Research Article

Optimization of Layout and Pipe Sizes for Irrigation Pipe Distribution Network Using Steiner Point Concept

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In tropical countries like India, irrigation is necessary to grow crops in the nonmonsoon period. The conventional methodology for conveying irrigation water from the source to the field is through open canals. However, considering huge losses due to evaporation and percolation, a modern system of irrigation like pipe irrigation network (PIN) is desired. Advancement in technology has led to the progress in the PIN as they are compatible with modern irrigation facilities such as sprinkler and drip irrigation systems. In the present study, the layout of the PIN is designed and optimized in two phases. Initially, the looped network is traced out for the Bakhari distributary of the Kanhan Branch Canal, India. Minimum spanning tree (MST) network is obtained from the looped network using Prim's algorithm to calculate the nodal demands. The layout optimization of the MST is carried out using the Steiner concept to obtain the initial Steiner tree (IST). The steady-state hydraulic analysis and design are carried out for the looped and IST network. The results show that the percentage of length decreasing from the looped network to the MST network is 51.58%. The IST network is the optimized network having the minimum length showing a 12.21% length reduction compared to the MST network. The total reduction in the cost of the Steiner tree is found to be 4.25% compared to the looped network. Steiner concept application to large irrigation networks can reduce the length of the network thereby minimizing the total project cost.

1. Introduction

Freshwater is a finite and vital resource that is essential for maintaining the life cycle on Earth. India constitutes 2.4% of the world's surface area and supports 16.7% of the world's population. It possesses only 4% of the world's water resources [1]. The estimated population of India is 1,210 million with a growth rate of 17.64% [2]. With the increase in population, the requirement for agricultural products would increase and the scarcity of water would certainly affect the production from agriculture [3, 4]. Moreover, in the last three decades, the annual and summer precipitation showed a decreasing trend of 5%, while a positive trend is observed for the temperature with a significant value of 5% [5]. This concludes that precipitation has been declining with the rapid warming in the last 30 years [6]. This indicates that the growing demands are to be satisfied with limited resources as the rainfall is also decreasing over the period. India accounts for 7.39% of total global agricultural output and as per the Economy Survey of India 2018–19, the agricultural sector contributes around 15–17% to the country's gross domestic product (GDP), which necessitates irrigation [7]. Therefore, to support the country's economy, it is necessary to save water and use it sustainably. In ancient times, the principal irrigation practice was conveying the flow of springs and streams by constructing temporary

barriers across them and irrigating the adjoining fields by the canal system. The major drawback of the conventional canal systems is the loss of water due to percolation, evaporation, and sometimes thefts in between the reaches. Besides, the issue of land acquisition also persists. Small traditional conventional earthen channels (200 m) exhibit a conveyance efficiency of around 75.07%, which indicates the extent of seepage loss in large irrigation networks [8, 9]. In the case of open canals, the overall project efficiency ranges from 41 to 48%, which further falls to 20 to 35% making Pipe Irrigation Network (PIN) a necessity [10]. A buried pipeline system may reduce the water demand to a significant extent with the use of a pumped irrigation system as compared to the earthen channels [11, 12]. Considering the huge seepage and evaporation losses in irrigation water conveyance through the canal system, it is the need of the hour to shift to another efficient system as far as Indian practices are concerned. Irrigation technology made rapid strides in the 21st century in terms of overall cost and water use efficiency. Using computer simulation, a reliable water network can be developed by forming the hydraulic models if a sufficient head is available [13, 14]. The underground pipes in an open field give an opportunity to freely design the layout and thus making PIN a better choice in terms of both water use efficiency and overall cost. Also, it requires less execution time for undulating fields as compared to the canal distribution system. The branching (tree) water distribution networks are popular for supplying water, where the demand is very high such as irrigation and industries as they are simple in comparison to the complicated loop networks [15, 16]. The irrigation sector is the one that requires a large amount of water in a calculated manner. An effective irrigation water supply system is required to satisfy all the demands. This is accomplished by providing an optimized pipe irrigation network.

