control parameter 'α' and discovering probability parameter 'P_a' (Yang, 2014). These two parameters govern the exploration and exploitation ability of the algorithm. To solve this problem, a self-adaptive version of this algorithm is proposed. The flowchart of the working of self-adaptive cuckoo search algorithm (SACSA) is shown in Fig. 5.3.

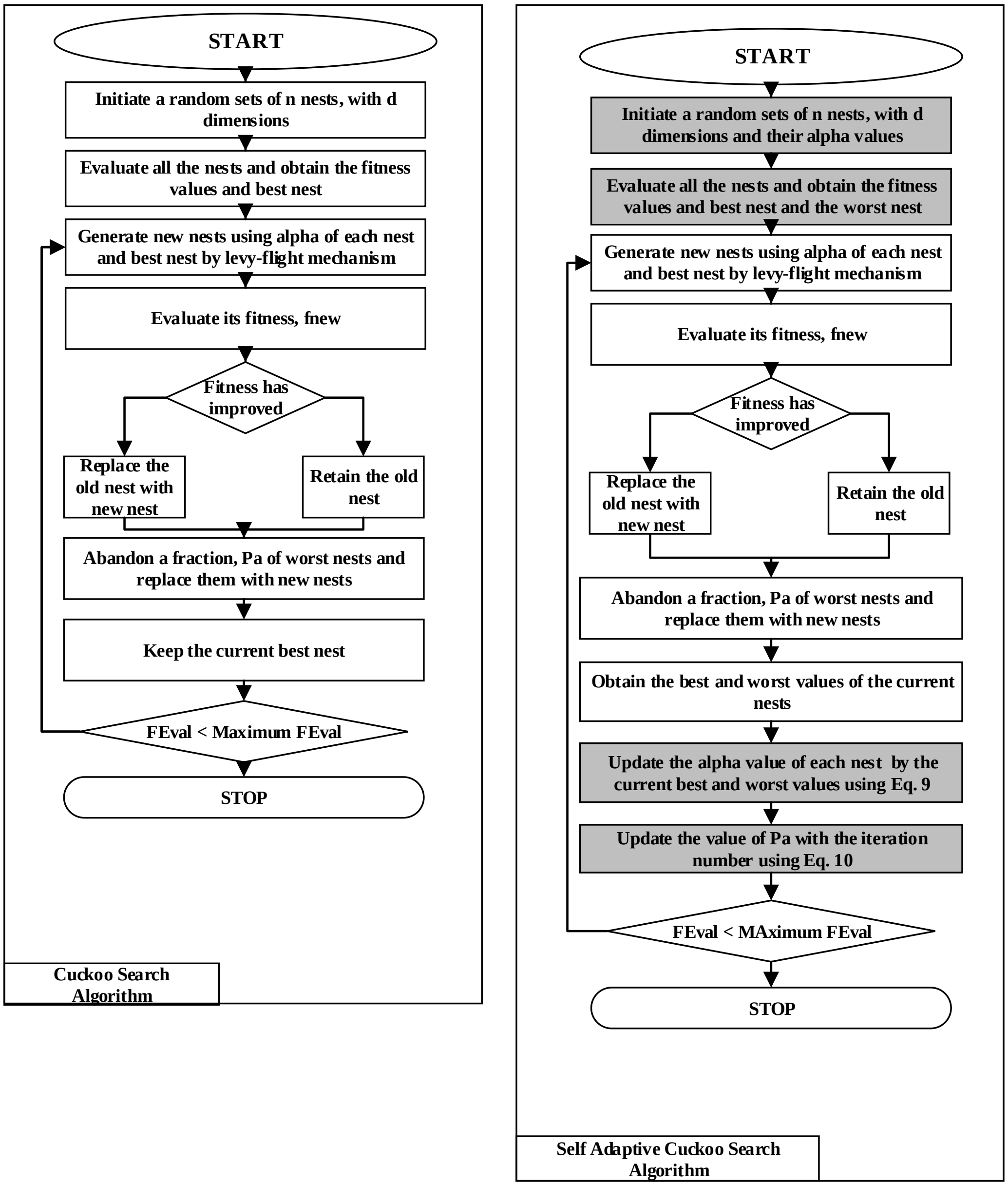

Figure 5.3 Flowchart of CSA and SACSA for Single Objective Optimization

SACSA attempts to dynamically update the values of both the step size (α) and discovering probability parameter (P_a) as the algorithm proceeds, as shown in Eq. 5.12 and Eq. 5.13.

$$\propto(i) = \left({}^{1}/_{t}\right)^{\left(\frac{F_{ideal}-F_i}{F_{ideal}-F_{anti-ideal}}\right)} \tag{5.12}$$

Here α- alpha, i - nest number, t – iteration number, $\mathrm{F_{ideal}}$- fitness value of best nest, $\mathrm{F_{anti-ideal}}$ - Fitness value of worst nest

$$Pa(t) = Pamax * e^{t/_{time}} \tag{5.13}$$

Here P_{amax} is maximum value of the discovering probability parameter (assumed 0.9), t is iteration number and time represents maximum number of iterations.

This enhancement enables the algorithm to search in larger search space, initially and as the iteration increases, the search space also decreases enabling a better convergence rate compared to original cuckoo search. As a result, two out of the three parameters are self-adapted and easy to set.

Similar to single objective cuckoo search algorithm, a self-adaptive algorithm for solving multi-objective optimization problems has been proposed in this study. For multiobjective optimization problems with K different objectives, the first and third basic rules are modified as follows:

(i) each cuckoo lays K eggs at a time and dumps them in a randomly chosen nest. Egg k corresponds to the solution to the kth objective;

(ii) each nest will be abandoned with a probability pa and a new nest with K eggs will be built according to the similarities/ differences of the eggs. Some random mixing can be used to generate diversity.

The flowchart of working of self-adaptive multiobjective cuckoo search algorithm is shown in Fig. 5.4. The first step starts with the initialization of the algorithm parameters, generating the initial population using objective functions. Determine the leader nest which has the least rank based on non-dominated sorting and highest crowding distance using the approach used in NSGA-II (one of the best algorithms available for non-dominated sorting approach and diversity preservation) by Deb *et al.* (2002). Generate new nests using Levy flights and update the population. Then, the new nests are replaced with the generated nests with a discovering probability P_a. Update the population and algorithm continues until the maximum function evaluations (FE) is met as the stopping criteria. The P_a dynamic adaptation is same as that of single objective algorithm (Eq. 5.13), but the step length α is updated using Eq. 5.12 using the current rank and crowding number of the nest and the nests in the first pareto front. Ideology behind this upgradation of alpha (step length) is that, the step length is reduced if there is an improvement in the performance of the nest, but the decrement is controlled by the exponential function such that it does not significant decrease (Kaveh and Bakshpoori, 2016). When the nests converge to a single pareto front, the step length should be minimum, this is ensured with the third if clause as shown below.

```
if rank of new $nest_i$ $<$ rank of old $nest_i$
        $alpha(i) = rand * \exp(\left(\frac{1}{t}\right) - 1)$
else if rank of new $nest_i$ $==$ old $nest_i$ && Crowding distance of new $nest_i$ $>$ old $nest_i$
        $alpha(i) = rand * \exp(\left(\frac{1}{t}\right) - 1)$
else if rank of new nest $== 1$,
                $alpha(i) = (\max$ of all values of variables in first pareto front
                        $-$ minimum of all varibles in first pareto front $)/100$
end if
```

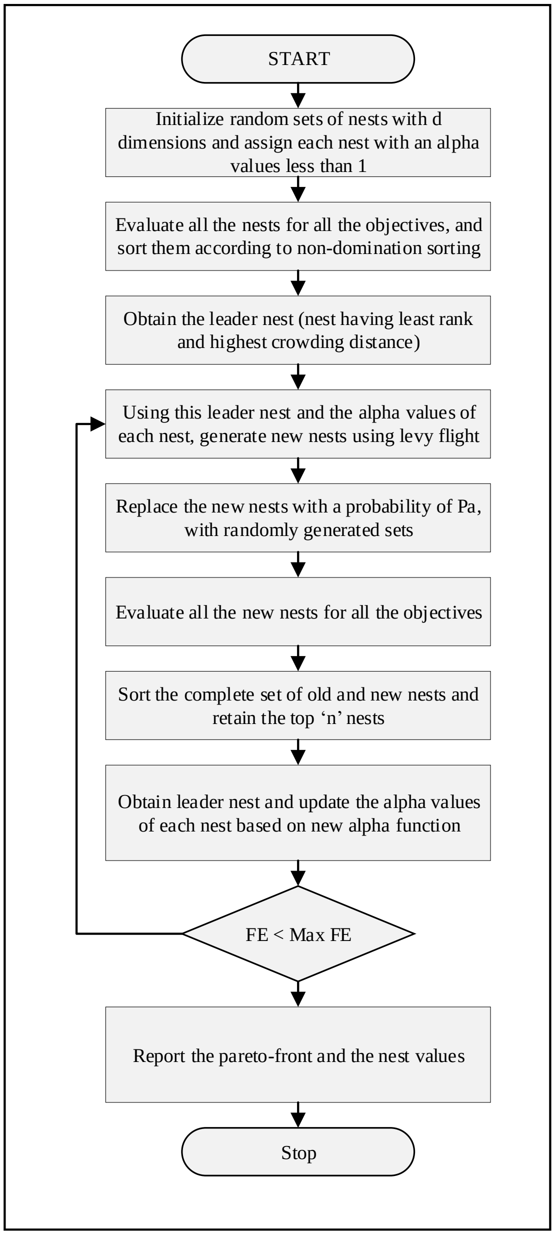

Figure 5.4 Flowchart of Self-Adaptive Multiobjective Cuckoo Search Algorithm (SAMOCSA)

5.4.3. Random multi-point crossover operator, Local search augmented with Non-dominated Sorting Genetic Algorithm - II (RLNSGA-II)

Deb *et al.* (2002) introduced a fast and elitist multiobjective genetic algorithm called Nondominated Sorting Genetic Algorithm-II (NSGA-II). In this study, the traditional NSGA-II algorithm is augmented with Random multi-point crossover operator, Local search, and periodic mutation, represented with symbol RLNSGA-II. In this study, RLNSGA -II algorithm is used for design of water distribution network. The complete procedure of working of RLNSGA-II algorithm is described below and shown in the flow chart (Fig. 5.5).

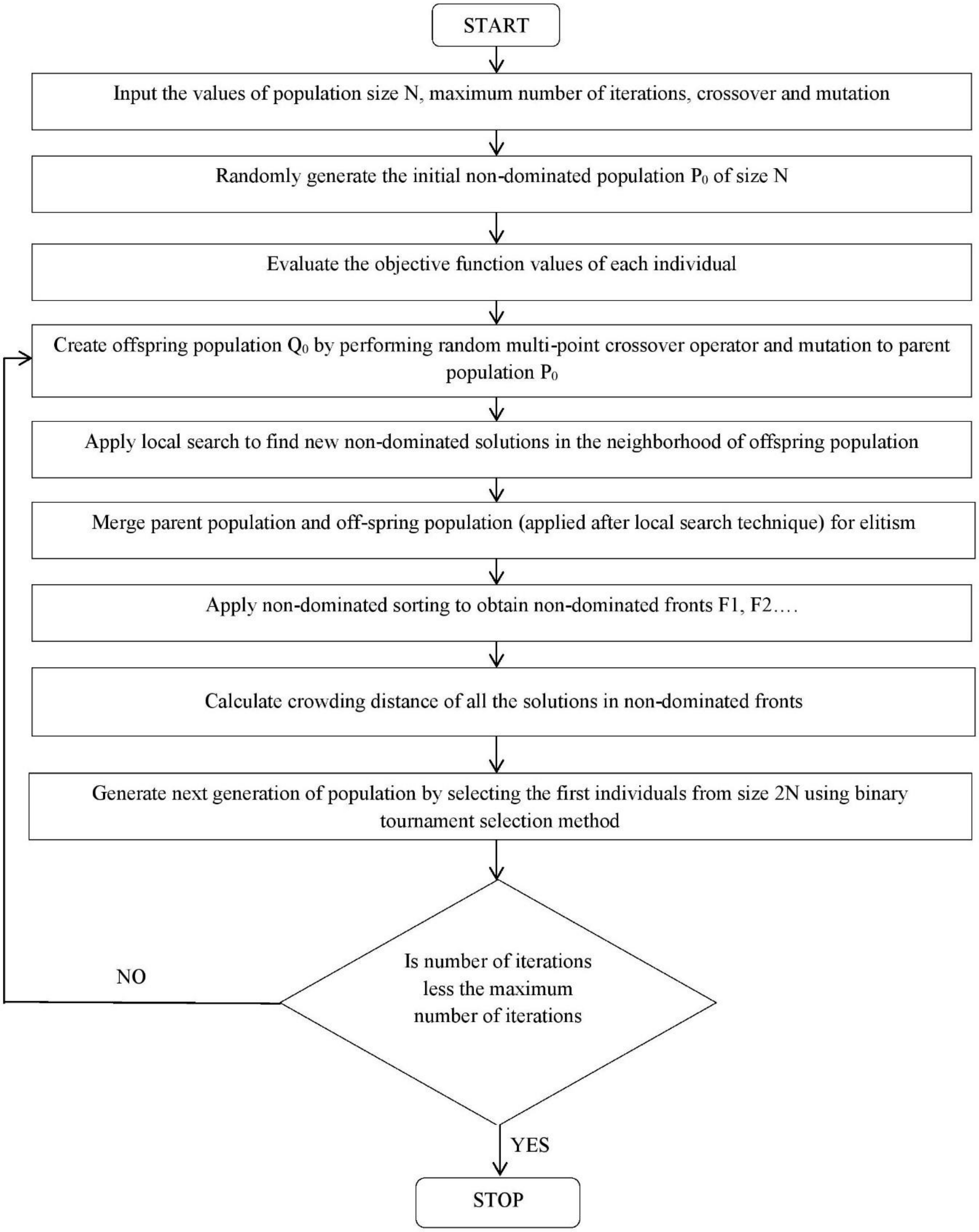

Figure 5.5 Flow Chart of RLNSGA-II algorithm

Step 1: Initialize parent population P_0 consists of m rows equal to population size and *n* columns equal to decision variables. Here decision variables are taken as the pipe diameters.

Step 2: Generate off-spring population Q_0 by applying random multi-point crossover operator, local search and periodic mutation to the parent population P_0 which is shown below.

a) Crossover operator

In crossover, there is an exchange of properties between two parents and as a result of which two off-spring solutions are produced. The crossover points are decided randomly and then perform exchange of values with respect to the crossover points. There are different crossover operators available namely single-point, two-point, random multi-point etc. To illustrate the working of RLNSGA-II, the difference between single-point crossover operator (used in traditional NSGA-II algorithm) and random multi-point crossover operator are explained below (Figs. 5.6 and 5.7).

Parent 1	1	2	3	4	5	6	7	8	9	10
Parent 2	1	3	5	7	9	11	12	15	17	9
Child 1	1	2	3	7	9	11	12	15	17	9
Child 2	1	3	5	4	5	6	7	8	9	10

Figure 5.6 Illustration of single-point crossover operator

In single-point crossover operator, there will be only one crossover point is selected then all data beyond that point in either string is swapped between two parents resulting in off-spring population.

b) Random multi-point crossover operator

In this scheme, multi-point crossover points are selected along the length randomly then alternate parts are swapped between parent populations in order to form child population.

Parent 1	1	2	3	4	5	6	7	8	9	10
Parent 2	1	3	5	7	9	11	12	15	17	9
Child 1	1	3	3	4	9	11	7	8	17	9
Child 2	1	2	5	7	5	6	12	15	9	10

Figure 5.7 Illustration of Random multi-point crossover operator

c) Local search

Local search is useful for obtaining the new non-dominated solutions in the less crowded areas of objective space. In this study, a simple local search is employed. The local search technique utilized in this study is illustrated in the following sections. Consider the following two-variable, two-objective test problem.

$$f_1(x) \; = \; -x_1^2 + x_2 \qquad (5.14)$$

$$f_2(x) \; = \frac{x_1}{2} + x_2 + 1 \qquad (5.15)$$

subject to the constraints $0 \le x_1 \le 10, \; 0 \le x_2 \le 10$

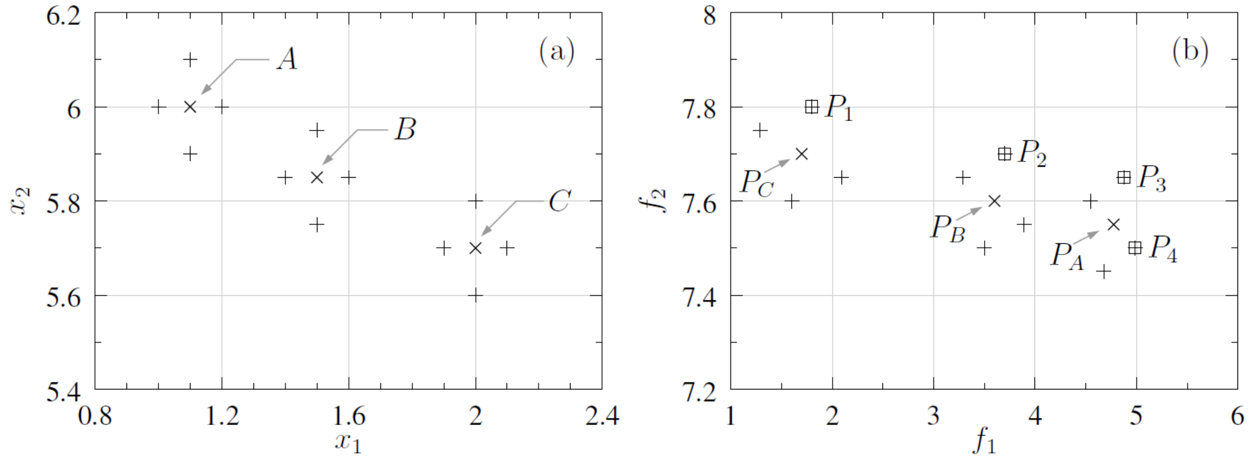

Figure 5.8 Demonstration of local search for the two variables, two objective optimization problem denoted by Equation 5.14 and 5.15 (Patil *et al.*, 2020)

Let the current non-dominated set comprises of three points A, B and C shown in Fig. 5.8(a) denoted by crosses, respectively. P_A, P_B and P_C represent the corresponding objective function values shown in Fig. 5.8(b) marked by crosses, respectively. Four neighbouring points centered on each existing solution were generated using equations 5.16 and 5.17 shown in Fig. 5.8(a), denoted by plus, respectively in order to improve the non-dominated set using local search.

$$x_1^{new} = x_1^{old} \pm \Delta x_1 \tag{5.16}$$

$$x_2^{new} = x_2^{old} \pm \Delta x_2 \tag{5.17}$$

The corresponding neighbours in the objective space are denoted in Fig. 5.8(b). From the full set of both old and new generated solutions, new non-dominated solutions P_1, P_2, P_3 and P_4 have been found which is shown in Fig. 5.8(b) denoted by combination of square and plus respectively. It is worth noting that the non-dominated set was improved in terms of the number of solutions as well as the quality of solutions.

Step 3: Merge parent population P_0 and off-spring population Q_0 for elitism

Step 4: Apply non-dominated sorting to obtain non-dominated fronts F1, F2, F3….

Step 5: Furthermore, select a new parent population that is equal to size P_0 from these non-dominated fronts depending upon crowding distance which completes one iteration.

Step 6: In the second iteration repeat step 2, 3, 4 and 5.

Step 7: The procedure is terminated until the maximum number of iterations is reached, else, repeat steps 2, 3, 4 and 5.

Table 5.1 shown below summarizes the key features, advantages and drawbacks of the optimization algorithms used in this study.

Table 5.1 Key Features, Advantages and Drawbacks of Optimization Algorithms

Optimization Algorithm	Key Features	Advantages	Drawbacks
MOPSOA	✓ Based on the social behaviour of birds flocking ✓ Uses a population of candidate solutions (particles) which move through the solution space	✓ Simple to implement ✓ Few parameters to adjust ✓ Fast convergence in many problems	✓ Can converge too early ✓ Can get stuck in local optima
SAMOCSA	✓ Inspired by the brood parasitism of some cuckoo species ✓ Uses Levy flights to explore the solution space	✓ The major parameters are self-adaptive in nature ✓ Efficient for global search ✓ Good balance between exploration and exploitation	✓ May be slower for some problems
RLNSGA-II	✓ Based on natural selection and genetics ✓ Uses crossover, mutation, and selection operations on a population of solutions	✓ Highly flexible ✓ Can handle a wide variety of optimization problems ✓ Good for global search	✓ Computationally expensive ✓ May require careful tuning of parameters

5.4.4. *Fast Newman Algorithm for Clustering*

The Fast Newman Algorithm as explained by Clauset *et al.* (2004), is one of the popular community detection algorithms employed for cluster identification due to its ability to decompose large networks quickly and reliably. Initially, the WDN is converted into an undirected and weighted graph, denoted as G = (V, E) where V represents demand nodes, reservoirs, and tanks, and E represents pipes, valves, and pumps. The edge weights are obtained by averaging the nodal pressure values between the two connected nodes, as expressed by the following equation:

$$w_{ij} = \frac{p_i + p_j}{2} \tag{5.18}$$

where w_{ij} denotes the weight of the edge between nodes *i* and *j*, P_i and P_j represent the nodal pressure values at nodes *i* and *j* respectively.

Modularity index (MI) is a property of a network that measures the quality of the division in a network is used in this algorithm. In an ideal scenario, the partitions discover dense interconnections within the communities while displaying sparse connections amongst them.

$$MI = \frac{1}{2m} \sum_{U_w} \left[A_{uw} - \frac{k_u k_w}{2m} \right] \delta(C_u, C_w) \tag{5.19}$$

where A_{uw} = ×element of the adjacency matrix of the network ((A_{uw}) =1, if vertices v and w are connected; otherwise (A_{uw}) =0)), $m = \frac{\sum_{u_w} A_{uw}}{2}$ total number of edges, $k_u = \sum_w A_{uw}$ is degree of vertex v, defined as the number of edges connected to vertex, $\delta(c_u, c_w) = 1$, if $c_v = c_w(otherwise = 0)$; c_v and c_w are two different communities, v and w = vertices in c_v and c_w, respectively; and $\frac{k_v k_m}{2m}$ is probability of an edge an edge existing between vertices v and w if connections are randomly made (respecting vertex degrees).

In this study, community detection or clustering within a WDN has been done using an open-source software named Gephi (gephi.org). The necessary details of the WDN are supplied as an input to the software. The clustered network is further reviewed based on the engineering judgement as deemed necessary from the practical and operational point of view. The resolution parameter within the software is responsible for the number of clusters to be identified within the WDN. The resolution value by default has been set to 1. The appropriate value of the resolution is decided based on trial and error to arrive at the number of the clusters for a WDN.

5.5. Hypervolume Performance Metric

In the present study, three multiobjective optimization algorithms have been used to determine the optimal design of WDNs. The comparison of performance of optimization algorithms has been evaluated using the hypervolume performance metric. Hypervolume metric provides a qualitative measure of convergence as well as diversity among the obtained pareto optimal front by each optimization algorithm (Deb, 2001). Hypervolume is a widely used performance metric to compare the performance of multiobjective optimization algorithms. Each multiobjective optimization algorithm converges to a pareto optimal set which consists of a non-dominated set of solutions. Fig. 5.9 shows an example of a pareto optimal set consisting of five points P1, P2, P3, P4 and P5 for a two-objective problem. Hypervolume represents the volume in the objective space covered by the pareto optimal set constructed with an assumed reference point. Mathematically, for each solution on the pareto optimal set, a hypercube is constructed with a reference point. The reference point can simply be found by constructing a vector of the worst objective function values. Hypervolume is the sum of all the hypercubes (Deb, 2001). An algorithm having a large value of hypervolume is desirable and represents the pareto-optimal set having a better converge and diversity compared to other optimization algorithms.

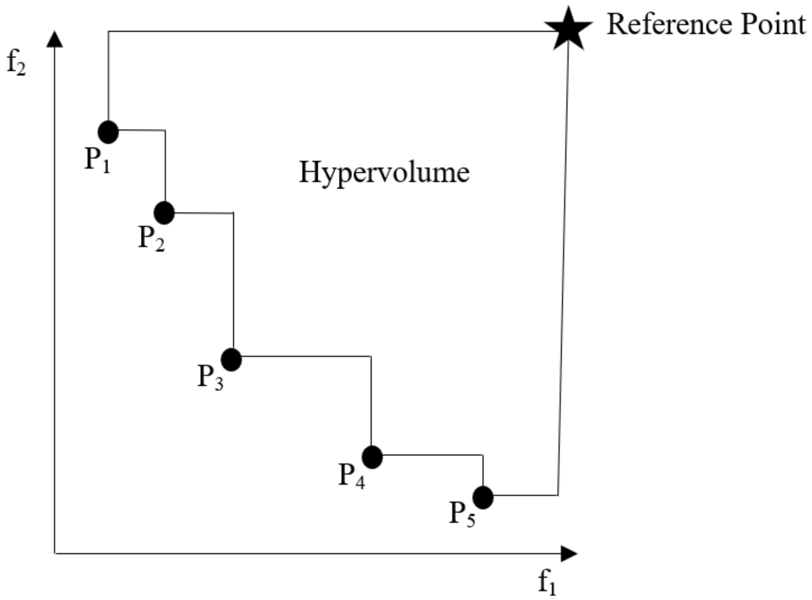

Figure 5.9 Illustration of Hypervolume Metric for Two Objective Problem

The next chapter describes the results and discussion, which includes three distinct scenarios. In the first scenario, two objectives, namely, network cost and network resilience have been considered. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity and the third scenario discusses in detail the results of determining the optimal design of DMAs.

Chapter 6

Results and Discussion

6.1. General

In this study, three distinct scenarios have been considered. The first two scenarios determine the optimal WDN design based on different objectives for continuous and intermittent water supply. An optimization-simulation model is developed for obtaining optimal design for WDNs. This model integrates the developed multiobjective optimization algorithm as well as water distribution system simulation software EPANET 2.2. The diameter values obtained from the optimization algorithm are passed to the simulation software. Although the continuity constraint and energy conservation constraint are satisfied externally via EPANET 2.2, other constraints must be satisfied by the optimization algorithm using exterior penalty function approach. For intermittent water supply analysis, the duration of the water supply has been assumed as two hours per day based on the discussion with the water engineers from the Government of Telangana. In the first scenario, two objectives, namely, network cost and network resilience have been considered. The formulated optimization-simulation model is applied to the three benchmark WDN problems and later this is also applied to two real-life WDNs located in Telangana, India to ensure practical relevance of the proposed methodology in the first scenario. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable distribution of water. This expanded set of objectives is examined in the context of two real-life WDNs. The third scenario focuses on determining the optimal design of DMAs for the two real-life WDNs. Sharanga High performance computing facility available with our Institute with a configuration of 32x2 cores AMD EPYC 7542, 256 GB of memory and 1x Tesla V100 PCIe 32GB has been used for running the simulations needed in this research study. The simulation durations on the high performance computing facility taken by New York Tunnel WDN is 5 days, Hanoi WDN took 8 days, BIN took 32 days, Pamapur WDN required 13 days and Vanasthalipuram WDN demanded 22 days.

6.2. Analysis of Results from Optimal Water Distribution Network Design - Scenario 1 (Network Cost and Network Resilience)

In this scenario, the proposed methodology has been tested on the five WDNs (New York Tunnel WDN, Hanoi WDN, BIN, Pampapur WDN and Vanasthalipuram WDN) using three optimization techniques (MOPSOA, SAMOCSA and RLNSGA-II) for continuous and intermittent water supply. Wang *et al.* (2015) have used five different multiobjective evolutionary algorithms, namely AMALGAM, NSGA-II, Borg, epsilon-NSGA-II, epsilon-MOEA to obtain best-known approximation of true pareto front of benchmark problems. Among these, AMALGAM is a hybrid algorithm consisting of four sub-algorithms simultaneously: NSGA-II, Particle Swarm Optimization, Differential Evolution and Adaptive metropolis search. Wang *et al.* (2015) has run each algorithm 30 times independently and combined all non-dominated solutions generated by each algorithm to obtain the best-known approximation of the true Pareto front. The results of New York Tunnel WDN, Hanoi WDN and BIN for continuous water supply are compared with the solutions of Wang *et al.* (2015) to test the efficacy of the developed optimization algorithms.

6.2.1. New York Tunnel WDN

Continuous Water Supply (CWS)

The parameters chosen after trial and error in various optimization algorithms is shown in Table 6.1. The population size and number of iterations have been fixed as 300 and 10,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.1 Parameters Chosen for Optimization Algorithms for New York Tunnel WDN (CWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Algorithm	**Parameters**
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.2 Comparison of Optimal Solutions obtained by Optimization Algorithms and Wang *et al.* (2015) for New York Tunnel WDN (CWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (\$ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	647	38.8142 238.2542	0.3906 0.7516	67830.77
Wang *et al.* (2015)	627	38.8142 238.2542	0.3906 0.7516	67877.67

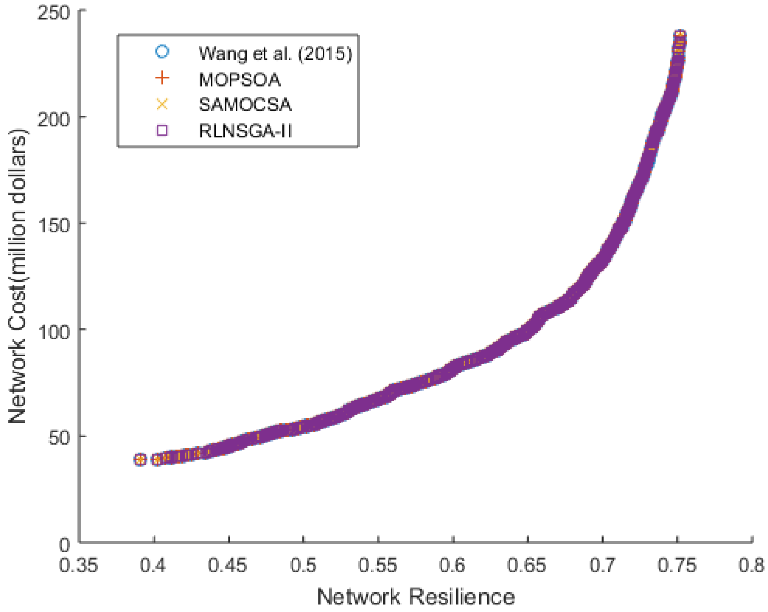

Figure 6.1 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II and Wang *et al.* (2015) for New York Tunnel WDN (CWS)

The results are compared with Wang *et al.* (2015), as shown in Table 6.2. It is observed that MOPSOA, SAMOCSA, RLNSGA-II has converged to more pareto front points for New York Tunnel WDN in comparison with Wang *et al.* (2015). It can be observed from Table 6.2 that the hypervolume of all the three optimization algorithms is almost similar when compared with Wang *et al.* (2015). In summary, the results highlight that MOPSOA, SAMOCSA and RLNSGA-II demonstrated better performance compared to Wang *et al.* (2015) with respect to the total number of points in the pareto front, capturing the extreme points and hypervolume for New York Tunnel WDN. The Pareto front obtained by each optimization algorithm is shown in Fig 6.1. It is observed from the figure that most of the points on the pareto front obtained by MOPSOA, SAMOCSA, RLNSGA-II and Wang *et al.* (2015) are similar.

Intermittent Water Supply (IWS)

The parameters chosen after trial and error in various optimization algorithms is shown in Table 6.3. The population size and number of iterations have been fixed as 300 and 10,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.3 Parameters Chosen for Optimization Algorithms for New York Tunnel WDN (IWS)

Algorithm	**Parameters**
MOPSOA	W =0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.4 Comparison of Optimal Solutions obtained by Optimization Algorithms for New York Tunnel WDN (IWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost ($ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	640	39.1842 238.2542	0.4455 0.8066	61970.79

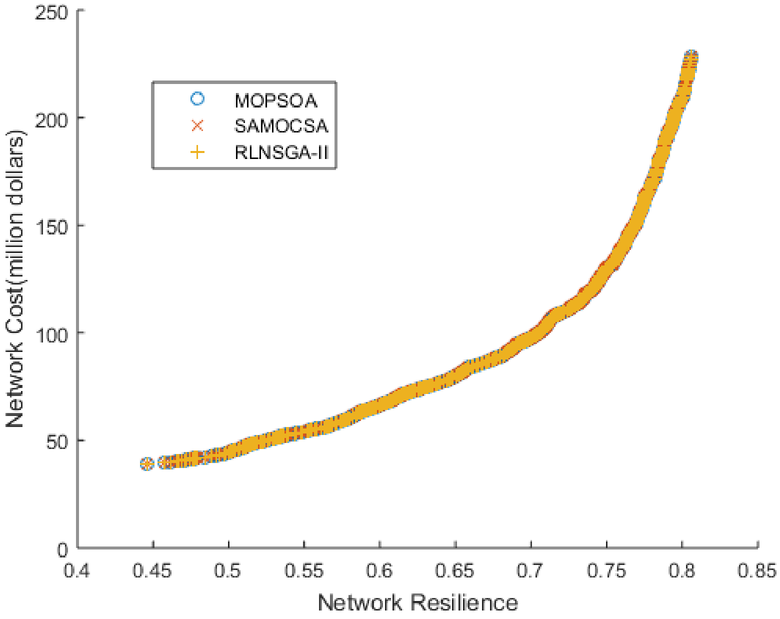

Figure 6.2 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for New York Tunnel WDN (IWS)

The results obtained by the optimization algorithms are shown in Table 6.4. The Pareto front obtained by each optimization algorithm is shown in Fig 6.2. It is observed from the results that the Pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II have converged to the same solution for New York Tunnel WDN. Results for New York Tunnel WDN for intermittent water supply have not been compared with any other published literature as they are not available.

The optimal solution representing the extreme points of Pareto front obtained by the best optimization algorithm for New York Tunnel WDN in CWS and IWS has been compared. The hydraulic analysis of the optimal WDN design for each extreme point has been carried out and the pipe velocity as well as nodal pressure are compared and shown in Tables 6.5 and 6.6.

Table 6.5 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point for New York Tunnel WDN in CWS and IWS

Leftmost Extreme Point-CWS (Network Cost=$38.8142x10^{6} and Network Resilience=0.3906)					**Leftmost Extreme Point-IWS (Network Cost=$39.1842x10^{6} and Network Resilience=0.4455)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	5181.6	3.1269	1	57.7193	1	5181.6	4.6389	1	58.8393
2	4876.8	3.0447	2	56.2289	2	5181.6	4.5567	2	57.3489
3	4572.0	2.7401	3	51.7819	3	5181.6	4.2521	3	52.9019
4	4267.2	2.6955	4	51.0962	4	4876.6	4.2075	4	52.2162
5	3962.4	2.6787	5	45.5160	5	4876.8	4.1907	5	46.6360
6	3657.6	2.4471	6	44.6220	6	4572	3.9591	6	45.7420
7	3352.8	2.1028	7	44.0447	7	4267.2	3.6148	7	45.1647
8	5181.6	1.9236	8	42.2837	8	5181.6	3.4356	8	43.4037
9	4876.8	1.8859	9	41.7470	9	5181.6	3.3979	9	42.8670
10	4572.0	1.8307	10	40.8757	10	4876.8	3.3427	10	41.9957
11	4267.2	1.7417	11	39.8355	11	4876.8	3.2537	11	40.9555
12	3962.4	1.6743	12	38.2761	12	4876.8	3.1863	12	39.3961
13	3657.6	1.6403	13	36.5820	13	4572	3.1523	13	37.7020
14	5181.6	1.4518	14	35.9710	14	5181.6	2.9638	14	37.0910
15	4876.8	1.4119	15	34.8477	15	5181.6	2.9239	15	35.9677
16	4572.0	1.3079	16	33.9779	16	4876.6	2.8199	16	35.0979
17	4267.2	1.2719	17	32.0000	17	4876.8	2.7839	17	33.1200
18	3962.4	1.2714	18	31.0657	18	4572	2.7834	18	32.1857
19	3657.6	1.2025	19	30.9756	19	4572	2.7145	19	32.0956
20	3352.8	0.8789	-	-	20	4572	1.6379	-	-
21	3352.8	0.7188	-	-	21	3962.4	1.4688	-	-

Table 6.6 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Rightmost Extreme Point for New York Tunnel WDN in CWS and IWS

Rightmost Extreme Point-CWS (Network Cost=$238.2542x10^{6} and Network Resilience=0.7516)					**Rightmost Extreme Point-IWS (Network Cost=$238.2542x10^{6} and Network Resilience=0.8066)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	5181.6	2.1428	1	59.2193	1	5181.6	3.6628	1	62.5452
2	5181.6	2.0594	2	57.7289	2	5181.6	3.5794	2	61.1189
3	5181.6	2.0389	3	53.2819	3	5181.6	3.5589	3	60.0866
4	5181.6	2.0036	4	52.5962	4	5181.6	3.5236	4	57.8353
5	5181.6	1.9591	5	47.0160	5	5181.6	3.4791	5	56.7315
6	5181.6	1.7107	6	46.1220	6	5181.6	3.2307	6	56.3876

Rightmost Extreme Point-CWS (Network Cost=\$238.2542x10^6 and Network Resilience=0.7516)					Rightmost Extreme Point-IWS (Network Cost=\$238.2542x10^6 and Network Resilience=0.8066)				
Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)	Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)
7	5181.6	1.5780	7	45.5447	7	5181.6	3.0980	7	56.0681
8	5181.6	1.3664	8	43.7837	8	5181.6	2.8864	8	56.0534
9	5181.6	1.2817	9	43.2470	9	5181.6	2.8017	9	54.6100
10	5181.6	1.2211	10	42.3757	10	5181.6	2.7411	10	53.9481
11	5181.6	0.9038	11	41.3355	11	5181.6	2.4238	11	53.3625
12	5181.6	0.7154	12	39.7761	12	5181.6	2.2354	12	53.1615
13	5181.6	0.6753	13	38.0820	13	5181.6	2.1953	13	52.9807
14	5181.6	0.6163	14	37.4710	14	5181.6	2.1363	14	52.9732
15	5181.6	0.5355	15	36.3477	15	5181.6	2.0555	15	52.8475
16	5181.6	0.5204	16	35.4779	16	5181.6	2.0404	16	52.7687
17	5181.6	0.5039	17	33.5000	17	5181.6	1.7120	17	52.3846
18	5181.6	0.4748	18	32.5657	18	5181.6	1.5170	18	52.0999
19	5181.6	0.3121	19	32.4756	19	5181.6	1.1230	19	51.7504
20	5181.6	0.3097	-	-	20	5181.6	1.0120	-	-
21	5181.6	0.1562	-	-	21	5181.6	0.5120	-	-

It is observed from Table 6.5, that three pipe diameters (Pipe Nos 1, 8 and 14) of the optimal WDN design for the leftmost extreme point in CWS and IWS scenarios are same. The optimal network cost is around 1% higher in IWS as compared to CWS scenario. Similarly, the optimal network resilience is around 14% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is 84% higher as compared to the pipe velocity in CWS scenario. In CWS and IWS scenarios, the pipe velocity is seen in a decreasing pattern from pipe 1 to pipe 21 as the network is a branched WDN. It is also observed that the rate of increase in velocity is relatively higher in the later part of the network (pipes 14-21) compared to those pipes which are closer to the source. The nodal pressure in IWS scenario is around 3% higher in comparison to CWS scenario. The demand in IWS scenario is met in 2 hours per day as compared to CWS. Moreover, the objective of maximizing the network resilience could be a possible reason for increased variation in the pipe velocity as compared to the nodal pressures in the WDN. It is observed from Table 6.6, that the optimal WDN design for the rightmost extreme point in CWS and IWS scenarios are same. The optimal network resilience is around 7% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is approximately 167% higher as compared to the pipe velocity in CWS scenario. In CWS and IWS scenarios, the pipe velocity is seen in a decreasing pattern from pipe 1 to pipe 21. It is also observed that the rate of increase in velocity is relatively higher in the later part of the network (pipes 12-21) compared to those pipes which are closer to the source. The nodal pressure in IWS scenario is around 31% higher in comparison to CWS scenario.

6.2.2. Hanoi WDN

Continuous Water Supply (CWS)

The parameters chosen after trial and error in various optimization algorithms is shown in Table 6.7. The population size and number of iterations have been fixed as 300 and 10,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.7 Parameters Chosen for Optimization Algorithms for Hanoi WDN (CWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.8 Comparison of Optimal Solutions obtained by Optimization Algorithms and Wang *et al.* (2015) for Hanoi Network (CWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (\$ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	754	6.0813 10.9705	0.1756 0.3538	1043.97
Wang *et al.* (2015)	574	6.1952 10.9698	0.2041 0.3538	1039.05

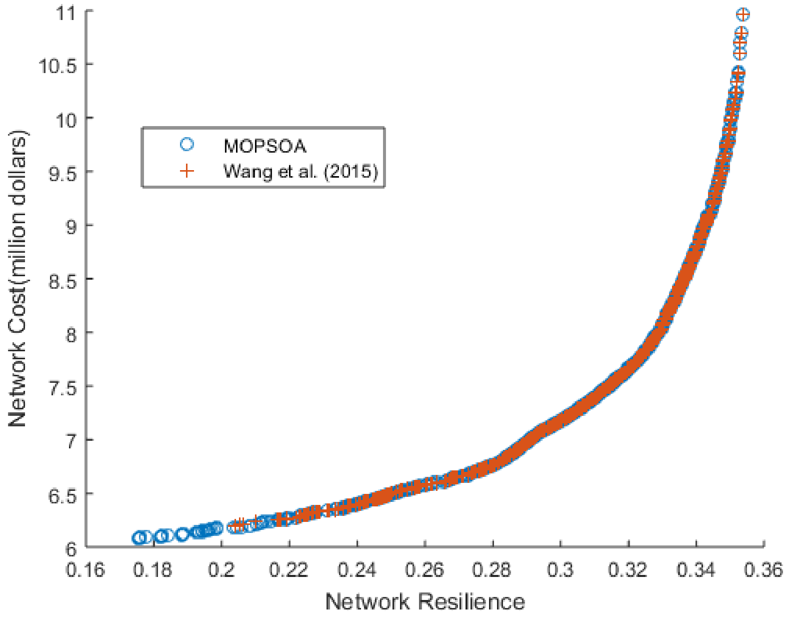

Figure 6.3 Pareto Front obtained by MOPSOA and Wang *et al.* (2015) for Hanoi WDN (CWS)

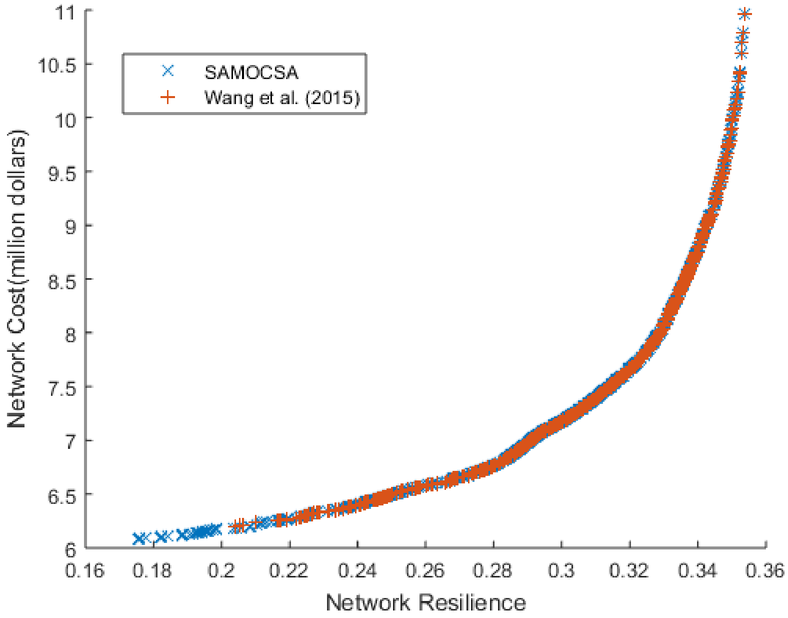

Figure 6.4 Pareto Front obtained by SAMOCSA and Wang *et al.* (2015) for Hanoi WDN (CWS)

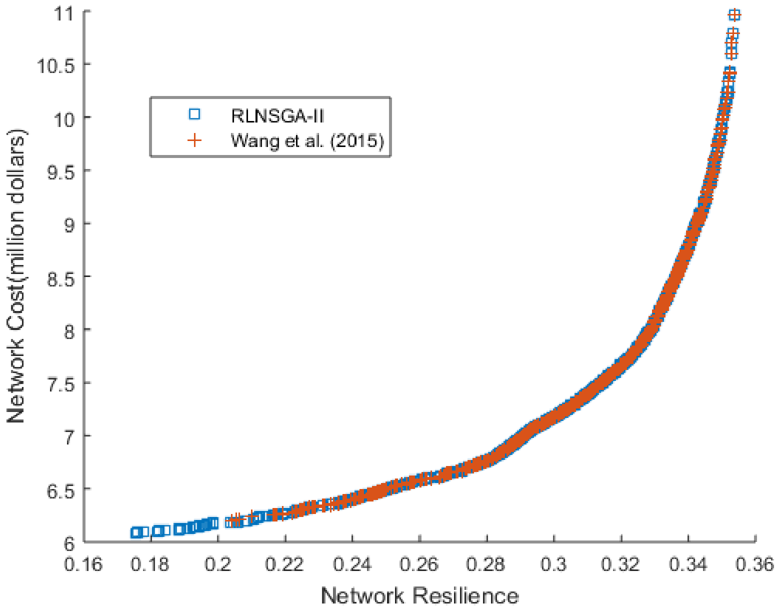

Figure 6.5 Pareto Front obtained by RLNSGA-II and Wang *et al.* (2015) for Hanoi WDN (CWS)

The results are compared with Wang *et al.* (2015), as shown in Table 6.8. It is observed that MOPSOA, SAMOCSA, RLNSGA-II has converged to more pareto front points for Hanoi WDN in comparison with Wang *et al.* (2015). It can be observed from Table 6.8 that the hypervolume of all the three optimization algorithms is better when compared with Wang *et al.* (2015). In summary, the results highlight that MOPSOA, SAMOCSA and RLNSGA-II demonstrated superior performance compared to Wang *et al.* (2015) with respect to the total number of points in the pareto front, capturing the extreme points and hypervolume for Hanoi WDN. The pareto front obtained by each optimization algorithm is shown in Figs 6.3, 6.4 and 6.5. It is observed from these figures that most of the points on the pareto front obtained by MOPSOA, SAMOCSA, RLNSGA-II and Wang *et al.* (2015) are similar. The lower leftmost points on the pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II are superior and has also found solutions in new search spaces in comparison with Wang *et al.* (2015).

Intermittent Water Supply (IWS)

The parameters chosen after trial and error in various optimization algorithms is shown in Table 6.9. The population size and number of iterations have been fixed as 300 and 10,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.9 Parameters Chosen for Optimization Algorithms for Hanoi WDN (IWS)

Algorithm	**Parameters**
MOPSOA	W =0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.10 Comparison of Optimal Solutions obtained by Optimization Algorithms for Hanoi Network (IWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume (x10^3)**
		Network Cost ($ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	745	6.6314 10.9705	0.2256 0.4050	1257.7

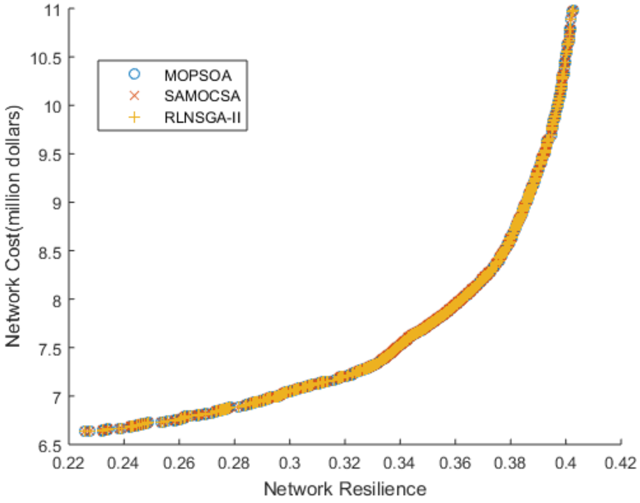

Figure 6.6 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for Hanoi WDN (IWS)

The results obtained by the optimization algorithms is shown in Table 6.10. The pareto front obtained by each optimization algorithm is shown in Fig 6.6. It is observed from the results that the pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II have converged to the same solution for Hanoi WDN. Results for Hanoi WDN for intermittent water supply have not been compared with any other published literature as they are not available.

The optimal solution representing the extreme points of pareto front obtained by the best optimization algorithm for Hanoi WDN in CWS and IWS has been compared. The hydraulic analysis of the optimal WDN design for each extreme point has been carried out and the pipe velocity as well as the nodal pressure are compared and shown in Tables 6.11 and 6.12.

Table 6.11 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point for Hanoi WDN in CWS and IWS

Leftmost Extreme Point-CWS (Network Cost=\$6.0813x10^6 and Network Resilience=0.1756)					**Leftmost Extreme Point-IWS (Network Cost=\$6.6314x10^6 and Network Resilience=0.2256)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	1016.0	6.8320	1	97.1407	1	1016.0	8.4298	1	99.1187
2	1016.0	6.5271	2	61.6704	2	1016.0	8.1249	2	63.6484
3	1016.0	2.7558	3	56.8813	3	1016.0	3.6114	3	58.8593
4	1016.0	2.7112	4	50.9439	4	1016.0	3.5669	4	52.9219
5	1016.0	2.4628	5	44.6780	5	1016.0	3.3185	5	46.6560
6	1016.0	2.1185	6	43.2067	6	1016.0	2.9742	6	45.1847
7	1016.0	1.6560	7	41.4457	7	1016.0	2.5116	7	43.4237
8	1016.0	1.4675	8	40.0377	8	1016.0	2.3232	8	42.0157
9	1016.0	1.2876	9	38.9975	9	1016.0	2.1433	9	40.9755
10	762.0	1.2182	10	37.4381	10	1016.0	2.2831	10	39.4161
11	609.6	1.4276	11	34.0097	11	1016.0	2.1117	11	35.9877
12	609.6	0.8946	12	30.1579	12	762.0	1.1987	12	31.7795
13	508.0	1.1997	13	35.1330	13	762.0	1.9900	13	37.1110
14	406.4	1.3236	14	33.1399	14	762.0	2.1282	14	35.1179
15	304.8	1.2871	15	30.2277	15	762.0	1.8661	15	32.2057
16	304.8	1.1579	16	30.3216	16	1016.0	1.7369	16	32.1156

Leftmost Extreme Point-CWS (Network Cost=\$6.0813x10^{6} and Network Resilience=0.1756)					**Leftmost Extreme Point-IWS (Network Cost=\$6.6314x10^{6} and Network Resilience=0.2256)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
17	406.4	1.9016	17	43.9680	17	1016.0	2.4806	17	45.7620
18	508.0	3.0604	18	55.5749	18	762.0	3.6394	18	57.3689
19	508.0	3.1426	19	50.4422	19	762.0	3.7216	19	52.2362
20	1016.0	2.6944	20	41.0930	20	762.0	3.2734	20	42.8870
21	508.0	1.9393	21	35.9280	21	762.0	2.5183	21	37.7220
22	304.8	1.8464	22	44.2134	22	762.0	2.4254	22	46.0074
23	1016.0	1.7727	23	38.9027	23	762.0	2.3517	23	40.6967
24	762.0	2.0536	24	35.5527	24	762.0	2.6326	24	37.3467
25	762.0	1.5541	25	31.5337	25	762.0	2.1331	25	33.3277
26	508.0	1.6705	26	30.1083	26	762.0	2.2495	26	31.9023
27	304.8	1.2141	27	35.4993	27	508.0	1.7931	27	37.2933
28	304.8	0.5945	28	30.7463	28	508.0	0.7735	28	32.5403
29	406.4	1.6221	29	30.1579	29	508.0	2.2011	29	31.5258
30	406.4	1.0011	30	30.1944	30	508.0	1.5801	30	31.9884
31	304.8	0.7092	31	30.1200	31	508.0	0.9882	31	31.7112
32	304.8	0.9613	32	30.0120	32	508.0	1.5403	32	31.5012
33	406.4	0.7656	-	-	33	508.0	1.3446	-	-
34	508	0.7585	-	-	34	508.0	0.9158	-	-

Table 6.12 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Rightmost Extreme Point for Hanoi WDN in CWS and IWS

Rightmost Extreme Point-CWS (Network Cost=\$10.9705x10^{6} and Network Resilience=0.3538)					**Rightmost Extreme Point-IWS (Network Cost=\$10.9705x10^{6} and Network Resilience=0.4050)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	1016	6.8320	1	97.1407	1	1016	9.3056	1	105.3908
2	1016	6.5271	2	61.6704	2	1016	9.0334	2	67.5754
3	1016	2.0136	3	58.9919	3	1016	2.8023	3	68.0809
4	1016	1.9691	4	55.7083	4	1016	2.7538	4	61.0244
5	1016	1.7207	5	52.4830	5	1016	2.4209	5	60.4304
6	1016	1.3764	6	51.8211	6	1016	1.9481	6	56.7105
7	1016	0.9138	7	51.2355	7	1016	1.3052	7	59.5831

Rightmost Extreme Point-CWS (Network Cost=$\$10.9705\text{x}10^{6}$ and Network Resilience=0.3538)					**Rightmost Extreme Point-IWS (Network Cost=$\$10.9705\text{x}10^{6}$ and Network Resilience=0.4050)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
8	1016	0.7254	8	50.8537	8	1016	1.0440	8	56.1932
9	1016	0.5455	9	50.6417	9	1016	0.7891	9	55.1822
10	1016	0.6853	10	50.2576	10	1016	1.0011	10	55.0375
11	1016	0.5139	11	49.9729	11	1016	0.7551	11	56.5495
12	1016	0.3221	12	49.7234	12	1016	0.4778	12	55.5573
13	1016	0.3197	13	50.7205	13	1016	0.4806	13	56.0545
14	1016	0.5304	14	50.8462	14	1016	0.7987	14	58.6299
15	1016	0.6263	15	51.0345	15	1016	0.9529	15	57.5937
16	1016	1.2917	16	54.6045	16	1016	1.9690	16	61.4286
17	1016	1.5880	17	57.9596	17	1016	2.4250	17	67.3328
18	1016	2.0489	18	60.4182	18	1016	3.1584	18	66.3744
19	1016	2.0694	19	54.2606	19	1016	3.2176	19	62.1674
20	1016	2.1528	20	53.9411	20	1016	3.3932	20	61.7826
21	1016	0.4848	21	53.9264	21	1016	0.7657	21	59.7529
22	1016	0.1662	22	51.0899	22	1016	0.2639	22	57.5672
23	1016	1.2311	23	50.8200	23	1016	1.9614	23	54.7629
24	1016	0.4927	24	50.7603	24	1016	0.7857	24	54.5873
25	1016	0.2118	25	50.7747	25	1016	0.3385	25	57.0241
26	1016	0.1240	26	50.8264	26	1016	0.2000	26	58.3445
27	1016	0.4324	27	50.8861	27	1016	0.6979	27	59.2010
28	1016	0.5591	28	50.7310	28	1016	0.9046	28	54.9412
29	1016	0.3803	29	50.6885	29	1016	0.6193	29	57.1200
30	1016	0.2810	30	50.6882	30	1016	0.4603	30	56.6157
31	1016	0.1576	31	49.9712	31	1016	0.2619	31	53.5287
32	1016	0.0343	32	49.1241	32	1016	0.0577	32	54.2189
33	1016	0.0217	-	-	33	1016	0.0366	-	-
34	1016	0.0017	-	-	34	1016	0.0029	-	-

It is observed from Table 6.11, that twelve pipe diameters (Pipe Nos 1 to 9, 24, 25 and 34) out of 34 pipes of the optimal WDN design for the leftmost extreme point in CWS and IWS scenarios are same. The optimal network cost is around 9% higher in IWS as compared to CWS scenario. Similarly, the optimal network resilience is around 28% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is 41% higher as compared to the pipe velocity in

CWS scenario. In CWS and IWS scenarios, as the WDN is a looped one, the pipe velocity varies depending upon its distance from the source. The pipe velocity is relatively higher in pipes 1, 2, 3, 4, 5, 6, 18, 19, 20 and 24. Similarly, pipe velocity is lower in pipes 12, 28 (lowest), 31, 32, 33 and 34. The nodal pressure in IWS scenario is around 5% higher in comparison to CWS scenario. The nodal pressure reduces to around one third of its initial value when the water reaches the last few nodes in the network in both the water supply scenarios.

It is observed from Table 6.12, that the optimal WDN design for the rightmost extreme point in CWS and IWS scenarios are same. The optimal network resilience is around 14% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is around 53% higher as compared to the pipe velocity in CWS scenario. In CWS and IWS scenarios, as the WDN is a looped one, the pipe velocity varies depending upon its distance from the source. The pipe velocity is relatively higher in pipes which are closer to the source. The velocity is the lowest in pipe 34 in both CWS and IWS scenario. The nodal pressure in IWS scenario is around 12% higher in comparison to CWS scenario. The nodal pressure reduces to around half of its initial value when the water reaches the last few nodes in the network in both the water supply scenarios.

6.2.3. BIN

Continuous Water Supply (CWS)

The parameters chosen after trial and error in various optimization algorithms are shown in Table 6.13. The population size and number of iterations have been fixed as 4500 and 1,00,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.13 Parameters Chosen for Optimization Algorithms for BIN (CWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.14 Comparison of Optimal Solutions obtained by Optimization Algorithms and Wang *et al.* (2015) for BIN (CWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (€ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	17587	1.9633 20.2487	0.3498 0.9552	13088.99
Wang *et al.* (2015)	1254	1.9986 20.0656	0.3935 0.9534	12887.44

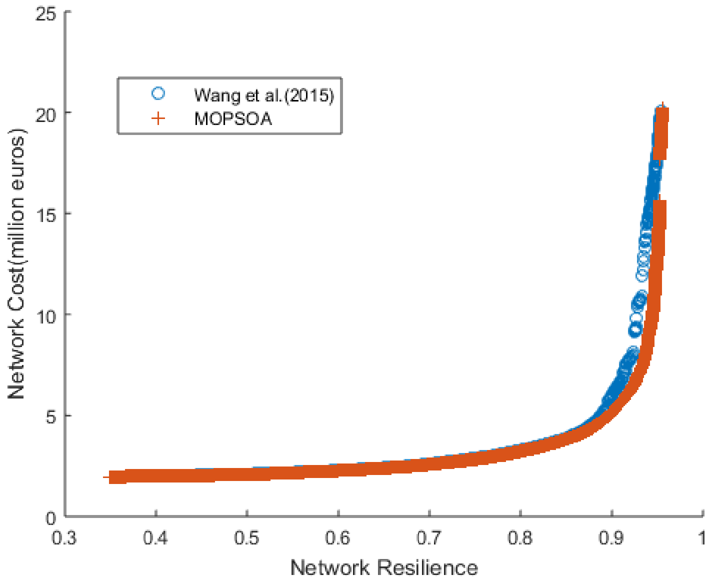

Figure 6.7 Pareto Front obtained by MOPSOA and Wang *et al.* (2015) for BIN (CWS)

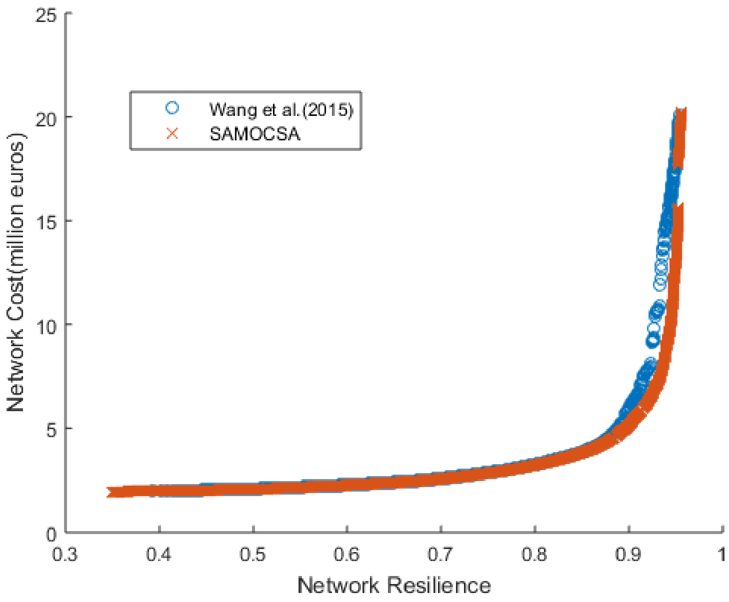

Figure 6.8 Pareto Front obtained by SAMOCSA and Wang *et al.* (2015) for BIN (CWS)

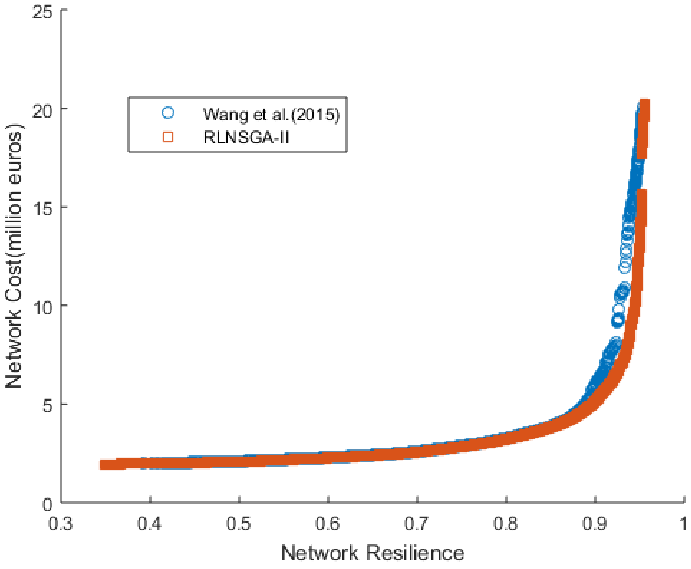

Figure 6.9 Pareto Front obtained by RLNSGA-II and Wang *et al.* (2015) for BIN (CWS)

The results are compared with Wang *et al.* (2015), as shown in Table 6.14. It is observed that MOPSOA, SAMOCSA, RLNSGA-II has converged to more Pareto front points for BIN in comparison with Wang *et al.* (2015). It can be observed from Table 6.14 that the hypervolume of all the three optimization algorithms is better when compared with Wang *et al.* (2015). In summary, the results highlight that MOPSOA, SAMOCSA and RLNSGA-II demonstrated superior performance compared to Wang *et al.* (2015) with respect to the total number of points in the Pareto front, capturing the extreme points and hypervolume for BIN. The Pareto front obtained by each optimization algorithm is shown in Figs 6.7, 6.8 and 6.9. The visible discontinuity in the rising limb of the graphs in Figs 6.7 to 6.9 could be due to the discrete diameters available in the market. The solutions or diameters might not be available in certain regions or sizes, leading to these discontinuities. In addition, this could also be possible when the search mechanism of an optimization algorithm finds it difficult to explore that search space in the pareto front. It is observed from these figures that most of the points on the pareto front obtained by MOPSOA, SAMOCSA, RLNSGA-II is more along the entire pareto front when compared with Wang *et al.* (2015). The middle as well as right upper points on the pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II are superior and has also found solutions in new search spaces in comparison with Wang *et al.* (2015). The optimization algorithms not only discover new pareto front points in the low resilience region but also identifies substantial points in the high resilience region as well in BIN. The proposed optimization algorithms have shown excellent exploration and exploitation search mechanisms for the large benchmark WDN as compared to smaller WDNs in this study. MOPSOA, SAMOCSA and RLNSGA-II solutions would save a substantial cost to achieve the same resilience for the network.

Intermittent Water Supply (IWS)

The parameters chosen after trial and error in various optimization algorithms is shown in Table 6.15. The population size and number of iterations have been fixed as 4500 and 100,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.15 Parameters Chosen for Optimization Algorithms for BIN (IWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.16 Comparison of Optimal Solutions obtained by Optimization Algorithms for BIN (IWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (€ 10^6)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	17579	2.1734 20.2487	0.3667 0.9721	15187.99

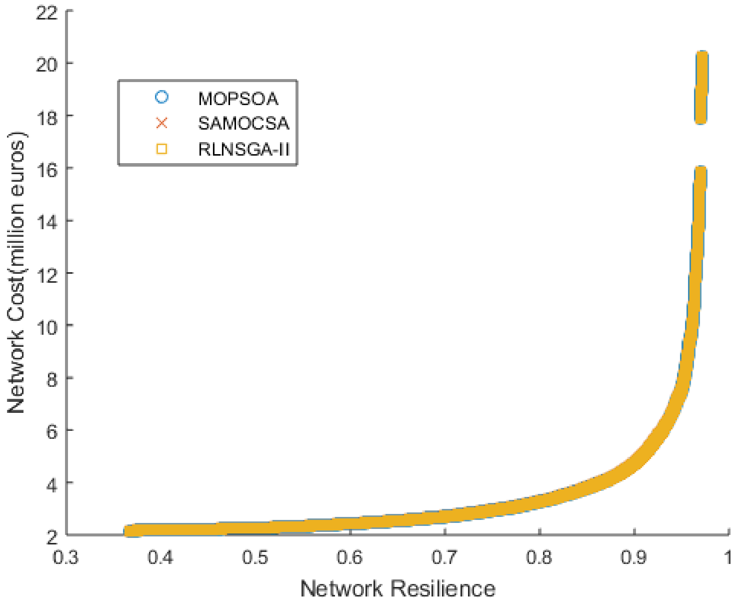

Figure 6.10 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for BIN (IWS)

The results obtained by the optimization algorithms are shown in Table 6.16. The Pareto front obtained by each optimization algorithm is shown in Fig. 6.10. It is observed from the results that the Pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II have converged to the same solution for BIN. Results for BIN for intermittent water supply have not been compared with any other published literature as they are not available. The optimal solution representing the extreme points of Pareto front obtained by the best optimization algorithm for BIN in CWS and IWS has been compared. The hydraulic analysis of the optimal WDN design for each extreme point has been carried out and the velocity in each pipe as well as pressure in each node are compared and shown in Tables A.1 and A.2 available in Appendix A.

It is observed from Table A.1, that 135 pipe diameters out of 454 pipes of the optimal WDN design for the leftmost extreme point in CWS and IWS scenarios are same. The optimal network cost is around 11% higher in IWS as compared to CWS scenario. Similarly, the optimal network resilience is around 5% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is around 64% higher as compared to the pipe velocity in CWS scenario. In CWS and IWS scenarios, as the WDN is a branched one, the pipe velocity is in a decreasing trend from the source towards the end of the network. The nodal pressure in IWS scenario is around 3% higher in comparison to CWS scenario. Approximately 63% reduction in nodal pressure from the initial value is observed when the water reaches the last few nodes in the network in both the water supply scenarios.

It is observed from Table A.2, that the optimal WDN design for the rightmost extreme point in CWS and IWS scenarios are the same. The optimal network resilience is around 2% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is around 66% higher as compared to the pipe velocity in CWS scenario. The pipe velocity is in a decreasing trend from the source towards the end of the network in both the scenarios. The nodal pressure in IWS scenario is around 9% higher in comparison to CWS scenario. The nodal pressure reduces to around 62% of its initial value when the water reaches the last few nodes in the network in both the water supply scenarios.

6.2.4. Pamapur WDN

Continuous Water Supply (CWS)

The parameters chosen after trial and error in various optimization algorithms are shown in Table 6.17. The population size and number of iterations have been fixed as 1000 and 50,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.17 Parameters Chosen for Optimization Algorithms for Pamapur WDN (CWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.18 Comparison of Optimal Solutions obtained by Optimization Algorithms for Pamapur WDN (CWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (million rupees)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	100	1.3043 3.4988	0.4061 0.8877	1257.97

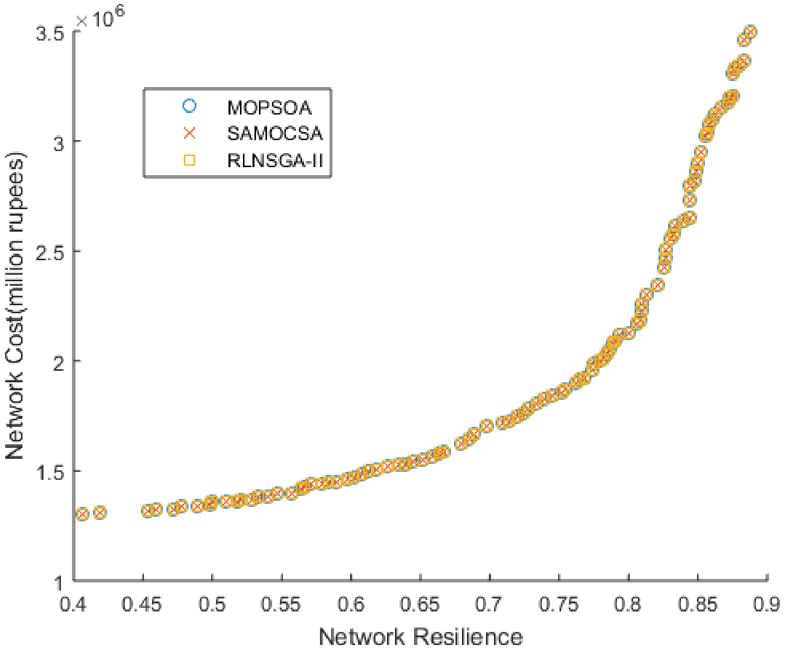

Figure 6.11 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for Pamapur WDN (CWS)

The results obtained from MOPSOA, SAMOCSA and RLNSGA-II for Pamapur WDN is shown in Table 6.18. It is observed from Fig. 6.11 that pareto optimal set for all the three optimization algorithms have converged to the same solution. It is observed from the pareto front that the least-cost design (with a cost of 1.3043 million rupees) has an associated network resilience of 0.4061. The network resilience can be significantly improved to more than 200% i.e. 0.8877 with a network cost of 3.4988 million rupees. In addition, there are also a number of good trade-off design options available to the engineers to choose from the pareto-front.

Intermittent Water Supply (IWS)

The parameters chosen after trial and error in various optimization algorithms are shown in Table 6.19. The population size and number of iterations have been fixed as 1000 and 50,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.19 Parameters Chosen for Optimization Algorithms for Pamapur WDN (IWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.20 Comparison of Optimal Solutions obtained by Optimization Algorithms for Pamapur WDN (IWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (million rupees)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	93	1.5543 3.4988	0.4761 0.9450	1142.7510

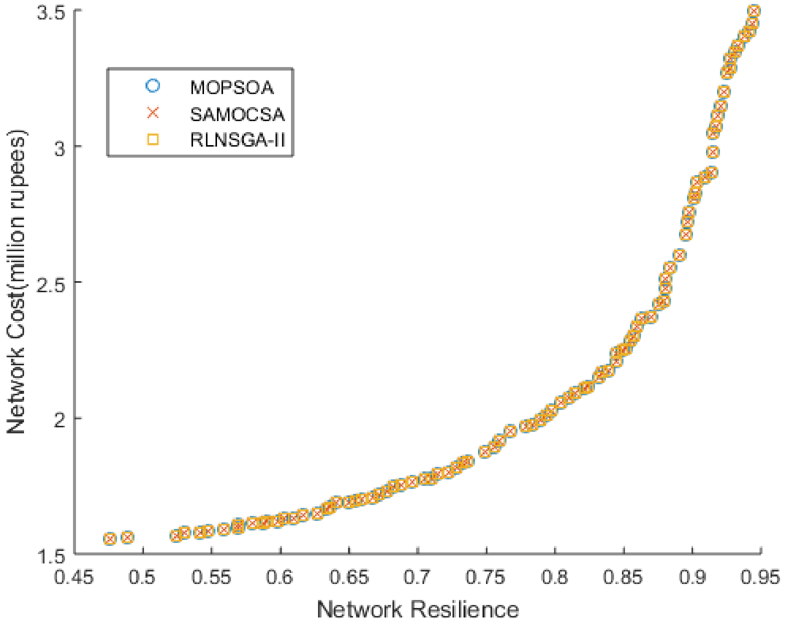

Figure 6.12 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for Pamapur WDN (IWS)

The results obtained by the optimization algorithms are shown in Table 6.20. It is observed from Fig. 6.12 that pareto optimal set for all the three optimization algorithms have converged to the same solution. It is observed from the pareto front that the least-cost design (with a cost of 1.5543 million rupees) has an associated network resilience of 0.4761. The network resilience can be significantly improved to more than 200% i.e. 0.9450 with a network cost of 3.4988 million rupees.

The optimal solution representing the extreme points of Pareto front obtained by the best optimization algorithm for Pamapur WDN in CWS and IWS has been compared. The hydraulic analysis of the optimal WDN design for each extreme point has been carried out and the velocity in each pipe, pressure as well as demand in each node are compared and shown in Tables A.3 and A.4 shown in Appendix A.

It is observed from Table A.3, that twelve pipe diameters (Pipe Nos 31, 32, 33, 43, 44, 59, 60, 98, 99, 111, 112 and 113) of the optimal WDN design for the leftmost extreme point in CWS and

IWS scenarios are same. The optimal network cost is around 19% higher in IWS as compared to CWS scenario. Similarly, the optimal network resilience is around 17% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is nearly 22% higher as compared to the pipe velocity in CWS scenario. The nodal pressure in IWS scenario is around 18% higher in comparison to CWS scenario. Approximately 50% reduction in nodal pressure from the initial value (Node 24) is observed when the water reaches the last node in the network (Node 59) in both the water supply scenarios.

It is observed from Table A.4, that the optimal WDN design for the rightmost extreme point in CWS and IWS scenarios are same. The optimal network resilience is around 6% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is approximately 21% higher as compared to the pipe velocity in CWS scenario. The nodal pressure in IWS scenario is around 18% higher in comparison to CWS scenario. As observed earlier for leftmost points, the nodal pressure is highest in Node 24 and lowest in Node 59 for CWS and IWS scenarios.

6.2.5. Vanasthalipuram WDN

Continuous Water Supply (CWS)

The parameters chosen after trial and error in various optimization algorithms are shown in Table 6.21. The population size and number of iterations have been fixed as 3000 and 70,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.21 Parameters Chosen for Optimization Algorithms for Vanasthalipuram WDN (CWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.22 Comparison of Optimal Solutions obtained by Optimization Algorithms for Vanasthalipuram WDN (CWS)

Algorithms	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (million rupees)	**Network Resilience**	
MOPSOA/ SAMOCSA/ RLNSGA-II	502	3.0952 5.7930	0.3541 0.4913	1577.97

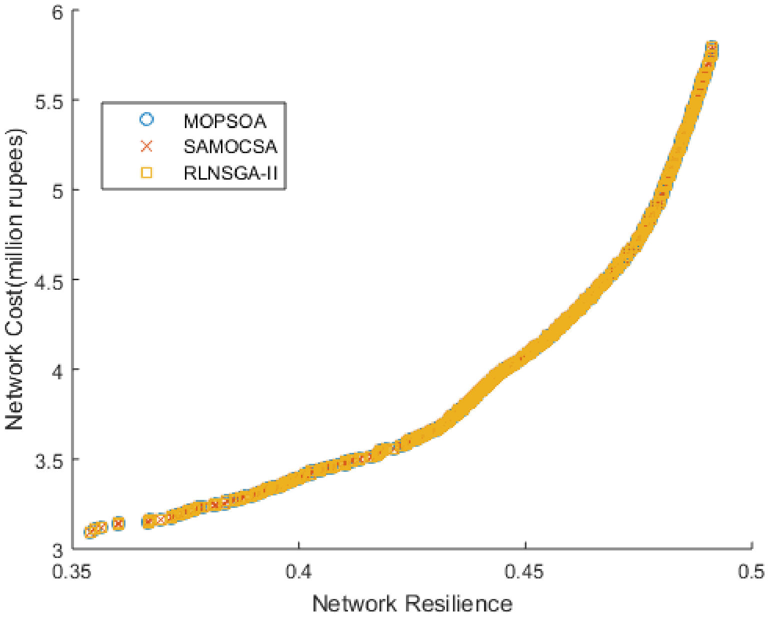

Figure 6.13 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for Vanasthalipuram WDN (CWS)

The results obtained from MOPSOA, SAMOCSA and RLNSGA-II for Pamapur WDN are shown in Table 6.22. It is observed from Fig. 6.13 that pareto optimal set for all the three optimization algorithms have converged to the same solution. It is observed from the pareto front that the least-cost design (with a cost of 3.0952 million rupees) has an associated network resilience of 0.3541. The network resilience could be increased to a maximum of around 39% i.e. 0.4913 with a network cost increase of 87% (5.7930 million rupees).

Intermittent Water Supply (IWS)

The parameter chosen after trial and error in various optimization algorithms is shown in Table 6.23. The population size and number of iterations have been fixed as 3000 and 70,000 for all the three optimization algorithms respectively. The parameters used in SAMOCSA are dynamically updated during the iterations as a part of the self-adaptive nature of the algorithm.

Table 6.23 Parameters Chosen for Optimization Algorithms for Vanasthalipuram WDN (IWS)

Algorithm	**Parameters**
MOPSOA	W = 0.4; C1, C2 = 2 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter
RLNSGA-II	Distribution index for crossover = 15; Mutation rate = 7; Crossover rate = 0.9 Local search is performed with a period of 100 between NPSO = 1000 and 5000, and with a period of 1000 thereafter

Table 6.24 Comparison of Optimal Solutions obtained by Optimization Algorithms for Vanasthalipuram WDN (IWS)

Algorithm	**No of points in pareto front**	**Extreme points in pareto front**		**Hypervolume ($x10^3$)**
		Network Cost (million rupees)	**Network Resilience**	
MOPSOA	475	3.4452 5.7930	0.4111 0.5443	1555.57

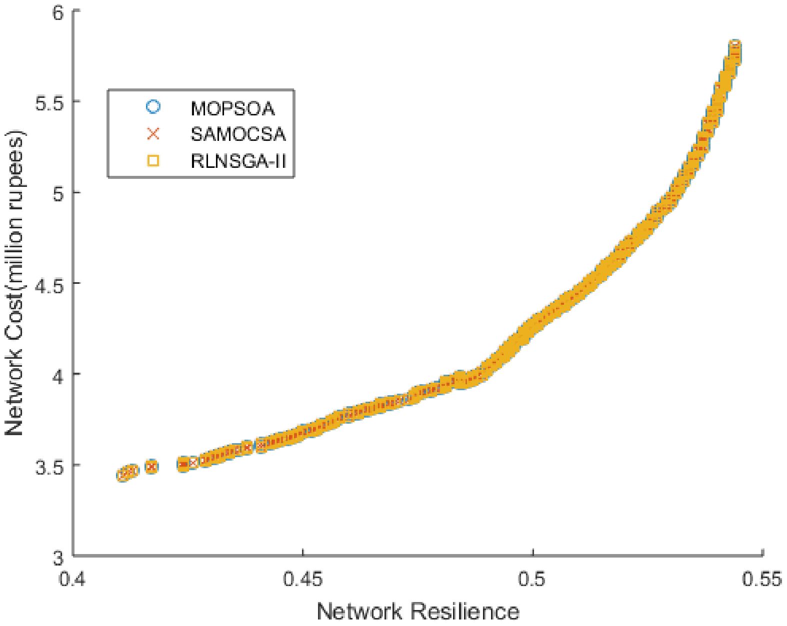

Figure 6.14 Pareto Front obtained by MOPSOA, SAMOCSA and RLNSGA-II for Vanasthalipuram WDN (IWS)

The results obtained by the optimization algorithms are shown in Table 6.24. The Pareto front obtained by each optimization algorithm is shown in Fig. 6.14. It is observed from the results that the Pareto front obtained by MOPSOA, SAMOCSA and RLNSGA-II have converged to the same solution for Vanasthalipuram WDN. It is observed from the pareto front that the least-cost design (with a cost of 3.4452 million rupees) has an associated network resilience of 0.4111. The network resilience could be increased to a maximum of around 32% i.e. 0.5443 with a network cost increase of 68% (5.7930 million rupees).

The optimal solution representing the extreme points of Pareto front obtained by the best optimization algorithm for Vanasthalipuram WDN in CWS and IWS has been compared. The hydraulic analysis of the optimal WDN design for each extreme point has been carried out and the velocity in each pipe and nodal pressure are compared and shown in Tables A.5 and A.6 available in Appendix A.

It is observed from Table A.5, that 47 out of 301 pipe diameters of the optimal WDN design for the leftmost extreme point in CWS and IWS scenarios are same. The optimal network cost is around 11% higher in IWS as compared to CWS scenario. Similarly, the optimal network resilience is around 16% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is nearly 37% higher as compared to the pipe velocity in CWS scenario. The nodal pressure in IWS scenario is around 42% higher in comparison to CWS scenario. The variation in pipe velocity and the nodal pressure between CWS and IWS scenarios are in an increasing trend from the beginning pipe diameter/ node. This could be attributed to the branched network type of the WDN. There is a significant reduction in the nodal pressure from the initial value (at Node 211) when the water reaches Node 8 in the network in both the water supply scenarios.

It is observed from Table A.6, that the optimal WDN design for the rightmost extreme point in CWS and IWS scenarios are same. The optimal network resilience is around 11% higher in IWS scenario in comparison with CWS. In IWS scenario, the pipe velocity is approximately 37% higher as compared to the pipe velocity in CWS scenario. The nodal pressure in IWS scenario is around 59% higher in comparison to CWS scenario. As observed earlier for leftmost points, the nodal pressure is highest in Node 211 and lowest in Node 8 for CWS and IWS scenarios. The variation in pipe velocity and the nodal pressure between CWS and IWS scenarios are in an increasing trend from the beginning pipe diameter/ node. The velocity is highest in pipe 221 (pipe from the source) and lowest in 231 for leftmost and rightmost extreme points in both CWS and IWS scenarios.

6.3. Analysis of Results from Optimal Water Distribution Network Design - Scenario 2 (Network Cost, Network Resilience and Network Equity)

In this scenario, focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable distribution of water represented as network equity. As the proposed methodology has already been tested on three different benchmark WDNs, the case studies chosen for this scenario will focus on the real-life case studies, i.e., Pampapur WDN and Vanasthalipuram WDN. In addition, the computation time for such large networks usually takes a substantial amount of time (around 30 days run on a high performance computing system) to converge to the pareto optimal set. As the real-life case studies are usually operated for intermittent water supply system, the present scenario proposes to determine the optimal WDN design in a multiobjective scenario considering network cost (minimizing), network resilience (maximizing) and network equity (maximizing). Since there is an interdependency between maximizing the network resilience and network equity, one of the objectives in the mathematical model is formulated considering the weighted sum of both the objectives. The first objective focuses on minimizing the network cost and the second objective is considered as maximizing the weighted sum of network resilience and network equity. The weightage of network resilience and network equity in the second objective is considered equal i.e., 0.5. As the computation time for optimization cum simulation for such large networks is taking enormous period, the variations in the weights of network resilience and network equity could not be considered in this study. As observed from the results of scenario 1, all three optimization algorithms have been performing very well for all the five WDNs. For scenario 2, one of the three developed optimization algorithms, i.e., RLNSGA-II has been considered to solve the formulated multiobjective mathematical model.

6.3.1. Pamapur WDN

The parameters chosen after trial and error for RLNSGA-II are population size = 1000, number of iterations = 50000, distribution index for crossover = 15, mutation rate = 7, crossover rate = 0.9, local search is performed with a period of 100 between NPSO = 1000 and 5000 and with a period of 1000 thereafter. Fig. 6.15 shows the pareto front obtained for Pamapur WDN using RLNSGA-II. The number of points on the pareto front is 31. It is observed that the number of points on the pareto front reduced significantly when the network resilience is combined with network equity and made as a single objective. The combined index (network resilience + network equity) varies from 0.60 to 0.93 for the cost range of 1.32 to 3.41 million rupees.