For a given layout, an optimized PIN is the one which satisfies all the demands as well as constraints with the minimum possible cost. The cost may further be reduced if there is freedom of variation in layout as well [17]. The issue of the simultaneous layout with the design of water distribution network (WDN) optimization has been dealt with by many researchers from the last few decades. Bhave and Lam suggested a two-step approach to obtain a minimum cost WDN layout. The concept gives a minimum length layout. The lengths of the links are considered in the Steiner tree approach while the nodal discharges or hydraulic gradient level (HGL) are not given weightage for determining the optimized layout [15]. A minimum cost layout including design of WDN wherein linear programming (LP) was used to design pipe diameters and the hydraulic network solver addressed the flow through the pipes and pressures at the nodes [18]. A model of the optimized layout of WDNs with single loading was presented in which a zero-one integer model selected the pipes considering the hydraulic properties and redundancy and in the following step, design models were used to optimize the pressures and diameters resulting in an optimized layout and design of WDN [19]. Comparison of the twin genetic algorithm (GA) with binary and integer coding for the optimized layout of the branched

network was carried out with dynamic programming (DP) based on time and storage requirement in both approaches [20]. An evolution program was developed in GA to optimize the looped WDN for the first time [21]. A maximum entropy-based method was developed in which the optimized cost along with reliability could be achieved for the optimized layouts [22]. A heuristic method was proposed based on reliability for the simultaneous layout and design of WDN. The network layout with the maximum number of pipes is considered initially, followed by a design float method to obtain the final least costly network [23]. An empirically derived objective function was developed for the optimal layout of the tree network using mixed integer linear programming (MILP). The data used for MILP was the location and demands of the users [24]. GIS was used in the backdrop as the classical graph theory (CGT) algorithm was used to find out the minimum length of the spanning tree [25]. A method was presented in which the pipes are removed sequentially to reach the minimum cost network to obtain the optimal layout and design of branched WDN. The design flows were obtained using Clements's method [26]. A six-looped water distribution system having seventeen links was used to demonstrate the multicriteria maximum entropy method for the optimization of link size, reliability, and network layout. The chief criterion being network, therefore, a compromise between entropy, redundancy, reliability, and network cost were observed sequentially within the population of the best solutions. As a smaller part of the network has been considered for layout and design, the efficiency of the method was improved [27]. For the optimal layout of the urban drainage network, loop-by-loop cutting algorithm based on graph theory and GA has been used [28]. A multiobjective evolutionary method was presented for the optimization of the design and layout of WDN [29]. Particle swarm optimization (PSO) technique was linked with MATLAB for irrigation WDN layout and cost optimization [30]. A fusion method of tree growing-jumping particle swarm optimization (TG-JPSO) was proposed which is a blend of layout and pipe size optimizers to achieve an optimal layout and design of WDN. A modified version of Labye's iterative discontinuous method (LIDM) was used which gives several solutions that finally converge to an optimized design [31]. Max-min ant system (MMAS) algorithm has been used to obtain the minimum cost design considering layout and pipe diameters of the network simultaneously [32]. The accuracy of various methods and their comparative studies were also carried out in the past. It was found that the ant algorithm (AA) application to the branched WDN gives better results as compared to GA [33], whereas recently developed Physarum algorithm performs better than the ant colony algorithm for optimization of branched WDNs [34]. A heuristic method based on a uniform flow network was suggested to achieve minimum variance in the pipe flows for increased reliability of the network. The system was evaluated through a variance of flow series and the obtained optimal layout network was designed using linear programming [35]. Thevenin theorem (TT) applied for electric circuits was applied for the model reduction and analysis of large WDN [36]. Recently

developed population-based Harris hawks algorithm (HHO) was developed for the WDN optimization of the Homashahr city in Iran [37]. A novel heuristic targeted path search algorithm (TPSA) based on the determination of optimal paths followed by the flow of water in a WDN was developed for three benchmark networks. In the process of optimization, the targeted trial of decrease in pipe diameters of the network was guided by two individual subroutines, thus exploring the search space [38]. Some of the hydraulic simulation software is also coupled with these heuristic techniques to obtain the optimized design of WDN [39]. The basics of hydraulic simulation and interoperability of the water distribution network were presented and a hydraulic WDN model was prepared for scheduling and science operations of WDN with the help of SCADA data and GIS data in WaterGEMS to optimize the network effectively [40]. Steiner point concept is coupled with LP for a small 8-node example to obtain an optimized layout [41].

In the present study, a layout optimization model is developed in a stepwise manner. The approach starts with the development of a looped network for calculating the demands which are further designed and optimized using WaterGems connect. The second step consists of the conversion of the looped network into the minimum spanning tree (MST) network using Prim's algorithm. The final step is the application of the Steiner concept to the MST to obtain the Steiner tree (ST), which gives the optimized layout and design of the network. A comparison of the looped network and the ST network shows a reduction of 4.25% in the total network cost. A flowchart depicting the methodology is shown in Figure 1. The abbreviations used in this paper are tabulated in Table 1.