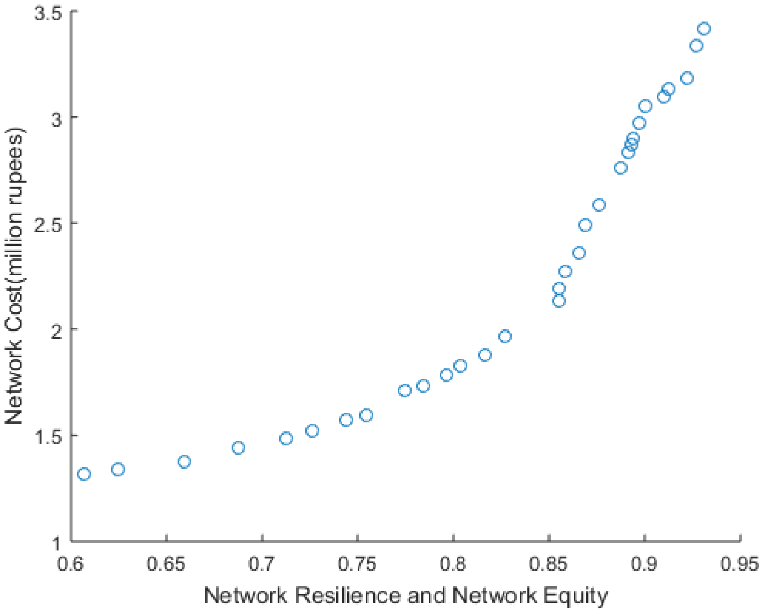

Figure 6.15 Pareto Front (Network Cost vs Network Resilience and Network Equity) obtained for Pamapur WDN (IWS) using RLNSGA-II

The optimal results obtained for Pamapur WDN (IWS) in scenario 1 and scenario 2 are compared and shown in Table 6.25. The network resilience and network equity for each scenario has been separately calculated and compared. The pareto fronts accordingly have been drawn for each scenario for network cost vs network resilience (shown in Fig. 6.16) and network cost vs network equity (shown in Fig. 6.17).

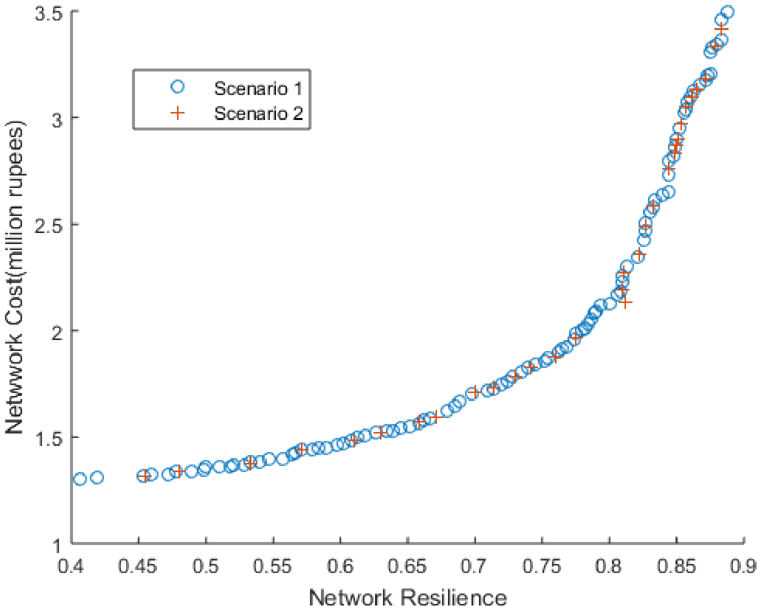

Figure 6.16 Comparison of Pareto Fronts (Network cost vs Network Resilience) obtained for Pamapur WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

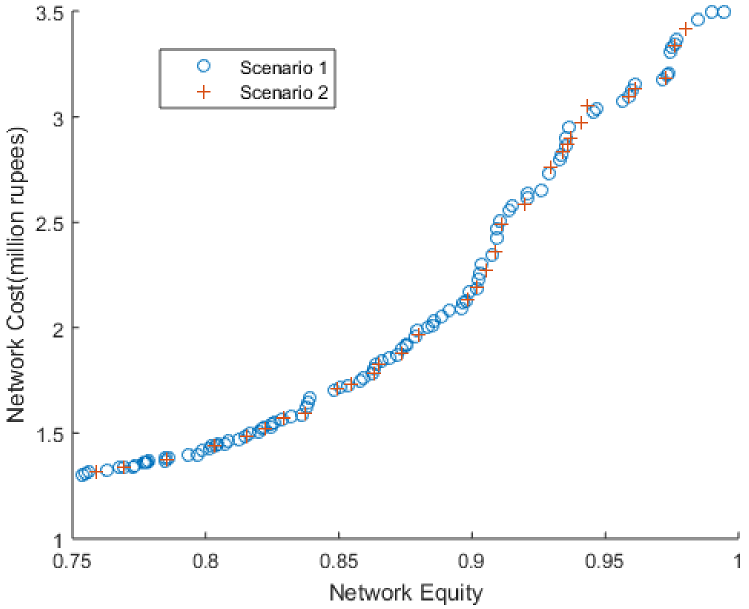

Figure 6.17 Comparison of Pareto Fronts (Network cost vs Network Equity) obtained for Pamapur WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

Table 6.25 Comparison of Optimal Solutions obtained for Pamapur WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

	Leftmost Extreme Point in Pareto Front		**Rightmost Extreme Point in Pareto Front**	
	Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
Network Cost (million rupees)	1.3043	1.3201	3.4986	3.4126
Network Resilience	0.4061	0.4551	0.8877	0.8829
Network Equity	0.7540	0.7591	0.9943	0.9799

It is observed from Figs. 6.16 and 6.17 that most of the non-dominated solutions on the pareto front from scenario 1 and scenario 2 are coinciding. It is observed from Table 6.25 that there is a 12% increase in network resilience for the leftmost extreme point in scenario 2 for a 1.2% increase in the network cost. Similarly, there is a marginal increase of 0.7% in the network equity in scenario 2 when compared to the results obtained in scenario 1 for leftmost extreme point. For the rightmost point, the network resilience has an equivalent value for a slightly lower network cost (around 2.5% lesser). The network equity is around 1.5% lower for a 2.5% reduced network cost in scenario 2 as compared to scenario 1.

The hydraulic analysis of the optimal WDN design for each extreme point on the pareto front has been carried out and the velocity in each pipe and nodal pressure are compared and shown in Table A.7 available in Appendix A.

It is observed from Table A.7, that 107 pipe diameters of the optimal WDN design for the leftmost extreme point in scenario 1 and scenario 2 are same. Fifteen diameters (that are different in both the scenarios) are of higher diameter in scenario 2. The pipe velocity is similar in both the scenarios, however, the nodal pressure around 8% higher in scenario 2. Pipe 105 (which is the closest to the source) has the highest velocity and Pipe 8 (located as the last pipe in the tail end) measures the lowest velocity. Similarly, Node 24 (which is the closest to the source) has the highest pressure of 19.0257 m and Node 59 (located at the tail end) measures the lowest pressure of 8.5917 m. For the rightmost extreme point, 114 pipe diameters are the same in the optimal WDN design from scenario 1 and scenario 2. It is observed that the pipe diameter values in the remaining eight pipes are lower in scenario 2. In this case too, the pipe velocity is similar in both the scenarios, however, the nodal pressure is around 4% higher in scenario 2. Pipe 105 and Pipe 8 measured the highest and lowest velocity here too. In a similar trend, Node 24 (which is the closest to the source) has the highest pressure of 21.896 m and Node 59 (located at the tail end) measures the lowest pressure of 9.7077 m.

6.3.2. Vanasthalipuram WDN

The parameters chosen after trial and error for RLNSGA-II are population size = 3000, number of iterations = 70000, distribution index for crossover = 15, mutation rate = 7, crossover rate = 0.9, local search is performed with a period of 100 between NPSO = 1000 and 5000 and with a period of 1000 thereafter. Fig. 6.18 shows the pareto front obtained for Vanasthalipuram WDN using RLNSGA-II. The number of points on the pareto front is 83. It is observed that the number of points on the pareto front reduced significantly when the network resilience is combined with network equity and made as a single objective. The combined index (network resilience + network equity) varies from 0.58 to 0.73 for the cost range of 3.20 to 4.77 million rupees. The optimal results obtained for Vanasthalipuram WDN (IWS) in scenario 1 and scenario 2 are compared and shown in Table 6.26. The network resilience and network equity for each scenario has been separately calculated and compared. The pareto fronts accordingly have been drawn for each scenario for network cost vs network resilience (shown in Fig. 6.19) and network cost vs network equity (shown in Fig. 6.20).

Table 6.26 Comparison of Optimal Solutions obtained for Vanasthalipuram WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

	Leftmost Extreme Point in Pareto Front		**Rightmost Extreme Point in Pareto Front**	
	Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
Network Cost (million rupees)	3.0952	3.2025	5.7930	4.7747
Network Resilience	0.3541	0.3680	0.4913	0.4810
Network Equity	0.7506	0.7946	0.9898	0.9833

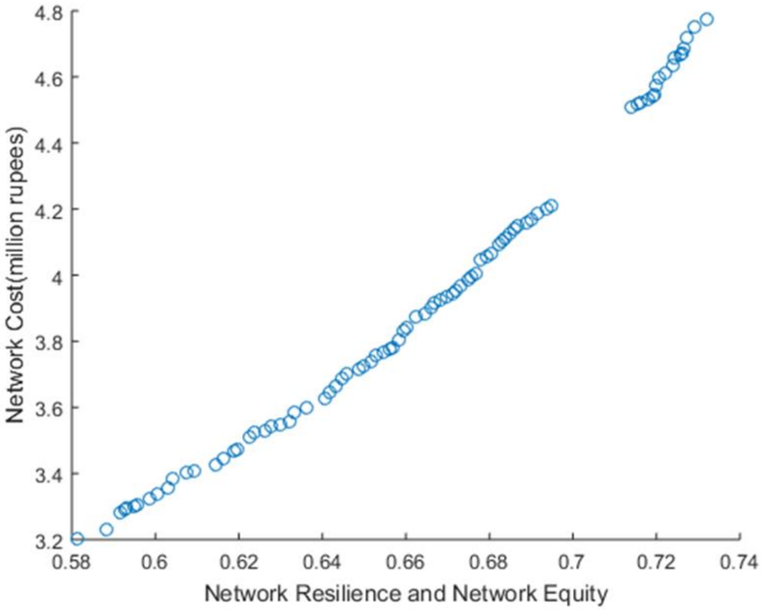

Figure 6.18 Pareto Front (Network Cost vs Network Resilience and Network Equity) obtained for Vanasthalipuram WDN (IWS) using RLNSGA-II

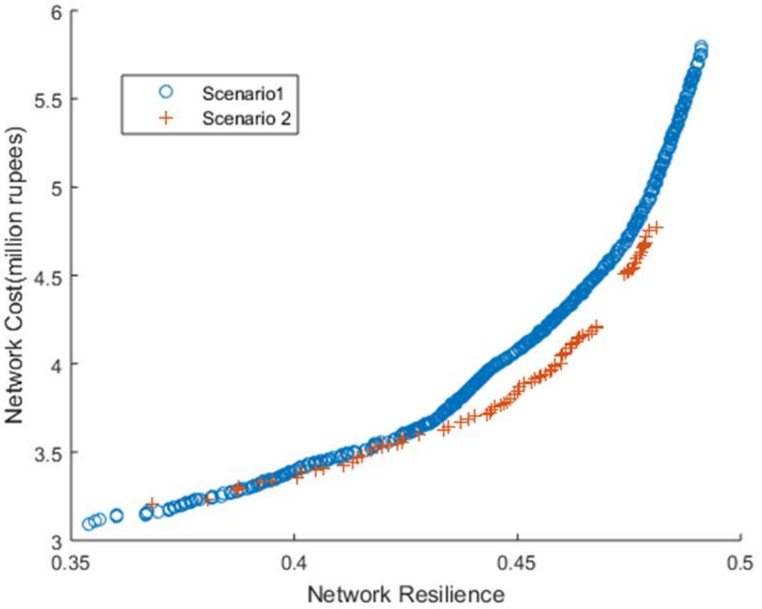

Figure 6.19 Comparison of Pareto Fronts (Network Cost vs Network Resilience) obtained for Vanasthalipuram WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

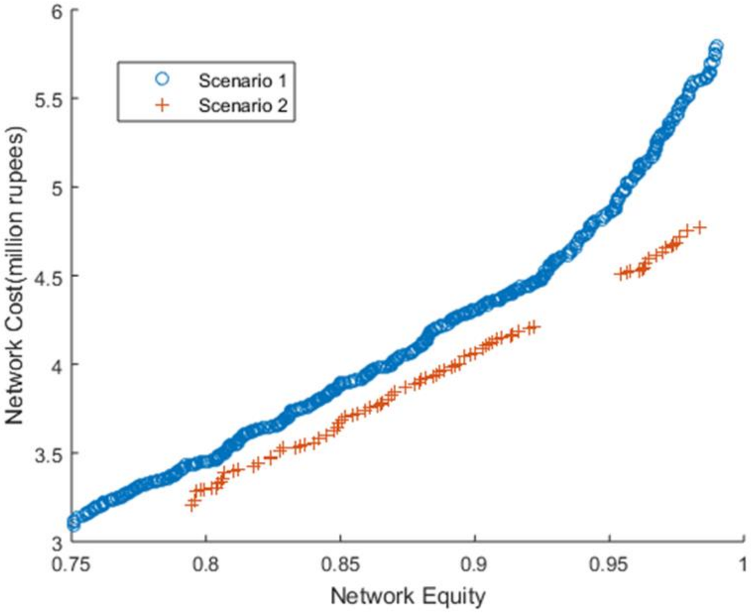

Figure 6.20 Comparison of Pareto Fronts (Network Cost vs Network Equity) obtained for Vanasthalipuram WDN (IWS) in Scenario 1 and 2 using RLNSGA-II

It is observed from Fig. 6.19 that most of the non-dominated solutions on the pareto front on the upper middle portion provide better network resilience for a lower network cost. Similarly, it is observed from Fig. 6.20 that all the points on the pareto front represent a better performance in terms of network equity for a lower cost when compared to the results obtained in scenario 1. It is observed from Table 6.26 that there is around 4% increase in network resilience for the leftmost extreme point in scenario 2 for a 3.5% increase in the network cost. Similarly, there is an increase of 6% in the network equity in scenario 2 when compared to the results obtained in scenario 1 for leftmost extreme point. For the rightmost point, the network resilience has an equivalent value for a slightly lower network cost (around 2.1% lesser). The network equity is around 0.7% lower for an 18% reduced network cost in scenario 2 as compared to scenario 1.

The hydraulic analysis of the optimal WDN design for each extreme point on the pareto front has been carried out and the velocity in each pipe and nodal pressure are compared and shown in Table A.8.

It is observed from Table A.8, that 276 out of 301 pipe diameters of the optimal WDN design for the leftmost extreme point in scenario 1 and scenario 2 are same. Twenty five diameters (that are different in both the scenarios) are of higher diameter in scenario 2. The pipe velocity is around 6.4% higher and the nodal pressure is around 8% higher in scenario 2. Pipe 221 (which is the closest to the source) has the highest velocity and Pipe 231 (located at the tail end) measures the lowest velocity. Similarly, Node 211 (which is the closest to the source) has the highest pressure of 41.89 m and Node 8 (located at the tail end) measures the lowest pressure of 10.40 m. For the rightmost extreme point, 263 pipe diameters are the same in the optimal WDN design from scenario 1 and scenario 2. It is observed that the pipe diameter values in the remaining 38 pipes are lower in scenario 2. In this case too, the pipe velocity is around 6% higher and the nodal pressure is around 7% higher in scenario 2. The pipes and nodes that measured the highest and lowest values representing the leftmost extreme point are the same in this case too. Pipe 105 and Pipe 8 measured the highest and lowest velocity here too. The nodal pressure varies from 61.16 m to 16.22 m.

6.4. Analysis of Results of Optimal Design of District Metered Areas – Scenario 3

The proposed methodology incorporates two key steps, including: (1) clustering to identify clusters using Fast Newman algorithm and (2) multiobjective optimization using RLNSGA-II that optimizes the boundaries of the clusters to finally provide the DMA configurations. In the first step, the WDN has been mapped into a weighted and undirected graph using the pressure at each node (obtained during the stead-state analysis for peak condition of the WDN). The number of initial clusters for the WDN and its connecting pipes is obtained using FNA (using Gephi software) which is taken as the initial input for the optimization problem. In the second step, three objectives for the optimization model are considered in this study. They are minimizing Network Cost, maximizing Network Resilience and maximizing Network Equity. In this scenario, the proposed methodology has been applied on Pamapur WDN and Vanasthalipuram WDN to determine the optimal number of DMAs. In this study, the size of flow meters and valves are assumed to be of the same pipe size. During optimization, if the sizes don’t match, the nearest larger size of valve and flow meter has been assumed.

6.4.1. Pamapur WDN

The pipe layout of Pampaur WDN has been given as an input to Gephi software to identify the initial clusters. Nine clusters have been identified with a modularity index 0.7495. This output of the network has been used to identify the optimal DMA layouts using RLNSGA-II. The parameters chosen after trial and error for RLNSGA-II are population size = 1000, number of iterations = 50000, distribution index for crossover = 15, mutation rate = 7, crossover rate = 0.9, local search is performed with a period of 100 between NPSO = 1000 and 5000 and with a period of 1000 thereafter. Fig. 6.21 shows the Pareto front obtained for Pamapur WDN using RLNSGA-II for three objectives Network Cost, Network Resilience and Network Equity. The number of points on the Pareto front is 12. The details of the pareto optimal solutions with the corresponding number of valves and flow meters along with the number of DMAs is shown in Table 6.27. The Pareto fronts for network cost vs network resilience, for network resilience vs network equity and for network cost vs network equity have been obtained and shown in Figures 6.22, 6.23 and 6.24 respectively.

Table 6.27 Details of the Pareto Optimal Solutions for Pamapur WDN

Solution No	Network Cost (Rs. in Lakhs)	Network Resilience	Network Equity	No of Flow Meters	No of Valves	No of DMAs
1	9.547	0.4500	0.9150	6	12	3
2	9.718	0.4700	0.9270	6	13	3
3	10.873	0.4800	0.9345	6	14	3
4	11.789	0.4900	0.9410	6	15	3
5	12.579	0.5010	0.9490	6	17	3
6	22.979	0.5050	0.9515	8	18	4
7	23.125	0.5100	0.9535	8	19	4
8	23.579	0.5200	0.9570	10	19	5
9	43.979	0.5270	0.9591	10	19	5
10	44.258	0.5350	0.9610	10	19	5
11	44.579	0.5410	0.9710	10	20	5
12	48.706	0.5500	0.9750	10	21	5

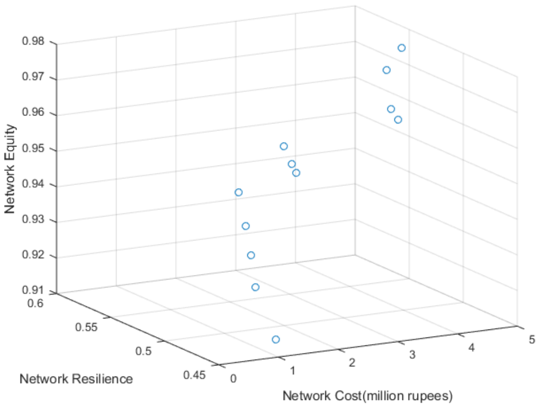

Figure 6.21 Pareto Front obtained by RLNSGA-II for Pamapur WDN (Network Cost, Network Resilience and Network Equity)

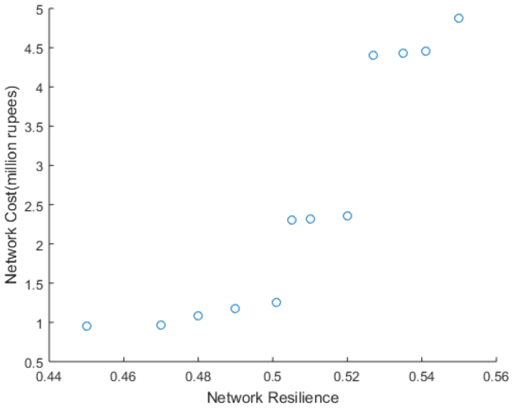

Figure 6.22 Pareto Front obtained by RLNSGA-II for Pamapur WDN (Network Cost, Network Resilience)

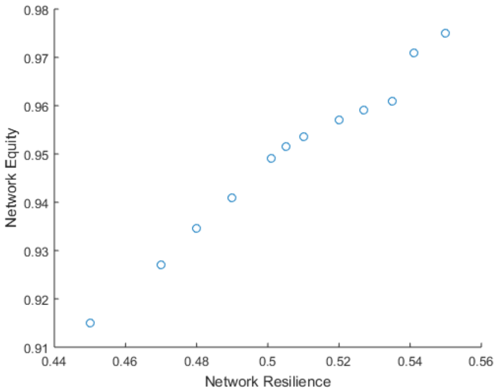

Figure 6.23 Pareto Front obtained by RLNSGA-II for Pamapur WDN (Network Equity, Network Resilience)

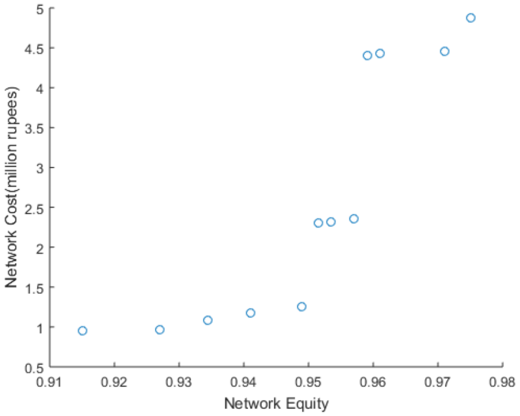

Figure 6.24 Pareto Front obtained by RLNSGA-II for Pamapur WDN (Network Cost, Network Equity)

It can be observed from Table 6.27 that the network cost varies from Rs.9.55 lakhs to Rs.48.71 lakhs for DMAs that vary between 3 to 5. Five different combinations of DMAs have been found for 3 and 5 numbers of DMAs. The number of valves and flow meters varies from 12 to 21 and 6 to 10 respectively for the different DMAs obtained in the pareto front. The network resilience increases from 0.45 to 0.55 (around 22% increase) and network equity increases from 0.9150 to 0.9750 (around 7% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front. It can be observed from Figure 6.22 that Network Cost for implementation of DMAs is directly proportional to Network Resilience and Network Equity. When the cost is less, a considerable number of boundary pipes within the WDN are closed. This leads to a change in the original layout of the network as water takes alternative routes to fulfill the nodal demands and subsequently, the resilience index decreases. This same phenomenon is also responsible for Network Equity variations for different DMA configurations. The hydraulic analysis of the WDN for the leftmost extreme point and the rightmost extreme point in the pareto front is carried out and the results of the same are presented in Table 6.28. The hydraulic analysis has been carried out for the WDN as per the initial layout without DMAs and then with the DMAs as obtained from the pareto front.

Table 6.28 Comparison of results for leftmost and rightmost extreme points in Pareto front for Pamapur WDN

DMA No	**No of Nodes**	**Total Pipe Length (m)**	**WDN without DMAs**				**WDN with DMAs**			
			Total Supply (10^{-3} m^3/s)	**Pressure (m)**			**Total Supply (10^{-3} m^3/s)**	**Pressure (m)**		
				Minimum	**Maximum**	**Average**		**Minimum**	**Maximum**	**Average**
Leftmost Extreme Point										
1	27	2254.12	3.0445	7.71	11.12	9.17	3.0328	7.57	11.02	9.02
2	19	891.28	2.7820	7.55	10.05	8.20	2.7695	7.09	9.89	8.04
3	56	4133.51	7.9188	7.17	8.51	7.52	7.9178	7.09	8.31	7.31
Rightmost Extreme Point										
1	27	2254.12	3.0445	7.71	11.12	9.17	3.0328	7.57	11.02	9.02
2	19	891.28	2.7820	7.55	10.05	8.20	2.7695	7.09	9.89	8.04
3	25	2783.15	4.5862	7.00	8.50	7.50	4.5743	6.79	8.29	7.29
4	21	1020.79	1.6798	7.00	8.30	7.57	1.6713	6.75	8.20	7.47
5	10	570.29	1.2595	7.00	8.50	7.45	1.2477	6.83	8.40	7.35

It is observed from Table 6.27 that average pressure in each DMA is slightly lower after partitioning for both the extreme points. The average pressure in DMA 3 is around 3% lower after partitioning for the leftmost point and it is around 3% lower in DMA 3 after partitioning for the rightmost point. It can be observed that the DMA 3 in leftmost and rightmost points have the maximum pipe length compared to the other DMAs. The total water supply for each DMA is slightly lower after partitioning for both the points. The first two DMAs in both points are the same and the third DMA in leftmost point has been expanded to more DMAs in the rightmost point. The maximum pressure (11.02 m) has been observed in DMA 1 and the minimum pressure (8.31 m) is observed in DMA 3 for the leftmost point. Similarly, for the rightmost point, the maximum pressure (11.02 m) is observed in DMA 1 and the minimum pressure in DMA 4 (8.20 m). The layout of the DMAs for the leftmost and rightmost extreme points are shown in Figs. 6.25 and 6.26 respectively.

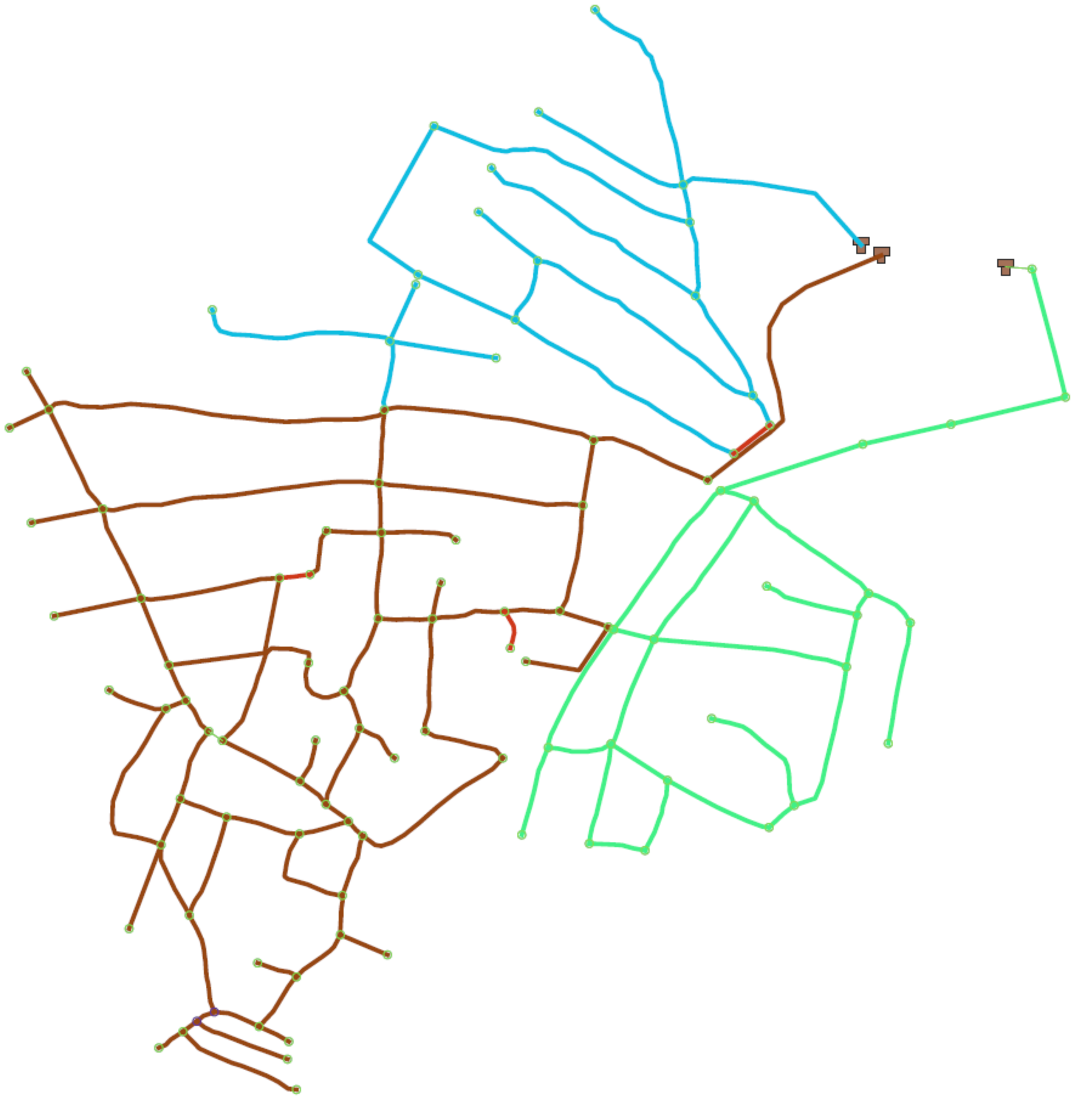

Figure 6.25 DMAs layout representing leftmost extreme point for Pamapur WDN (Green-DMA 1, Blue-DMA 2 and Brown-DMA 3)

Figure 6.26 DMAs layout representing rightmost extreme point for Pamapur WDN (Light Green-DMA 1, Teal-DMA 2, Brown-DMA 3, Dark Green-DMA 4 and Blue-DMA 5)

6.4.2. Vanasthalipuram WDN

The number of initial clusters obtained from Gephi software for Vanasthalipuram WDN is 14 with a modularity index 0.7291. This output of the network has been used to identify the optimal DMA layouts using RLNSGA-II. The parameters chosen after trial and error for RLNSGA-II are population size = 3000, number of iterations = 70000, distribution index for crossover = 15, mutation rate = 7, crossover rate = 0.9, local search is performed with a period of 100 between NPSO = 1000 and 5000 and with a period of 1000 thereafter. Fig. 6.27 shows the Pareto front obtained for Vanasthalipuram WDN using RLNSGA-II for three objectives Network Cost, Network Resilience and Network Equity. The number of points on the Pareto front is 17. The details of the pareto optimal solutions with the corresponding number of valves and flow meters along with the number of DMAs are shown in Table 6.29. The Pareto fronts for network cost vs network resilience, for network resilience vs network equity and for network cost vs network equity have been obtained and shown in Figures 6.28, 6.29 and 6.30 respectively.

Table 6.29 Details of the Pareto Optimal Solutions for Vanasthalipuram WDN

Solution No	**Network Cost (Rs. in Lakhs)**	**Network Resilience**	**Network Equity**	**No of Flow Meters**	**No of Valves**	**No of DMAs**
1	11.117	0.3503	0.7511	7	23	3
2	11.288	0.3511	0.7530	7	24	4
3	12.443	0.3513	0.7535	8	25	4
4	13.359	0.3520	0.7548	8	27	5
5	14.149	0.3521	0.7554	9	29	5
6	24.549	0.3523	0.7573	9	30	5
7	24.695	0.3528	0.7622	9	31	5
8	25.149	0.3531	0.7641	10	32	5
9	45.549	0.3535	0.7647	10	34	5
10	45.828	0.3538	0.7653	11	36	5
11	46.149	0.3543	0.7666	11	37	5
12	50.276	0.3550	0.7670	11	39	5
13	51.359	0.3559	0.7675	12	41	5
14	51.695	0.3562	0.7676	13	42	6
15	53.141	0.3570	0.7681	13	43	7
16	54.349	0.3572	0.7688	14	44	7
17	55.083	0.3577	0.7700	15	45	7

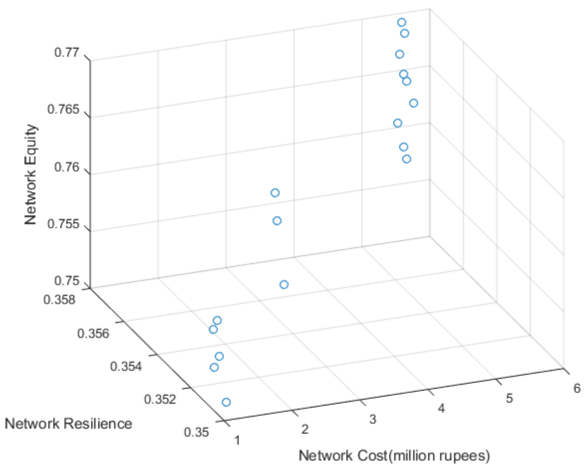

Figure 6.27 Pareto Front obtained by RLNSGA-II for Vanasthalipuram WDN (Network Cost, Network Resilience and Network Equity)

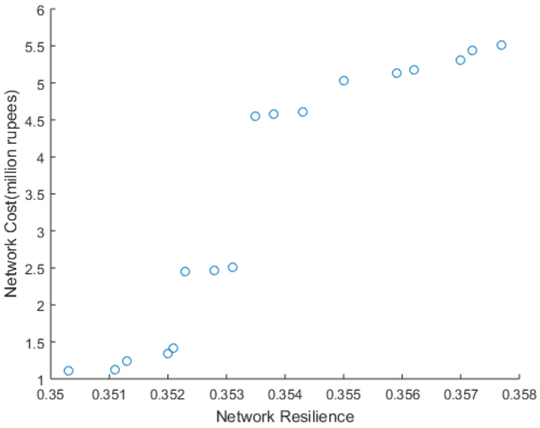

Figure 6.28 Pareto Front obtained by RLNSGA-II for Vanasthalipuram WDN (Network Cost, Network Resilience)

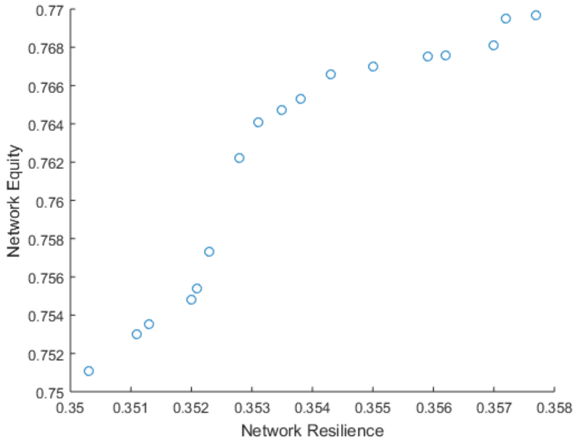

Figure 6.29 Pareto Front obtained by RLNSGA-II for Vanasthalipuram WDN (Network Equity, Network Resilience)

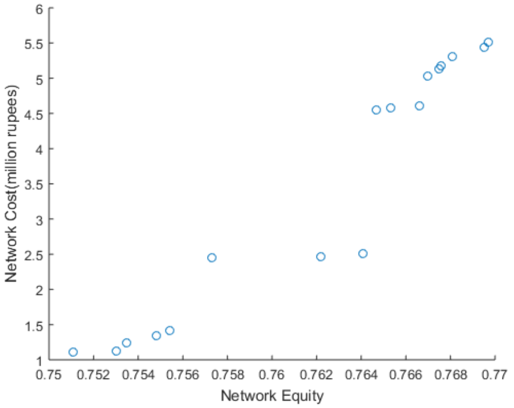

Figure 6.30 Pareto Front obtained by RLNSGA-II for Vanasthalipuram WDN (Network Cost, Network Equity)

It can be observed from Table 6.29 that the network cost varies from Rs.11.12 lakhs to Rs.55.08 lakhs for DMAs that vary between 3 to 7. Ten different combinations of DMAs have been found for 5 numbers of DMAs. The number of valves and flow meters varies from 23 to 45 and 7 to 15 respectively for the different DMAs obtained in the pareto front. The network resilience marginally increases (around 2% increase) and network equity also marginally increases (around 2% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front. It can be observed from Figure 6.27 that Network Cost for implementation of

DMAs is directly proportional to Network Resilience and Network Equity. When the cost is less, a considerable number of boundary pipes within the WDN are closed. This leads to a change in the original layout of the network as water takes alternative routes to fulfill the nodal demands and subsequently, the resilience index decreases. This same phenomenon is also responsible for Network Equity variations for different DMA configurations. The hydraulic analysis of the WDN for the leftmost extreme point and the rightmost extreme point in the pareto front is carried out and the results of the same are presented in Table 6.30. The hydraulic analysis has been carried out for the WDN as per the initial layout without DMAs and then with the DMAs as obtained from the pareto front.

Table 6.30 Comparison of results for leftmost and rightmost extreme points in Pareto front for Vanasthalipuram WDN

DMA No	**No of Nodes**	**Total Pipe Length (m)**	**WDN without DMAs**				**WDN with DMAs**			
			Total Supply (10^{-3} m^3/s)	**Pressure (m)**			**Total Supply (10^{-3} m^3/s)**	**Pressure (m)**		
				Minimum	**Maximum**	**Average**		**Minimum**	**Maximum**	**Average**
Leftmost Extreme Point										
1	89	7527.93	29.67	9.17	19.17	13.17	29.66	9.02	19.02	13.02
2	51	4961.59	38.00	7.19	12.75	10.17	37.99	7.03	12.59	10.01
3	71	4619.41	39.76	8.12	15.71	12.01	39.75	7.91	15.50	11.80
Rightmost Extreme Point										
1	23	1864.95	10.17	8.12	19.17	13.55	10.14	7.97	19.02	13.40
2	33	2675.80	16.93	7.79	17.57	12.58	16.91	7.63	17.41	12.42
3	47	3810.99	27.88	7.19	15.57	11.28	27.86	7.01	15.36	11.07
4	32	2594.72	19.18	7.71	15.91	11.71	19.17	7.61	15.81	11.61
5	25	2027.12	14.67	8.21	17.95	12.98	14.66	8.11	17.85	12.88
6	24	1946.04	11.28	7.59	14.91	11.15	11.28	7.44	14.76	11.00
7	27	2189.29	16.93	7.77	13.12	10.35	16.92	7.67	13.02	10.25

It is observed from Table 6.30 that average pressure in each DMA is slightly lower (below 2%) after partitioning for both the extreme points. The average pressure in DMA 3 is around 1.75% lower after partitioning for the leftmost point and it is around 1.86% lower in DMA 3 after partitioning for the rightmost point. It can be observed that DMA 3 in the rightmost point has the maximum pipe length compared to the other DMAs. The total water supply for each DMA is slightly lower after partitioning for both the points. The maximum pressure (19.02 m) has been observed in DMA 1 and the minimum pressure (7.03 m) is observed in DMA 2 for the leftmost point. Similarly, for the rightmost point, the maximum pressure (19.02 m) is observed in DMA 1 and the minimum pressure in DMA 3 (7.01 m). The layout of the DMAs for the leftmost and rightmost extreme points are shown in Figs. 6.31 and 6.32 respectively.

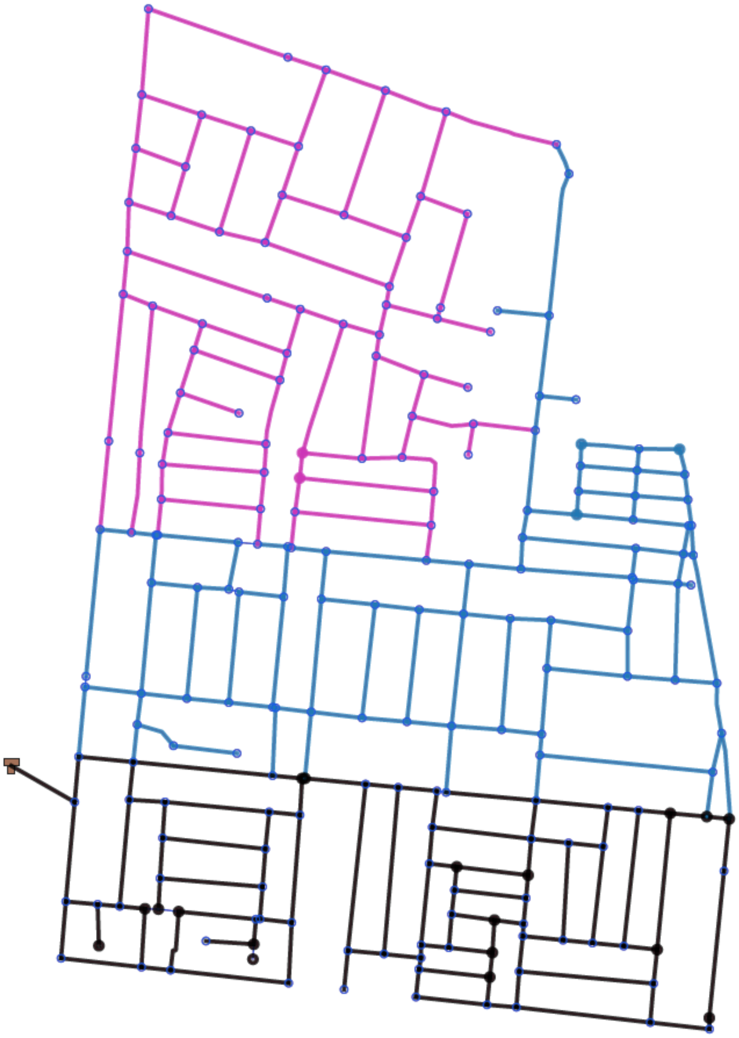

Figure 6.31 DMAs layout representing leftmost extreme point for Vanasthalipuram WDN (Black-DMA 1, Blue-DMA 2 and Purple-DMA 3)

Figure 6.32 DMAs layout representing rightmost extreme point for Vanasthalipuram WDN (Black-DMA 1, Red-DMA 2, Blue-DMA 3, Brown-DMA 4, Purple-DMA 5, Orange-DMA 6 and Green-DMA 7)

The next chapter presents the summary and conclusions inferred from the above studies.

SUMMARY

Water distribution networks are one of the major essential public infrastructures designed to meet the daily water requirements of a community. Dividing a water distribution network into subsystems named as district metered areas can improve the efficiency and ease of achieving management goals. Properly designed and maintained DMAs can help water utilities reduce water losses, improve system efficiency and enhance the overall reliability of their distribution networks. Determining an optimal design based on multiple objectives such as cost, resilience, equitable water distribution and identifying the most suitable layout for DMAs of a water distribution network poses a complex challenge for engineers, as it consists simultaneous consideration of multiple interconnected factors. This research study explores the optimal design of a WDN in a multiobjective framework and identifying optimal DMA design of a WDN using metaheuristic algorithms. The proposed methodology has been tested on three benchmark WDNs and two real-life WDNs located in Telangana, India.

In this study, three distinct scenarios have been considered. The first two scenarios determine the optimal WDN design based on different objectives for continuous and intermittent water supply. The hydraulic simulation of the WDN has been carried out using the widely used EPANET 2.2 software. In the first scenario, two objectives, namely, network cost and network resilience have been considered for continuous and intermittent water supply. The formulated mathematical model is applied to the three benchmark WDN problems (New York WDN, Hanoi WDN and BIN) and later this is also applied to two real-life WDNs located in Telangana, India (Pamapur WDN and Vanasthalipuram WDN) to ensure practical relevance of the proposed methodology using MOPSOA, SAMOCSA and RLNSGA-II. The results of New York WDN, Hanoi WDN and BIN for continuous water supply are compared with the solutions of Wang *et al.* (2015) to test the efficacy of the developed optimization algorithms. In the second scenario, the focus extends beyond cost and resilience to include the critical consideration of network equity, aiming to ensure a fair and equitable distribution of water. This expanded set of objectives is examined in the context of two real-life WDNs for intermittent water supply using RLNSGA-II algorithm. The third scenario focuses on determining the optimal design of DMAs considering three

objectives for the optimization model. The initial clusters have been identified using Fast Newman algorithm. The objectives considered are minimizing Network Cost, maximizing Network Resilience and maximizing Network Equity. In this scenario, the proposed methodology has been applied on Pamapur WDN and Vanasthalipuram WDN to determine the optimal number of DMAs. The following conclusions are drawn from the three scenarios of the research study.

Scenario 1

- ✓ The results obtained by MOPSOA, SAMOSCA, RLNSGA-II optimization algorithms for CWS scenario in New York WDN, Hanoi WDN and BIN are compared with Wang *et al.* (2015). It is observed that the three optimization algorithms have converged to more pareto front points for all the three benchmark WDNs in comparison with Wang *et al.* (2015). In summary, the results highlight that MOPSOA, SAMOCSA and RLNSGA-II demonstrated better performance when compared to Wang *et al.* (2015) with respect to the total number of points in the pareto front, capturing the extreme points and hypervolume for all the three benchmark WDNs. For BIN, the optimal solutions obtained from the three optimization algorithms would save a substantial cost to achieve the same resilience for the network.
- ✓ Normally, the complexity of any problem increases with the dimensionality of the problem. The optimization algorithms developed in this research work have proved to be very good for solving large WDNs. The application of the three optimization algorithms to the multiobjective optimization of WDNs maintains the balance between exploration and exploitation. This characteristic of these algorithms enhances the search mechanism in maintaining population diversity and exploring larger areas to discover newer solutions that converge to better quality optimal solutions.
- ✓ The results show that the pareto front obtained by MOPSOA, SAMOSCA and RLNSGA-II have converged to the same solution for all the five WDNs for IWS scenario. Results for these WDNs for IWS have not been compared with any other published literature as they are not available.
- ✓ The hydraulic parameters of the WDN representing the extreme points in the pareto front for CWS and IWS have been compared for all five WDNs. It is observed that the network

cost, network resilience, pipe velocity and nodal pressure for the extreme points is higher for the WDN design in IWS scenario. The variation in the pipe velocity and nodal pressure for CWS and IWS scenarios for WDN design representing the extreme points are similar for larger WDNs. For the rightmost extreme point in all WDNs, the network cost remains the same for CWS and IWS scenario. For larger networks, the network cost is around 11 to 19% higher in IWS scenario as compared to CWS scenario for leftmost extreme point. Similarly, the network resilience is around 16% higher for leftmost extreme point and around 6-11% higher for rightmost extreme point in all real-life WDNs.

- ✓ The pareto front for Pamapur WDN (CWS scenario) shows that the least-cost design (with a cost of 1.3043 million rupees) has an associated network resilience of 0.4061. The network resilience can be significantly improved to more than 200% i.e. 0.8877 with a network cost of 3.4988 million rupees. In addition, there are also a number of good trade-off design options available to the engineers to choose from the pareto-front. It is observed from the pareto front for IWS scenario that the least-cost design (with a cost of 1.5543 million rupees) has an associated network resilience of 0.4761. The network resilience can be significantly improved to more than 200% i.e. 0.9450 with a network cost of 3.4988 million rupees.
- ✓ It is observed from the pareto front for Vanasthalipuram WDN (CWS scenario) that the least-cost design (with a cost of 3.0952 million rupees) has an associated network resilience of 0.3541. The network resilience could be increased to a maximum of around 39% i.e. 0.4913 with a network cost increase of 87% (5.7930 million rupees). For IWS scenario, the least-cost design (with a cost of 3.4452 million rupees) has an associated network resilience of 0.4111. The network resilience could be increased to a maximum of around 32% i.e. 0.5443 with a network cost increase of 68% (5.7930 million rupees).

Scenario 2

- ✓ Pamapur WDN: It is observed that most of the non-dominated solutions on the pareto front from scenario 1 and scenario 2 are coinciding. It is also observed that there is a 12% increase in network resilience for the leftmost extreme point in scenario 2 for a 1.2% increase in the network cost. Similarly, there is a marginal increase of 0.7% in the network equity in scenario 2 when compared to the results obtained in scenario 1 for leftmost extreme point. For the rightmost point, the network resilience has an equivalent value for a slightly lower network cost (around 2.5% lesser). The network equity is around 1.5% lower for a 2.5% reduced network cost in scenario 2 as compared to scenario 1.

- ✓ Pampaur WDN: It is observed that 107 pipe diameters of the optimal WDN design for the leftmost extreme point in scenario 1 and scenario 2 are same. Fifteen diameters (that are different in both the scenarios) are of higher diameter in scenario 2. The pipe velocity is similar in both the scenarios, however, the nodal pressure around 8% higher in scenario 2. For the rightmost extreme point, 114 pipe diameters are the same in the optimal WDN design from scenario 1 and scenario 2. It is observed that the pipe diameter values in the remaining eight pipes are lower in scenario 2. In this case too, the pipe velocity is similar in both the scenarios, however, the nodal pressure is around 4% higher in scenario 2.
- ✓ Vanasthalipuram WDN: It is observed that most of the non-dominated solutions on the pareto front on the upper middle portion provide better network resilience for a lower network cost. Similarly, it is observed that all the points on the pareto front represent a better performance in terms of network equity for a lower cost when compared to the results obtained in scenario 1. Around 4% increase in network resilience for the leftmost extreme point in scenario 2 is observed for a 3.5% increase in the network cost. Similarly, there is an increase of 6% in the network equity in scenario 2 when compared to the results obtained in scenario 1 for leftmost extreme point. For the rightmost point, the network resilience has an equivalent value for a slightly lower network cost (around 2.1% lesser). The network equity is around 0.7% lower for an 18% reduced network cost in scenario 2 as compared to scenario 1.
- ✓ Vanasthalipuram WDN: It is observed that 276 out of 301 pipe diameters of the optimal WDN design for the leftmost extreme point in scenario 1 and scenario 2 are same. Twenty five diameters (that are different in both the scenarios) are of higher diameter in scenario 2. The pipe velocity is around 6.4% higher and the nodal pressure is around 8% higher in scenario 2. For the rightmost extreme point, 263 pipe diameters are the same in the optimal WDN design from scenario 1 and scenario 2. It is observed that the pipe diameter values in the remaining 38 pipes are lower in scenario 2. In this case too, the

pipe velocity is around 6% higher and the nodal pressure is around 7% higher in scenario 2.

Scenario 3

- ✓ Pampaur WDN: It can be observed that the network cost varies from Rs.9.55 lakhs to Rs.48.71 lakhs for DMAs that vary between 3 to 5. Five different combinations of DMAs have been found for 3 and 5 numbers of DMAs. The number of valves and flow meters varies from 12 to 21 and 6 to 10 respectively for the different DMAs obtained in the pareto front. The network resilience increases from 0.45 to 0.55 (around 22% increase) and network equity increases from 0.9150 to 0.9750 (around 7% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front.
- ✓ Pampaur WDN: The average pressure in each DMA is slightly lower after partitioning for both the extreme points. The average pressure in DMA 3 is around 3% lower after partitioning for the leftmost point and it is around 3% lower in DMA 3 after partitioning for the rightmost point. It can be observed that the DMA 3 in leftmost and rightmost points have the maximum pipe length compared to the other DMAs. The total water supply for each DMA is slightly lower after partitioning for both the points.
- ✓ Vanasthalipuram WDN: It can be observed that the network cost varies from Rs.11.12 lakhs to Rs.55.08 lakhs for DMAs that vary between 3 to 7. Ten different combinations of DMAs have been found for 5 numbers of DMAs. The number of valves and flow meters varies from 23 to 45 and 7 to 15 respectively for the different DMAs obtained in the pareto front. The network resilience marginally increases (around 2% increase) and network equity also marginally increases (around 2% increase) when compared between the DMA configuration of leftmost and rightmost point on the pareto front.
- ✓ Vanasthalipuram WDN: The average pressure in each DMA is slightly lower (below 2%) after partitioning for both the extreme points. The average pressure in DMA 3 is around 1.75% lower after partitioning for the leftmost point and it is around 1.86% lower in DMA 3 after partitioning for the rightmost point. It can be observed that DMA 3 in the rightmost point has the maximum pipe length compared to the other DMAs.

- ✓ The proposed methodology efficiently identifies DMAs while simultaneously addressing multiple objectives, including minimizing network cost, maximizing network resilience and enhancing network equity for real-life WDNs.

CONCLUSIONS

In summary, the proposed research methodologies can be applied to optimize the design and operation of WDNs, reducing both capital and operational expenditures. This involves selecting cost-effective materials, optimizing pump and valve operations, and minimizing energy consumption. Enhancing the resilience of WDNs ensures that they can handle disruptions, such as pipe bursts, supply interruptions, or natural disasters, without significant service degradation. The methodologies identify critical points in the network and suggest improvements to bolster overall system robustness. Equity in water distribution is crucial for ensuring that all users receive an adequate and consistent water supply. The methodologies consider factors such as pressure management and distribution efficiency to achieve a fair allocation of water. The proposed solutions from various research studies have certain challenges while these need to be implemented in the real-world. There are assumptions made while modeling and simulating WDN that do not reflect the true nature of real-world scenarios. In addition, the hydraulic simulation in an intermittent water supply system also posed a challenge while using hydraulic simulation software tools like EPANET 2.2. However, the solutions proposed from these methodologies can be effectively translated to real-world implementations with reasonable savings, enhanced resilience as well as equity in comparison with the traditional design approaches used by the engineers.

CONTRIBUTIONS FROM THE STUDY

- ✓ Three optimization algorithms (MOPSOA, SAMOCSA and RLNSGA-II) have been modified to enhance their search efficiency. They have consistently outperformed, when compared with the best algorithms available in literature, yielding better converged and distributed solutions for the three benchmark problems (New York WDN, Hanoi WDN and Balerma Irrigation Network). These algorithms surpass the best-known approximation solutions published in the literature, showcasing their effectiveness and robustness. It is particularly noteworthy to mention their exploration and exploitation capabilities of large search spaces for finding better optimal solutions i.e., their ability to achieve substantial cost savings as network complexity increases.
- ✓ First comprehensive study on the multiobjective design of WDNs considering three objectives, namely, minimizing Network Cost, maximizing Network Resilience and maximizing Network Equity for Pamapur and Vanasthalipuram WDNs located in Telangana, India.
- ✓ First comprehensive study on the identifying the DMAs of WDNs for Pamapur and Vanasthalipuram WDNs located in Telangana, India considering three objectives, namely, minimizing Network Cost, maximizing Network Resilience and maximizing Network Equity.

SCOPE FOR FURTHER WORK

- ✓ The optimal design of WDNs can focus on addressing design optimization under intermittent water supply while considering sustainability, uncertainty in water demand etc., in the mathematical model.
- ✓ Hybrid and hyper heuristic optimization algorithms can be developed to address the high computational time associated while solving with optimization techniques for their application to large-scale water distribution networks.
- ✓ A fuzzy optimization approach may be applied to determine the best possible WDN design that simplifies the decision-making of the design engineer/ manager. Also, the fuzzy multiobjective model can be further extended with fuzzification of the constraints to account for uncertainties in pipe roughness and nodal demands of larger WDN.
- ✓ WDN clustering could be done considering network parameters such as similarity in demand, pressure, length of pipes and number of nodes.
- ✓ More objectives such as average water age, leakage reduction and many more could be considered while determining the optimal DMAs of a WDN.
- ✓ Multicriteria decision making methods can be considered for determining the optimal WDN design/ DMA from a pareto optimal front.

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APPENDIX A

Table A.1 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point for BIN in CWS and IWS

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	14777.7	6.9969	1	79.9665	1	14777.7	9.4481	1	82.0915
2	14777.7	6.9820	2	79.7691	2	14777.7	9.4585	2	81.8941
3	14777.7	6.9723	3	79.6088	3	14777.7	9.4559	3	81.7338
4	14777.7	6.9397	4	79.5852	4	14777.7	9.4239	4	81.7102
5	14777.7	6.9335	5	79.5594	5	14777.7	9.4308	5	81.6844
6	14777.7	6.9305	6	79.4139	6	14777.7	9.4376	6	81.5389
7	14777.7	6.9276	7	79.3744	7	14777.7	9.4376	7	81.4994
8	14777.7	6.9166	8	79.2618	8	14777.7	9.4388	8	81.3868
9	14777.7	6.9064	9	79.0227	9	14777.7	9.4282	9	81.1477
10	14777.7	6.8970	10	78.9282	10	14777.7	9.4388	10	81.0532
11	14777.7	6.8938	11	78.7979	11	14777.7	9.4390	11	80.9229
12	14777.7	6.8236	12	78.7096	12	14777.7	9.3615	12	80.8346
13	14777.7	6.7865	13	78.6852	13	14777.7	9.3134	13	80.8102
14	14777.7	6.7443	14	78.6507	14	14777.7	9.2774	14	80.7757
15	14777.7	6.7416	15	78.6153	15	14777.7	9.2887	15	80.7403
16	14777.7	6.7207	16	78.5186	16	14777.7	9.2684	16	80.6436
17	14777.7	6.7054	17	78.2146	17	14777.7	9.2515	17	80.3396
18	14777.7	6.6876	18	78.1734	18	14777.7	9.2342	18	80.2984
19	14777.7	6.6580	19	78.1057	19	14777.7	9.1964	19	80.2307
20	14777.7	6.6349	20	78.0997	20	14777.7	9.1710	20	80.2247
21	14777.7	6.6144	21	78.0982	21	14777.7	9.1447	21	80.2232
22	14777.7	6.6064	22	77.9267	22	14777.7	9.1366	22	80.0517
23	14777.7	6.6026	23	77.8772	23	14777.7	9.1381	23	80.0022
24	14777.7	6.5957	24	77.8217	24	14777.7	9.1393	24	79.9467
25	14777.7	6.5872	25	77.8172	25	14777.7	9.1299	25	79.9422
26	14777.7	6.5777	26	77.7377	26	14777.7	9.1229	26	79.4877
27	14777.7	6.5699	27	77.6907	27	14777.7	9.1139	27	79.4407
28	14777.7	6.5475	28	77.3408	28	14777.7	9.0882	28	79.0908
29	14777.7	6.5421	29	77.0909	29	14777.7	9.0837	29	78.8409
30	14777.7	6.5266	30	77.0168	30	14777.7	9.0907	30	78.7668
31	14777.7	6.4828	31	76.9158	31	14777.7	9.0353	31	78.6658
32	14777.7	6.4728	32	76.8838	32	14777.7	9.0256	32	78.6338
33	14777.7	6.4634	33	76.8060	33	14777.7	9.0256	33	78.556
34	14777.7	6.4309	34	76.6796	34	14777.7	8.9938	34	78.4296

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^{6} and Network Resilience=0.3498)					Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^{6} and Network Resilience=0.3667)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
35	14777.7	6.4308	35	76.6234	35	14777.7	8.9983	35	78.3734
36	14777.7	6.4051	36	76.4742	36	14777.7	8.9677	36	78.2242
37	14777.7	6.3909	37	76.3836	37	14777.7	8.9584	37	78.1336
38	14777.7	6.3831	38	76.3744	38	14777.7	8.9492	38	78.1244
39	14777.7	6.3697	39	76.3147	39	14777.7	8.9374	39	78.0647
40	14777.7	6.3663	40	76.2929	40	14777.7	8.9379	40	78.0429
41	11485.9	6.3575	41	76.0395	41	14777.7	8.9258	41	77.7895
42	11485.9	6.3445	42	75.8940	42	14777.7	8.9134	42	77.644
43	11485.9	6.3429	43	75.8649	43	14777.7	8.9143	43	77.6149
44	11485.9	6.2741	44	75.7883	44	14777.7	8.8215	44	77.5383
45	11485.9	6.2436	45	75.7094	45	14777.7	8.7979	45	77.4594
46	11485.9	6.2267	46	75.4263	46	14777.7	8.7743	46	77.1763
47	11485.9	6.2016	47	75.2361	47	11485.9	8.7451	47	76.9861
48	11485.9	6.2005	48	75.2333	48	11485.9	8.7450	48	76.9833
49	11485.9	6.1926	49	75.1832	49	11485.9	8.7378	49	76.9332
50	11485.9	6.1763	50	75.0674	50	11485.9	8.7234	50	76.8174
51	11485.9	6.1626	51	74.9188	51	11485.9	8.7071	51	76.6688
52	11485.9	6.1536	52	74.8740	52	11485.9	8.6945	52	76.624
53	11485.9	6.1246	53	74.6417	53	11485.9	8.6567	53	76.3917
54	11485.9	6.1180	54	74.6134	54	11485.9	8.6481	54	76.3634
55	11485.9	6.1136	55	74.5062	55	11485.9	8.6525	55	76.2562
56	11485.9	6.1043	56	74.5018	56	11485.9	8.6406	56	76.2518
57	11485.9	6.0711	57	74.3818	57	11485.9	8.5957	57	76.1318
58	11485.9	6.0691	58	74.2194	58	11485.9	8.5952	58	75.9694
59	11485.9	6.0532	59	74.0033	59	11485.9	8.5776	59	75.7533
60	11485.9	6.0494	60	73.8787	60	11485.9	8.5742	60	75.6287
61	11485.9	5.9945	61	73.6118	61	11485.9	8.5152	61	75.3618
62	11485.9	5.9549	62	73.5451	62	11485.9	8.4612	62	75.2951
63	11485.9	5.9414	63	73.2311	63	11485.9	8.4494	63	74.9811
64	11485.9	5.9092	64	73.1029	64	11485.9	8.4060	64	74.8529
65	11485.9	5.8968	65	73.0049	65	11485.9	8.3962	65	74.7549
66	11485.9	5.8924	66	72.9176	66	11485.9	8.3929	66	74.6676
67	11485.9	5.8872	67	72.8584	67	11485.9	8.3889	67	74.6084
68	11485.9	5.8787	68	72.4861	68	11485.9	8.3783	68	74.2361
69	11485.9	5.8552	69	72.4298	69	11485.9	8.3490	69	74.1798
70	11485.9	5.8267	70	72.3955	70	11485.9	8.3131	70	74.1455
71	11485.9	5.8081	71	72.3355	71	11485.9	8.2945	71	74.0855
72	11485.9	5.8034	72	72.2000	72	11485.9	8.2944	72	73.95
73	11485.9	5.7938	73	72.0543	73	11485.9	8.2872	73	73.8043
74	11485.9	5.7901	74	71.9203	74	11485.9	8.2826	74	73.6703

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
75	11485.9	5.7870	75	71.8920	75	11485.9	8.2788	75	73.642
76	11485.9	5.7679	76	71.6864	76	11485.9	8.2584	76	73.4364
77	11485.9	5.7362	77	71.6167	77	11485.9	8.2327	77	73.3667
78	11485.9	5.7344	78	71.5921	78	11485.9	8.2302	78	73.3421
79	11485.9	5.7134	79	71.4957	79	11485.9	8.2004	79	73.2457
80	11485.9	5.7066	80	71.4781	80	11485.9	8.2055	80	73.2281
81	11485.9	5.6916	81	71.4528	81	11485.9	8.1877	81	73.2028
82	11485.9	5.6883	82	71.3989	82	11485.9	8.1974	82	73.1489
83	11485.9	5.6811	83	71.3605	83	11485.9	8.1930	83	73.1105
84	11485.9	5.6634	84	71.3571	84	11485.9	8.1702	84	73.1071
85	11485.9	5.6363	85	71.3225	85	11485.9	8.1324	85	73.0725
86	11485.9	5.6316	86	71.2039	86	11485.9	8.1471	86	72.9539
87	11485.9	5.6142	87	71.1197	87	11485.9	8.1299	87	72.8697
88	9189.7	5.6137	88	71.1163	88	11485.9	8.1295	88	72.8663
89	9189.7	5.6040	89	71.1091	89	11485.9	8.1242	89	72.8591
90	9189.7	5.5837	90	71.0721	90	11485.9	8.0957	90	72.8221
91	9189.7	5.5834	91	70.8428	91	11485.9	8.0979	91	72.5928
92	9189.7	5.5686	92	70.5147	92	11485.9	8.0797	92	72.2647
93	9189.7	5.5560	93	70.2702	93	11485.9	8.0687	93	72.0202
94	9189.7	5.5487	94	70.0538	94	11485.9	8.0734	94	71.8038
95	9189.7	5.5486	95	70.0261	95	11485.9	8.0754	95	71.7761
96	9189.7	5.5117	96	70.0234	96	11485.9	8.0265	96	71.7734
97	9189.7	5.4948	97	69.9243	97	11485.9	8.0035	97	71.6743
98	9189.7	5.4917	98	69.9185	98	11485.9	8.0007	98	71.6685
99	9189.7	5.4779	99	69.8312	99	11485.9	7.9892	99	71.5812
100	9189.7	5.4751	100	69.8129	100	11485.9	7.9965	100	71.5629
101	9189.7	5.4733	101	69.8123	101	11485.9	7.9946	101	71.5623
102	9189.7	5.4621	102	69.8090	102	11485.9	7.9882	102	71.559
103	9189.7	5.4553	103	69.7977	103	11485.9	7.9835	103	71.5477
104	9189.7	5.4475	104	69.6291	104	11485.9	7.9742	104	71.3791
105	9189.7	5.4439	105	69.5023	105	11485.9	7.9781	105	71.2523
106	9189.7	5.4402	106	69.4446	106	9189.7	7.9848	106	71.1946
107	9189.7	5.4318	107	69.2427	107	9189.7	7.9739	107	70.9927
108	9189.7	5.4270	108	69.1633	108	9189.7	7.9682	108	70.9133
109	9189.7	5.4176	109	69.1275	109	9189.7	7.9634	109	70.8775
110	9189.7	5.4097	110	69.0861	110	9189.7	7.9702	110	70.8361
111	9189.7	5.4060	111	69.0687	111	9189.7	7.9653	111	70.8187
112	9189.7	5.4054	112	68.7514	112	9189.7	7.9653	112	70.5014
113	9189.7	5.3785	113	68.4798	113	9189.7	7.9259	113	70.2298
114	9189.7	5.3783	114	68.1631	114	9189.7	7.9333	114	69.9131

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
115	9189.7	5.3720	115	67.8942	115	9189.7	7.9256	115	69.6442
116	9189.7	5.3547	116	67.8438	116	9189.7	7.9016	116	69.5938
117	9189.7	5.3390	117	67.7957	117	9189.7	7.8869	117	69.5457
118	9189.7	5.3375	118	67.7610	118	9189.7	7.8851	118	69.511
119	9189.7	5.3363	119	67.7268	119	9189.7	7.8848	119	69.4768
120	9189.7	5.2913	120	67.6868	120	9189.7	7.8290	120	69.4368
121	9189.7	5.2435	121	67.5847	121	9189.7	7.7632	121	69.3347
122	9189.7	5.2415	122	67.4254	122	9189.7	7.7810	122	69.1754
123	9189.7	5.2403	123	67.3767	123	9189.7	7.7908	123	69.1267
124	9189.7	5.2193	124	67.3598	124	9189.7	7.7622	124	69.1098
125	9189.7	5.2162	125	67.3053	125	9189.7	7.7585	125	69.0553
126	9189.7	5.1800	126	67.2937	126	9189.7	7.7228	126	69.0437
127	9189.7	5.1786	127	67.2434	127	9189.7	7.7287	127	68.9934
128	9189.7	5.1710	128	67.1235	128	9189.7	7.7269	128	68.8735
129	9189.7	5.1685	129	67.0453	129	9189.7	7.7295	129	68.7953
130	7239.0	5.1552	130	67.0183	130	9189.7	7.7227	130	68.7683
131	7239.0	5.1132	131	66.6871	131	9189.7	7.6730	131	68.4371
132	7239.0	5.1102	132	66.5704	132	9189.7	7.6818	132	68.3204
133	7239.0	5.1046	133	66.4222	133	9189.7	7.6802	133	68.1722
134	7239.0	5.1023	134	66.3315	134	9189.7	7.6773	134	68.0815
135	7239.0	5.0894	135	66.1451	135	9189.7	7.6834	135	67.8951
136	7239.0	5.0784	136	66.0172	136	9189.7	7.6794	136	67.7672
137	7239.0	5.0523	137	65.1260	137	9189.7	7.6400	137	66.876
138	7239.0	5.0398	138	65.1118	138	9189.7	7.6290	138	66.8618
139	7239.0	5.0272	139	65.0425	139	9189.7	7.6369	139	66.7925
140	7239.0	5.0075	140	65.0412	140	9189.7	7.6250	140	66.7912
141	7239.0	4.9985	141	64.9567	141	9189.7	7.6116	141	66.7067
142	7239.0	4.9959	142	64.9127	142	9189.7	7.6143	142	66.6627
143	7239.0	4.9768	143	64.9100	143	9189.7	7.5894	143	66.66
144	7239.0	4.9657	144	64.8157	144	7239.0	7.5795	144	66.5657
145	7239.0	4.9637	145	64.7175	145	7239.0	7.5768	145	66.4675
146	7239.0	4.9334	146	64.6922	146	7239.0	7.5308	146	66.4422
147	7239.0	4.9330	147	64.6409	147	7239.0	7.5343	147	66.3909
148	7239.0	4.9229	148	64.5596	148	7239.0	7.5242	148	66.3096
149	7239.0	4.9222	149	64.4819	149	7239.0	7.5258	149	66.2319
150	7239.0	4.9221	150	64.1594	150	7239.0	7.5286	150	65.9094
151	7239.0	4.9147	151	64.0739	151	7239.0	7.5193	151	65.8239
152	7239.0	4.8892	152	64.0283	152	7239.0	7.4843	152	65.7783
153	7239.0	4.8524	153	63.7931	153	7239.0	7.4456	153	65.5431
154	7239.0	4.8516	154	63.7688	154	9189.7	7.4621	154	65.5188

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
155	7239.0	4.8443	155	63.1258	155	9189.7	7.4577	155	64.8758
156	7239.0	4.8419	156	63.0888	156	9189.7	7.4558	156	64.8388
157	7239.0	4.8407	157	62.9428	157	9189.7	7.4569	157	64.6928
158	7239.0	4.8140	158	62.8347	158	9189.7	7.4159	158	64.5847
159	7239.0	4.8112	159	62.7441	159	9189.7	7.4117	159	64.4941
160	7239.0	4.7906	160	62.6582	160	9189.7	7.3829	160	64.4082
161	7239.0	4.7871	161	62.6260	161	9189.7	7.3985	161	64.376
162	7239.0	4.7864	162	62.5999	162	9189.7	7.4024	162	64.3499
163	7239.0	4.7793	163	62.5635	163	9189.7	7.3950	163	64.3135
164	7239.0	4.7641	164	62.5406	164	9189.7	7.3772	164	64.2906
165	7239.0	4.7558	165	62.5265	165	9189.7	7.3644	165	64.2765
166	7239.0	4.7350	166	62.5254	166	9189.7	7.3357	166	64.2754
167	7239.0	4.7258	167	62.1849	167	9189.7	7.3238	167	63.9349
168	7239.0	4.7240	168	61.9516	168	7239.0	7.3279	168	63.7016
169	7239.0	4.7037	169	61.8576	169	7239.0	7.2978	169	63.6076
170	5745.5	4.6883	170	61.7942	170	7239.0	7.2788	170	63.5442
171	5745.5	4.6754	171	61.5965	171	7239.0	7.2602	171	63.3465
172	5745.5	4.6591	172	61.5103	172	7239.0	7.2623	172	63.2603
173	5745.5	4.6472	173	61.4725	173	7239.0	7.2518	173	63.2225
174	5745.5	4.6299	174	61.3295	174	7239.0	7.2368	174	63.0795
175	5745.5	4.6212	175	61.1401	175	7239.0	7.2357	175	62.8901
176	5745.5	4.6208	176	61.1162	176	7239.0	7.2352	176	62.8662
177	5745.5	4.5876	177	60.9908	177	7239.0	7.1909	177	62.7408
178	5745.5	4.5849	178	60.9046	178	9189.7	7.1977	178	62.6546
179	5745.5	4.5833	179	60.8925	179	9189.7	7.1984	179	62.6425
180	5745.5	4.5159	180	60.7644	180	9189.7	7.0969	180	62.5144
181	5745.5	4.4991	181	60.7370	181	9189.7	7.0926	181	62.487
182	5745.5	4.4967	182	60.5154	182	9189.7	7.0995	182	62.2654
183	5745.5	4.4887	183	60.4901	183	9189.7	7.1026	183	62.2401
184	5745.5	4.4805	184	60.1648	184	9189.7	7.0925	184	61.9148
185	5745.5	4.4644	185	60.1578	185	9189.7	7.0736	185	61.9078
186	5745.5	4.4530	186	60.0990	186	9189.7	7.0567	186	61.849
187	5745.5	4.4480	187	60.0419	187	9189.7	7.0616	187	61.7919
188	5745.5	4.4423	188	59.9940	188	9189.7	7.0539	188	61.744
189	5745.5	4.4262	189	59.9719	189	9189.7	7.0291	189	61.7219
190	5745.5	4.3899	190	59.9314	190	9189.7	6.9715	190	61.6814
191	5745.5	4.3712	191	59.6914	191	9189.7	6.9465	191	61.4414
192	5745.5	4.3634	192	59.6333	192	7239.0	6.9348	192	61.3833
193	5745.5	4.3542	193	59.5792	193	7239.0	6.9289	193	61.3292
194	5745.5	4.3499	194	59.4181	194	7239.0	6.9226	194	61.1681

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
195	5745.5	4.3467	195	59.2522	195	7239.0	6.9252	195	61.0022
196	5745.5	4.3400	196	59.2262	196	7239.0	6.9187	196	60.9762
197	5745.5	4.3344	197	59.1566	197	7239.0	6.9295	197	60.9066
198	5745.5	4.3137	198	59.0746	198	7239.0	6.8979	198	60.8246
199	5745.5	4.3107	199	59.0547	199	7239.0	6.8980	199	60.8047
200	5745.5	4.2972	200	58.9942	200	7239.0	6.8817	200	60.7442
201	5745.5	4.2787	201	58.6732	201	7239.0	6.8613	201	60.4232
202	5745.5	4.2453	202	58.6486	202	7239.0	6.8089	202	60.3986
203	5745.5	4.2399	203	58.6120	203	7239.0	6.8033	203	60.362
204	5745.5	4.2316	204	58.5915	204	7239.0	6.7900	204	60.3415
205	5745.5	4.2148	205	58.5341	205	7239.0	6.7758	205	60.2841
206	5745.5	4.2140	206	58.3572	206	7239.0	6.7750	206	60.1072
207	5745.5	4.2026	207	57.9739	207	7239.0	6.7576	207	59.7239
208	5745.5	4.1873	208	57.9059	208	7239.0	6.7394	208	59.6559
209	5745.5	4.1852	209	57.8499	209	7239.0	6.7365	209	59.5999
210	5745.5	4.1838	210	57.6286	210	7239.0	6.7492	210	59.3786
211	5745.5	4.1803	211	57.5570	211	7239.0	6.7471	211	59.307
212	5745.5	4.1661	212	57.5405	212	7239.0	6.7284	212	59.2905
213	5745.5	4.1566	213	57.3201	213	7239.0	6.7145	213	59.0701
214	5745.5	4.1503	214	57.1650	214	7239.0	6.7084	214	58.915
215	5745.5	4.1313	215	57.1640	215	7239.0	6.6808	215	58.914
216	5745.5	4.0993	216	57.0439	216	7239.0	6.6312	216	58.7939
217	5745.5	4.0803	217	57.0102	217	7239.0	6.6143	217	58.7602
218	5745.5	4.0338	218	56.9373	218	7239.0	6.5411	218	58.6873
219	5745.5	4.0326	219	56.9301	219	7239.0	6.5474	219	58.6801
220	5745.5	3.9947	220	56.9263	220	7239.0	6.4903	220	58.6763
221	5745.5	3.9886	221	56.6582	221	7239.0	6.4932	221	58.4082
222	5745.5	3.9711	222	56.4461	222	7239.0	6.4685	222	58.1961
223	5745.5	3.9700	223	56.4280	223	7239.0	6.4721	223	58.178
224	4592.3	3.9421	224	56.3941	224	7239.0	6.4300	224	58.1441
225	4592.3	3.9374	225	56.1657	225	7239.0	6.4484	225	57.9157
226	4592.3	3.9256	226	56.1515	226	7239.0	6.4403	226	57.9015
227	4592.3	3.9114	227	56.0795	227	7239.0	6.4173	227	57.8295
228	4592.3	3.9069	228	56.0095	228	7239.0	6.4117	228	57.7595
229	4592.3	3.9058	229	55.9858	229	7239.0	6.4155	229	57.7358
230	4592.3	3.8771	230	55.8135	230	7239.0	6.3730	230	57.5635
231	4592.3	3.8108	231	55.7883	231	7239.0	6.2658	231	57.5383
232	4592.3	3.8024	232	55.6907	232	7239.0	6.2626	232	57.4407
233	4592.3	3.7890	233	55.4920	233	7239.0	6.2410	233	57.242
234	4592.3	3.7796	234	55.3397	234	7239.0	6.2320	234	57.0897

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
235	4592.3	3.7473	235	55.1100	235	7239.0	6.1811	235	56.86
236	4592.3	3.7363	236	55.0851	236	7239.0	6.1771	236	56.8351
237	4592.3	3.7156	237	55.0249	237	7239.0	6.1432	237	56.7749
238	4592.3	3.7104	238	54.9824	238	7239.0	6.1520	238	56.7324
239	4592.3	3.7098	239	54.9114	239	7239.0	6.1533	239	56.6614
240	4592.3	3.6762	240	54.6319	240	7239.0	6.1022	240	56.3819
241	4592.3	3.6711	241	54.2019	241	7239.0	6.1055	241	55.9519
242	4592.3	3.6638	242	54.1647	242	7239.0	6.1003	242	55.9147
243	4592.3	3.6503	243	53.7893	243	7239.0	6.0802	243	55.5393
244	4592.3	3.6402	244	53.3705	244	7239.0	6.0668	244	55.1205
245	4592.3	3.5959	245	53.3101	245	7239.0	5.9992	245	55.0601
246	4592.3	3.5949	246	53.2831	246	7239.0	5.9982	246	55.0331
247	4592.3	3.5774	247	52.9938	247	7239.0	5.9697	247	54.7438
248	4592.3	3.5761	248	52.9821	248	7239.0	5.9731	248	54.7321
249	4592.3	3.5460	249	52.8213	249	7239.0	5.9234	249	54.5713
250	4592.3	3.5387	250	52.5937	250	7239.0	5.9148	250	54.3437
251	4592.3	3.5359	251	52.5441	251	7239.0	5.9161	251	54.2941
252	4592.3	3.5267	252	52.4214	252	7239.0	5.9036	252	54.1714
253	4592.3	3.5143	253	52.3108	253	7239.0	5.8848	253	54.0608
254	4592.3	3.5022	254	52.2828	254	7239.0	5.8762	254	54.0328
255	4592.3	3.4906	255	52.2271	255	7239.0	5.8632	255	53.9771
256	4592.3	3.4871	256	52.2165	256	7239.0	5.8621	256	53.9665
257	4592.3	3.4319	257	52.0795	257	7239.0	5.7703	257	53.8295
258	4592.3	3.4143	258	51.9495	258	7239.0	5.7478	258	53.6995
259	4592.3	3.4131	259	51.8987	259	7239.0	5.7477	259	53.6487
260	4592.3	3.3933	260	51.5035	260	7239.0	5.7166	260	53.2535
261	4592.3	3.3915	261	51.4651	261	7239.0	5.7147	261	53.2151
262	4592.3	3.3808	262	51.3896	262	7239.0	5.6981	262	53.1396
263	4592.3	3.3791	263	51.3597	263	7239.0	5.6983	263	53.1097
264	4592.3	3.3760	264	51.0378	264	7239.0	5.6958	264	52.7878
265	4592.3	3.3446	265	50.7214	265	7239.0	5.6489	265	52.4714
266	4592.3	3.3296	266	50.4757	266	7239.0	5.6411	266	52.2257
267	4592.3	3.3235	267	50.3865	267	7239.0	5.6326	267	52.1365
268	4135.1	3.3032	268	50.3415	268	7239.0	5.6037	268	52.0915
269	4135.1	3.2998	269	50.3187	269	7239.0	5.6033	269	52.0687
270	4135.1	3.2881	270	50.1277	270	7239.0	5.5860	270	51.8777
271	4135.1	3.2414	271	50.1176	271	7239.0	5.5093	271	51.8676
272	4135.1	3.2222	272	50.1044	272	7239.0	5.4774	272	51.8544
273	4135.1	3.2152	273	50.0942	273	7239.0	5.4709	273	51.8442
274	4135.1	3.2059	274	49.9538	274	7239.0	5.4591	274	51.7038

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
275	4135.1	3.1986	275	49.8920	275	7239.0	5.4643	275	51.642
276	4135.1	3.1745	276	49.8209	276	7239.0	5.4236	276	51.5709
277	4135.1	3.1578	277	49.7683	277	7239.0	5.3960	277	51.5183
278	4135.1	3.1576	278	49.4564	278	7239.0	5.4061	278	51.2064
279	4135.1	3.1304	279	49.3096	279	7239.0	5.3597	279	51.0596
280	4135.1	3.1047	280	49.2283	280	7239.0	5.3183	280	50.9783
281	4135.1	3.0873	281	48.7736	281	7239.0	5.2938	281	50.5236
282	4135.1	3.0846	282	48.4175	282	7239.0	5.2930	282	50.1675
283	4135.1	3.0286	283	48.3643	283	7239.0	5.2017	283	50.1143
284	4135.1	3.0255	284	48.2516	284	7239.0	5.2003	284	50.0016
285	4135.1	3.0151	285	47.8252	285	7239.0	5.1932	285	49.5752
286	4135.1	3.0119	286	47.7704	286	7239.0	5.1882	286	49.5204
287	4135.1	2.9976	287	47.7253	287	7239.0	5.1664	287	49.4753
288	4135.1	2.9926	288	47.5007	288	7239.0	5.1639	288	49.2507
289	4135.1	2.9850	289	47.3341	289	7239.0	5.1578	289	49.0841
290	4135.1	2.9729	290	47.2654	290	7239.0	5.1391	290	49.0154
291	4135.1	2.9550	291	46.9993	291	7239.0	5.1084	291	48.7493
292	4135.1	2.9051	292	46.9066	292	7239.0	5.0231	292	48.6566
293	4135.1	2.9049	293	46.8906	293	7239.0	5.0287	293	48.6406
294	4135.1	2.9046	294	46.6834	294	7239.0	5.0290	294	48.4334
295	4135.1	2.8986	295	46.6714	295	7239.0	5.0267	295	48.4214
296	4135.1	2.8949	296	46.6059	296	7239.0	5.0209	296	48.3559
297	4135.1	2.8806	297	46.5101	297	7239.0	4.9983	297	48.2601
298	4135.1	2.8442	298	46.4521	298	7239.0	4.9354	298	48.2021
299	4135.1	2.8078	299	46.3194	299	7239.0	4.8826	299	48.0694
300	4135.1	2.7996	300	46.3122	300	7239.0	4.8755	300	48.0622
301	4135.1	2.7954	301	46.2903	301	7239.0	4.8701	301	48.0403
302	4135.1	2.7895	302	46.2827	302	7239.0	4.8599	302	48.0327
303	4135.1	2.7841	303	46.2649	303	7239.0	4.8507	303	48.0149
304	4135.1	2.7732	304	46.1593	304	7239.0	4.8345	304	47.9093
305	4135.1	2.7649	305	46.0512	305	7239.0	4.8202	305	47.8012
306	4135.1	2.7644	306	45.6193	306	7239.0	4.8282	306	47.3693
307	4135.1	2.7638	307	45.5738	307	7239.0	4.8303	307	47.3238
308	4135.1	2.7494	308	45.5461	308	5745.5	4.8104	308	47.2961
309	4135.1	2.7411	309	45.4685	309	5745.5	4.7965	309	47.2185
310	4135.1	2.7279	310	45.4575	310	5745.5	4.7758	310	47.2075
311	4135.1	2.7271	311	45.3248	311	5745.5	4.7798	311	47.0748
312	4135.1	2.6912	312	45.1926	312	5745.5	4.7170	312	46.9426
313	4135.1	2.6504	313	44.9700	313	5745.5	4.6488	313	46.72
314	4135.1	2.6376	314	44.8677	314	5745.5	4.6297	314	46.6177