2. Characterization of the Study Area

The area selected for the present study is Bakhari distributary of the Pench irrigation project, located in Parseoni, a small town and a municipal council in Nagpur district in the state of Maharashtra, India. The study area with latitude $21°19'34.15''$ N and longitude $79°11'15.55''$ E is well-connected via state and national highway. Bakhari distributary offtakes from Left Bank Canal (LBC) of Pench irrigation project having discharge capacity of 1.58 cumecs to irrigate 2057.17 Ha culturable command area (CCA). The schematic sketch of the study area is presented in Figure 2.

3. Materials and Methods

3.1. Looped Network. Looped networks are complex compared to the branched networks but are more reliable. On the other hand, for large irrigation networks branched networks are more economical. For the present study, the looped gravity-fed network is traced out in AutoCAD Map 3D along the road lines of the study area as shown in Figure 3.

The pipeline along the roads avoids the problem of land acquisition, while for layout optimization, some of the field area may be covered. The underground pipe system suffices for the utilization of the complete field area. The looped

network consists of 1 source reservoir, 60 nodes, and 87 pipes to supply irrigation water to the field. It covers a total length of 59.17 Km to irrigate 2057.17 Ha CCA with a discharge capacity of 1.578 cumecs. For the PIN, the seepage and evaporation losses are almost eliminated. However, leakage losses may be present. Considering 10% leakage losses, the gross irrigation requirement (GIR) and net irrigation requirement (NIR) for the different crops in the area are calculated as shown in Table 2.

The looped network consists of 27 polygons and the demand for each of the polygon is calculated as the percentage of the total demand (GIR) as per the area of each polygon as shown in Table 3.

The nodal demands are found out by using the Thiessen polygon tool in WaterGEMS. Pipe sizing of the PIN is carried out followed by steady-state simulation by taking a set of designed commercial diameters to optimize the total cost of the looped network as shown in Figure 3.

3.2. Minimum Spanning Tree (MST) Network. The looped PIN is converted to a branch network known as MST which is a network consisting of a set of pipes resulting in a tree connecting each node in the system. Prim's algorithm (PA) is used to obtain the MST for the study area. In the field of computer science, PA is used to find the minimum spanning tree for a connected weighted undirected graph. This means it obtains a subset of the edges forming a tree that includes every vertex, keeping into account that the total weight of all the edges in the tree is minimized. Czech mathematician Vojtèch Jarnik developed this algorithm in 1930. It was later independently developed by computer scientist Robert C. Prim in 1957 and rediscovered by Edsger Dijkstra in 1959. Therefore, it is also sometimes called the Jarnik algorithm, the DJP algorithm, or the Prim–Jarnik algorithm [42]. PA is a greedy algorithm that finds a set of the pipes forming a tree, which includes each node, where the total length of all the links in the tree is minimum. This algorithm is directly based on the MST property, which finds the global optimum solution for the minimum length. The obtained MST consists of 1 reservoir, 60 nodes, and 60 pipes with a total length of 28.65 Km to irrigate 2057.17 Ha CCA as shown in Figure 4.