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
315	4135.1	2.6218	315	44.7767	315	5745.5	4.6069	315	46.5267
316	3672.8	2.5971	316	44.7590	316	5745.5	4.5652	316	46.509
317	3672.8	2.5919	317	44.7151	317	5745.5	4.5590	317	46.4651
318	3672.8	2.5468	318	44.6684	318	5745.5	4.4829	318	46.4184
319	3672.8	2.5457	319	44.5231	319	5745.5	4.4816	319	46.2731
320	3672.8	2.5323	320	44.5093	320	5745.5	4.4595	320	46.2593
321	3672.8	2.5063	321	44.3542	321	5745.5	4.4143	321	46.1042
322	3672.8	2.4918	322	44.3009	322	5745.5	4.3993	322	46.0509
323	3672.8	2.4804	323	44.1798	323	5745.5	4.3825	323	45.9298
324	3672.8	2.4549	324	44.1364	324	5745.5	4.3381	324	45.8864
325	3672.8	2.4429	325	44.1103	325	5745.5	4.3187	325	45.8603
326	3672.8	2.4242	326	44.0910	326	5745.5	4.2861	326	45.841
327	3672.8	2.4090	327	43.9520	327	5745.5	4.2678	327	45.702
328	3672.8	2.3737	328	43.8806	328	5745.5	4.2061	328	45.6306
329	3672.8	2.3720	329	43.8173	329	5745.5	4.2080	329	45.5673
330	3672.8	2.3671	330	43.7716	330	5745.5	4.1995	330	45.5216
331	3672.8	2.3663	331	43.5416	331	5745.5	4.1986	331	45.2916
332	3672.8	2.3450	332	43.3874	332	5745.5	4.1721	332	45.1374
333	3672.8	2.3426	333	43.3597	333	5745.5	4.1784	333	45.1097
334	3672.8	2.3054	334	43.1482	334	5745.5	4.1122	334	44.8982
335	3672.8	2.2756	335	43.0312	335	5745.5	4.0670	335	44.7812
336	3672.8	2.2730	336	43.0256	336	5745.5	4.0637	336	44.7756
337	3672.8	2.2722	337	42.9947	337	5745.5	4.0623	337	44.7447
338	3672.8	2.2564	338	42.7714	338	5745.5	4.0404	338	44.5214
339	3672.8	2.2537	339	42.5042	339	5745.5	4.0363	339	44.2542
340	3672.8	2.2508	340	42.4475	340	5745.5	4.0328	340	44.1975
341	3672.8	2.2362	341	42.3035	341	5745.5	4.0088	341	44.0535
342	3672.8	2.2359	342	42.1824	342	5745.5	4.0093	342	43.9324
343	3672.8	2.2340	343	42.1302	343	5745.5	4.0079	343	43.8802
344	3672.8	2.2330	344	41.8934	344	5745.5	4.0068	344	43.6434
345	3672.8	2.1799	345	41.8440	345	5745.5	3.9125	345	43.594
346	3672.8	2.1775	346	41.7391	346	5745.5	3.9097	346	43.4891
347	3672.8	2.1551	347	41.7059	347	5745.5	3.8710	347	43.4559
348	3672.8	2.1383	348	41.6827	348	5745.5	3.8432	348	43.4327
349	3672.8	2.1344	349	41.6687	349	5745.5	3.8373	349	43.4187
350	3672.8	2.1248	350	41.6491	350	5745.5	3.8228	350	43.3991
351	3672.8	2.1066	351	41.5150	351	5745.5	3.7902	351	43.265
352	3672.8	2.1052	352	41.4851	352	5745.5	3.7882	352	43.2351
353	3672.8	2.1046	353	41.4801	353	5745.5	3.7907	353	43.2301
354	3672.8	2.0844	354	41.4216	354	5745.5	3.7583	354	43.1716

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
355	3672.8	2.0837	355	41.3905	355	5745.5	3.7608	355	43.1405
356	3672.8	2.0687	356	41.2534	356	5745.5	3.7337	356	43.0034
357	3672.8	2.0656	357	41.1731	357	5745.5	3.7297	357	42.9231
358	3672.8	2.0626	358	40.9841	358	5745.5	3.7269	358	42.7341
359	3672.8	2.0611	359	40.9642	359	5745.5	3.7272	359	42.7142
360	3672.8	2.0540	360	40.6830	360	5745.5	3.7144	360	42.433
361	3215.6	2.0501	361	40.6202	361	5745.5	3.7114	361	42.3702
362	3215.6	2.0226	362	40.3865	362	5745.5	3.6635	362	42.1365
363	3215.6	2.0095	363	40.3516	363	5745.5	3.6400	363	42.1016
364	3215.6	1.9988	364	40.1849	364	5745.5	3.6206	364	41.9349
365	3215.6	1.9972	365	40.1650	365	5745.5	3.6179	365	41.915
366	3215.6	1.9814	366	39.9963	366	5745.5	3.5926	366	41.7463
367	3215.6	1.9811	367	39.9368	367	5745.5	3.5929	367	41.6868
368	3215.6	1.9668	368	39.8639	368	5745.5	3.5724	368	41.6139
369	3215.6	1.9262	369	39.8102	369	5745.5	3.5021	369	41.5602
370	3215.6	1.9215	370	39.5451	370	5745.5	3.4950	370	41.2951
371	3215.6	1.9111	371	39.4046	371	5745.5	3.4765	371	41.1546
372	3215.6	1.8856	372	38.9957	372	5745.5	3.4331	372	40.7457
373	3215.6	1.8791	373	38.4345	373	5745.5	3.4225	373	40.1845
374	3215.6	1.8531	374	38.3780	374	5745.5	3.3791	374	40.128
375	3215.6	1.8522	375	38.3445	375	5745.5	3.3778	375	40.0945
376	3215.6	1.8522	376	38.1449	376	5745.5	3.3783	376	39.8949
377	3215.6	1.8058	377	37.9524	377	5745.5	3.2943	377	39.7024
378	3215.6	1.8047	378	37.7611	378	5745.5	3.2969	378	39.5111
379	3215.6	1.8036	379	37.5923	379	5745.5	3.2982	379	39.3423
380	3215.6	1.7925	380	37.4233	380	5745.5	3.2785	380	39.1733
381	3215.6	1.7809	381	37.3909	381	5745.5	3.2580	381	39.1409
382	3215.6	1.7673	382	37.2866	382	5745.5	3.2356	382	39.0366
383	3215.6	1.7590	383	36.8004	383	5745.5	3.2280	383	38.5504
384	3215.6	1.7520	384	36.7739	384	5745.5	3.2158	384	38.5239
385	3215.6	1.7492	385	36.5915	385	5745.5	3.2164	385	38.3415
386	3215.6	1.7436	386	36.5487	386	5745.5	3.2069	386	38.2987
387	3215.6	1.7385	387	36.4798	387	5745.5	3.1983	387	38.2298
388	3215.6	1.7252	388	36.2768	388	5745.5	3.1759	388	38.0268
389	3215.6	1.7211	389	36.1930	389	5745.5	3.1721	389	37.943
390	3215.6	1.7089	390	36.1750	390	5745.5	3.1515	390	37.925
391	3215.6	1.7050	391	36.0456	391	5745.5	3.1462	391	37.7956
392	3215.6	1.6737	392	35.8783	392	5745.5	3.0888	392	37.6283
393	3215.6	1.6621	393	35.7015	393	5745.5	3.0740	393	37.4515
394	3215.6	1.6585	394	35.6974	394	5745.5	3.0684	394	37.4474

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^{6} and Network Resilience=0.3498)					Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^{6} and Network Resilience=0.3667)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
395	3215.6	1.6549	395	35.6965	395	5745.5	3.0704	395	37.4465
396	3215.6	1.6529	396	35.6231	396	5745.5	3.0693	396	37.3731
397	3215.6	1.6355	397	35.5592	397	5745.5	3.0373	397	37.3092
398	3215.6	1.6343	398	35.4218	398	5745.5	3.0404	398	37.1718
399	3215.6	1.6291	399	35.4023	399	5745.5	3.0323	399	37.1523
400	3215.6	1.6289	400	35.2781	400	5745.5	3.0326	400	37.0281
401	3215.6	1.6241	401	35.2534	401	5745.5	3.0248	401	37.0034
402	3215.6	1.6100	402	35.2411	402	5745.5	3.0033	402	36.9911
403	3215.6	1.6036	403	34.7975	403	5745.5	2.9928	403	36.5475
404	3215.6	1.6013	404	34.7314	404	5745.5	2.9900	404	36.4814
405	3215.6	1.5916	405	34.7244	405	5745.5	2.9724	405	36.4744
406	3215.6	1.5911	406	34.6199	406	5745.5	2.9742	406	36.3699
407	3215.6	1.5602	407	34.5936	407	5745.5	2.9177	407	36.3436
408	3215.6	1.5541	408	34.5083	408	5745.5	2.9064	408	36.2583
409	3215.6	1.5490	409	34.2951	409	5745.5	2.9007	409	36.0451
410	3215.6	1.5393	410	34.2699	410	5745.5	2.8853	410	36.0199
411	2870.2	1.5312	411	33.6798	411	5745.5	2.8746	411	35.4298
412	2870.2	1.5250	412	33.6681	412	5745.5	2.8679	412	35.4181
413	2870.2	1.5225	413	33.5107	413	5745.5	2.8663	413	35.2607
414	2870.2	1.5200	414	33.4639	414	5745.5	2.8641	414	35.2139
415	2870.2	1.5174	415	33.4291	415	5745.5	2.8595	415	35.1791
416	2870.2	1.5009	416	33.4090	416	5745.5	2.8303	416	35.159
417	2870.2	1.4924	417	33.3080	417	5745.5	2.8157	417	35.058
418	2870.2	1.4852	418	32.9548	418	4135.1	2.8025	418	34.7048
419	2870.2	1.4641	419	32.9515	419	4135.1	2.7646	419	34.7015
420	2870.2	1.4440	420	32.8670	420	4135.1	2.7278	420	34.617
421	2870.2	1.4373	421	32.7976	421	4135.1	2.7173	421	34.5476
422	2870.2	1.4287	422	32.6989	422	4135.1	2.7047	422	34.4489
423	2870.2	1.3851	423	32.6096	423	4135.1	2.6222	423	34.3596
424	2870.2	1.3804	424	32.5718	424	3215.6	2.6191	424	34.3218
425	2870.2	1.3723	425	32.5657	425	3215.6	2.6050	425	34.3157
426	2870.2	1.3695	426	32.5323	426	3215.6	2.6058	426	34.2823
427	2870.2	1.3601	427	32.3894	427	3215.6	2.5899	427	34.1394
428	2870.2	1.3564	428	32.3539	428	3215.6	2.5867	428	34.1039
429	2870.2	1.3402	429	32.1127	429	3215.6	2.5568	429	33.8627
430	2870.2	1.3298	430	31.8213	430	3215.6	2.5383	430	33.5713
431	2870.2	1.3254	431	31.8057	431	3215.6	2.5310	431	33.5557
432	2870.2	1.3225	432	31.7712	432	3215.6	2.5264	432	33.5212
433	2870.2	1.3125	433	31.6036	433	2870.2	2.5077	433	33.3536
434	2870.2	1.3080	434	31.5135	434	2870.2	2.5001	434	33.2635

Leftmost Extreme Point-CWS (Network Cost=€1.9633 x10^6 and Network Resilience=0.3498)					**Leftmost Extreme Point-IWS (Network Cost=€2.1734 x10^6 and Network Resilience=0.3667)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
435	2870.2	1.2972	435	31.4666	435	2870.2	2.4822	435	33.2166
436	2870.2	1.2907	436	31.2575	436	2870.2	2.4727	436	33.0075
437	2870.2	1.2781	437	31.0309	437	2870.2	2.4524	437	32.7809
438	2870.2	1.2703	438	30.9882	438	2870.2	2.4385	438	32.7382
439	2870.2	1.2559	439	30.8586	439	2870.2	2.4120	439	32.6086
440	2870.2	1.2234	440	30.7181	440	2870.2	2.3515	440	32.4681
441	2870.2	1.2194	441	30.2917	441	2870.2	2.3463	441	32.0417
442	2870.2	1.1919	442	30.0329	442	2870.2	2.2989	442	31.7829
443	2870.2	1.1853	443	30.0171	443	2870.2	2.2905	443	31.7671
444	2870.2	1.1800	-	-	444	2870.2	2.2884	-	-
445	2870.2	1.1514	-	-	445	2870.2	2.2333	-	-
446	2870.2	1.1508	-	-	446	2870.2	2.2333	-	-
447	2870.2	1.1466	-	-	447	2870.2	2.2276	-	-
448	2870.2	1.1299	-	-	448	2870.2	2.1955	-	-
449	2870.2	1.1232	-	-	449	2870.2	2.1828	-	-
450	2870.2	1.1019	-	-	450	2870.2	2.1420	-	-
451	2870.2	1.0797	-	-	451	2870.2	2.0989	-	-
452	2870.2	1.0620	-	-	452	2870.2	2.0680	-	-
453	2870.2	1.0469	-	-	453	2870.2	2.0396	-	-
454	2870.2	1.0031	-	-	454	2870.2	1.9558	-	-

Table A.2 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Rightmost Extreme Point for BIN in CWS and IWS

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					**Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	14777.7	5.8769	1	81.7615	1	14777.7	7.9684	1	86.9786
2	14777.7	5.8620	2	81.5641	2	14777.7	7.9548	2	86.2318
3	14777.7	5.8523	3	81.4038	3	14777.7	7.9556	3	87.1363
4	14777.7	5.8197	4	81.3802	4	14777.7	7.9201	4	91.0389
5	14777.7	5.8135	5	81.3544	5	14777.7	7.9131	5	91.3517
6	14777.7	5.8105	6	81.2089	6	14777.7	7.9113	6	89.8147
7	14777.7	5.8076	7	81.1694	7	14777.7	7.9086	7	89.9369
8	14777.7	5.7966	8	81.0568	8	14777.7	7.9004	8	86.6003
9	14777.7	5.7864	9	80.8177	9	14777.7	7.8868	9	88.5830
10	14777.7	5.7770	10	80.7232	10	14777.7	7.8861	10	89.9943
11	14777.7	5.7738	11	80.5929	11	14777.7	7.8842	11	87.2263
12	14777.7	5.7036	12	80.5046	12	14777.7	7.8025	12	90.8957
13	14777.7	5.6665	13	80.4802	13	14777.7	7.7584	13	85.0837
14	14777.7	5.6243	14	80.4457	14	14777.7	7.7339	14	86.5335
15	14777.7	5.6216	15	80.4103	15	14777.7	7.7319	15	87.7206
16	14777.7	5.6007	16	80.3136	16	14777.7	7.7044	16	84.7187
17	14777.7	5.5854	17	80.0096	17	14777.7	7.6883	17	88.6550
18	14777.7	5.5676	18	79.9684	18	14777.7	7.6668	18	87.5274
19	14777.7	5.5380	19	79.9007	19	14777.7	7.6299	19	87.2794
20	14777.7	5.5149	20	79.8947	20	14777.7	7.6019	20	89.1943
21	14777.7	5.4944	21	79.8932	21	14777.7	7.5742	21	89.3766
22	14777.7	5.4864	22	79.7217	22	14777.7	7.5724	22	88.7400
23	14777.7	5.4826	23	79.6722	23	14777.7	7.5811	23	85.6816
24	14777.7	5.4757	24	79.6167	24	14777.7	7.5722	24	86.4778
25	14777.7	5.4672	25	79.6122	25	14777.7	7.5644	25	88.3837
26	14777.7	5.4577	26	79.5327	26	14777.7	7.5523	26	84.2083
27	14777.7	5.4499	27	79.4857	27	14777.7	7.5551	27	84.1578
28	14777.7	5.4275	28	79.1358	28	14777.7	7.5376	28	84.8012
29	14777.7	5.4221	29	78.8859	29	14777.7	7.5376	29	86.1411
30	14777.7	5.4066	30	78.8118	30	14777.7	7.5282	30	88.8849
31	14777.7	5.3628	31	78.7108	31	14777.7	7.4684	31	87.1197
32	14777.7	5.3528	32	78.6788	32	14777.7	7.4577	32	84.5757
33	14777.7	5.3434	33	78.601	33	14777.7	7.4639	33	84.3638
34	14777.7	5.3109	34	78.4746	34	14777.7	7.4329	34	87.7368
35	14777.7	5.3108	35	78.4184	35	14777.7	7.4369	35	88.0585
36	14777.7	5.2851	36	78.2692	36	14777.7	7.4021	36	86.1855
37	14777.7	5.2709	37	78.1786	37	14777.7	7.3911	37	83.6847

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
38	14777.7	5.2631	38	78.1694	38	14777.7	7.3816	38	82.6323
39	14777.7	5.2497	39	78.1097	39	14777.7	7.3840	39	87.2533
40	14777.7	5.2463	40	78.0879	40	14777.7	7.3828	40	85.6451
41	14777.7	5.2375	41	77.8345	41	14777.7	7.3777	41	87.6299
42	14777.7	5.2245	42	77.689	42	14777.7	7.3637	42	81.9528
43	14777.7	5.2229	43	77.6599	43	14777.7	7.3614	43	85.1751
44	14777.7	5.1541	44	77.5833	44	14777.7	7.2720	44	83.2320
45	14777.7	5.1236	45	77.5044	45	14777.7	7.2456	45	86.5119
46	14777.7	5.1067	46	77.2213	46	14777.7	7.2246	46	82.2622
47	14777.7	5.0816	47	77.0311	47	14777.7	7.1895	47	83.6097
48	14777.7	5.0805	48	77.0283	48	14777.7	7.1920	48	83.3040
49	14777.7	5.0726	49	76.9782	49	14777.7	7.2043	49	85.9174
50	14777.7	5.0563	50	76.8624	50	14777.7	7.1950	50	84.8676
51	14777.7	5.0426	51	76.7138	51	14777.7	7.1768	51	81.8236
52	14777.7	5.0336	52	76.669	52	14777.7	7.1644	52	82.4536
53	14777.7	5.0046	53	76.4367	53	14777.7	7.1250	53	81.0768
54	14777.7	4.9980	54	76.4084	54	14777.7	7.1215	54	84.3333
55	14777.7	4.9936	55	76.3012	55	14777.7	7.1178	55	83.6016
56	14777.7	4.9843	56	76.2968	56	14777.7	7.1280	56	81.1479
57	14777.7	4.9511	57	76.1768	57	14777.7	7.0830	57	80.8855
58	14777.7	4.9491	58	76.0144	58	14777.7	7.0898	58	82.7102
59	14777.7	4.9332	59	75.7983	59	14777.7	7.0676	59	85.0948
60	14777.7	4.9294	60	75.6737	60	14777.7	7.0624	60	82.8002
61	14777.7	4.8745	61	75.4068	61	14777.7	6.9860	61	79.3759
62	14777.7	4.8349	62	75.3401	62	14777.7	6.9295	62	79.4317
63	14777.7	4.8214	63	75.0261	63	14777.7	6.9231	63	83.6095
64	14777.7	4.7892	64	74.8979	64	14777.7	6.8865	64	81.3474
65	14777.7	4.7768	65	74.7999	65	14777.7	6.8754	65	80.8296
66	14777.7	4.7724	66	74.7126	66	14777.7	6.8786	66	83.1679
67	14777.7	4.7672	67	74.6534	67	14777.7	6.8720	67	80.5617
68	14777.7	4.7587	68	74.2811	68	14777.7	6.8710	68	81.1586
69	14777.7	4.7352	69	74.2248	69	14777.7	6.8582	69	82.1618
70	14777.7	4.7067	70	74.1905	70	14777.7	6.8535	70	83.0724
71	14777.7	4.6881	71	74.1305	71	14777.7	6.8271	71	79.7863
72	14777.7	4.6834	72	73.995	72	14777.7	6.8255	72	81.5432
73	14777.7	4.6738	73	73.8493	73	14777.7	6.8161	73	83.3010
74	14777.7	4.6701	74	73.7153	74	14777.7	6.8150	74	77.8491
75	14777.7	4.6670	75	73.687	75	14777.7	6.8107	75	80.8318
76	14777.7	4.6479	76	73.4814	76	14777.7	6.7881	76	79.5885
77	14777.7	4.6162	77	73.4117	77	14777.7	6.7559	77	78.8978

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
78	14777.7	4.6144	78	73.3871	78	14777.7	6.7577	78	78.6054
79	14777.7	4.5934	79	73.2907	79	14777.7	6.7336	79	81.4041
80	14777.7	4.5866	80	73.2731	80	14777.7	6.7298	80	82.7706
81	14777.7	4.5716	81	73.2478	81	14777.7	6.7259	81	78.0035
82	14777.7	4.5683	82	73.1939	82	14777.7	6.7309	82	81.4276
83	14777.7	4.5611	83	73.1555	83	14777.7	6.7233	83	77.9592
84	14777.7	4.5434	84	73.1521	84	14777.7	6.7065	84	82.6172
85	14777.7	4.5163	85	73.1175	85	14777.7	6.6871	85	81.4661
86	14777.7	4.5116	86	72.9989	86	14777.7	6.6802	86	79.1263
87	14777.7	4.4942	87	72.9147	87	14777.7	6.6550	87	80.8120
88	14777.7	4.4937	88	72.9113	88	14777.7	6.6699	88	79.4637
89	14777.7	4.4840	89	72.9041	89	14777.7	6.6568	89	81.2676
90	14777.7	4.4637	90	72.8671	90	14777.7	6.6359	90	78.5887
91	14777.7	4.4634	91	72.6378	91	14777.7	6.6380	91	76.6953
92	14777.7	4.4486	92	72.3097	92	14777.7	6.6205	92	79.3439
93	14777.7	4.4360	93	72.0652	93	14777.7	6.6040	93	80.9159
94	14777.7	4.4287	94	71.8488	94	14777.7	6.6070	94	76.5550
95	14777.7	4.4286	95	71.8211	95	14777.7	6.6187	95	77.8964
96	14777.7	4.3917	96	71.8184	96	14777.7	6.5721	96	79.7136
97	14777.7	4.3748	97	71.7193	97	14777.7	6.5523	97	75.5301
98	14777.7	4.3717	98	71.7135	98	14777.7	6.5489	98	80.7283
99	14777.7	4.3579	99	71.6262	99	14777.7	6.5332	99	79.5834
100	14777.7	4.3551	100	71.6079	100	14777.7	6.5531	100	78.3896
101	14777.7	4.3533	101	71.6073	101	14777.7	6.5523	101	76.2408
102	14777.7	4.3421	102	71.604	102	14777.7	6.5531	102	78.0366
103	14777.7	4.3353	103	71.5927	103	14777.7	6.5509	103	78.1383
104	14777.7	4.3275	104	71.4241	104	14777.7	6.5408	104	80.6763
105	14777.7	4.3239	105	71.2973	105	14777.7	6.5354	105	79.7381
106	14777.7	4.3202	106	71.2396	106	14777.7	6.5453	106	80.2865
107	14777.7	4.3118	107	71.0377	107	14777.7	6.5332	107	78.4480
108	14777.7	4.3070	108	70.9583	108	14777.7	6.5420	108	76.7968
109	14777.7	4.2976	109	70.9225	109	14777.7	6.5277	109	79.7735
110	14777.7	4.2897	110	70.8811	110	14777.7	6.5205	110	77.1441
111	14777.7	4.2860	111	70.8637	111	14777.7	6.5189	111	75.7209
112	14777.7	4.2854	112	70.5464	112	14777.7	6.5205	112	76.3103
113	14777.7	4.2585	113	70.2748	113	14777.7	6.4813	113	77.7525
114	14777.7	4.2583	114	69.9581	114	14777.7	6.5037	114	76.5821
115	14777.7	4.2520	115	69.6892	115	14777.7	6.5076	115	77.3920
116	14777.7	4.2347	116	69.6388	116	14777.7	6.4834	116	78.6667
117	14777.7	4.2190	117	69.5907	117	14777.7	6.4644	117	78.4283

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
118	14777.7	4.2175	118	69.556	118	14777.7	6.4724	118	76.0112
119	14777.7	4.2163	119	69.5218	119	14777.7	6.4736	119	78.3587
120	14777.7	4.1713	120	69.4818	120	14777.7	6.4119	120	73.5986
121	14777.7	4.1235	121	69.3797	121	14777.7	6.3646	121	73.1342
122	14777.7	4.1215	122	69.2204	122	14777.7	6.3658	122	74.3668
123	14777.7	4.1203	123	69.1717	123	14777.7	6.3655	123	75.8409
124	14777.7	4.0993	124	69.1548	124	14777.7	6.3360	124	75.5500
125	14777.7	4.0962	125	69.1003	125	14777.7	6.3354	125	77.5372
126	14777.7	4.0600	126	69.0887	126	14777.7	6.2859	126	75.5308
127	14777.7	4.0586	127	69.0384	127	14777.7	6.2844	127	74.8762
128	14777.7	4.0510	128	68.9185	128	14777.7	6.2750	128	75.3564
129	14777.7	4.0485	129	68.8403	129	14777.7	6.2834	129	76.2057
130	14777.7	4.0352	130	68.8133	130	14777.7	6.2682	130	72.3458
131	14777.7	3.9932	131	68.4821	131	14777.7	6.2111	131	76.2941
132	14777.7	3.9902	132	68.3654	132	14777.7	6.2072	132	72.5631
133	14777.7	3.9846	133	68.2172	133	14777.7	6.1999	133	74.2393
134	14777.7	3.9823	134	68.1265	134	14777.7	6.2039	134	72.9326
135	14777.7	3.9694	135	67.9401	135	14777.7	6.1848	135	73.3432
136	14777.7	3.9584	136	67.8122	136	14777.7	6.1690	136	74.7929
137	14777.7	3.9323	137	66.921	137	14777.7	6.1298	137	71.1751
138	14777.7	3.9198	138	66.9068	138	14777.7	6.1120	138	71.7443
139	14777.7	3.9072	139	66.8375	139	14777.7	6.1026	139	71.2393
140	14777.7	3.8875	140	66.8362	140	14777.7	6.0749	140	71.2210
141	14777.7	3.8785	141	66.7517	141	14777.7	6.0610	141	71.8347
142	14777.7	3.8759	142	66.7077	142	14777.7	6.0624	142	74.7411
143	14777.7	3.8568	143	66.705	143	14777.7	6.0399	143	72.5542
144	14777.7	3.8457	144	66.6107	144	14777.7	6.0238	144	72.0939
145	14777.7	3.8437	145	66.5125	145	14777.7	6.0216	145	70.7918
146	14777.7	3.8134	146	66.4872	146	14777.7	5.9775	146	74.9652
147	14777.7	3.8130	147	66.4359	147	14777.7	5.9852	147	71.9233
148	14777.7	3.8029	148	66.3546	148	14777.7	5.9789	148	74.1552
149	14777.7	3.8022	149	66.2769	149	14777.7	5.9823	149	72.8533
150	14777.7	3.8021	150	65.9544	150	14777.7	5.9827	150	71.2393
151	14777.7	3.7947	151	65.8689	151	14777.7	5.9734	151	73.7847
152	14777.7	3.7692	152	65.8233	152	14777.7	5.9380	152	73.2474
153	14777.7	3.7324	153	65.5881	153	14777.7	5.8856	153	71.3071
154	14777.7	3.7316	154	65.5638	154	14777.7	5.8959	154	73.1114
155	14777.7	3.7243	155	64.9208	155	14777.7	5.8856	155	72.8331
156	14777.7	3.7219	156	64.8838	156	14777.7	5.8874	156	70.3560
157	14777.7	3.7207	157	64.7378	157	14777.7	5.8911	157	69.7062

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					**Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
158	14777.7	3.6940	158	64.6297	158	14777.7	5.8511	158	70.9461
159	14777.7	3.6912	159	64.5391	159	14777.7	5.8469	159	72.4231
160	14777.7	3.6706	160	64.4532	160	14777.7	5.8143	160	71.2959
161	14777.7	3.6671	161	64.421	161	14777.7	5.8106	161	69.5873
162	14777.7	3.6664	162	64.3949	162	14777.7	5.8176	162	71.4008
163	14777.7	3.6593	163	64.3585	163	14777.7	5.8091	163	72.4888
164	14777.7	3.6441	164	64.3356	164	14777.7	5.7900	164	70.3462
165	14777.7	3.6358	165	64.3215	165	14777.7	5.7771	165	70.3168
166	14777.7	3.6150	166	64.3204	166	14777.7	5.7457	166	69.1373
167	14777.7	3.6058	167	63.9799	167	14777.7	5.7333	167	67.5435
168	14777.7	3.6040	168	63.7466	168	14777.7	5.7380	168	67.8620
169	14777.7	3.5837	169	63.6526	169	14777.7	5.7125	169	67.3087
170	14777.7	3.5683	170	63.5892	170	14777.7	5.6892	170	69.1265
171	14777.7	3.5554	171	63.3915	171	14777.7	5.6758	171	66.6084
172	14777.7	3.5391	172	63.3053	172	14777.7	5.6519	172	71.1046
173	14777.7	3.5272	173	63.2675	173	14777.7	5.6367	173	69.6840
174	14777.7	3.5099	174	63.1245	174	14777.7	5.6101	174	66.2879
175	14777.7	3.5012	175	62.9351	175	14777.7	5.6027	175	66.2348
176	14777.7	3.5008	176	62.9112	176	14777.7	5.6106	176	67.1060
177	14777.7	3.4676	177	62.7858	177	14777.7	5.5686	177	68.2103
178	14777.7	3.4649	178	62.6996	178	14777.7	5.5673	178	66.4729
179	14777.7	3.4633	179	62.6875	179	14777.7	5.5689	179	65.8652
180	14777.7	3.3959	180	62.5594	180	14777.7	5.4612	180	69.3262
181	14777.7	3.3791	181	62.532	181	14777.7	5.4371	181	67.4301
182	14777.7	3.3767	182	62.3104	182	14777.7	5.4364	182	69.3163
183	14777.7	3.3687	183	62.2851	183	14777.7	5.4273	183	67.5751
184	14777.7	3.3605	184	61.9598	184	14777.7	5.4162	184	67.2217
185	14777.7	3.3444	185	61.9528	185	14777.7	5.3934	185	65.2944
186	14777.7	3.3330	186	61.894	186	14777.7	5.3764	186	65.2345
187	14777.7	3.3280	187	61.8369	187	14777.7	5.3844	187	65.3794
188	14777.7	3.3223	188	61.789	188	14777.7	5.3809	188	67.8148
189	14777.7	3.3062	189	61.7669	189	14777.7	5.3568	189	66.0465
190	14777.7	3.2699	190	61.7264	190	14777.7	5.2998	190	68.9675
191	14777.7	3.2512	191	61.4864	191	14777.7	5.2701	191	68.7773
192	14777.7	3.2434	192	61.4283	192	14777.7	5.2618	192	69.2352
193	14777.7	3.2342	193	61.3742	193	14777.7	5.2476	193	66.8434
194	14777.7	3.2299	194	61.2131	194	14777.7	5.2416	194	65.3526
195	14777.7	3.2267	195	61.0472	195	14777.7	5.2365	195	65.2043
196	14777.7	3.2200	196	61.0212	196	14777.7	5.2288	196	66.6927
197	14777.7	3.2144	197	60.9516	197	14777.7	5.2255	197	67.7153

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
198	14777.7	3.1937	198	60.8696	198	14777.7	5.2134	198	65.6056
199	14777.7	3.1907	199	60.8497	199	14777.7	5.2178	199	66.1375
200	14777.7	3.1772	200	60.7892	200	14777.7	5.1995	200	66.9378
201	14777.7	3.1587	201	60.4682	201	14777.7	5.1826	201	67.9292
202	14777.7	3.1253	202	60.4436	202	14777.7	5.1298	202	64.2471
203	14777.7	3.1199	203	60.407	203	14777.7	5.1283	203	66.8857
204	14777.7	3.1116	204	60.3865	204	14777.7	5.1150	204	66.1968
205	14777.7	3.0948	205	60.3291	205	14777.7	5.0912	205	65.4368
206	14777.7	3.0940	206	60.1522	206	14777.7	5.0909	206	67.4149
207	14777.7	3.0826	207	59.7689	207	14777.7	5.0825	207	64.6367
208	14777.7	3.0673	208	59.7009	208	14777.7	5.0614	208	63.5407
209	14777.7	3.0652	209	59.6449	209	14777.7	5.0600	209	65.6492
210	14777.7	3.0638	210	59.4236	210	14777.7	5.0622	210	65.3612
211	14777.7	3.0603	211	59.352	211	14777.7	5.0566	211	63.8767
212	14777.7	3.0461	212	59.3355	212	14777.7	5.0331	212	66.1138
213	14777.7	3.0366	213	59.1151	213	14777.7	5.0289	213	66.7976
214	14777.7	3.0303	214	58.96	214	14777.7	5.0214	214	66.5351
215	14777.7	3.0113	215	58.959	215	14777.7	4.9964	215	62.5061
216	14777.7	2.9793	216	58.8389	216	14777.7	4.9436	216	62.8740
217	14777.7	2.9603	217	58.8052	217	14777.7	4.9146	217	61.8566
218	14777.7	2.9138	218	58.7323	218	14777.7	4.8375	218	64.5230
219	14777.7	2.9126	219	58.7251	219	14777.7	4.8409	219	62.1819
220	14777.7	2.8747	220	58.7213	220	14777.7	4.7798	220	63.5715
221	14777.7	2.8686	221	58.4532	221	14777.7	4.7811	221	65.5100
222	14777.7	2.8511	222	58.2411	222	14777.7	4.7557	222	63.7071
223	14777.7	2.8500	223	58.223	223	14777.7	4.7571	223	62.8529
224	14777.7	2.8221	224	58.1891	224	14777.7	4.7143	224	62.0684
225	14777.7	2.8174	225	57.9607	225	14777.7	4.7090	225	62.9033
226	14777.7	2.8056	226	57.9465	226	14777.7	4.6965	226	65.2765
227	14777.7	2.7914	227	57.8745	227	14777.7	4.6789	227	61.3425
228	14777.7	2.7869	228	57.8045	228	14777.7	4.6734	228	62.8717
229	14777.7	2.7858	229	57.7808	229	14777.7	4.6743	229	64.6308
230	14777.7	2.7571	230	57.6085	230	14777.7	4.6306	230	60.6889
231	14777.7	2.6908	231	57.5833	231	14777.7	4.5194	231	63.6485
232	14777.7	2.6824	232	57.4857	232	14777.7	4.5093	232	64.8622
233	14777.7	2.6690	233	57.287	233	14777.7	4.4876	233	61.4496
234	14777.7	2.6596	234	57.1347	234	14777.7	4.4737	234	60.6029
235	14777.7	2.6273	235	56.905	235	14777.7	4.4244	235	62.8699
236	14777.7	2.6163	236	56.8801	236	14777.7	4.4069	236	63.8625
237	14777.7	2.5956	237	56.8199	237	14777.7	4.3734	237	62.4377

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
238	14777.7	2.5904	238	56.7774	238	14777.7	4.3665	238	63.7042
239	14777.7	2.5898	239	56.7064	239	14777.7	4.3662	239	60.4192
240	14777.7	2.5562	240	56.4269	240	14777.7	4.3108	240	62.6538
241	14777.7	2.5511	241	55.9969	241	14777.7	4.3041	241	60.3479
242	14777.7	2.5438	242	55.9597	242	14777.7	4.2920	242	60.6318
243	14777.7	2.5303	243	55.5843	243	14777.7	4.2826	243	59.0560
244	14777.7	2.5202	244	55.1655	244	14777.7	4.2658	244	61.5382
245	14777.7	2.4759	245	55.1051	245	14777.7	4.1915	245	60.6153
246	14777.7	2.4749	246	55.0781	246	14777.7	4.1946	246	61.0863
247	14777.7	2.4574	247	54.7888	247	14777.7	4.1660	247	61.0571
248	14777.7	2.4561	248	54.7771	248	14777.7	4.1657	248	57.8105
249	14777.7	2.4260	249	54.6163	249	14777.7	4.1229	249	61.5014
250	14777.7	2.4187	250	54.3887	250	14777.7	4.1120	250	59.2731
251	14777.7	2.4159	251	54.3391	251	14777.7	4.1073	251	60.3388
252	14777.7	2.4067	252	54.2164	252	14777.7	4.0958	252	60.1473
253	14777.7	2.3943	253	54.1058	253	14777.7	4.0773	253	60.4086
254	14777.7	2.3822	254	54.0778	254	14777.7	4.0601	254	57.4588
255	14777.7	2.3706	255	54.0221	255	14777.7	4.0407	255	58.6996
256	14777.7	2.3671	256	54.0115	256	14777.7	4.0381	256	59.3828
257	14777.7	2.3119	257	53.8745	257	14777.7	3.9441	257	60.5859
258	14777.7	2.2943	258	53.7445	258	14777.7	3.9199	258	60.0222
259	14777.7	2.2931	259	53.6937	259	14777.7	3.9197	259	60.2247
260	14777.7	2.2733	260	53.2985	260	14777.7	3.8868	260	58.4472
261	14777.7	2.2715	261	53.2601	261	14777.7	3.8879	261	58.4061
262	14777.7	2.2608	262	53.1846	262	14777.7	3.8790	262	59.4813
263	14777.7	2.2591	263	53.1547	263	14777.7	3.8805	263	55.9607
264	14777.7	2.2560	264	52.8328	264	14777.7	3.8761	264	59.2168
265	14777.7	2.2246	265	52.5164	265	14777.7	3.8260	265	56.8552
266	14777.7	2.2096	266	52.2707	266	14777.7	3.8014	266	55.0364
267	14777.7	2.2035	267	52.1815	267	14777.7	3.7909	267	57.9054
268	14777.7	2.1832	268	52.1365	268	14777.7	3.7573	268	55.3891
269	14777.7	2.1798	269	52.1137	269	14777.7	3.7530	269	55.3194
270	14777.7	2.1681	270	51.9227	270	14777.7	3.7335	270	57.0359
271	14777.7	2.1214	271	51.9126	271	14777.7	3.6534	271	55.5651
272	14777.7	2.1022	272	51.8994	272	14777.7	3.6246	272	55.8402
273	14777.7	2.0952	273	51.8892	273	14777.7	3.6137	273	56.1515
274	14777.7	2.0859	274	51.7488	274	14777.7	3.5994	274	56.0186
275	14777.7	2.0786	275	51.687	275	14777.7	3.5885	275	55.8682
276	14777.7	2.0545	276	51.6159	276	14777.7	3.5488	276	56.7147
277	14777.7	2.0378	277	51.5633	277	14777.7	3.5227	277	54.8299

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
278	14777.7	2.0376	278	51.2514	278	14777.7	3.5334	278	54.5852
279	14777.7	2.0104	279	51.1046	279	14777.7	3.4937	279	54.0467
280	14777.7	1.9847	280	51.0233	280	14777.7	3.4491	280	54.8937
281	14777.7	1.9673	281	50.5686	281	14777.7	3.4193	281	56.2104
282	14777.7	1.9646	282	50.2125	282	14777.7	3.4200	282	53.6636
283	14777.7	1.9086	283	50.1593	283	14777.7	3.3253	283	55.6382
284	14777.7	1.9055	284	50.0466	284	14777.7	3.3242	284	55.3228
285	14777.7	1.8951	285	49.6202	285	14777.7	3.3093	285	55.3725
286	14777.7	1.8919	286	49.5654	286	14777.7	3.3039	286	55.3268
287	14777.7	1.8776	287	49.5203	287	14777.7	3.2810	287	53.1585
288	14777.7	1.8726	288	49.2957	288	14777.7	3.2725	288	52.9805
289	14777.7	1.8650	289	49.1291	289	14777.7	3.2610	289	53.6412
290	14777.7	1.8529	290	49.0604	290	14777.7	3.2428	290	52.7902
291	14777.7	1.8350	291	48.7943	291	14777.7	3.2118	291	54.4811
292	14777.7	1.7851	292	48.7016	292	14777.7	3.1259	292	54.2937
293	14777.7	1.7849	293	48.6856	293	14777.7	3.1255	293	53.2893
294	14777.7	1.7846	294	48.4784	294	14777.7	3.1255	294	51.9222
295	14777.7	1.7786	295	48.4664	295	14777.7	3.1173	295	53.5285
296	14777.7	1.7749	296	48.4009	296	14777.7	3.1128	296	51.7257
297	14777.7	1.7606	297	48.3051	297	14777.7	3.0879	297	52.4842
298	14777.7	1.7242	298	48.2471	298	14777.7	3.0257	298	52.1438
299	14777.7	1.6878	299	48.1144	299	14777.7	2.9623	299	52.5933
300	14777.7	1.6796	300	48.1072	300	14777.7	2.9494	300	54.3292
301	14777.7	1.6754	301	48.0853	301	14777.7	2.9454	301	53.3948
302	14777.7	1.6695	302	48.0777	302	14777.7	2.9388	302	54.2526
303	14777.7	1.6641	303	48.0599	303	14777.7	2.9317	303	51.3656
304	14777.7	1.6532	304	47.9543	304	14777.7	2.9200	304	52.3797
305	14777.7	1.6449	305	47.8462	305	14777.7	2.9053	305	50.4354
306	14777.7	1.6444	306	47.4143	306	14777.7	2.9054	306	52.6560
307	14777.7	1.6438	307	47.3688	307	14777.7	2.9045	307	52.0184
308	14777.7	1.6294	308	47.3411	308	14777.7	2.8790	308	52.9545
309	14777.7	1.6211	309	47.2635	309	14777.7	2.8649	309	53.3634
310	14777.7	1.6079	310	47.2525	310	14777.7	2.8501	310	53.1288
311	14777.7	1.6071	311	47.1198	311	14777.7	2.8499	311	51.0195
312	14777.7	1.5712	312	46.9876	312	14777.7	2.7915	312	49.3383
313	14777.7	1.5304	313	46.765	313	14777.7	2.7213	313	51.1268
314	14777.7	1.5176	314	46.6627	314	14777.7	2.6988	314	49.7713
315	14777.7	1.5018	315	46.5717	315	14777.7	2.6717	315	49.7173
316	14777.7	1.4771	316	46.554	316	14777.7	2.6283	316	50.0951
317	14777.7	1.4719	317	46.5101	317	14777.7	2.6200	317	49.1926