3.3. Initial Steiner Tree (IST). Further layout optimization is carried out with the concept of the Steiner tree (ST). Steiner points are the additional nodal points in an existing system to produce an optimal layout. The connecting links between different nodes and the Steiner points are considered as straight lines with link diameters as a continuous variable. The characteristics of the Steiner tree for a multinode network are as follows. (i) ST for an N-node network can have a maximum of up to N-2 Steiner points; however, it may be less when some of the given nodes also act as junction nodes. (ii) Each Steiner point is connected to three points (given nodes or other Steiner points) such that the angle between the connecting link is 120°. Computer algorithms and several methodologies are there to obtain the Steiner tree [43–45]. Additional Steiner points are obtained for the already existing system of nodes to obtain optimal layout using
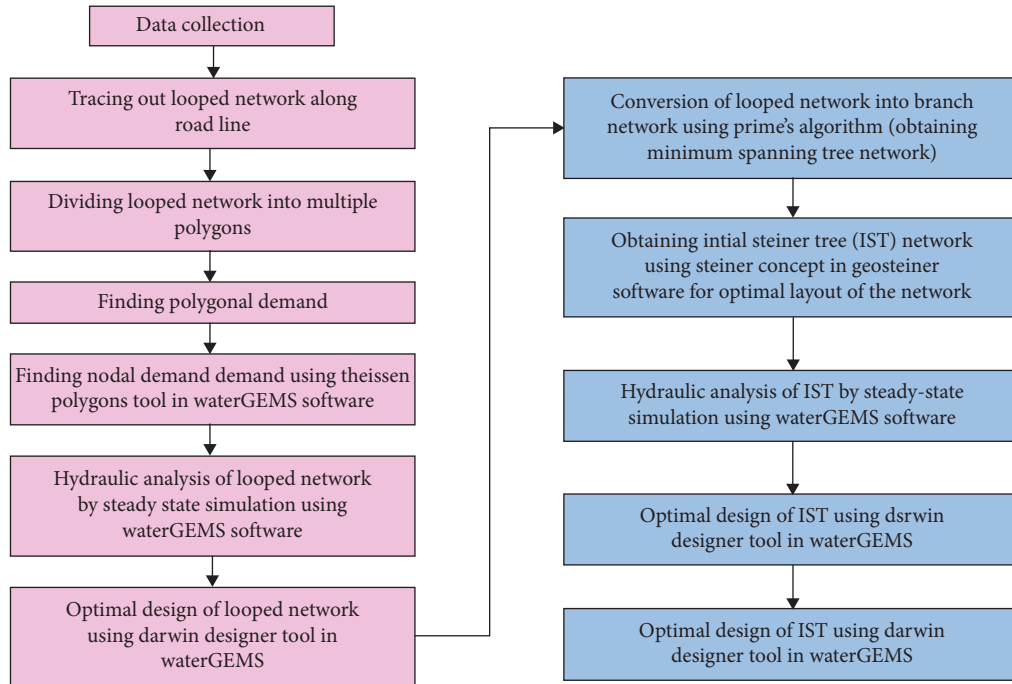
FIGURE 1: Flow chart depicting the methodology of the study.

TABLE 1: List of abbreviations.

Abbreviations	
AA	Ant algorithm
CCA	Culturable command area
CGT	Classical graph theory
DP	Dynamic programming
GA	Genetic algorithm
GDP	Gross domestic product
GIR	Gross irrigation requirement
HHO	Harris Hawks algorithm
HGL	Hydraulic gradient level
IST	Initial Steiner tree
LBC	Left bank canal
LIDM	Labye's iterative discontinuous method
LP	Linear programming
MILP	Mixed integer linear programming
MMAS	Max-min ant system
MST	Minimum spanning tree
MST	Minimum spanning tree
NIR	Net irrigation requirement
PA	Prim's algorithm
PIN	Pipe irrigation network
PSO	Particle swarm optimization
ST	Steiner tree
TPSA	Targeted path search algorithm
TG-JPSO	Tree growing-jumping particle swarm optimization
TT	Thevenin theorem
WDN	Water distribution network

GeoSteiner software. The computation of the exact solutions to the Steiner tree problems is obtained with the help of the GeoSteiner software package which has a very fast (publicly available) program [46]. A complete written programmed code which is with a clear method to generate the Steiner tree

is recorded [47]. For the present study, a new initial Steiner tree network is formulated in ArcMap which consists of 60 nodes, 21 Steiner points, 81 pipes, and 1 source reservoir as shown in Figure 5 to convey the irrigation water to all demand nodes. The total length of the network is reduced to 25.15 Km to irrigate the same CCA. After layout optimization pipe sizing of the initial Steiner tree is carried out for the same set of designed diameters, the same network is then optimized for pipe sizing by using the Darwin designer tool in WaterGEMS, which works on GA parameters.

The optimized design study has no true optimality and only knows the best solution relative to other solutions already found during computation. In general, population size and random number seed are the common parameters to change in computing the model under consideration. The sensitivity of the existing model is tested by a random number of seeds for the model being optimized. With GA optimization having a stochastic nature, it might be beneficial to change population size up or down. Faster runs are obtained using a smaller population size, but the model is less diverse and potentially optimized results with the population being less [48]. Pressure constraints are set to maintain positive pressure at the nodes.

4. Results and Discussion

The initial looped network consists of 87 links and 60 nodes with a total length of 56.17 km. The analysis of the network is carried out by considering the minimum and maximum pressure of 0.17 m and 20 m, respectively. Based on these pressures, a set of designed diameters are selected in which minimum and maximum diameters are 50 mm and 1600 mm, respectively. After optimizing the network, it is
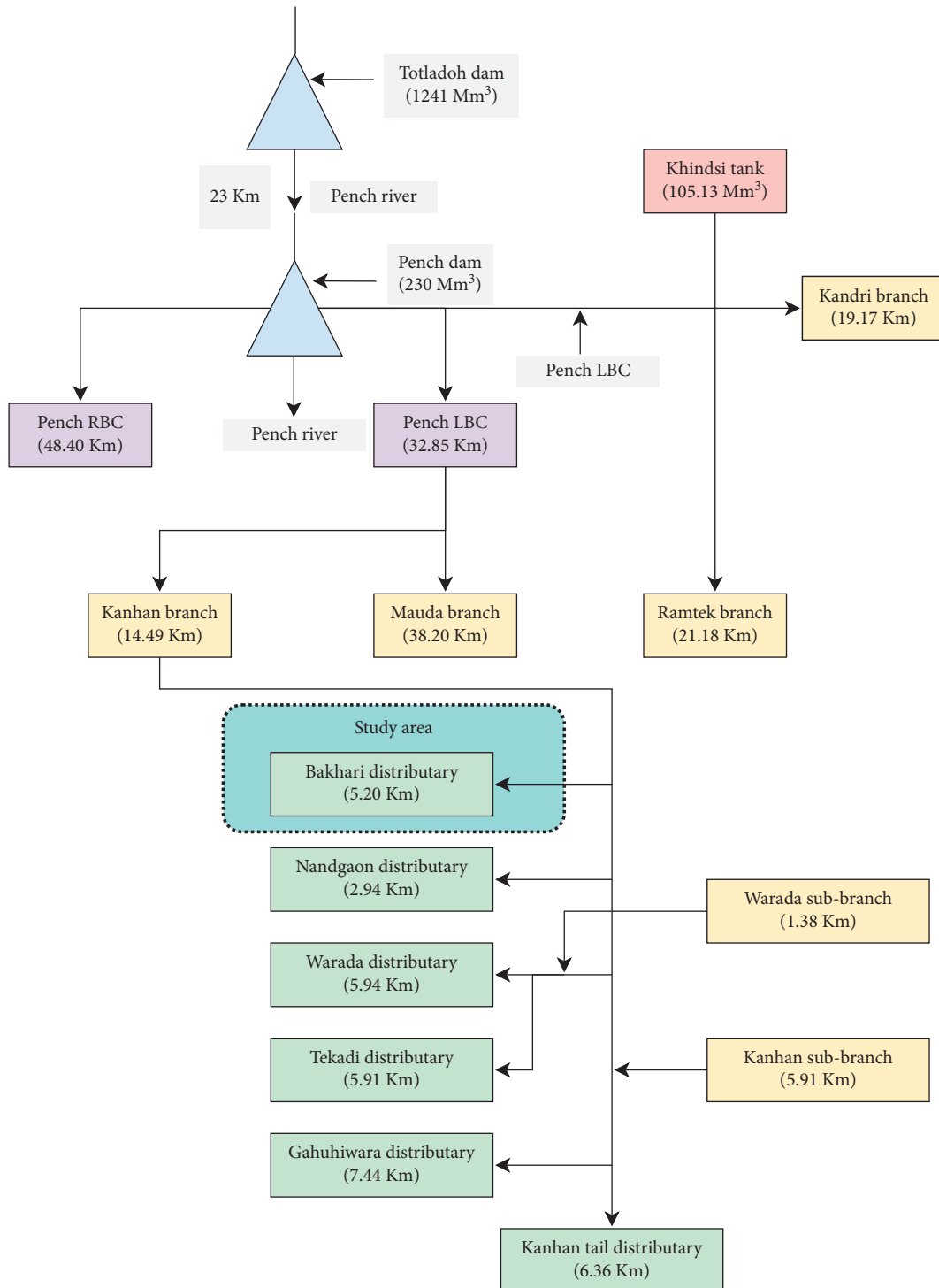
FIGURE 2: Schematic sketch of study area.

observed that out of 87 pipe diameters, 25 pipes (3, 7, 10, 12, 17, 18, 20, 27, 32, 33, 34, 36, 45, 50, 51, 55, 59, 68, 71, 72, 73, 74, 79, 85, 87) diameters have a value less than the designed diameter and 2 pipes (25, 77) are having a diameter equal to the designed diameter as shown in Figure 6. The cost reduction is brought about as a result of the reduction in the pipe sizes of the optimized design.