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^{6} and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
318	14777.7	1.4268	318	46.4634	318	14777.7	2.5421	318	51.5652
319	14777.7	1.4257	319	46.3181	319	14777.7	2.5407	319	51.4076
320	14777.7	1.4123	320	46.3043	320	14777.7	2.5169	320	50.6321
321	14777.7	1.3863	321	46.1492	321	14777.7	2.4710	321	49.7050
322	14777.7	1.3718	322	46.0959	322	14777.7	2.4459	322	51.4701
323	14777.7	1.3604	323	45.9748	323	14777.7	2.4262	323	50.3059
324	14777.7	1.3349	324	45.9314	324	14777.7	2.3814	324	51.7465
325	14777.7	1.3229	325	45.9053	325	14777.7	2.3619	325	51.4794
326	14777.7	1.3042	326	45.886	326	14777.7	2.3289	326	49.4890
327	14777.7	1.2890	327	45.747	327	14777.7	2.3034	327	50.0340
328	14777.7	1.2537	328	45.6756	328	14777.7	2.2413	328	49.2262
329	14777.7	1.2520	329	45.6123	329	14777.7	2.2390	329	50.1655
330	14777.7	1.2471	330	45.5666	330	14777.7	2.2305	330	50.7489
331	14777.7	1.2463	331	45.3366	331	14777.7	2.2294	331	50.3087
332	14777.7	1.2250	332	45.1824	332	14777.7	2.1935	332	47.8953
333	14777.7	1.2226	333	45.1547	333	14777.7	2.1892	333	50.3832
334	14777.7	1.1854	334	44.9432	334	14777.7	2.1237	334	47.2808
335	14777.7	1.1556	335	44.8262	335	14777.7	2.0725	335	48.5537
336	14777.7	1.1530	336	44.8206	336	14777.7	2.0725	336	49.6842
337	14777.7	1.1522	337	44.7897	337	14777.7	2.0733	337	49.8290
338	14777.7	1.1364	338	44.5664	338	14777.7	2.0455	338	48.1042
339	14777.7	1.1337	339	44.2992	339	14777.7	2.0410	339	49.1539
340	14777.7	1.1308	340	44.2425	340	14777.7	2.0398	340	49.6127
341	14777.7	1.1162	341	44.0985	341	14777.7	2.0136	341	47.1593
342	14777.7	1.1159	342	43.9774	342	14777.7	2.0170	342	46.6322
343	14777.7	1.1140	343	43.9252	343	14777.7	2.0165	343	46.9124
344	14777.7	1.1130	344	43.6884	344	14777.7	2.0146	344	47.0961
345	14777.7	1.0599	345	43.639	345	14777.7	1.9212	345	46.8232
346	14777.7	1.0575	346	43.5341	346	14777.7	1.9178	346	48.9410
347	14777.7	1.0351	347	43.5009	347	14777.7	1.8790	347	45.8545
348	14777.7	1.0183	348	43.4777	348	14777.7	1.8514	348	47.7130
349	14777.7	1.0144	349	43.4637	349	14777.7	1.8460	349	46.2033
350	14777.7	1.0048	350	43.4441	350	14777.7	1.8289	350	48.5302
351	14777.7	0.9866	351	43.31	351	14777.7	1.7961	351	46.0561
352	14777.7	0.9852	352	43.2801	352	14777.7	1.7936	352	47.1829
353	14777.7	0.9846	353	43.2751	353	14777.7	1.7948	353	48.8985
354	14777.7	0.9838	354	43.2166	354	14777.7	1.7972	354	46.6062
355	14777.7	0.9772	355	43.1855	355	14777.7	1.7885	355	45.5074
356	14777.7	0.9769	356	43.0484	356	14777.7	1.7880	356	45.9366
357	14777.7	0.9697	357	42.9681	357	14777.7	1.7751	357	46.4841

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
358	14777.7	0.9659	358	42.7791	358	14777.7	1.7688	358	46.0600
359	14777.7	0.9651	359	42.7592	359	14777.7	1.7688	359	45.6826
360	14777.7	0.9570	360	42.478	360	14777.7	1.7552	360	47.7831
361	14777.7	0.9485	361	42.4152	361	14777.7	1.7420	361	46.8542
362	14777.7	0.9463	362	42.1815	362	14777.7	1.7381	362	47.5372
363	14777.7	0.9252	363	42.1466	363	14777.7	1.6995	363	45.7307
364	14777.7	0.8771	364	41.9799	364	14777.7	1.6120	364	47.2369
365	14777.7	0.8697	365	41.96	365	14777.7	1.5993	365	44.0776
366	14777.7	0.8696	366	41.7913	366	14777.7	1.6012	366	45.9213
367	14777.7	0.8550	367	41.7318	367	14777.7	1.5746	367	46.4928
368	14777.7	0.8318	368	41.6589	368	14777.7	1.5354	368	44.5183
369	14777.7	0.8099	369	41.6052	369	14777.7	1.4951	369	46.7891
370	14777.7	0.8092	370	41.3401	370	14777.7	1.4952	370	45.9314
371	14777.7	0.7981	371	41.1996	371	14777.7	1.4748	371	45.9835
372	14777.7	0.7973	372	40.7907	372	14777.7	1.4743	372	44.7016
373	14777.7	0.7826	373	40.2295	373	14777.7	1.4473	373	44.7918
374	14777.7	0.7815	374	40.173	374	14777.7	1.4457	374	43.2391
375	14777.7	0.7755	375	40.1395	375	14777.7	1.4352	375	42.8640
376	14777.7	0.7597	376	39.9399	376	14777.7	1.4059	376	42.9350
377	14777.7	0.7555	377	39.7474	377	14777.7	1.3986	377	43.5934
378	14777.7	0.7493	378	39.5561	378	14777.7	1.3875	378	44.1602
379	14777.7	0.7378	379	39.3873	379	14777.7	1.3665	379	42.2719
380	14777.7	0.7371	380	39.2183	380	14777.7	1.3657	380	42.4422
381	14777.7	0.7200	381	39.1859	381	14777.7	1.3345	381	43.8476
382	14777.7	0.7164	382	39.0816	382	14777.7	1.3289	382	42.9577
383	14777.7	0.7139	383	38.5954	383	14777.7	1.3249	383	43.5856
384	14777.7	0.7002	384	38.5689	384	14777.7	1.3020	384	41.1259
385	14777.7	0.6962	385	38.3865	385	14777.7	1.2975	385	42.8461
386	14777.7	0.6917	386	38.3437	386	14777.7	1.2904	386	42.3341
387	14777.7	0.6802	387	38.2748	387	14777.7	1.2708	387	40.9508
388	14777.7	0.6760	388	38.0718	388	14777.7	1.2629	388	41.4245
389	14777.7	0.6660	389	37.988	389	14777.7	1.2444	389	41.1002
390	14777.7	0.6653	390	37.97	390	14777.7	1.2464	390	41.6894
391	14777.7	0.6608	391	37.8406	391	14777.7	1.2399	391	42.1560
392	14777.7	0.6586	392	37.6733	392	14777.7	1.2360	392	39.8736
393	14777.7	0.6555	393	37.4965	393	14777.7	1.2320	393	41.8354
394	14777.7	0.6422	394	37.4924	394	14777.7	1.2071	394	41.8898
395	14777.7	0.6389	395	37.4915	395	14777.7	1.2013	395	40.4294
396	14777.7	0.6344	396	37.4181	396	14777.7	1.1931	396	40.5764
397	14777.7	0.6258	397	37.3542	397	14777.7	1.1770	397	40.9320

Rightmost Extreme Point-CWS (Network Cost=€20.2487 $x10^6$ and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 $x10^6$ and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
398	14777.7	0.6048	398	37.2168	398	14777.7	1.1378	398	41.1642
399	14777.7	0.6035	399	37.1973	399	14777.7	1.1357	399	41.2666
400	14777.7	0.6013	400	37.0731	400	14777.7	1.1317	400	41.1745
401	14777.7	0.5970	401	37.0484	401	14777.7	1.1240	401	40.0541
402	14777.7	0.5603	402	37.0361	402	14777.7	1.0567	402	40.1599
403	14777.7	0.5584	403	36.5925	403	14777.7	1.0535	403	41.2217
404	14777.7	0.5512	404	36.5264	404	14777.7	1.0405	404	40.0270
405	14777.7	0.5480	405	36.5194	405	14777.7	1.0345	405	40.8279
406	14777.7	0.5452	406	36.4149	406	14777.7	1.0292	406	39.0407
407	14777.7	0.5231	407	36.3886	407	14777.7	0.9880	407	40.0197
408	14777.7	0.5177	408	36.3033	408	14777.7	0.9781	408	39.8272
409	14777.7	0.5141	409	36.0901	409	14777.7	0.9716	409	40.6763
410	14777.7	0.5125	410	36.0649	410	14777.7	0.9686	410	38.1160
411	14777.7	0.4998	411	35.4748	411	14777.7	0.9465	411	38.6689
412	14777.7	0.4991	412	35.4631	412	14777.7	0.9457	412	38.7160
413	14777.7	0.4883	413	35.3057	413	14777.7	0.9260	413	37.3257
414	14777.7	0.4778	414	35.2589	414	14777.7	0.9070	414	39.5736
415	14777.7	0.4733	415	35.2241	415	14777.7	0.8995	415	39.4774
416	14777.7	0.4692	416	35.204	416	14777.7	0.8931	416	38.2005
417	14777.7	0.4575	417	35.103	417	14777.7	0.8710	417	39.0534
418	14777.7	0.4531	418	34.7498	418	14777.7	0.8631	418	36.9000
419	14777.7	0.4299	419	34.7465	419	14777.7	0.8196	419	38.2067
420	14777.7	0.4279	420	34.662	420	14777.7	0.8164	420	37.1178
421	14777.7	0.4235	421	34.5926	421	14777.7	0.8083	421	37.5555
422	14777.7	0.4231	422	34.4939	422	14777.7	0.8082	422	38.5476
423	14777.7	0.4198	423	34.4046	423	14777.7	0.8020	423	36.6649
424	14777.7	0.4186	424	34.3668	424	14777.7	0.7998	424	36.9205
425	14777.7	0.4054	425	34.3607	425	14777.7	0.7750	425	37.4072
426	14777.7	0.3945	426	34.3273	426	14777.7	0.7544	426	36.9714
427	14777.7	0.3932	427	34.1844	427	14777.7	0.7524	427	38.0773
428	14777.7	0.3895	428	34.1489	428	14777.7	0.7454	428	38.5541
429	14777.7	0.3883	429	33.9077	429	14777.7	0.7431	429	36.0345
430	14777.7	0.3770	430	33.6163	430	14777.7	0.7224	430	35.9342
431	14777.7	0.3585	431	33.6007	431	14777.7	0.6874	431	37.1684
432	14777.7	0.3544	432	33.5662	432	14777.7	0.6796	432	36.2528
433	14777.7	0.3510	433	33.3986	433	14777.7	0.6742	433	37.6702
434	14777.7	0.3502	434	33.3085	434	14777.7	0.6732	434	37.5648
435	14777.7	0.3486	435	33.2616	435	14777.7	0.6709	435	36.6375
436	14777.7	0.3434	436	33.0525	436	14777.7	0.6622	436	36.9794
437	14777.7	0.3406	437	32.8259	437	14777.7	0.6573	437	35.5226

Rightmost Extreme Point-CWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9552)					Rightmost Extreme Point-IWS (Network Cost=€20.2487 x10^6 and Network Resilience=0.9721)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
438	14777.7	0.3233	438	32.7832	438	14777.7	0.6249	438	36.0797
439	14777.7	0.3216	439	32.6536	439	14777.7	0.6216	439	36.8600
440	14777.7	0.3183	440	32.5131	440	14777.7	0.6154	440	35.5940
441	14777.7	0.3049	441	32.0867	441	14777.7	0.5896	441	36.0875
442	14777.7	0.2986	442	31.8279	442	14777.7	0.5776	442	35.2535
443	14777.7	0.2929	443	31.8121	443	14777.7	0.5667	443	34.6346
444	14777.7	0.2737	-	-	444	14777.7	0.5303	-	-
445	14777.7	0.2732	-	-	445	14777.7	0.5296	-	-
446	14777.7	0.2491	-	-	446	14777.7	0.4834	-	-
447	14777.7	0.2461	-	-	447	14777.7	0.4777	-	-
448	14777.7	0.2455	-	-	448	14777.7	0.4768	-	-
449	14777.7	0.2390	-	-	449	14777.7	0.4643	-	-
450	14777.7	0.2199	-	-	450	14777.7	0.4272	-	-
451	14777.7	0.2088	-	-	451	14777.7	0.4058	-	-
452	14777.7	0.2078	-	-	452	14777.7	0.4047	-	-
453	14777.7	0.2010	-	-	453	14777.7	0.3915	-	-
454	14777.7	0.1997	-	-	454	14777.7	0.3891	-	-

Table A.3 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point for Pamapur WDN in CWS and IWS

Leftmost Extreme Point-CWS (Network Cost=1.3043 million rupees and Network Resilience=0.4061)					**Leftmost Extreme Point-IWS (Network Cost=1.5543 million rupees and Network Resilience=0.4761)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	66.8	0.1100	1	8.3900	1	98.6	0.1320	1	10.1117
2	66.8	0.5500	2	9.2200	2	98.6	0.6603	2	10.8231
3	66.8	0.4100	3	10.8100	3	98.6	0.4925	3	13.4601
4	66.8	0.7900	4	8.6900	4	98.6	0.9490	4	10.1797
5	66.8	0.6500	5	9.9100	5	98.6	0.7808	5	12.3799
6	66.8	0.3300	6	12.6200	6	98.6	0.3965	6	14.8107
7	66.8	0.4300	7	13.7600	7	80.4	0.5171	7	16.1751
8	66.8	0.0100	8	12.2400	8	80.4	0.0118	8	14.8755
9	66.8	0.0900	9	11.3400	9	80.4	0.1082	9	13.1341
10	66.8	1.2900	10	10.7900	10	80.4	1.5515	10	12.6026
11	66.8	0.0900	11	10.6700	11	80.4	0.1083	11	11.9496
12	98.6	0.5200	12	11.8100	12	125.4	0.6257	12	14.3347
13	66.8	0.9500	13	13.7500	13	80.4	1.1432	13	16.2908
14	66.8	0.4800	14	10.1900	14	80.4	0.5776	14	12.2004
15	66.8	0.1500	15	12.2300	15	80.4	0.1805	15	14.9170
16	98.6	0.6000	16	13.0000	16	80.4	0.7222	16	14.7299
17	66.8	0.0250	17	12.9900	17	80.4	0.0120	17	15.9606
18	143.4	0.8400	18	14.0500	18	80.4	1.0119	18	17.3617
19	66.8	0.0800	19	10.8000	19	80.4	0.0964	19	12.3531
20	66.8	0.3000	20	11.8400	20	80.4	0.3616	20	14.3131
21	66.8	0.1700	21	9.2200	21	80.4	0.2050	21	10.6115
22	66.8	0.3800	22	10.4000	22	80.4	0.4584	22	11.8654
23	66.8	0.0700	23	8.7300	23	80.4	0.0845	23	9.8260
24	66.8	0.3200	24	14.5500	24	80.4	0.3863	24	17.4542
25	66.8	0.0700	25	11.8000	25	80.4	0.0845	25	13.9285
26	66.8	0.0600	26	11.7300	26	80.4	0.0725	26	14.3618
27	98.6	0.7300	27	11.8200	27	112	0.8822	27	13.4760
28	66.8	0.0600	28	11.2500	28	98.6	0.0725	28	12.6723
29	66.8	0.0700	29	13.1000	29	98.6	0.0846	29	15.2573
30	66.8	0.0600	30	10.6300	30	98.6	0.0726	30	12.4514
31	66.8	0.0900	31	11.4900	31	66.8	0.1088	31	13.9923
32	98.6	0.7300	32	11.4500	32	98.6	0.8831	32	12.8194
33	66.8	0.7300	33	11.6200	33	66.8	0.8836	33	12.8715
34	66.8	0.0500	34	11.8700	34	98.6	0.0605	34	14.1743
35	98.6	0.2800	35	12.1300	35	98.6	0.3391	35	13.3959
36	66.8	0.2100	36	12.9800	36	98.6	0.2543	36	14.5432
37	66.8	0.0500	37	13.2400	37	98.6	0.0606	37	15.9434

Leftmost Extreme Point-CWS (Network Cost=1.3043 million rupees and Network Resilience=0.4061)					Leftmost Extreme Point-IWS (Network Cost=1.5543 million rupees and Network Resilience=0.4761)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
38	66.8	0.3300	38	8.7300	38	98.6	0.4001	38	10.2783
39	112.0	1.1300	39	7.9700	39	125.4	1.3704	39	9.4157
40	98.6	0.9900	40	8.1400	40	112	1.2006	40	9.9412
41	66.8	0.0300	41	8.6100	41	98.6	0.0364	41	10.4960
42	66.8	0.5100	42	7.7900	42	98.6	0.6186	42	9.1554
43	66.8	0.5500	43	9.6000	43	66.8	0.6675	43	10.9584
44	66.8	0.0500	44	9.8200	44	66.8	0.0607	44	10.9783
45	66.8	0.6000	45	10.2200	45	98.6	0.7289	45	12.6012
46	66.8	0.2200	46	9.5400	46	98.6	0.2673	46	11.8825
47	161.4	1.4800	47	9.5600	47	98.6	1.7982	47	11.8676
48	66.8	0.0500	48	11.9000	48	98.6	0.0608	48	14.2291
49	66.8	0.4900	49	9.1200	49	98.6	0.5955	49	10.1559
50	98.6	0.1600	50	8.7100	50	112	0.1944	50	9.6786
51	66.8	0.2600	51	8.3800	51	98.6	0.3160	51	9.4473
52	66.8	0.0400	52	8.8400	52	98.6	0.0486	52	9.7660
53	66.8	0.0600	53	11.9200	53	98.6	0.0729	53	14.4082
54	112.0	0.8100	54	11.0000	54	125.4	0.9848	54	12.3379
55	112.0	0.6300	55	12.3400	55	125.4	0.7680	55	14.7511
56	112.0	1.2000	56	9.5000	56	125.4	1.4631	56	11.5755
57	66.8	0.5900	57	10.8300	57	98.6	0.7195	57	12.8329
58	66.8	0.0400	58	10.8000	58	98.6	0.0489	58	12.4914
59	66.8	0.1900	59	7.0100	59	66.8	0.2321	59	8.0124
60	66.8	0.2100	60	11.1800	60	66.8	0.2568	60	12.8093
61	98.6	0.4900	61	11.2800	61	112	0.5995	61	12.9484
62	66.8	0.1300	62	12.7000	62	98.6	0.1591	62	15.4654
63	143.4	0.8700	63	12.0500	63	98.6	1.0653	63	14.1655
64	66.8	0.3000	64	10.1800	64	98.6	0.3674	64	11.5965
65	66.8	0.1400	65	8.6200	65	98.6	0.1715	65	10.4291
66	112.0	0.7700	66	11.2500	66	143.4	0.9432	66	12.6500
67	66.8	0.0300	67	11.1300	67	98.6	0.0368	67	13.7807
68	66.8	0.0300	68	7.0800	68	98.6	0.0368	68	8.0240
69	66.8	0.0300	69	12.0000	69	98.6	0.0368	69	13.3505
70	66.8	0.0300	70	10.8100	70	98.6	0.0368	70	12.0105
71	66.8	0.1700	71	10.1100	71	98.6	0.2084	71	12.2880
72	66.8	0.0300	72	11.2400	72	98.6	0.0368	72	13.7426
73	98.6	0.8400	73	11.5000	73	112	1.0298	73	13.9272
74	66.8	0.1600	74	10.7600	74	98.6	0.1962	74	13.0598
75	112.0	1.1200	75	10.5200	75	143.4	1.3735	75	13.0888
76	66.8	0.0300	76	10.6400	76	98.6	0.0368	76	12.4484

Leftmost Extreme Point-CWS (Network Cost=1.3043 million rupees and Network Resilience=0.4061)					**Leftmost Extreme Point-IWS (Network Cost=1.5543 million rupees and Network Resilience=0.4761)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
77	66.8	0.0300	77	10.4200	77	98.6	0.0368	77	12.6921
78	112.0	1.0000	78	11.3700	78	143.4	1.2275	78	13.2277
79	66.8	0.0600	79	11.7100	79	98.6	0.0737	79	14.5387
80	66.8	0.3800	80	12.0600	80	98.6	0.4666	80	13.2684
81	66.8	0.0200	81	11.9100	81	98.6	0.0246	81	14.8540
82	66.8	0.0900	82	11.7200	82	98.6	0.1105	82	13.8944
83	66.8	0.0200	83	10.6100	83	98.6	0.0246	83	12.2224
84	98.6	0.6200	84	10.7900	84	98.6	0.7620	84	12.7713
85	66.8	0.7800	85	10.5600	85	98.6	0.9586	85	12.0909
86	66.8	0.5600	86	10.9900	86	98.6	0.6883	86	12.3512
87	66.8	0.1100	87	11.2000	87	98.6	0.1352	87	13.4376
88	66.8	0.4000	88	10.9700	88	98.6	0.4920	88	13.1929
89	66.8	0.2400	89	10.8400	89	98.6	0.2953	89	13.2125
90	66.8	0.4900	90	11.7100	90	98.6	0.6032	90	13.4934
91	66.8	0.0700	91	12.2900	91	98.6	0.0862	91	13.9800
92	112.0	0.7500	92	12.1200	92	143.4	0.9237	92	13.9592
93	66.8	0.5900	93	13.2300	93	98.6	0.7272	93	15.2052
94	66.8	0.5700	94	12.7600	94	98.6	0.7026	94	15.8112
95	66.8	0.7900	95	12.5300	95	98.6	0.9739	95	15.2040
96	66.8	0.5500	96	13.1100	96	98.6	0.6781	96	14.9878
97	66.8	0.4100	97	13.9400	97	98.6	0.5056	97	16.6015
98	66.8	0.3900	98	13.9000	98	66.8	0.4812	98	16.8872
99	66.8	0.1800	99	12.0500	99	66.8	0.2222	99	14.7844
100	98.6	0.6300	100	11.8600	100	112	0.7783	100	14.6506
101	112.0	1.0400	101	12.5300	101	143.4	1.2853	101	14.9026
102	143.4	1.0300	102	12.0400	102	224.4	1.2730	102	15.0121
103	201.8	1.5800	-	-	103	179.4	1.9532	-	-
104	143.4	0.9800	-	-	104	179.4	1.2120	-	-
105	201.8	1.5950	-	-	105	251.4	1.9957	-	-
106	143.4	0.9400	-	-	106	179.4	1.1636	-	-
107	80.4	0.6000	-	-	107	98.6	0.7429	-	-
108	201.8	1.3400	-	-	108	201.8	1.6594	-	-
109	66.8	0.6200	-	-	109	98.6	0.7679	-	-
110	66.8	0.7200	-	-	110	98.6	0.8920	-	-
111	66.8	0.1700	-	-	111	66.8	0.2106	-	-
112	66.8	0.2900	-	-	112	66.8	0.3593	-	-
113	66.8	0.1700	-	-	113	66.8	0.2106	-	-
114	98.6	1.0100	-	-	114	112	1.2520	-	-
115	143.4	1.0200	-	-	115	179.4	1.2646	-	-

Leftmost Extreme Point-CWS (Network Cost=1.3043 million rupees and Network Resilience=0.4061)					**Leftmost Extreme Point-IWS (Network Cost=1.5543 million rupees and Network Resilience=0.4761)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
116	66.8	0.1500	-	-	116	98.6	0.1860	-	-
117	66.8	0.1100	-	-	117	98.6	0.1364	-	-
118	143.4	0.8900	-	-	118	179.4	1.1041	-	-
119	66.8	0.1400	-	-	119	98.6	0.1737	-	-
120	66.8	0.8500	-	-	120	98.6	1.0545	-	-
121	66.8	0.7900	-	-	121	98.6	0.9805	-	-
122	66.8	0.3500	-	-	122	98.6	0.4344	-	-

Table A.4 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Rightmost Extreme Point for Pamapur WDN in CWS and IWS

Rightmost Extreme Point-CWS (Network Cost=3.4988 million rupees and Network Resilience=0.8877)					Rightmost Extreme Point-IWS (Network Cost=3.4988 million rupees and Network Resilience=0.9450)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	251.4	0.0989	1	9.6755	1	251.4	0.1187	1	11.3262
2	251.4	0.4934	2	10.8591	2	251.4	0.5930	2	12.1244
3	251.4	0.3677	3	12.3370	3	251.4	0.4421	3	15.0840
4	251.4	0.7077	4	10.2327	4	251.4	0.8505	4	11.4208
5	251.4	0.5806	5	11.4916	5	251.4	0.6994	5	13.8978
6	251.4	0.2946	6	14.1824	6	251.4	0.3551	6	16.6284
7	251.4	0.3835	7	15.6616	7	251.4	0.4629	7	18.1710
8	251.4	0.0089	8	14.2135	8	251.4	0.0105	8	16.7206
9	251.4	0.0801	9	13.0816	9	251.4	0.0965	9	14.7850
10	251.4	1.1478	10	12.2348	10	251.4	1.3826	10	14.1960
11	251.4	0.0796	11	12.1289	11	251.4	0.0963	11	13.4615
12	251.4	0.4592	12	13.8722	12	251.4	0.5561	12	16.1516
13	251.4	0.8382	13	15.9942	13	251.4	1.0126	13	18.3589
14	251.4	0.4221	14	11.5156	14	251.4	0.5100	14	13.7583
15	251.4	0.1319	15	14.3107	15	251.4	0.1594	15	16.8364
16	251.4	0.5275	16	14.9254	16	251.4	0.6365	16	16.6296
17	251.4	0.0220	17	14.9692	17	251.4	0.0106	17	18.0232
18	251.4	0.7368	18	16.4316	18	251.4	0.8912	18	19.6070
19	251.4	0.0702	19	12.3993	19	251.4	0.0848	19	13.9576
20	251.4	0.2630	20	13.2727	20	251.4	0.3179	20	16.1735
21	251.4	0.1490	21	10.3746	21	251.4	0.1801	21	12.0079
22	251.4	0.3329	22	12.0783	22	251.4	0.4023	22	13.4276
23	251.4	0.0613	23	10.0502	23	251.4	0.0741	23	11.1332
24	251.4	0.2797	24	17.2398	24	251.4	0.3377	24	21.2015
25	251.4	0.0612	25	13.2944	25	251.4	0.0739	25	15.8127
26	251.4	0.0524	26	13.4459	26	251.4	0.0632	26	16.3120
27	251.4	0.6372	27	13.6902	27	251.4	0.7692	27	15.3061
28	251.4	0.0524	28	12.6879	28	251.4	0.0632	28	14.4150
29	251.4	0.0610	29	15.5014	29	251.4	0.0738	29	17.3830
30	251.4	0.0523	30	12.3768	30	251.4	0.0630	30	14.2027
31	251.4	0.0782	31	13.5970	31	251.4	0.0942	31	15.9607
32	251.4	0.6338	32	13.3294	32	251.4	0.7635	32	14.6253
33	251.4	0.6331	33	13.0260	33	251.4	0.7639	33	14.6935
34	251.4	0.0433	34	13.5574	34	251.4	0.0522	34	16.1823
35	251.4	0.2421	35	13.6806	35	251.4	0.2918	35	15.2971
36	251.4	0.1814	36	15.1095	36	251.4	0.2185	36	16.6112
37	251.4	0.0431	37	14.8851	37	251.4	0.0520	37	18.2126
38	251.4	0.2830	38	10.1895	38	251.4	0.3428	38	11.7456
39	251.4	0.9683	39	9.1928	39	251.4	1.1724	39	10.7650
40	251.4	0.8477	40	9.2909	40	251.4	1.0266	40	11.3899
41	251.4	0.0256	41	9.9544	41	251.4	0.0311	41	12.0302

Rightmost Extreme Point-CWS (Network Cost=3.4988 million rupees and Network Resilience=0.8877)					Rightmost Extreme Point-IWS (Network Cost=3.4988 million rupees and Network Resilience=0.9450)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
42	251.4	0.4349	42	9.1103	42	251.4	0.5284	42	10.4952
43	251.4	0.4688	43	11.2987	43	251.4	0.5683	43	12.5666
44	251.4	0.0426	44	11.2155	44	251.4	0.0516	44	12.6004
45	251.4	0.5106	45	11.6691	45	251.4	0.6181	45	14.4650
46	251.4	0.1872	46	10.9152	46	251.4	0.2263	46	13.6523
47	251.4	1.2550	47	11.1531	47	251.4	1.5214	47	13.6359
48	251.4	0.0423	48	14.0453	48	251.4	0.0513	48	16.3722
49	251.4	0.4133	49	10.7007	49	251.4	0.5027	49	11.6894
50	251.4	0.1349	50	10.2892	50	251.4	0.1639	50	11.1557
51	251.4	0.2190	51	9.8967	51	251.4	0.2659	51	10.8945
52	251.4	0.0337	52	10.0077	52	251.4	0.0408	52	11.2639
53	251.4	0.0505	53	14.0598	53	251.4	0.0611	53	16.6529
54	251.4	0.6810	54	13.0589	54	251.4	0.8248	54	14.2679
55	251.4	0.5295	55	14.4861	55	251.4	0.6426	55	17.0605
56	251.4	1.0065	56	11.2219	56	251.4	1.2214	56	13.3954
57	251.4	0.4941	57	12.1807	57	251.4	0.6005	57	14.8518
58	251.4	0.0335	58	12.5850	58	251.4	0.0408	58	14.4620
59	251.4	0.1582	59	8.0102	59	251.4	0.1934	59	9.2895
60	251.4	0.1745	60	13.0227	60	251.4	0.2139	60	14.8550
61	251.4	0.4072	61	13.3283	61	251.4	0.4988	61	15.0167
62	251.4	0.1080	62	14.5562	62	251.4	0.1323	62	17.9619
63	251.4	0.7223	63	14.1427	63	251.4	0.8858	63	16.4545
64	251.4	0.2485	64	11.5214	64	251.4	0.3054	64	13.4769
65	251.4	0.1155	65	9.9680	65	251.4	0.1424	65	12.1204
66	251.4	0.6342	66	13.0941	66	251.4	0.7827	66	14.7137
67	251.4	0.0247	67	13.0218	67	251.4	0.0305	67	16.0581
68	251.4	0.0247	68	8.0814	68	251.4	0.0303	68	9.3561
69	251.4	0.0246	69	13.6615	69	251.4	0.0302	69	15.5686
70	251.4	0.0246	70	12.8003	70	251.4	0.0301	70	14.0145
71	251.4	0.1392	71	11.7585	71	251.4	0.1705	71	14.3514
72	251.4	0.0246	72	12.6621	72	251.4	0.0301	72	16.0583
73	251.4	0.6869	73	13.3853	73	251.4	0.8415	73	16.2869
74	251.4	0.1307	74	12.1958	74	251.4	0.1603	74	15.2731
75	251.4	0.9135	75	12.3546	75	251.4	1.1151	75	15.3474
76	251.4	0.0244	76	12.5607	76	251.4	0.0298	76	14.6178
77	251.4	0.0244	77	11.9137	77	251.4	0.0298	77	14.9129
78	251.4	0.8141	78	12.8422	78	251.4	0.9943	78	15.5464
79	251.4	0.0488	79	13.7427	79	251.4	0.0596	79	17.0886
80	251.4	0.3091	80	13.7762	80	251.4	0.3761	80	15.5988
81	251.4	0.0163	81	13.5496	81	251.4	0.0198	81	17.4652
82	251.4	0.0728	82	13.2905	82	251.4	0.0889	82	16.3438
83	251.4	0.0161	83	11.9345	83	251.4	0.0197	83	14.4010
84	251.4	0.4997	84	12.5017	84	251.4	0.6103	84	15.0503
85	251.4	0.6278	85	12.1257	85	251.4	0.7674	85	14.2617

Rightmost Extreme Point-CWS (Network Cost=3.4988 million rupees and Network Resilience=0.8877)					**Rightmost Extreme Point-IWS (Network Cost=3.4988 million rupees and Network Resilience=0.9450)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
86	251.4	0.4504	86	12.8859	86	251.4	0.5506	86	14.5790
87	251.4	0.0881	87	12.9260	87	251.4	0.1081	87	15.8804
88	251.4	0.3203	88	12.5819	88	251.4	0.3927	88	15.5951
89	251.4	0.1918	89	12.1874	89	251.4	0.2357	89	15.6320
90	251.4	0.3895	90	13.2904	90	251.4	0.4804	90	15.9754
91	251.4	0.0555	91	14.2327	91	251.4	0.0685	91	16.5522
92	251.4	0.5946	92	13.9228	92	251.4	0.7314	92	16.5339
93	251.4	0.4676	93	15.6520	93	251.4	0.5757	93	18.0382
94	251.4	0.4515	94	14.3415	94	251.4	0.5553	94	18.7610
95	251.4	0.6242	95	14.4226	95	251.4	0.7673	95	18.0415
96	251.4	0.4345	96	15.1768	96	251.4	0.5341	96	17.7880
97	251.4	0.3231	97	15.7436	97	251.4	0.3963	97	19.7174
98	251.4	0.3073	98	16.0943	98	251.4	0.3771	98	20.0622
99	251.4	0.1412	99	14.2192	99	251.4	0.1735	99	17.5768
100	251.4	0.4929	100	13.4476	100	251.4	0.6076	100	17.4190
101	251.4	0.8127	101	14.1701	101	251.4	1.0026	101	17.7269
102	251.4	0.8030	102	13.5365	102	251.4	0.9928	102	17.8625
103	251.4	1.2315	-	-	103	251.4	1.5217	-	-
104	251.4	0.7634	-	-	104	251.4	0.9434	-	-
105	251.4	1.2712	-	-	105	251.4	1.5492	-	-
106	251.4	0.7280	-	-	106	251.4	0.9002	-	-
107	251.4	0.4642	-	-	107	251.4	0.5739	-	-
108	251.4	1.0356	-	-	108	251.4	1.2809	-	-
109	251.4	0.4781	-	-	109	251.4	0.5918	-	-
110	251.4	0.5539	-	-	110	251.4	0.6860	-	-
111	251.4	0.1303	-	-	111	251.4	0.1616	-	-
112	251.4	0.2216	-	-	112	251.4	0.2751	-	-
113	251.4	0.1299	-	-	113	251.4	0.1611	-	-
114	251.4	0.7716	-	-	114	251.4	0.9542	-	-
115	251.4	0.7756	-	-	115	251.4	0.9620	-	-
116	251.4	0.1140	-	-	116	251.4	0.1413	-	-
117	251.4	0.0835	-	-	117	251.4	0.1035	-	-
118	251.4	0.6748	-	-	118	251.4	0.8374	-	-
119	251.4	0.1056	-	-	119	251.4	0.1316	-	-
120	251.4	0.6414	-	-	120	251.4	0.7983	-	-
121	251.4	0.5960	-	-	121	251.4	0.7421	-	-
122	251.4	0.2628	-	-	122	251.4	0.3282	-	-

Table A.5 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point for Vanasthalipuram WDN in CWS and IWS

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					**Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	112	1.9570	1	7.3100	1	161.4	3.1682	1	9.8689
2	112	0.0100	2	7.5000	2	251.4	0.0125	2	10.1259
3	112	0.0400	3	11.6600	3	161.4	0.0502	3	15.7464
4	251.4	0.5900	4	12.5900	4	251.4	0.7407	4	17.0080
5	251.4	0.3300	5	7.6500	5	251.4	0.4144	5	10.3395
6	251.4	0.4500	6	7.1400	6	251.4	0.5655	6	9.6526
7	161.4	0.2100	7	7.4800	7	251.4	0.2640	7	10.1156
8	251.4	0.2300	8	7.0750	8	251.4	0.2892	8	9.5512
9	112	0.1100	9	13.6200	9	251.4	0.1383	9	18.4551
10	112	0.0800	10	18.4900	10	161.4	0.1006	10	25.0623
11	112	0.0500	11	18.8300	11	161.4	0.0629	11	25.5232
12	161.4	0.1500	12	8.9900	12	161.4	0.1889	12	12.1922
13	112	0.1600	13	7.1500	13	161.4	0.2016	13	9.7014
14	161.4	0.0200	14	7.1520	14	161.4	0.0252	14	9.7052
15	112	0.0200	15	9.7600	15	161.4	0.0252	15	13.2451
16	161.4	0.4500	16	10.1700	16	161.4	0.5674	16	13.8114
17	112	0.0200	17	16.0200	17	161.4	0.0252	17	21.7601
18	112	0.2900	18	13.0300	18	251.4	0.3666	18	17.6997
19	251.4	0.3500	19	15.0800	19	251.4	0.4426	19	20.4902
20	161.4	0.1300	20	16.5100	20	251.4	0.1644	20	22.4631
21	112	0.3300	21	17.1000	21	251.4	0.4176	21	23.2684
22	161.4	0.1900	22	9.6000	22	251.4	0.2405	22	13.0663
23	112	0.0600	23	11.3600	23	161.4	0.0760	23	15.4649
24	161.4	0.6900	24	7.1200	24	161.4	0.8743	24	9.6975
25	161.4	0.1000	25	10.1600	25	161.4	0.1267	25	13.8400
26	161.4	0.1500	26	22.5100	26	161.4	0.1901	26	30.7101
27	161.4	0.1200	27	12.9900	27	251.4	0.1523	27	17.7235
28	112	0.1800	28	11.2400	28	251.4	0.2285	28	15.3528
29	112	0.0800	29	14.5200	29	251.4	0.1016	29	19.8441
30	251.4	0.0800	30	12.1600	30	251.4	0.1016	30	16.6305
31	251.4	0.0500	31	8.2200	31	251.4	0.0636	31	11.2475
32	251.4	0.4500	32	9.0100	32	251.4	0.5724	32	12.3302
33	161.4	0.0600	33	15.1200	33	251.4	0.0764	33	20.6965
34	251.4	0.0300	34	26.3200	34	251.4	0.0382	34	36.0540
35	251.4	0.3400	35	7.1570	35	251.4	0.4334	35	9.8094
36	161.4	0.1200	36	26.6800	36	251.4	0.1531	36	36.5848
37	251.4	0.1000	37	27.3800	37	251.4	0.1276	37	37.5550

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
38	112	0.1100	38	12.3600	38	251.4	0.1404	38	16.9594
39	112	0.0700	39	11.4000	39	161.4	0.0896	39	15.6547
40	112	0.2000	40	7.4600	40	161.4	0.2561	40	10.2622
41	161.4	0.1300	41	7.5400	41	161.4	0.1666	41	10.3728
42	251.4	0.2500	42	14.0400	42	161.4	0.3208	42	19.3195
43	251.4	0.2300	43	18.9800	43	251.4	0.2952	43	26.1195
44	161.4	0.1000	44	16.6500	44	251.4	0.1285	44	22.9154
45	251.4	0.2500	45	14.0500	45	161.4	0.3214	45	19.3504
46	112	0.0700	46	8.4600	46	161.4	0.0901	46	11.6586
47	112	0.1400	47	13.5600	47	161.4	0.1801	47	18.6896
48	112	0.0800	48	13.5900	48	161.4	0.1031	48	18.7316
49	161.4	0.1600	49	13.7900	49	161.4	0.2063	49	19.0301
50	251.4	0.1900	50	11.8000	50	161.4	0.2451	50	16.2877
51	251.4	0.3200	51	10.9100	51	161.4	0.4129	51	15.0675
52	161.4	0.0800	52	14.1300	52	161.4	0.1034	52	19.5275
53	251.4	0.1100	53	14.6500	53	251.4	0.1422	53	20.2471
54	112	0.1300	54	13.3700	54	251.4	0.1680	54	18.4830
55	112	0.1200	55	15.7700	55	251.4	0.1552	55	21.8110
56	112	0.1700	56	11.9800	56	251.4	0.2199	56	16.5805
57	161.4	0.4400	57	7.4200	57	251.4	0.5702	57	10.2752
58	251.4	0.1600	58	13.1000	58	251.4	0.2074	58	18.1410
59	251.4	0.4000	59	11.2700	59	251.4	0.5193	59	15.6301
60	161.4	0.1800	60	9.7700	60	251.4	0.2340	60	13.5610
61	251.4	0.2400	61	10.1900	61	251.4	0.3120	61	14.1559
62	112	0.3200	62	7.0800	62	251.4	0.4160	62	9.8408
63	112	0.2600	63	13.5600	63	161.4	0.3381	63	18.8546
64	112	0.0100	64	12.1700	64	251.4	0.0130	64	16.9316
65	161.4	0.2300	65	12.5900	65	251.4	0.2993	65	17.5373
66	112	0.2800	66	12.8200	66	161.4	0.3644	66	17.8595
67	112	0.1500	67	17.1800	67	161.4	0.1952	67	23.9463
68	161.4	0.4800	68	16.9600	68	161.4	0.6248	68	23.6404
69	112	0.3700	69	15.6000	69	161.4	0.4827	69	21.7456
70	161.4	0.4300	70	7.4500	70	161.4	0.5618	70	10.3870
71	112	0.1800	71	7.3120	71	161.4	0.2354	71	10.2000
72	161.4	0.7000	72	15.9600	72	161.4	0.9155	72	22.2683
73	112	0.1000	73	14.2200	73	251.4	0.1308	73	19.8664
74	112	0.2400	74	23.2700	74	251.4	0.3140	74	32.5121
75	251.4	0.0800	75	23.3700	75	251.4	0.1047	75	32.6537
76	161.4	0.1250	76	7.4800	76	251.4	0.157	76	10.4566
77	112	0.4800	77	14.2500	77	251.4	0.6282	77	19.9229