Pipe sizing is carried out by considering pressure constraints in which minimum and maximum pressures are set to 0.17 and 20 m. It is found that all the simulated pressures are positive which are well within the minimum and maximum pressure limits as shown in Figure 7. However, for only one junction (17), the pressure exceeds the upper pressure limit which is 20.95 and can be neglected.
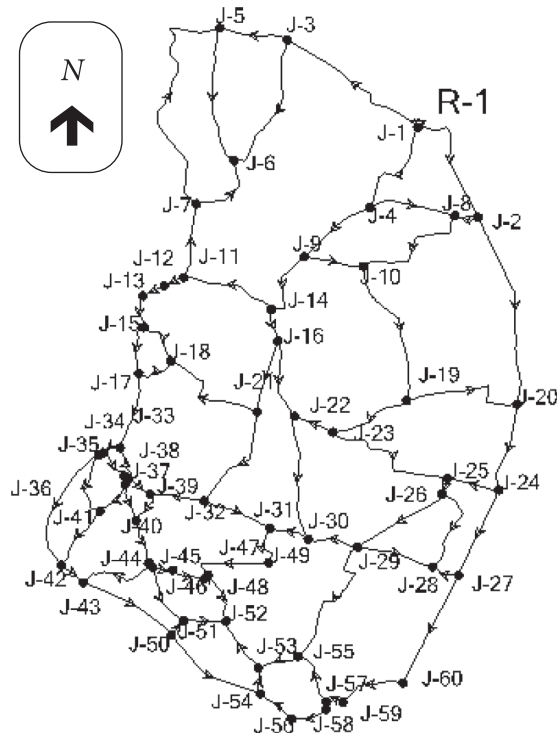
FIGURE 3: Looped network for Bakhari.

TABLE 2: NIR and GIR for 90% efficiency.

		Demand (approved) in m^3			
Crop	%	Area (m^2)	Delta (m)	NIR at field (m^3)	GIR at field (m^3)
Sugar cane	6	3464944.26	1.17	4042758.36	4447034.19
Other perennial crops	2	1154981.42	0.9	1039541.03	1143495.13
Paddy (Kharif)	70	40424349.64	0.31	12588950.96	13847846.06
Cotton	10	5774907.09	0.26	1497722.15	1647494.37
Wheat	12	6929888.51	0.25	1728175.6	1900993.16
Total	**100**		**57749070.91**		**22986862.91**

TABLE 3: Areawise demand for 90% efficiency.

Polygon no.	Area (m^2)	% Area	GIR (m^3)	Demand (m^3/s)
1	1392956.3	2.41	554462.5	0.11
2	1186152.14	2.05	472144.7	0.09
3	759288.51	1.31	302232.8	0.06
4	1138073.57	1.97	453007.1	0.09
5	776647.09	1.34	309142.3	0.06
6	1171101.22	2.03	466153.7	0.09
7	1748101.88	3.03	695827.3	0.13
8	292008.07	0.51	116233	0.02
9	347877.22	0.6	138471.6	0.03
10	261804.95	0.45	104210.8	0.02
11	224658.3	0.39	89424.64	0.02
12	446383.18	0.77	177681.6	0.03
13	258386.8	0.45	102850.2	0.02
14	60371.55	0.1	24030.73	0
15	145458.28	0.25	57899.28	0.01
16	39453.71	0.07	15704.44	0
17	1217991.22	2.11	484818.1	0.09
18	122548.94	0.21	48780.28	0.01
19	283491.6	0.49	112843.1	0.02

TABLE 3: Continued.

Polygon no.	Area (m^2)	% Area	GIR (m^3)	Demand (m^3/s)
20	1071211.4	1.85	426392.8	0.08
21	1874704.24	3.25	746221	0.14
22	560513.73	0.97	223111	0.04
23	706984.8	1.22	281413.4	0.05
24	784147.43	1.36	312127.8	0.06
25	488044.43	0.85	194264.8	0.04
26	2873835.73	4.98	1143923	0.22
27	339504.17	0.59	135138.7	0.03
Total		**20571700.46**		**1.58**
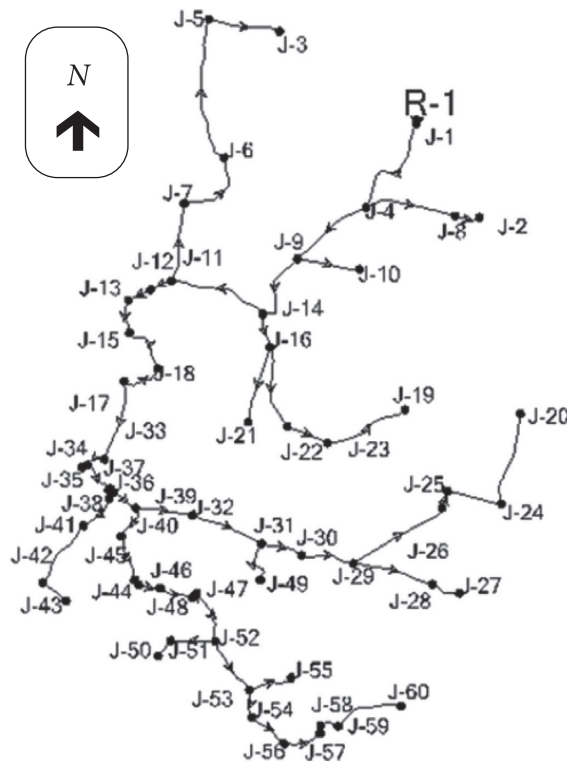
FIGURE 4: Minimum spanning tree network.

Steiner tree network consists of 81 pipes, 60 nodes, 21 Steiner points, and 1 source reservoir with a total length of 25.15 km. Out of 81 pipes, it is observed that 23 pipes (1, 2, 3, 5, 18, 26, 28, 29, 30, 34, 35, 41, 46, 49, 50, 66, 70, 71, 72, 76, 77, 79, 80) are having a diameter less than the designed diameter and 6 pipes (4, 10, 36, 40, 47, 81) have diameters equal to the designed diameter, as shown in Figure 8. The cost of the network is reduced due to the reduction in the pipe size of 23 pipes.

Steady-state simulation analysis of the Steiner tree model is carried out which results in pressure values within the permissible limit. On optimizing the network for pipe sizing, it is observed that all pressure heads are positive with

simulated value ranges from 0.85 to 21.72 m having zero violation in pressure at each node. The obtained optimized solution is for pressure constraints of 0.65 to 23 m. Figure 9 indicates pressure variation at each node for the initial Steiner tree. It is clear from Figure 9 that the simulated pressures are well within the considered limits.

The overall comparison between the initial looped WDS and IST is shown in Table 4 which indicates the comparison parameters as length, area, material, number of nodes and pipes, discharge capacity, and total cost of both the networks. Along with these parameters, the comparison based on hydraulic properties such as minimum and maximum
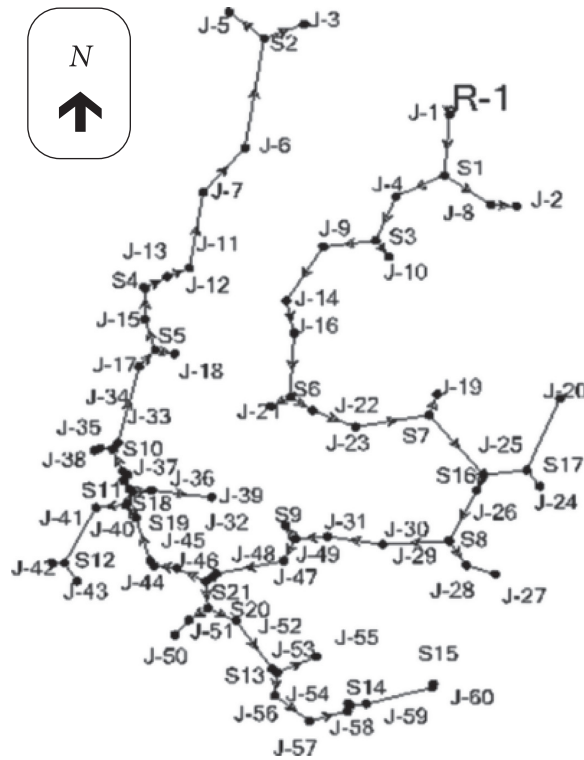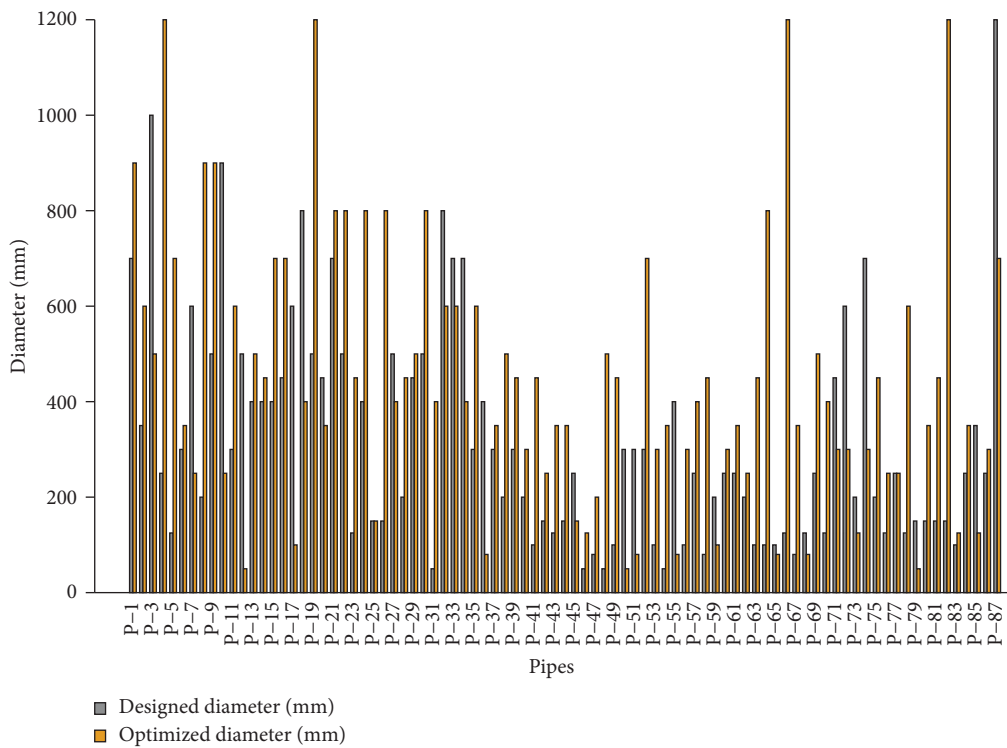
Figure 5: Steiner tree.