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					**Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
78	161.4	0.0200	78	14.2000	78	251.4	0.0262	78	19.8656
79	112	0.0700	79	20.4800	79	251.4	0.0918	79	28.6638
80	161.4	0.1000	80	18.9700	80	251.4	0.1312	80	26.5963
81	161.4	0.1400	81	7.2570	81	251.4	0.1836	81	10.1756
82	161.4	0.0300	82	15.4900	82	251.4	0.0394	82	21.7223
83	161.4	0.1400	83	9.3100	83	161.4	0.1838	83	13.0713
84	112	0.0800	84	7.1520	84	251.4	0.1051	84	10.0465
85	112	0.3500	85	7.7000	85	251.4	0.4600	85	10.8225
86	251.4	0.1900	86	7.7000	86	251.4	0.2499	86	10.8284
87	112	0.2400	87	12.3800	87	251.4	0.3159	87	17.4221
88	112	0.0900	88	11.0600	88	251.4	0.1185	88	15.5708
89	161.4	0.0800	89	13.0800	89	251.4	0.1054	89	18.4194
90	112	0.3800	90	19.9600	90	251.4	0.5012	90	28.1384
91	161.4	0.0200	91	11.7900	91	251.4	0.0264	91	16.6660
92	112	0.1300	92	7.1230	92	251.4	0.1716	92	10.0792
93	161.4	0.0100	93	14.6300	93	251.4	0.0132	93	20.7028
94	112	0.3800	94	18.0000	94	251.4	0.5018	94	25.4799
95	112	0.3500	95	24.1100	95	161.4	0.4626	95	34.1357
96	251.4	0.1400	96	14.5900	96	251.4	0.1851	96	20.6582
97	161.4	0.1000	97	25.6200	97	251.4	0.1322	97	36.2954
98	112	0.3900	98	13.8400	98	251.4	0.5158	98	19.6088
99	161.4	0.5100	99	14.6500	99	251.4	0.6747	99	20.7887
100	112	0.9000	100	15.7900	100	251.4	1.1915	100	22.4094
101	161.4	0.0800	101	20.6600	101	251.4	0.1059	101	29.3224
102	161.4	0.0300	102	7.2570	102	251.4	0.0397	102	10.2998
103	161.4	0.2200	103	12.0000	103	251.4	0.2915	103	17.0369
104	161.4	0.2800	104	8.4400	104	251.4	0.3712	104	11.9910
105	112	0.1500	105	11.2500	105	251.4	0.1993	105	15.9934
106	112	0.2100	106	20.0400	106	251.4	0.2791	106	28.4962
107	251.4	0.2900	107	19.8400	107	161.4	0.3859	107	28.2208
108	112	0.1400	108	15.3800	108	251.4	0.1863	108	21.8779
109	112	0.1400	109	7.1250	109	251.4	0.1863	109	10.1423
110	161.4	0.6500	110	7.1250	110	161.4	0.8654	110	10.1450
111	112	0.3900	111	12.0000	111	161.4	0.5194	111	17.0936
112	161.4	0.4300	112	18.3200	112	161.4	0.5731	112	26.1845
113	112	0.0500	113	7.2100	113	161.4	0.0667	113	10.3131
114	161.4	0.0600	114	16.3500	114	161.4	0.0800	114	23.3910
115	112	0.1400	115	15.4000	115	161.4	0.1871	115	22.0617
116	112	0.0600	116	12.9200	116	161.4	0.0802	116	18.5127
117	251.4	0.2000	117	13.1900	117	251.4	0.2674	117	18.9151

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					**Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
118	161.4	0.1600	118	10.9700	118	251.4	0.2140	118	15.7483
119	112	0.1200	119	10.7900	119	251.4	0.1605	119	15.5013
120	161.4	0.2100	120	8.0700	120	251.4	0.2812	120	11.5958
121	112	0.0400	121	13.6200	121	251.4	0.0536	121	19.5730
122	161.4	0.2400	122	7.5270	122	161.4	0.3216	122	10.8170
123	161.4	0.0100	123	7.9000	123	251.4	0.0134	123	11.3608
124	161.4	0.0200	124	7.9800	124	251.4	0.0268	124	11.4759
125	161.4	0.1500	125	7.1230	125	161.4	0.2012	125	10.2480
126	112	0.4300	126	11.5200	126	161.4	0.5773	126	16.5741
127	112	0.1300	127	12.0100	127	161.4	0.1746	127	17.2816
128	251.4	0.2700	128	9.3200	128	161.4	0.3629	128	13.4307
129	161.4	0.1400	129	7.4900	129	161.4	0.1883	129	10.7940
130	112	0.1100	130	14.9000	130	161.4	0.1480	130	21.4741
131	112	0.1300	131	12.6100	131	161.4	0.1750	131	18.1984
132	251.4	0.1800	132	21.7400	132	251.4	0.2424	132	31.3907
133	161.4	0.1000	133	14.8700	133	251.4	0.1350	133	21.4759
134	112	0.3800	134	12.1600	134	251.4	0.5130	134	17.5664
135	161.4	0.3700	135	11.4500	135	251.4	0.4999	135	16.5484
136	112	0.1600	136	11.3300	136	251.4	0.2163	136	16.3752
137	161.4	0.2100	137	14.9700	137	251.4	0.2840	137	21.6389
138	161.4	0.1700	138	14.0800	138	251.4	0.2302	138	20.3924
139	161.4	0.2600	139	9.7100	139	161.4	0.3523	139	14.0663
140	161.4	0.1000	140	11.8200	140	251.4	0.1356	140	17.1443
141	112	0.0900	141	7.1230	141	251.4	0.1221	141	10.3365
142	112	0.3100	142	8.2800	142	161.4	0.4207	142	12.0161
143	251.4	0.1700	143	13.0200	143	161.4	0.2308	143	18.9107
144	112	0.2400	144	13.2100	144	161.4	0.3260	144	19.1885
145	161.4	0.1300	145	12.0700	145	161.4	0.1766	145	17.5361
146	112	0.0700	146	9.1700	146	161.4	0.0951	146	13.3283
147	112	0.0100	147	10.4200	147	161.4	0.0136	147	15.1555
148	251.4	0.5000	148	7.9600	148	161.4	0.6809	148	11.6033
149	161.4	0.1500	149	7.1245	149	251.4	0.2044	149	10.3875
150	112	0.2800	150	7.8300	150	251.4	0.3817	150	11.4271
151	161.4	0.0600	151	7.1240	151	251.4	0.0819	151	10.4026
152	112	0.3700	152	7.5100	152	251.4	0.5051	152	10.9757
153	161.4	0.2100	153	7.9800	153	251.4	0.2868	153	11.6659
154	161.4	0.2700	154	13.0700	154	161.4	0.3688	154	19.1128
155	161.4	0.1600	155	16.9800	155	251.4	0.2186	155	24.8393
156	161.4	0.1800	156	22.0500	156	251.4	0.2464	156	32.2844
157	112	0.2400	157	7.1245	157	161.4	0.3290	157	10.4328

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
158	112	0.0912	158	7.1245	158	251.4	0.1235	158	10.4418
159	251.4	0.0100	159	7.1254	159	251.4	0.0137	159	10.4522
160	112	0.1800	160	7.1700	160	251.4	0.2477	160	10.5195
161	161.4	0.0100	161	10.4400	161	251.4	0.0138	161	15.3239
162	112	0.1100	162	11.0100	162	251.4	0.1517	162	16.1640
163	112	0.3100	163	10.5000	163	161.4	0.4279	163	15.4156
164	251.4	0.1300	164	10.7900	164	251.4	0.1795	164	15.8543
165	161.4	0.2600	165	16.1800	165	251.4	0.3591	165	23.7905
166	112	0.0400	166	8.5600	166	161.4	0.0553	166	12.5950
167	161.4	0.2200	167	9.8800	167	161.4	0.3040	167	14.5524
168	112	0.2300	168	14.8500	168	161.4	0.3179	168	21.8758
169	161.4	0.1500	169	15.1600	169	161.4	0.2076	169	22.3373
170	161.4	0.0900	170	21.4100	170	161.4	0.1246	170	31.5768
171	161.4	0.2400	171	18.0600	171	161.4	0.3324	171	26.6406
172	161.4	0.4100	172	25.8800	172	161.4	0.5679	172	38.1871
173	112	0.2000	173	13.4000	173	251.4	0.2770	173	19.7796
174	112	0.3700	174	9.1300	174	251.4	0.5126	174	13.4957
175	251.4	0.1600	175	17.8100	175	251.4	0.2217	175	26.3328
176	112	0.3100	176	16.4300	176	251.4	0.4296	176	24.3071
177	161.4	0.1000	177	15.2200	177	251.4	0.1386	177	22.5279
178	112	0.0200	178	16.5600	178	161.4	0.0278	178	24.5291
179	112	0.2800	179	12.2600	179	251.4	0.3889	179	18.1740
180	251.4	0.4400	180	12.1100	180	251.4	0.6113	180	17.9675
181	161.4	0.0900	181	7.6000	181	161.4	0.1250	181	11.2784
182	112	0.0300	182	10.5400	182	251.4	0.0417	182	15.6489
183	161.4	0.2300	183	11.6300	183	251.4	0.3196	183	17.2727
184	112	0.1000	184	11.8600	184	251.4	0.1391	184	17.6172
185	161.4	0.1000	185	11.7000	185	251.4	0.1392	185	17.3798
186	161.4	0.1000	186	7.4000	186	251.4	0.1393	186	11.0244
187	161.4	0.1400	187	18.7100	187	161.4	0.1951	187	27.8792
188	161.4	0.0200	188	11.0200	188	251.4	0.0279	188	16.4220
189	112	0.4900	189	10.9200	189	251.4	0.6835	189	16.2739
190	112	0.1200	190	12.4300	190	161.4	0.1678	190	18.5299
191	251.4	0.1100	191	11.4700	191	161.4	0.1538	191	17.1021
192	112	0.5000	192	14.8100	192	161.4	0.6992	192	22.0879
193	161.4	0.0300	193	8.1600	193	161.4	0.0420	193	12.1720
194	112	0.0500	194	16.6300	194	161.4	0.0700	194	24.8103
195	112	0.1700	195	17.0200	195	161.4	0.2379	195	25.4094
196	251.4	0.3000	196	14.1000	196	161.4	0.4199	196	21.0548
197	161.4	0.2900	197	12.0500	197	251.4	0.4059	197	17.9982

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
198	112	0.1200	198	17.9600	198	251.4	0.1680	198	26.8357
199	161.4	0.0300	199	14.7400	199	251.4	0.0420	199	22.0432
200	112	0.3300	200	14.7000	200	251.4	0.4623	200	21.9842
201	161.4	0.5400	201	10.9900	201	251.4	0.7570	201	16.4389
202	161.4	0.2300	202	11.1600	202	161.4	0.3225	202	16.6935
203	161.4	0.0400	203	14.2500	203	251.4	0.0561	203	21.3187
204	161.4	0.1900	204	16.2700	204	251.4	0.2667	204	24.3427
205	112	0.2700	205	11.6700	205	161.4	0.3792	205	17.4642
206	112	0.2300	206	20.8400	206	251.4	0.3230	206	31.2127
207	251.4	0.2200	207	10.7500	207	251.4	0.3091	207	16.1026
208	112	0.2200	208	9.8200	208	251.4	0.3092	208	14.7213
209	161.4	0.0800	209	9.9900	209	251.4	0.1124	209	14.9793
210	112	0.2400	210	9.9800	210	251.4	0.3373	210	14.9646
211	112	0.1100	211	27.5790	211	161.4	0.1548	211	39.1271
212	251.4	0.0200	-	-	212	251.4	0.0282	-	-
213	161.4	0.2400	-	-	213	251.4	0.3381	-	-
214	112	0.2400	-	-	214	161.4	0.3381	-	-
215	161.4	0.4900	-	-	215	161.4	0.6908	-	-
216	112	0.1100	-	-	216	161.4	0.1551	-	-
217	161.4	0.1200	-	-	217	161.4	0.1694	-	-
218	161.4	0.0900	-	-	218	161.4	0.1271	-	-
219	161.4	0.0800	-	-	219	161.4	0.1131	-	-
220	161.4	0.3900	-	-	220	161.4	0.5513	-	-
221	251.4	2.7123	-	-	221	251.4	3.1718	-	-
222	161.4	0.2000	-	-	222	251.4	0.2831	-	-
223	112	0.1000	-	-	223	251.4	0.1416	-	-
224	112	0.3300	-	-	224	251.4	0.4674	-	-
225	251.4	0.4700	-	-	225	251.4	0.6660	-	-
226	161.4	0.2700	-	-	226	161.4	0.3837	-	-
227	112	0.1900	-	-	227	251.4	0.2708	-	-
228	161.4	0.0900	-	-	228	251.4	0.1284	-	-
229	112	0.1200	-	-	229	161.4	0.1713	-	-
230	161.4	0.0500	-	-	230	251.4	0.0714	-	-
231	112	0.0100	-	-	231	161.4	0.0858	-	-
232	161.4	0.1100	-	-	232	251.4	0.1572	-	-
233	161.4	0.1600	-	-	233	251.4	0.2287	-	-
234	112	0.3300	-	-	234	251.4	0.4718	-	-
235	161.4	0.0900	-	-	235	161.4	0.1288	-	-
236	112	0.0700	-	-	236	251.4	0.1002	-	-
237	112	0.0500	-	-	237	251.4	0.0716	-	-

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
238	251.4	0.0300	-	-	238	161.4	0.0430	-	-
239	161.4	0.0100	-	-	239	161.4	0.0143	-	-
240	112	0.2100	-	-	240	161.4	0.3018	-	-
241	161.4	0.0100	-	-	241	161.4	0.0144	-	-
242	112	0.3000	-	-	242	161.4	0.4318	-	-
243	161.4	0.0400	-	-	243	161.4	0.0576	-	-
244	161.4	0.1200	-	-	244	161.4	0.1732	-	-
245	161.4	0.0900	-	-	245	251.4	0.1300	-	-
246	161.4	0.0800	-	-	246	251.4	0.1156	-	-
247	112	0.1300	-	-	247	251.4	0.1879	-	-
248	161.4	0.0400	-	-	248	251.4	0.0578	-	-
249	112	0.3200	-	-	249	251.4	0.4628	-	-
250	112	0.1900	-	-	250	161.4	0.2752	-	-
251	251.4	0.1400	-	-	251	251.4	0.2032	-	-
252	161.4	0.1800	-	-	252	251.4	0.2612	-	-
253	112	0.2200	-	-	253	161.4	0.3194	-	-
254	161.4	0.1900	-	-	254	251.4	0.2761	-	-
255	112	0.1600	-	-	255	251.4	0.2327	-	-
256	161.4	0.2100	-	-	256	251.4	0.3066	-	-
257	161.4	0.1500	-	-	257	251.4	0.2191	-	-
258	161.4	0.1600	-	-	258	251.4	0.2337	-	-
259	161.4	0.2400	-	-	259	161.4	0.3506	-	-
260	112	0.1600	-	-	260	251.4	0.2339	-	-
261	161.4	0.1800	-	-	261	251.4	0.2635	-	-
262	112	0.3000	-	-	262	161.4	0.4392	-	-
263	112	0.1700	-	-	263	161.4	0.2490	-	-
264	251.4	0.0600	-	-	264	161.4	0.0879	-	-
265	161.4	0.0600	-	-	265	161.4	0.0880	-	-
266	112	0.2400	-	-	266	161.4	0.3520	-	-
267	161.4	0.0900	-	-	267	161.4	0.1321	-	-
268	112	0.1100	-	-	268	161.4	0.1614	-	-
269	161.4	0.1100	-	-	269	251.4	0.1616	-	-
270	161.4	0.1000	-	-	270	251.4	0.1472	-	-
271	161.4	0.0700	-	-	271	251.4	0.1031	-	-
272	161.4	0.0400	-	-	272	251.4	0.0589	-	-
273	112	0.1100	-	-	273	251.4	0.1621	-	-
274	161.4	0.5100	-	-	274	161.4	0.7516	-	-
275	112	0.1200	-	-	275	251.4	0.1770	-	-
276	112	0.2300	-	-	276	251.4	0.3392	-	-
277	251.4	0.2500	-	-	277	161.4	0.3687	-	-

Leftmost Extreme Point-CWS (Network Cost=3.0952 million rupees and Network Resilience=0.3541)					Leftmost Extreme Point-IWS (Network Cost= 3.4452 million rupees and Network Resilience=0.4111)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
278	161.4	0.2200	-	-	278	251.4	0.3247	-	-
279	112	0.1100	-	-	279	251.4	0.1624	-	-
280	161.4	0.2500	-	-	280	251.4	0.3693	-	-
281	112	1.7600	-	-	281	251.4	2.6026	-	-
282	161.4	0.4200	-	-	282	251.4	0.6212	-	-
283	161.4	0.0500	-	-	283	161.4	0.0740	-	-
284	161.4	0.1700	-	-	284	251.4	0.2516	-	-
285	161.4	0.1700	-	-	285	251.4	0.2516	-	-
286	112	0.0900	-	-	286	161.4	0.1334	-	-
287	161.4	0.1900	-	-	287	161.4	0.2818	-	-
288	112	0.0100	-	-	288	161.4	0.0148	-	-
289	112	0.1400	-	-	289	161.4	0.2077	-	-
290	251.4	0.2600	-	-	290	161.4	0.3864	-	-
291	161.4	0.2200	-	-	291	161.4	0.3271	-	-
292	112	0.3300	-	-	292	161.4	0.4910	-	-
293	161.4	0.2700	-	-	293	251.4	0.4018	-	-
294	112	0.3600	-	-	294	251.4	0.5364	-	-
295	161.4	0.3700	-	-	295	251.4	0.5516	-	-
296	161.4	0.0400	-	-	296	251.4	0.0597	-	-
297	161.4	0.0200	-	-	297	251.4	0.0299	-	-
298	161.4	0.0600	-	-	298	161.4	0.0899	-	-
299	112	0.0300	-	-	299	251.4	0.0449	-	-
300	161.4	0.0500	-	-	300	251.4	0.0749	-	-
301	161.4	0.0400	-	-	301	161.4	0.0600	-	-

Table A.6 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Rightmost Extreme Point for Vanasthalipuram WDN in CWS and IWS

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					**Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	251.4	1.8967	1	10.7494	1	251.4	2.3738	1	14.5429
2	251.4	0.0075	2	8.8901	2	251.4	0.0094	2	14.9216
3	251.4	0.0299	3	13.9633	3	251.4	0.0374	3	23.2040
4	251.4	0.4413	4	18.2607	4	251.4	0.5518	4	25.0631
5	251.4	0.2461	5	8.8474	5	251.4	0.3080	5	15.2365
6	251.4	0.3354	6	10.0311	6	251.4	0.4197	6	14.2242
7	251.4	0.1561	7	10.7400	7	251.4	0.1958	7	14.9064
8	251.4	0.1707	8	8.1789	8	251.4	0.2143	8	13.9808
9	251.4	0.0816	9	17.9919	9	251.4	0.1024	9	27.1956
10	251.4	0.0593	10	23.5120	10	251.4	0.0744	10	36.9320
11	251.4	0.0370	11	26.7548	11	251.4	0.0465	11	37.6113
12	251.4	0.1110	12	11.2362	12	251.4	0.1396	12	17.9666
13	251.4	0.1182	13	10.2856	13	251.4	0.1489	13	14.2961
14	251.4	0.0147	14	8.6580	14	251.4	0.0186	14	14.3016
15	251.4	0.0147	15	14.1742	15	251.4	0.0186	15	19.5181
16	251.4	0.3317	16	14.9918	16	251.4	0.4180	16	20.3526
17	251.4	0.0147	17	19.4945	17	251.4	0.0186	17	32.0659
18	251.4	0.2133	18	15.2141	18	251.4	0.2695	18	26.0824
19	251.4	0.2574	19	20.2367	19	251.4	0.3253	19	30.1946
20	251.4	0.0955	20	19.0415	20	251.4	0.1207	20	33.1019
21	251.4	0.2424	21	24.6228	21	251.4	0.3059	21	34.2886
22	251.4	0.1395	22	14.0927	22	251.4	0.1757	22	19.2547
23	251.4	0.0440	23	15.8683	23	251.4	0.0555	23	22.7892
24	251.4	0.5046	24	8.7944	24	251.4	0.6362	24	14.2904
25	251.4	0.0731	25	13.7793	25	251.4	0.0921	25	20.3948
26	251.4	0.1097	26	33.2836	26	251.4	0.1379	26	45.2548
27	251.4	0.0876	27	19.0099	27	251.4	0.1104	27	26.1175
28	251.4	0.1314	28	15.3109	28	251.4	0.1656	28	22.6240
29	251.4	0.0582	29	20.7249	29	251.4	0.0736	29	29.2424
30	251.4	0.0581	30	17.5427	30	251.4	0.0736	30	24.5069
31	251.4	0.0363	31	11.0645	31	251.4	0.0460	31	16.5745
32	251.4	0.3264	32	10.3637	32	251.4	0.4137	32	18.1699
33	251.4	0.0435	33	18.7177	33	251.4	0.0549	33	30.4985
34	251.4	0.0218	34	34.2471	34	251.4	0.0274	34	53.1296
35	251.4	0.2464	35	9.3093	35	251.4	0.3110	35	14.4552
36	251.4	0.0869	36	38.8549	36	251.4	0.1097	36	53.9117
37	251.4	0.0722	37	32.1352	37	251.4	0.0910	37	55.3414

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)				
Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)	Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)
38	251.4	0.0794	38	15.6844	38	251.4	0.1001	38	24.9916
39	251.4	0.0505	39	13.8165	39	251.4	0.0638	39	23.0690
40	251.4	0.1441	40	9.2214	40	251.4	0.1820	40	15.1225
41	251.4	0.0933	41	10.5917	41	251.4	0.1184	41	15.2855
42	251.4	0.1792	42	17.5622	42	251.4	0.2277	42	28.4694
43	251.4	0.1646	43	23.4037	43	251.4	0.2094	43	38.4900
44	251.4	0.0714	44	19.9614	44	251.4	0.0909	44	33.7683
45	251.4	0.1784	45	17.2429	45	251.4	0.2268	45	28.5150
46	251.4	0.0499	46	12.1498	46	251.4	0.0635	46	17.1803
47	251.4	0.0997	47	17.3891	47	251.4	0.1265	47	27.5412
48	251.4	0.0568	48	18.7940	48	251.4	0.0724	48	27.6030
49	251.4	0.1135	49	20.3752	49	251.4	0.1447	49	28.0430
50	251.4	0.1346	50	15.3314	50	251.4	0.1717	50	24.0017
51	251.4	0.2264	51	14.8573	51	251.4	0.2885	51	22.2036
52	251.4	0.0565	52	21.0446	52	251.4	0.0722	52	28.7760
53	251.4	0.0776	53	18.7172	53	251.4	0.0990	53	29.8363
54	251.4	0.0916	54	18.4848	54	251.4	0.1168	54	27.2367
55	251.4	0.0843	55	19.8728	55	251.4	0.1078	55	32.1409
56	251.4	0.1194	56	17.4908	56	251.4	0.1525	56	24.4332
57	251.4	0.3086	57	9.3005	57	251.4	0.3954	57	15.1417
58	251.4	0.1119	58	16.4193	58	251.4	0.1438	58	26.7328
59	251.4	0.2796	59	16.5385	59	251.4	0.3600	59	23.0328
60	251.4	0.1256	60	12.9209	60	251.4	0.1621	60	19.9837
61	251.4	0.1674	61	12.4573	61	251.4	0.2161	61	20.8603
62	251.4	0.2228	62	8.2060	62	251.4	0.2881	62	14.5015
63	251.4	0.1809	63	16.4018	63	251.4	0.2338	63	27.7844
64	251.4	0.0069	64	15.2833	64	251.4	0.0090	64	24.9506
65	251.4	0.1598	65	18.7151	65	251.4	0.2065	65	25.8431
66	251.4	0.1941	66	18.2593	66	251.4	0.2513	66	26.3179
67	251.4	0.1039	67	23.8053	67	251.4	0.1346	67	35.2875
68	251.4	0.3322	68	24.4945	68	251.4	0.4298	68	34.8367
69	251.4	0.2561	69	20.2379	69	251.4	0.3318	69	32.0445
70	251.4	0.2973	70	10.4025	70	251.4	0.3859	70	15.3065
71	251.4	0.1241	71	9.6405	71	251.4	0.1613	71	15.0308
72	251.4	0.4823	72	22.9377	72	251.4	0.6264	72	32.8148
73	251.4	0.0689	73	18.5299	73	251.4	0.0894	73	29.2753
74	251.4	0.1652	74	33.7646	74	251.4	0.2146	74	47.9102
75	251.4	0.0550	75	26.9483	75	251.4	0.0713	75	48.1189
76	251.4	0.0979	76	11.2096	76	251.4	0.1257	76	15.4089
77	251.4	0.3285	77	17.7601	77	251.4	0.4277	77	29.3586

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
78	251.4	0.0137	78	16.4966	78	251.4	0.0178	78	29.2742
79	251.4	0.0478	79	24.6423	79	251.4	0.0624	79	42.2392
80	251.4	0.0682	80	24.9998	80	251.4	0.0889	80	39.1926
81	251.4	0.0954	81	10.6032	81	251.4	0.1243	81	14.9948
82	251.4	0.0204	82	19.3501	82	251.4	0.0267	82	32.0102
83	251.4	0.0952	83	13.2616	83	251.4	0.1243	83	19.2620
84	251.4	0.0543	84	8.6513	84	251.4	0.0710	84	14.8047
85	251.4	0.2367	85	10.8258	85	251.4	0.3093	85	15.9481
86	251.4	0.1282	86	9.5196	86	251.4	0.1678	86	15.9569
87	251.4	0.1619	87	14.5916	87	251.4	0.2112	87	25.6734
88	251.4	0.0607	88	16.0206	88	251.4	0.0792	88	22.9453
89	251.4	0.0539	89	18.1850	89	251.4	0.0704	89	27.1430
90	251.4	0.2552	90	29.6474	90	251.4	0.3344	90	41.4651
91	251.4	0.0134	91	17.6233	91	251.4	0.0176	91	24.5593
92	251.4	0.0872	92	9.5245	92	251.4	0.1145	92	14.8528
93	251.4	0.0067	93	21.4636	93	251.4	0.0088	93	30.5078
94	251.4	0.2539	94	23.7029	94	251.4	0.3344	94	37.5475
95	251.4	0.2337	95	35.2340	95	251.4	0.3080	95	50.3027
96	251.4	0.0934	96	16.9003	96	251.4	0.1233	96	30.4421
97	251.4	0.0667	97	30.6173	97	251.4	0.0880	97	53.4853
98	251.4	0.2599	98	19.5037	98	251.4	0.3432	98	28.8957
99	251.4	0.3398	99	18.8525	99	251.4	0.4480	99	30.6344
100	251.4	0.5994	100	20.3339	100	251.4	0.7909	100	33.0228
101	251.4	0.0532	101	28.1110	101	251.4	0.0703	101	43.2098
102	251.4	0.0199	102	8.4062	102	251.4	0.0264	102	15.1779
103	251.4	0.1460	103	15.4282	103	251.4	0.1934	103	25.1058
104	251.4	0.1855	104	9.8736	104	251.4	0.2462	104	17.6701
105	251.4	0.0990	105	15.6527	105	251.4	0.1322	105	23.5681
106	251.4	0.1382	106	26.6960	106	251.4	0.1851	106	41.9924
107	251.4	0.1909	107	23.3443	107	251.4	0.2556	107	41.5865
108	251.4	0.0920	108	19.8739	108	251.4	0.1231	108	32.2395
109	251.4	0.0918	109	9.2666	109	251.4	0.1227	109	14.9459
110	251.4	0.4261	110	9.8379	110	251.4	0.5698	110	14.9497
111	251.4	0.2556	111	14.7172	111	251.4	0.3411	111	25.1893
112	251.4	0.2818	112	21.5879	112	251.4	0.3758	112	38.5858
113	251.4	0.0327	113	9.4717	113	251.4	0.0437	113	15.1974
114	251.4	0.0392	114	22.9723	114	251.4	0.0524	114	34.4693
115	251.4	0.0915	115	21.0194	115	251.4	0.1224	115	32.5104
116	251.4	0.0392	116	18.9305	116	251.4	0.0523	116	27.2804
117	251.4	0.1300	117	16.3355	117	251.4	0.1743	117	27.8734

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					**Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
118	251.4	0.1040	118	13.4606	118	251.4	0.1394	118	23.2069
119	251.4	0.0779	119	13.2990	119	251.4	0.1046	119	22.8428
120	251.4	0.1362	120	11.5687	120	251.4	0.1828	120	17.0877
121	251.4	0.0259	121	19.0114	121	251.4	0.0347	121	28.8430
122	251.4	0.1554	122	10.9704	122	251.4	0.2080	122	15.9400
123	251.4	0.0065	123	11.0509	123	251.4	0.0087	123	16.7413
124	251.4	0.0129	124	11.0234	124	251.4	0.0173	124	16.9111
125	251.4	0.0969	125	9.2873	125	251.4	0.1300	125	15.1016
126	251.4	0.2770	126	15.5172	126	251.4	0.3719	126	24.4237
127	251.4	0.0837	127	17.9743	127	251.4	0.1124	127	25.4664
128	251.4	0.1737	128	13.8408	128	251.4	0.2333	128	19.7917
129	251.4	0.0901	129	9.4965	129	251.4	0.1210	129	15.9061
130	251.4	0.0703	130	17.9457	130	251.4	0.0951	130	31.6445
131	251.4	0.0831	131	16.3423	131	251.4	0.1124	131	26.8174
132	251.4	0.1147	132	29.2200	132	251.4	0.1555	132	46.2577
133	251.4	0.0637	133	17.2553	133	251.4	0.0865	133	31.6471
134	251.4	0.2419	134	17.6727	134	251.4	0.3280	134	25.8861
135	251.4	0.2348	135	16.7519	135	251.4	0.3189	135	24.3859
136	251.4	0.1012	136	15.0011	136	251.4	0.1379	136	24.1306
137	251.4	0.1328	137	18.3121	137	251.4	0.1810	137	31.8873
138	251.4	0.1071	138	19.7480	138	251.4	0.1463	138	30.0504
139	251.4	0.1631	139	13.5445	139	251.4	0.2229	139	20.7283
140	251.4	0.0627	140	15.4991	140	251.4	0.0857	140	25.2640
141	251.4	0.0562	141	8.6167	141	251.4	0.0771	141	15.2319
142	251.4	0.1934	142	11.8241	142	251.4	0.2637	142	17.7071
143	251.4	0.1059	143	19.0219	143	251.4	0.1446	143	27.8670
144	251.4	0.1494	144	15.8504	144	251.4	0.2040	144	28.2764
145	251.4	0.0809	145	17.8501	145	251.4	0.1105	145	25.8414
146	251.4	0.0435	146	10.5463	146	251.4	0.0595	146	19.6407
147	251.4	0.0062	147	13.5833	147	251.4	0.0085	147	22.3332
148	251.4	0.3101	148	9.1851	148	251.4	0.4250	148	17.0988
149	251.4	0.0930	149	8.7780	149	251.4	0.1275	149	15.3071
150	251.4	0.1735	150	10.9420	150	251.4	0.2378	150	16.8392
151	251.4	0.0372	151	9.9234	151	251.4	0.0510	151	15.3294
152	251.4	0.2291	152	9.3334	152	251.4	0.3144	152	16.1738
153	251.4	0.1300	153	10.0891	153	251.4	0.1784	153	17.1910
154	251.4	0.1664	154	15.4570	154	251.4	0.2293	154	28.1648
155	251.4	0.0985	155	19.7742	155	251.4	0.1358	155	36.6035
156	251.4	0.1108	156	31.2172	156	251.4	0.1530	156	47.5746
157	251.4	0.1477	157	9.0033	157	251.4	0.2040	157	15.3739

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
158	251.4	0.1200	158	9.4944	158	251.4	0.1579	158	15.3871
159	251.4	0.0061	159	10.5681	159	251.4	0.0085	159	15.4025
160	251.4	0.1102	160	9.9243	160	251.4	0.1529	160	15.5017
161	251.4	0.0061	161	13.7348	161	251.4	0.0084	161	22.5814
162	251.4	0.0670	162	15.1639	162	251.4	0.0928	162	23.8195
163	251.4	0.1889	163	14.5212	163	251.4	0.2612	163	22.7166
164	251.4	0.0792	164	13.2777	164	251.4	0.1095	164	23.3631
165	251.4	0.1584	165	23.1651	165	251.4	0.2187	165	35.0579
166	251.4	0.0244	166	11.3503	166	251.4	0.0336	166	18.5602
167	251.4	0.1339	167	12.8629	167	251.4	0.1849	167	21.4446
168	251.4	0.1400	168	20.7627	168	251.4	0.1931	168	32.2364
169	251.4	0.0913	169	20.3802	169	251.4	0.1260	169	32.9165
170	251.4	0.0547	170	26.5324	170	251.4	0.0755	170	46.5319
171	251.4	0.1453	171	21.2443	171	251.4	0.2014	171	39.2579
172	251.4	0.2483	172	35.0981	172	251.4	0.3435	172	56.2730
173	251.4	0.1211	173	18.5722	173	251.4	0.1675	173	29.1475
174	251.4	0.2240	174	12.3785	174	251.4	0.3093	174	19.8875
175	251.4	0.0967	175	23.8083	175	251.4	0.1336	175	38.8043
176	251.4	0.1872	176	21.6123	176	251.4	0.2587	176	35.8192
177	251.4	0.0604	177	19.2279	177	251.4	0.0835	177	33.1973
178	251.4	0.0121	178	21.5420	178	251.4	0.0167	178	36.1464
179	251.4	0.1689	179	17.3812	179	251.4	0.2338	179	26.7814
180	251.4	0.2644	180	18.1500	180	251.4	0.3668	180	26.4772
181	251.4	0.0540	181	9.4449	181	251.4	0.0750	181	16.6200
182	251.4	0.0180	182	15.0429	182	251.4	0.0250	182	23.0604
183	251.4	0.1378	183	13.9224	183	251.4	0.1905	183	25.4532
184	251.4	0.0599	184	13.7865	184	251.4	0.0829	184	25.9609
185	251.4	0.0598	185	15.3139	185	251.4	0.0829	185	25.6110
186	251.4	0.0596	186	9.9681	186	251.4	0.0830	186	16.2456
187	251.4	0.0834	187	23.0284	187	251.4	0.1159	187	41.0831
188	251.4	0.0119	188	13.2313	188	251.4	0.0166	188	24.1996
189	251.4	0.2913	189	15.1459	189	251.4	0.4057	189	23.9814
190	251.4	0.0713	190	15.8349	190	251.4	0.0995	190	27.3058
191	251.4	0.0653	191	15.2398	191	251.4	0.0910	191	25.2018
192	251.4	0.2966	192	20.6325	192	251.4	0.4137	192	32.5489
193	251.4	0.0178	193	11.0842	193	251.4	0.0248	193	17.9369
194	251.4	0.0296	194	22.0703	194	251.4	0.0412	194	36.5607
195	251.4	0.1004	195	24.1980	195	251.4	0.1399	195	37.4436
196	251.4	0.1771	196	19.5965	196	251.4	0.2467	196	31.0266
197	251.4	0.1711	197	15.2050	197	251.4	0.2384	197	26.5223

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					**Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
198	251.4	0.0708	198	25.8849	198	251.4	0.0986	198	39.5454
199	251.4	0.0176	199	20.3602	199	251.4	0.0247	199	32.4831
200	251.4	0.1936	200	19.9255	200	251.4	0.2711	200	32.3961
201	251.4	0.3163	201	12.7119	201	251.4	0.4434	201	24.2246
202	251.4	0.1345	202	16.1031	202	251.4	0.1888	202	24.5998
203	251.4	0.0233	203	16.9561	203	251.4	0.0328	203	31.4155
204	251.4	0.1106	204	23.4963	204	251.4	0.1561	204	35.8717
205	251.4	0.1571	205	14.7990	205	251.4	0.2212	205	25.7354
206	251.4	0.1338	206	27.0983	206	251.4	0.1882	206	45.9953
207	251.4	0.1279	207	15.3491	207	251.4	0.1800	207	23.7290
208	251.4	0.1273	208	11.7796	208	251.4	0.1793	208	21.6934
209	251.4	0.0461	209	13.6147	209	251.4	0.0652	209	22.0736
210	251.4	0.1383	210	14.7277	210	251.4	0.1950	210	22.0520
211	251.4	0.0632	211	39.1241	211	251.4	0.0894	211	57.1212
212	251.4	0.0115	-	-	212	251.4	0.0163	-	-
213	251.4	0.1377	-	-	213	251.4	0.1951	-	-
214	251.4	0.1371	-	-	214	251.4	0.1951	-	-
215	251.4	0.2795	-	-	215	251.4	0.3986	-	-
216	251.4	0.0626	-	-	216	251.4	0.0895	-	-
217	251.4	0.0682	-	-	217	251.4	0.0977	-	-
218	251.4	0.0511	-	-	218	251.4	0.0731	-	-
219	251.4	0.0454	-	-	219	251.4	0.0650	-	-
220	251.4	0.2206	-	-	220	251.4	0.3167	-	-
221	251.4	1.9171	-	-	221	251.4	2.4171	-	-
222	251.4	0.1130	-	-	222	251.4	0.1623	-	-
223	251.4	0.0565	-	-	223	251.4	0.0811	-	-
224	251.4	0.1860	-	-	224	251.4	0.2678	-	-
225	251.4	0.2639	-	-	225	251.4	0.3807	-	-
226	251.4	0.1516	-	-	226	251.4	0.2190	-	-
227	251.4	0.1066	-	-	227	251.4	0.1543	-	-
228	251.4	0.0505	-	-	228	251.4	0.0731	-	-
229	251.4	0.0672	-	-	229	251.4	0.0974	-	-
230	251.4	0.0280	-	-	230	251.4	0.0406	-	-
231	251.4	0.0049	-	-	231	251.4	0.0051	-	-
232	251.4	0.0614	-	-	232	251.4	0.0887	-	-
233	251.4	0.0892	-	-	233	251.4	0.1288	-	-
234	251.4	0.1833	-	-	234	251.4	0.2654	-	-
235	251.4	0.0500	-	-	235	251.4	0.0722	-	-
236	251.4	0.0389	-	-	236	251.4	0.0562	-	-
237	251.4	0.0277	-	-	237	251.4	0.0401	-	-

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					**Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
238	251.4	0.0165	-	-	238	251.4	0.0241	-	-
239	251.4	0.0055	-	-	239	251.4	0.0080	-	-
240	251.4	0.1155	-	-	240	251.4	0.1685	-	-
241	251.4	0.0055	-	-	241	251.4	0.0080	-	-
242	251.4	0.1647	-	-	242	251.4	0.2408	-	-
243	251.4	0.0219	-	-	243	251.4	0.0321	-	-
244	251.4	0.0656	-	-	244	251.4	0.0962	-	-
245	251.4	0.0492	-	-	245	251.4	0.0722	-	-
246	251.4	0.0435	-	-	246	251.4	0.0639	-	-
247	251.4	0.0707	-	-	247	251.4	0.1039	-	-
248	251.4	0.0217	-	-	248	251.4	0.0319	-	-
249	251.4	0.1733	-	-	249	251.4	0.2554	-	-
250	251.4	0.1026	-	-	250	251.4	0.1515	-	-
251	251.4	0.0756	-	-	251	251.4	0.1117	-	-
252	251.4	0.0969	-	-	252	251.4	0.1435	-	-
253	251.4	0.1184	-	-	253	251.4	0.1746	-	-
254	251.4	0.1018	-	-	254	251.4	0.1505	-	-
255	251.4	0.0857	-	-	255	251.4	0.1264	-	-
256	251.4	0.1125	-	-	256	251.4	0.1664	-	-
257	251.4	0.0803	-	-	257	251.4	0.1188	-	-
258	251.4	0.0855	-	-	258	251.4	0.1263	-	-
259	251.4	0.1282	-	-	259	251.4	0.1892	-	-
260	251.4	0.0851	-	-	260	251.4	0.1262	-	-
261	251.4	0.0957	-	-	261	251.4	0.1420	-	-
262	251.4	0.1586	-	-	262	251.4	0.2368	-	-
263	251.4	0.0898	-	-	263	251.4	0.1337	-	-
264	251.4	0.0316	-	-	264	251.4	0.0472	-	-
265	251.4	0.0316	-	-	265	251.4	0.0471	-	-
266	251.4	0.1265	-	-	266	251.4	0.1873	-	-
267	251.4	0.0474	-	-	267	251.4	0.0702	-	-
268	251.4	0.0579	-	-	268	251.4	0.0856	-	-
269	251.4	0.0579	-	-	269	251.4	0.0852	-	-
270	251.4	0.0526	-	-	270	251.4	0.0776	-	-
271	251.4	0.0367	-	-	271	251.4	0.0540	-	-
272	251.4	0.0209	-	-	272	251.4	0.0309	-	-
273	251.4	0.0575	-	-	273	251.4	0.0849	-	-
274	251.4	0.2663	-	-	274	251.4	0.3926	-	-
275	251.4	0.0626	-	-	275	251.4	0.0923	-	-
276	251.4	0.1197	-	-	276	251.4	0.1769	-	-
277	251.4	0.1296	-	-	277	251.4	0.1919	-	-

Rightmost Extreme Point-CWS (Network Cost=5.7930 million rupees and Network Resilience=0.4913)					Rightmost Extreme Point-IWS (Network Cost=5.7930 million rupees and Network Resilience=0.5443)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
278	251.4	0.1140	-	-	278	251.4	0.1689	-	-
279	251.4	0.0570	-	-	279	251.4	0.0844	-	-
280	251.4	0.1293	-	-	280	251.4	0.1918	-	-
281	251.4	0.9090	-	-	281	251.4	1.3507	-	-
282	251.4	0.2168	-	-	282	251.4	0.3223	-	-
283	251.4	0.0257	-	-	283	251.4	0.0384	-	-
284	251.4	0.0874	-	-	284	251.4	0.1304	-	-
285	251.4	0.0869	-	-	285	251.4	0.1301	-	-
286	251.4	0.0460	-	-	286	251.4	0.0687	-	-
287	251.4	0.0970	-	-	287	251.4	0.1451	-	-
288	251.4	0.0051	-	-	288	251.4	0.0076	-	-
289	251.4	0.0712	-	-	289	251.4	0.1067	-	-
290	251.4	0.1322	-	-	290	251.4	0.1984	-	-
291	251.4	0.1117	-	-	291	251.4	0.1676	-	-
292	251.4	0.1675	-	-	292	251.4	0.2513	-	-
293	251.4	0.1369	-	-	293	251.4	0.2056	-	-
294	251.4	0.1821	-	-	294	251.4	0.2744	-	-
295	251.4	0.1870	-	-	295	251.4	0.2820	-	-
296	251.4	0.0202	-	-	296	251.4	0.0304	-	-
297	251.4	0.0101	-	-	297	251.4	0.0152	-	-
298	251.4	0.0302	-	-	298	251.4	0.0455	-	-
299	251.4	0.0151	-	-	299	251.4	0.0227	-	-
300	251.4	0.0251	-	-	300	251.4	0.0377	-	-
301	251.4	0.0201	-	-	301	251.4	0.0302	-	-

Table A.7 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point and Rightmost Extreme Point for Pamapur WDN (IWS)

Leftmost Extreme Point (Network Cost=1.3201 million rupees, Network Resilience=0.4551 and Network Equity=0.7591)					**Rightmost Extreme Point (Network Cost=3.4126 million rupees, Network Resilience=0.8829 and Network Equity=0.9799)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	98.6	0.1315	1	10.9280	1	251.4	0.1185	1	11.8830
2	125.4	0.6571	2	11.7914	2	251.4	0.5895	2	12.5744
3	125.4	0.4900	3	14.7439	3	251.4	0.4401	3	15.6046
4	125.4	0.9451	4	10.9232	4	251.4	0.8432	4	11.8702
5	125.4	0.7788	5	13.4650	5	251.4	0.6945	5	14.2667
6	98.6	0.3947	6	16.1062	6	251.4	0.3538	6	17.3076
7	80.4	0.5158	7	17.5606	7	251.4	0.4608	7	18.6684
8	80.4	0.0118	8	16.1196	8	251.4	0.0105	8	17.3729
9	98.6	0.1080	9	14.4344	9	251.4	0.0964	9	15.5066
10	98.6	1.5453	10	13.5537	10	251.4	1.3635	10	14.7893
11	98.6	0.1081	11	12.9866	11	251.4	0.0962	11	14.1223
12	125.4	0.6227	12	15.6075	12	251.4	0.5530	12	16.8439
13	80.4	1.1403	13	17.4459	13	251.4	1.0023	13	19.0153
14	80.4	0.5763	14	13.2896	14	251.4	0.5074	14	14.2179
15	98.6	0.1800	15	16.3363	15	251.4	0.1591	15	17.4956
16	98.6	0.7193	16	15.9356	16	251.4	0.6324	16	17.1154
17	98.6	0.0120	17	17.2872	17	251.4	0.0106	17	18.6234
18	98.6	1.0069	18	18.6212	18	251.4	0.8833	18	20.3904
19	98.6	0.0962	19	13.4332	19	251.4	0.0847	19	14.5810
20	98.6	0.3603	20	15.6894	20	251.4	0.3169	20	16.6517
21	98.6	0.2042	21	11.4201	21	251.4	0.1798	21	12.4848
22	98.6	0.4569	22	12.7296	22	251.4	0.4006	22	13.8998
23	80.4	0.0843	23	10.5692	23	251.4	0.0740	23	11.4084
24	80.4	0.3848	24	19.0257	24	251.4	0.3366	24	21.8196
25	80.4	0.0843	25	15.2095	25	251.4	0.0738	25	16.1788
26	80.4	0.0722	26	15.6390	26	251.4	0.0631	26	17.0643
27	112	0.8794	27	14.6086	27	251.4	0.7633	27	15.9240
28	98.6	0.0722	28	13.6788	28	251.4	0.0632	28	15.0609
29	98.6	0.0842	29	16.6189	29	251.4	0.0737	29	18.2240
30	98.6	0.0722	30	13.5330	30	251.4	0.0629	30	14.7555
31	66.8	0.1084	31	15.2504	31	251.4	0.0941	31	16.5258
32	98.6	0.8802	32	13.7648	32	251.4	0.7576	32	15.1617
33	66.8	0.8801	33	14.0328	33	251.4	0.7581	33	15.4227
34	98.6	0.0604	34	15.4558	34	251.4	0.0521	34	16.8103
35	98.6	0.3380	35	14.7074	35	251.4	0.2909	35	15.9940
36	98.6	0.2535	36	15.9228	36	251.4	0.2180	36	17.1877
37	98.6	0.0604	37	17.1446	37	251.4	0.0520	37	18.5878
38	98.6	0.3990	38	11.2905	38	251.4	0.3416	38	12.0664
39	125.4	1.3667	39	10.1311	39	251.4	1.1587	39	11.1580
40	112	1.1956	40	10.7020	40	251.4	1.0161	40	11.6524

Leftmost Extreme Point (Network Cost=1.3201 million rupees, Network Resilience=0.4551 and Network Equity=0.7591)					Rightmost Extreme Point (Network Cost=3.4126 million rupees, Network Resilience=0.8829 and Network Equity=0.9799)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
41	98.6	0.0362	41	11.2335	41	251.4	0.0311	41	12.4420
42	98.6	0.6159	42	9.8789	42	251.4	0.5256	42	10.7600
43	66.8	0.6660	43	11.8157	43	251.4	0.5651	43	12.9406
44	66.8	0.0605	44	11.9399	44	251.4	0.0515	44	12.8941
45	98.6	0.7261	45	13.6331	45	251.4	0.6143	45	14.9402
46	98.6	0.2665	46	12.7807	46	251.4	0.2258	46	14.2198
47	98.6	1.7924	47	12.8382	47	251.4	1.4983	47	14.2226
48	98.6	0.0605	48	15.2911	48	251.4	0.0513	48	17.1551
49	98.6	0.5937	49	11.1204	49	251.4	0.5001	49	12.1886
50	112	0.1938	50	10.3996	50	251.4	0.1636	50	11.4901
51	98.6	0.3146	51	10.3013	51	201.8	0.2652	51	11.4001
52	98.6	0.0485	52	10.6694	52	201.8	0.0408	52	11.6668
53	98.6	0.0726	53	15.4232	53	201.8	0.0611	53	17.1195
54	125.4	0.9808	54	13.2542	54	251.4	0.8180	54	14.6253
55	125.4	0.7663	55	15.7972	55	251.4	0.6385	55	17.4247
56	125.4	1.4559	56	12.6667	56	251.4	1.2065	56	13.7320
57	98.6	0.7168	57	13.7493	57	251.4	0.5968	57	15.5614
58	98.6	0.0487	58	13.6155	58	251.4	0.0407	58	14.7983
59	66.8	0.2316	59	8.5917	59	251.4	0.1931	59	9.7077
60	66.8	0.2563	60	14.0145	60	251.4	0.2134	60	15.2197
61	112	0.5983	61	13.9940	61	251.4	0.4963	61	15.7026
62	98.6	0.1586	62	16.5597	62	251.4	0.1322	62	18.6437
63	98.6	1.0614	63	15.2500	63	251.4	0.8779	63	16.8813
64	98.6	0.3657	64	12.6556	64	251.4	0.3045	64	14.0688
65	98.6	0.1708	65	11.3309	65	251.4	0.1422	65	12.6491
66	143.4	0.9396	66	13.8655	66	251.4	0.7766	66	15.0502
67	98.6	0.0367	67	15.0508	67	251.4	0.0305	67	16.4618
68	98.6	0.0367	68	8.6105	68	251.4	0.0303	68	9.7125
69	98.6	0.0366	69	14.6741	69	251.4	0.0302	69	16.0318
70	98.6	0.0367	70	13.1174	70	251.4	0.0301	70	14.4072
71	98.6	0.2076	71	13.1533	71	251.4	0.1702	71	14.9782
72	98.6	0.0367	72	14.9846	72	251.4	0.0301	72	16.6765
73	112	1.0264	73	15.1050	73	251.4	0.8344	73	16.9480
74	98.6	0.1952	74	13.9876	74	251.4	0.1600	74	15.8981
75	143.4	1.3691	75	14.0499	75	251.4	1.1027	75	16.0835
76	98.6	0.0367	76	13.3484	76	251.4	0.0298	76	14.9628
77	98.6	0.0367	77	13.8120	77	251.4	0.0298	77	15.4827
78	143.4	1.2230	78	14.2463	78	251.4	0.9844	78	16.0858
79	98.6	0.0734	79	15.6183	79	251.4	0.0596	79	17.7020
80	98.6	0.4652	80	14.4082	80	251.4	0.3747	80	16.0146
81	98.6	0.0245	81	16.3084	81	251.4	0.0198	81	18.2065
82	98.6	0.1101	82	15.1242	82	251.4	0.0888	82	16.7972
83	98.6	0.0245	83	13.3309	83	251.4	0.0197	83	14.7750

Leftmost Extreme Point (Network Cost=1.3201 million rupees, Network Resilience=0.4551 and Network Equity=0.7591)					Rightmost Extreme Point (Network Cost=3.4126 million rupees, Network Resilience=0.8829 and Network Equity=0.9799)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
84	98.6	0.7588	84	13.7551	84	251.4	0.6066	84	15.7448
85	98.6	0.9563	85	13.0122	85	251.4	0.7615	85	14.5586
86	98.6	0.6851	86	13.2297	86	251.4	0.5476	86	14.8865
87	98.6	0.1348	87	14.6457	87	251.4	0.1079	87	16.4066
88	98.6	0.4902	88	14.3171	88	251.4	0.3912	88	15.9377
89	98.6	0.2938	89	14.3299	89	251.4	0.2352	89	16.4039
90	98.6	0.6003	90	14.7867	90	251.4	0.4781	90	16.5963
91	98.6	0.0858	91	15.3636	91	251.4	0.0684	91	17.2091
92	143.4	0.9207	92	15.2545	92	251.4	0.7261	92	17.0272
93	98.6	0.7240	93	16.3821	93	251.4	0.5724	93	18.6563
94	98.6	0.7003	94	17.2388	94	251.4	0.5523	94	19.1454
95	98.6	0.9709	95	16.6147	95	251.4	0.7614	95	18.5106
96	98.6	0.6753	96	16.3005	96	251.4	0.5312	96	18.6018
97	98.6	0.5042	97	18.1732	97	201.8	0.3948	97	20.1517
98	66.8	0.4800	98	18.5388	98	201.8	0.3757	98	20.6504
99	66.8	0.2216	99	16.1021	99	201.8	0.1732	99	18.3642
100	112	0.7761	100	15.6845	100	201.8	0.6039	100	18.0872
101	143.4	1.2825	101	16.0282	101	201.8	0.9925	101	18.5678
102	224.4	1.2684	102	16.0750	102	251.4	0.9829	102	18.6935
103	179.4	1.9438	-	-	103	251.4	1.4986	-	-
104	179.4	1.2068	-	-	104	251.4	0.9345	-	-
105	251.4	1.9903	-	-	105	251.4	1.5252	-	-
106	179.4	1.1588	-	-	106	251.4	0.8921	-	-
107	98.6	0.7413	-	-	107	251.4	0.5706	-	-
108	201.8	1.6522	-	-	108	251.4	1.2645	-	-
109	98.6	0.7656	-	-	109	251.4	0.5883	-	-
110	98.6	0.8893	-	-	110	251.4	0.6813	-	-
111	66.8	0.2097	-	-	111	251.4	0.1613	-	-
112	66.8	0.3582	-	-	112	251.4	0.2744	-	-
113	66.8	0.2101	-	-	113	251.4	0.1609	-	-
114	112	1.2474	-	-	114	251.4	0.9451	-	-
115	179.4	1.2613	-	-	115	251.4	0.9527	-	-
116	98.6	0.1855	-	-	116	251.4	0.1411	-	-
117	98.6	0.1360	-	-	117	251.4	0.1034	-	-
118	179.4	1.1018	-	-	118	251.4	0.8304	-	-
119	98.6	0.1731	-	-	119	251.4	0.1314	-	-
120	98.6	1.0524	-	-	120	251.4	0.7919	-	-
121	98.6	0.9784	-	-	121	251.4	0.7366	-	-
122	98.6	0.4333	-	-	122	251.4	0.3272	-	-

Table A.8 Comparison of Optimal Pipe Diameter, Velocity and Node Pressure representing Leftmost Extreme Point and Rightmost Extreme Point for Vanasthalipuram WDN (IWS)

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					**Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
1	251.4	2.9915	1	10.7035	1	251.4	2.2083	1	15.7727
2	251.4	0.0119	2	10.9446	2	251.4	0.0087	2	16.1281
3	161.4	0.0470	3	17.0472	3	251.4	0.0355	3	25.1210
4	251.4	0.7019	4	18.2901	4	251.4	0.5201	4	26.9524
5	251.4	0.3876	5	11.1857	5	251.4	0.2878	5	16.4834
6	251.4	0.5272	6	10.4955	6	251.4	0.3970	6	15.4663
7	251.4	0.2484	7	11.0109	7	251.4	0.1846	7	16.2258
8	251.4	0.2724	8	10.4015	8	251.4	0.2026	8	15.2254
9	251.4	0.1303	9	19.7715	9	251.4	0.0973	9	29.1355
10	251.4	0.0938	10	27.2909	10	251.4	0.0704	10	40.2161
11	251.4	0.0591	11	27.5634	11	251.4	0.0438	11	40.6177
12	251.4	0.1789	12	13.0623	12	251.4	0.1307	12	19.2487
13	251.4	0.1907	13	10.4103	13	251.4	0.1401	13	15.3407
14	251.4	0.0239	14	10.4420	14	251.4	0.0176	14	15.3874
15	251.4	0.0238	15	14.2169	15	251.4	0.0174	15	20.9502
16	161.4	0.5349	16	14.9813	16	251.4	0.3964	16	22.0766
17	161.4	0.0237	17	23.6662	17	251.4	0.0176	17	34.8747
18	251.4	0.3473	18	19.2400	18	251.4	0.2513	18	28.3523
19	251.4	0.4142	19	22.1999	19	251.4	0.3046	19	32.7140
20	251.4	0.1550	20	24.3943	20	251.4	0.1134	20	35.9477
21	251.4	0.3913	21	24.9440	21	251.4	0.2868	21	36.7577
22	251.4	0.2265	22	14.1176	22	251.4	0.1640	22	20.8038
23	251.4	0.0711	23	16.5656	23	251.4	0.0527	23	24.4112
24	251.4	0.8263	24	10.5341	24	251.4	0.5977	24	15.5232
25	251.4	0.1199	25	14.9045	25	251.4	0.0868	25	21.9635
26	161.4	0.1800	26	33.3690	26	251.4	0.1309	26	49.1729
27	251.4	0.1417	27	19.2211	27	251.4	0.1033	27	28.3244
28	251.4	0.2126	28	16.5310	28	251.4	0.1547	28	24.3603
29	251.4	0.0946	29	21.3171	29	251.4	0.0689	29	31.4131
30	251.4	0.0956	30	17.9077	30	251.4	0.0698	30	26.3890
31	251.4	0.0602	31	12.1382	31	251.4	0.0434	31	17.8869
32	251.4	0.5395	32	13.3237	32	251.4	0.3858	32	19.6339
33	251.4	0.0714	33	22.3113	33	251.4	0.0514	33	32.8781
34	251.4	0.0356	34	39.1200	34	251.4	0.0259	34	57.6476
35	251.4	0.4042	35	10.5013	35	251.4	0.2953	35	15.4748
36	251.4	0.1425	36	39.4198	36	251.4	0.1037	36	58.0895
37	251.4	0.1208	37	40.3240	37	251.4	0.0851	37	59.4219
38	251.4	0.1331	38	18.2727	38	251.4	0.0942	38	26.9269
39	161.4	0.0848	39	16.8541	39	251.4	0.0594	39	24.8364

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					**Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
40	251.4	0.2419	40	10.9844	40	251.4	0.1726	40	16.1867
41	251.4	0.1558	41	11.2411	41	251.4	0.1124	41	16.5650
42	251.4	0.3034	42	20.9316	42	251.4	0.2135	42	30.8450
43	251.4	0.2770	43	28.3831	43	251.4	0.1981	43	41.8256
44	251.4	0.1217	44	24.7194	44	251.4	0.0850	44	36.4268
45	161.4	0.3016	45	20.9510	45	251.4	0.2123	45	30.8736
46	161.4	0.0847	46	12.6298	46	251.4	0.0598	46	18.6114
47	251.4	0.1680	47	20.1309	47	251.4	0.1196	47	29.6651
48	251.4	0.0980	48	20.1621	48	251.4	0.0680	48	29.7111
49	251.4	0.1945	49	20.6247	49	251.4	0.1352	49	30.3929
50	161.4	0.2321	50	17.4364	50	251.4	0.1605	50	25.6945
51	161.4	0.3916	51	16.4054	51	251.4	0.2719	51	24.1752
52	161.4	0.0964	52	21.1391	52	251.4	0.0680	52	31.1509
53	251.4	0.1339	53	21.7191	53	251.4	0.0921	53	32.0055
54	251.4	0.1578	54	20.1237	54	251.4	0.1089	54	29.6545
55	251.4	0.1472	55	23.5418	55	251.4	0.1008	55	34.6915
56	251.4	0.2063	56	18.0506	56	251.4	0.1442	56	26.5995
57	251.4	0.5370	57	11.1945	57	251.4	0.3751	57	16.4963
58	251.4	0.1945	58	19.5141	58	251.4	0.1364	58	28.7561
59	251.4	0.4929	59	16.8927	59	251.4	0.3401	59	24.8933
60	251.4	0.2220	60	14.5137	60	251.4	0.1535	60	21.3876
61	251.4	0.2935	61	15.1913	61	251.4	0.2037	61	22.3861
62	251.4	0.3884	62	10.5989	62	251.4	0.2698	62	15.6186
63	161.4	0.3164	63	20.4660	63	251.4	0.2217	63	30.1589
64	251.4	0.0122	64	18.2252	64	251.4	0.0084	64	26.8569
65	251.4	0.2831	65	18.9590	65	251.4	0.1942	65	27.9382
66	161.4	0.3415	66	19.2454	66	251.4	0.2361	66	28.3602
67	251.4	0.1853	67	25.9818	67	251.4	0.1276	67	38.2871
68	251.4	0.5846	68	25.7609	68	251.4	0.4072	68	37.9616
69	251.4	0.4545	69	23.4622	69	251.4	0.3150	69	34.5742
70	251.4	0.5279	70	11.1296	70	251.4	0.3645	70	16.4007
71	251.4	0.2193	71	10.9345	71	251.4	0.1508	71	16.1132
72	251.4	0.8560	72	23.9768	72	251.4	0.5833	72	35.3325
73	251.4	0.1217	73	21.3731	73	251.4	0.0849	73	31.4957
74	251.4	0.2935	74	35.3842	74	251.4	0.2035	74	52.1426
75	251.4	0.0985	75	35.2691	75	251.4	0.0668	75	51.9729
76	251.4	0.1477	76	11.3097	76	251.4	0.1180	76	16.6660
77	251.4	0.5903	77	21.3381	77	251.4	0.4043	77	31.4440
78	251.4	0.0247	78	21.3622	78	251.4	0.0166	78	31.4796
79	251.4	0.0864	79	31.1190	79	251.4	0.0587	79	45.8573
80	251.4	0.1242	80	28.7442	80	251.4	0.0834	80	42.3578
81	251.4	0.1725	81	11.0791	81	251.4	0.1173	81	16.3263

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
82	251.4	0.0371	82	23.4764	82	251.4	0.0252	82	34.5951
83	161.4	0.1744	83	14.0942	83	251.4	0.1158	83	20.7694
84	251.4	0.0991	84	10.9435	84	251.4	0.0661	84	16.1265
85	251.4	0.4361	85	11.7097	85	251.4	0.2877	85	17.2556
86	251.4	0.2343	86	11.7903	86	251.4	0.1586	86	17.3743
87	251.4	0.2987	87	18.9068	87	251.4	0.1990	87	27.8613
88	251.4	0.1112	88	16.6953	88	251.4	0.0741	88	24.6024
89	251.4	0.0995	89	19.8138	89	251.4	0.0669	89	29.1978
90	251.4	0.4686	90	30.2277	90	251.4	0.3137	90	44.5439
91	251.4	0.0247	91	17.9709	91	251.4	0.0166	91	26.4821
92	251.4	0.1626	92	10.8859	92	251.4	0.1077	92	16.0416
93	251.4	0.0124	93	22.5003	93	251.4	0.0083	93	33.1566
94	251.4	0.4752	94	27.6608	94	251.4	0.3165	94	40.7613
95	161.4	0.4385	95	36.9236	95	251.4	0.2891	95	54.4111
96	251.4	0.1739	96	22.3187	96	251.4	0.1161	96	32.8890
97	251.4	0.1251	97	39.0532	97	251.4	0.0831	97	57.5492
98	251.4	0.4825	98	21.2520	98	251.4	0.3229	98	31.3172
99	251.4	0.6405	99	22.5049	99	251.4	0.4220	99	33.1635
100	251.4	1.1277	100	24.3261	100	161.4	0.7373	100	35.8472
101	251.4	0.0988	101	31.8840	101	161.4	0.0662	101	46.9847
102	251.4	0.0371	102	11.0263	102	161.4	0.0247	102	16.2484
103	251.4	0.2758	103	18.4392	103	161.4	0.1827	103	27.1722
104	251.4	0.3490	104	12.8780	104	161.4	0.2327	104	18.9771
105	251.4	0.1872	105	17.3896	105	161.4	0.1251	105	25.6255
106	251.4	0.2640	106	31.0200	106	161.4	0.1736	106	45.7114
107	161.4	0.3595	107	30.6745	107	161.4	0.2397	107	45.2023
108	251.4	0.1759	108	23.4264	108	251.4	0.1146	108	34.5213
109	251.4	0.1734	109	10.9592	109	251.4	0.1142	109	16.1497
110	161.4	0.8103	110	10.9289	110	251.4	0.5322	110	16.1050
111	161.4	0.4870	111	18.3141	111	251.4	0.3198	111	26.9879
112	161.4	0.5382	112	28.1474	112	251.4	0.3504	112	41.4784
113	161.4	0.0623	113	11.0472	113	161.4	0.0410	113	16.2792
114	161.4	0.0757	114	25.1366	114	161.4	0.0493	114	37.0416
115	161.4	0.1773	115	24.0188	115	161.4	0.1156	115	35.3944
116	161.4	0.0756	116	20.1072	116	161.4	0.0489	116	29.6302
117	251.4	0.2535	117	20.2535	117	161.4	0.1635	117	29.8458
118	251.4	0.2016	118	17.1556	118	161.4	0.1324	118	25.2807
119	251.4	0.1493	119	16.8747	119	161.4	0.0980	119	24.8667
120	251.4	0.2637	120	12.4182	120	161.4	0.1702	120	18.2996
121	251.4	0.0503	121	21.0721	121	251.4	0.0326	121	31.0520
122	161.4	0.3026	122	11.7292	122	251.4	0.1951	122	17.2843
123	251.4	0.0126	123	12.1632	123	251.4	0.0081	123	17.9238

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					**Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
124	251.4	0.0253	124	12.3350	124	251.4	0.0164	124	18.1770
125	161.4	0.1876	125	11.0282	125	251.4	0.1230	125	16.2513
126	161.4	0.5437	126	18.0107	126	251.4	0.3468	126	26.5408
127	161.4	0.1635	127	18.6717	127	251.4	0.1050	127	27.5148
128	161.4	0.3444	128	14.4019	128	251.4	0.2173	128	21.2228
129	161.4	0.1782	129	11.5796	129	251.4	0.1143	129	17.0639
130	161.4	0.1403	130	23.1510	130	251.4	0.0887	130	34.1156
131	161.4	0.1658	131	19.5303	131	251.4	0.1050	131	28.7800
132	251.4	0.2293	132	34.1810	132	251.4	0.1451	132	50.3695
133	251.4	0.1270	133	23.0349	133	251.4	0.0814	133	33.9445
134	251.4	0.4856	134	18.8761	134	251.4	0.3080	134	27.8161
135	251.4	0.4697	135	17.7157	135	251.4	0.2971	135	26.1060
136	251.4	0.2025	136	17.8132	136	251.4	0.1294	136	26.2497
137	251.4	0.2648	137	23.4656	137	251.4	0.1719	137	34.5792
138	251.4	0.2152	138	21.9030	138	251.4	0.1382	138	32.2766
139	161.4	0.3278	139	15.1468	139	161.4	0.2111	139	22.3204
140	251.4	0.1282	140	18.5488	140	161.4	0.0802	140	27.3338
141	251.4	0.1156	141	11.1866	141	161.4	0.0732	141	16.4847
142	161.4	0.3919	142	12.8731	142	161.4	0.2482	142	18.9699
143	161.4	0.2152	143	20.3012	143	161.4	0.1354	143	29.9161
144	161.4	0.3072	144	20.5983	144	161.4	0.1916	144	30.3539
145	161.4	0.1673	145	19.0641	145	161.4	0.1046	145	28.0930
146	161.4	0.0901	146	14.4158	146	161.4	0.0564	146	21.2432
147	161.4	0.0129	147	16.2775	147	251.4	0.0080	147	23.9867
148	161.4	0.6359	148	12.5723	148	251.4	0.4006	148	18.5267
149	251.4	0.1908	149	11.1353	149	251.4	0.1188	149	16.4091
150	251.4	0.3556	150	12.2280	150	251.4	0.2226	150	18.0193
151	251.4	0.0772	151	11.2476	151	251.4	0.0483	151	16.5747
152	251.4	0.4752	152	11.8222	152	251.4	0.2939	152	17.4213
153	251.4	0.2688	153	12.5833	153	251.4	0.1680	153	18.5429
154	161.4	0.3454	154	20.5554	154	251.4	0.2146	154	30.2907
155	251.4	0.2034	155	26.8294	155	251.4	0.1281	155	39.5360
156	251.4	0.2310	156	34.7141	156	251.4	0.1437	156	51.1550
157	161.4	0.3064	157	11.1643	157	161.4	0.1897	157	16.4518
158	251.4	0.1150	158	11.3659	158	161.4	0.1479	158	16.7489
159	251.4	0.0128	159	11.2872	159	161.4	0.0079	159	16.6330
160	251.4	0.2340	160	11.3024	160	161.4	0.1442	160	16.6553
161	251.4	0.0128	161	16.6678	161	161.4	0.0080	161	24.5618
162	251.4	0.1438	162	17.3344	162	161.4	0.0868	162	25.5442
163	161.4	0.3991	163	16.6587	163	161.4	0.2430	163	24.5484
164	251.4	0.1701	164	17.0181	164	161.4	0.1030	164	25.0781
165	251.4	0.3347	165	25.9152	165	251.4	0.2063	165	38.1890

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					**Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)**				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
166	161.4	0.0518	166	13.7148	166	251.4	0.0316	166	20.2102
167	161.4	0.2852	167	15.7142	167	161.4	0.1728	167	23.1566
168	161.4	0.2990	168	23.4802	168	161.4	0.1819	168	34.6007
169	161.4	0.1951	169	24.2185	169	161.4	0.1192	169	35.6886
170	161.4	0.1170	170	34.2651	170	161.4	0.0711	170	50.4934
171	161.4	0.3112	171	28.7611	171	161.4	0.1910	171	42.3827
172	161.4	0.5331	172	41.4991	172	161.4	0.3234	172	61.1536
173	251.4	0.2621	173	21.4954	173	161.4	0.1569	173	31.6758
174	251.4	0.4831	174	14.5944	174	161.4	0.2907	174	21.5064
175	251.4	0.2078	175	28.5885	175	251.4	0.1250	175	42.1284
176	251.4	0.4037	176	26.2399	176	251.4	0.2442	176	38.6674
177	251.4	0.1313	177	24.4552	177	251.4	0.0781	177	36.0375
178	161.4	0.0259	178	26.6857	178	251.4	0.0156	178	39.3243
179	251.4	0.3629	179	19.7938	179	251.4	0.2189	179	29.1683
180	251.4	0.5767	180	19.2724	180	251.4	0.3475	180	28.4001
181	161.4	0.1184	181	12.2092	181	251.4	0.0702	181	17.9916
182	251.4	0.0389	182	16.9789	182	251.4	0.0235	182	25.0203
183	251.4	0.3016	183	18.5477	183	251.4	0.1791	183	27.3321
184	251.4	0.1314	184	19.0068	184	251.4	0.0781	184	28.0086
185	251.4	0.1298	185	18.6979	185	251.4	0.0772	185	27.5534
186	251.4	0.1301	186	11.8922	186	251.4	0.0786	186	17.5245
187	161.4	0.1843	187	30.2099	187	251.4	0.1088	187	44.5176
188	251.4	0.0260	188	17.6546	188	251.4	0.0156	188	26.0160
189	251.4	0.6476	189	17.6970	189	251.4	0.3841	189	26.0784
190	161.4	0.1565	190	20.0257	190	251.4	0.0935	190	29.5100
191	161.4	0.1436	191	18.6113	191	251.4	0.0859	191	27.4258
192	161.4	0.6579	192	23.8398	192	251.4	0.3866	192	35.1306
193	161.4	0.0398	193	13.1149	193	251.4	0.0236	193	19.3263
194	161.4	0.0664	194	26.8911	194	251.4	0.0386	194	39.6270
195	161.4	0.2252	195	27.5727	195	251.4	0.1312	195	40.6314
196	161.4	0.3928	196	22.9112	196	251.4	0.2340	196	33.7622
197	251.4	0.3816	197	19.2805	197	251.4	0.2224	197	28.4119
198	251.4	0.1579	198	29.1347	198	251.4	0.0920	198	42.9332
199	251.4	0.0392	199	23.6603	199	251.4	0.0231	199	34.8660
200	251.4	0.4372	200	23.8892	200	251.4	0.2525	200	35.2034
201	251.4	0.7171	201	17.6322	201	251.4	0.4155	201	25.9830
202	161.4	0.3035	202	18.0264	202	251.4	0.1756	202	26.5638
203	251.4	0.0531	203	23.1689	203	251.4	0.0307	203	34.1420
204	251.4	0.2521	204	26.3284	204	251.4	0.1481	204	38.7978
205	161.4	0.3581	205	18.7829	205	251.4	0.2101	205	27.6787
206	251.4	0.3059	206	33.6238	206	251.4	0.1756	206	49.5483
207	251.4	0.2925	207	17.4019	207	251.4	0.1698	207	25.6436

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)				
Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)	Pipe No	Diameter (10^{-3} m)	Velocity (m/s)	Node	Pressure (m)
208	251.4	0.2914	208	16.0280	208	251.4	0.1694	208	23.6190
209	251.4	0.1046	209	16.1127	209	251.4	0.0618	209	23.7438
210	251.4	0.3147	210	16.2036	210	251.4	0.1846	210	23.8778
211	161.4	0.1448	211	41.8955	211	251.4	0.0843	211	61.1628
212	251.4	0.0264	-	-	212	251.4	0.0152	-	-
213	251.4	0.3195	-	-	213	251.4	0.1824	-	-
214	161.4	0.3196	-	-	214	251.4	0.1815	-	-
215	161.4	0.6560	-	-	215	251.4	0.3730	-	-
216	161.4	0.1448	-	-	216	251.4	0.0844	-	-
217	161.4	0.1586	-	-	217	251.4	0.0917	-	-
218	161.4	0.1188	-	-	218	251.4	0.0684	-	-
219	161.4	0.1067	-	-	219	251.4	0.0606	-	-
220	161.4	0.5150	-	-	220	251.4	0.3000	-	-
221	251.4	2.9809	-	-	221	251.4	2.2856	-	-
222	251.4	0.2683	-	-	222	251.4	0.1531	-	-
223	251.4	0.1320	-	-	223	251.4	0.0765	-	-
224	251.4	0.4421	-	-	224	251.4	0.2497	-	-
225	251.4	0.6289	-	-	225	251.4	0.3565	-	-
226	161.4	0.3623	-	-	226	251.4	0.2080	-	-
227	251.4	0.2525	-	-	227	251.4	0.1450	-	-
228	251.4	0.1216	-	-	228	251.4	0.0687	-	-
229	161.4	0.1602	-	-	229	251.4	0.0918	-	-
230	251.4	0.0667	-	-	230	251.4	0.0378	-	-
231	161.4	0.0117	-	-	231	251.4	0.0067	-	-
232	251.4	0.1469	-	-	232	251.4	0.0833	-	-
233	251.4	0.2141	-	-	233	251.4	0.1209	-	-
234	251.4	0.4409	-	-	234	251.4	0.2509	-	-
235	161.4	0.1214	-	-	235	251.4	0.0675	-	-
236	251.4	0.0933	-	-	236	251.4	0.0531	-	-
237	251.4	0.0672	-	-	237	251.4	0.0376	-	-
238	161.4	0.0401	-	-	238	251.4	0.0226	-	-
239	161.4	0.0134	-	-	239	251.4	0.0075	-	-
240	161.4	0.2819	-	-	240	251.4	0.1576	-	-
241	161.4	0.0135	-	-	241	251.4	0.0075	-	-
242	161.4	0.4050	-	-	242	251.4	0.2250	-	-
243	161.4	0.0541	-	-	243	251.4	0.0300	-	-
244	161.4	0.1624	-	-	244	251.4	0.0895	-	-
245	251.4	0.1231	-	-	245	251.4	0.0675	-	-
246	251.4	0.1086	-	-	246	251.4	0.0600	-	-
247	251.4	0.1766	-	-	247	251.4	0.0975	-	-
248	251.4	0.0540	-	-	248	251.4	0.0300	-	-
249	251.4	0.4343	-	-	249	251.4	0.2377	-	-

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
250	161.4	0.2605	-	-	250	251.4	0.1426	-	-
251	251.4	0.1925	-	-	251	251.4	0.1046	-	-
252	251.4	0.2447	-	-	252	251.4	0.1356	-	-
253	161.4	0.3021	-	-	253	251.4	0.1632	-	-
254	251.4	0.2598	-	-	254	251.4	0.1425	-	-
255	251.4	0.2176	-	-	255	251.4	0.1198	-	-
256	251.4	0.2872	-	-	256	251.4	0.1571	-	-
257	251.4	0.2068	-	-	257	251.4	0.1120	-	-
258	251.4	0.2184	-	-	258	251.4	0.1196	-	-
259	161.4	0.3306	-	-	259	251.4	0.1788	-	-
260	251.4	0.2218	-	-	260	251.4	0.1174	-	-
261	251.4	0.2465	-	-	261	251.4	0.1332	-	-
262	161.4	0.4109	-	-	262	251.4	0.2226	-	-
263	161.4	0.2362	-	-	263	251.4	0.1263	-	-
264	161.4	0.0822	-	-	264	251.4	0.0439	-	-
265	161.4	0.0834	-	-	265	251.4	0.0440	-	-
266	161.4	0.3282	-	-	266	251.4	0.1754	-	-
267	161.4	0.1231	-	-	267	251.4	0.0665	-	-
268	161.4	0.1515	-	-	268	251.4	0.0805	-	-
269	251.4	0.1508	-	-	269	251.4	0.0796	-	-
270	251.4	0.1395	-	-	270	251.4	0.0736	-	-
271	251.4	0.0975	-	-	271	251.4	0.0505	-	-
272	251.4	0.0559	-	-	272	251.4	0.0288	-	-
273	251.4	0.1517	-	-	273	251.4	0.0805	-	-
274	161.4	0.7096	-	-	274	251.4	0.3725	-	-
275	251.4	0.1655	-	-	275	251.4	0.0876	-	-
276	251.4	0.3186	-	-	276	251.4	0.1664	-	-
277	251.4	0.3479	-	-	277	251.4	0.1790	-	-
278	251.4	0.3025	-	-	278	251.4	0.1593	-	-
279	251.4	0.1516	-	-	279	251.4	0.0795	-	-
280	251.4	0.3470	-	-	280	251.4	0.1817	-	-
281	251.4	2.4661	-	-	281	251.4	1.2655	-	-
282	251.4	0.5890	-	-	282	251.4	0.3027	-	-
283	161.4	0.0693	-	-	283	251.4	0.0359	-	-
284	251.4	0.2354	-	-	284	251.4	0.1235	-	-
285	251.4	0.2341	-	-	285	251.4	0.1213	-	-
286	161.4	0.1241	-	-	286	251.4	0.0647	-	-
287	251.4	0.2654	-	-	287	251.4	0.1375	-	-
288	161.4	0.0140	-	-	288	251.4	0.0072	-	-
289	161.4	0.1957	-	-	289	251.4	0.0995	-	-
290	161.4	0.3602	-	-	290	251.4	0.1847	-	-
291	161.4	0.3069	-	-	291	251.4	0.1591	-	-

Leftmost Extreme Point (Network Cost=3.2025 million rupees, Network Resilience=0.3680 and Network Equity =0.7946)					Rightmost Extreme Point (Network Cost=4.7747 million rupees, Network Resilience=0.4810 and Network Equity =0.9833)				
Pipe No	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**	**Pipe No**	**Diameter (10^{-3} m)**	**Velocity (m/s)**	**Node**	**Pressure (m)**
292	161.4	0.4603	-	-	292	251.4	0.2340	-	-
293	251.4	0.3740	-	-	293	251.4	0.1915	-	-
294	251.4	0.5070	-	-	294	251.4	0.2573	-	-
295	251.4	0.5205	-	-	295	251.4	0.2652	-	-
296	251.4	0.0563	-	-	296	251.4	0.0286	-	-
297	251.4	0.0279	-	-	297	251.4	0.0143	-	-
298	161.4	0.0839	-	-	298	251.4	0.0431	-	-
299	251.4	0.0418	-	-	299	251.4	0.0211	-	-
300	251.4	0.0709	-	-	300	251.4	0.0355	-	-
301	251.4	0.0560	-	-	301	251.4	0.0281	-	-

PUBLICATIONS FROM THE STUDY

Journals

1. Mahesh B. Patil, Maddukuri Naveen Naidu, A Vasan, Murari R R Varma. "Water distribution system design using Multi-objective Particle Swarm Optimization", *Sadhana*, 45:21, 2020.
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1. M Naveen Naidu, A Vasan, Murari RR Varma, *"Water Distribution Network Optimization – A Review"*, 50th IWWA Annual Convention 2018, Kala Academy, Panaji, Goa, February 19-21, 2018.
2. M Naveen Naidu, Sriman Pankaj, A Vasan, Murari RR Varma, *"Optimization of Water Distribution Networks Using Cuckoo Search Algorithm"*, International Conference on Advanced Engineering Optimization Through Intelligent Techniques (AEOTIT), S.V. National Institute of Technology, Surat, Gujarat, India, August 03-05, 2018.
3. M Naveen Naidu, A Vasan, Murari RR Varma, *"Nature Inspired Multiobjective Optimization of Water Distribution Network Design"*, International Conference on Sustainable Practices and Innovations in Civil Engineering (SPICE 2019), Department of Civil Engineering, S.S.N. College of Engineering, Chennai, India, March 26-27, 2019.

4. M Naveen Naidu, A Vasan, Murari RR Varma, *“Many objective optimization of water distribution networks using NSGA-II”*, Water Future Conference 2019 – Towards a Sustainable Water Future, Divecha Centre for Climate Change, IISc Bengaluru, India, September 24-27, 2019.
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6. Vasan A, M. Naveen Naidu and Murari RR Varma, “*Enhancing Equitable Distribution and Network Resilience in Intermittent Water Supply Systems*”, 20th Annual Meeting of the Asia Oceania Geosciences Society (AOGS 2023), 30 July to 04 August, 2023, Singapore.
7. Naveen Naidu M, A Vasan and Murari RR Varma, “*Optimal Design of District Metered Areas for Water Distribution Networks*”, 3rd International Conference on Environment sustainability: New Paradigms and Developments (ICES 2023), November 27-29, 2023, BITS Pilani Dubai Campus, Dubai, UAE.

BIOGRAPHY

Biography of Candidate

M. Naveen Naidu's academic journey in civil engineering showcases a strong commitment to excellence and a profound interest in water resources management. After obtaining his Bachelor of Technology in Civil Engineering from Sri Venkateswara University, Tirupati in 2013, where he demonstrated exceptional dedication, M. Naveen Naidu achieved an impressive 99.00 percentile in the Graduate Aptitude Test in Engineering (GATE). He then pursued a Master's degree in Water Resources Engineering at the esteemed National Institute of Technology (NIT) Nagpur, graduating in 2015 with continued academic success. Transitioning into academia, Naidu served as an Assistant Professor for nine months, contributing to the institution's academic and research endeavors. Naidu's dedication and passion underscore his significant contributions to civil engineering. Following this, he has been pursuing his PhD at BITS Pilani Hyderabad Campus, while concurrently serving as a Senior Research Fellow (SRF) in a Council of Scientific and Industrial Research (CSIR) Project from 2017 to 2020. In his PhD journey, he has been awarded a travel grant by CSIR for presenting a paper in a prestigious conference "Computing and Control for Water Industry (CCWI)" conducted by University of Exeter, United Kingdom in 2019. He has published four journal papers and seven conference papers from this research work.

Biography of Supervisor

Prof. A Vasan is a Professor in the Department of Civil Engineering at BITS Pilani, Hyderabad Campus. He has been actively involved in teaching, research and academic administration for nearly twenty-four years. He holds a PhD in Water Resources Engineering and did his Post-Doctoral studies at Western University, Canada. His research interests include Optimization of Reservoir Operation using Nature Inspired Algorithms, Water Distribution Network design optimization, Leak Detection in Water Distribution Networks using Machine Learning and IoTs. He is a recipient of awards for various research papers and has also received sponsored research funding from various agencies. He has published more than 100 research papers and has been serving as a reviewer for numerous reputed international journals.

Biography of Co-Supervisor

Prof. Murari R R Varma is an Associate Professor in the Department of Civil Engineering at Birla Institute of Technology and Science, Pilani, Hyderabad Campus, India and currently is the Head of the Department. He received his PhD from the Department of Civil Engineering, Indian Institute of Science, Bangalore. His research interests are in experimental and field hydrology, and water quality of natural water systems. He is actively publishing research articles in reputed journals and conferences. He also has completed or ongoing sponsored and consultancy projects under CSIR as well as the Government of Telangana State.