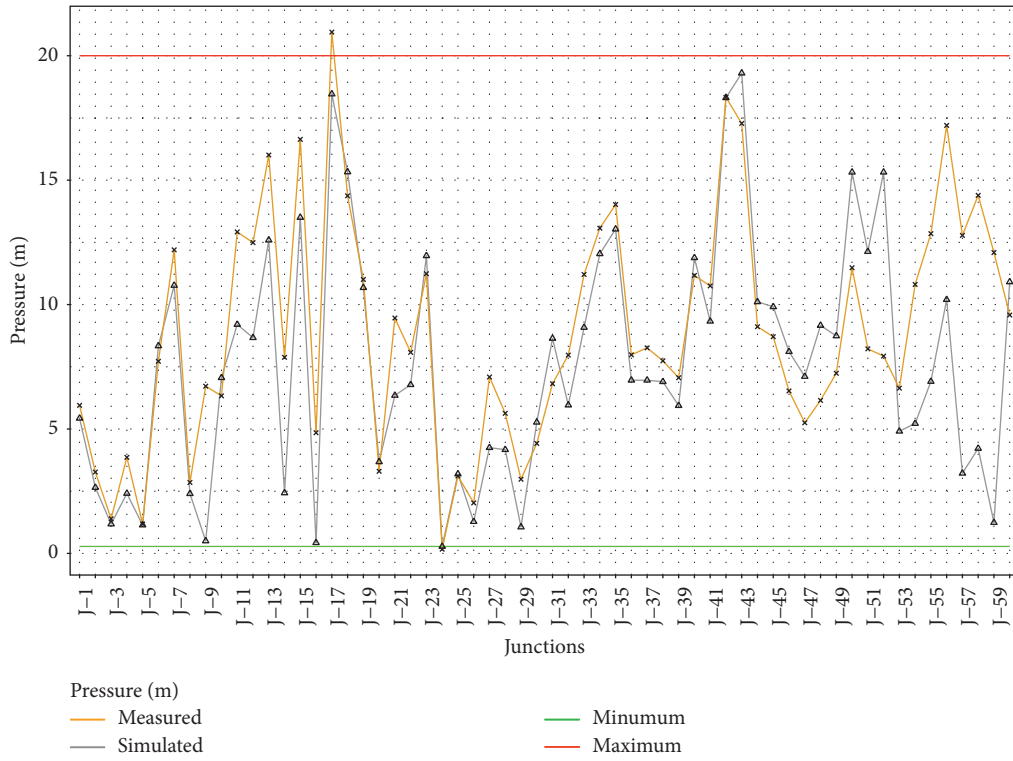Figure 6: Designed diameter versus optimized diameter of the looped network.

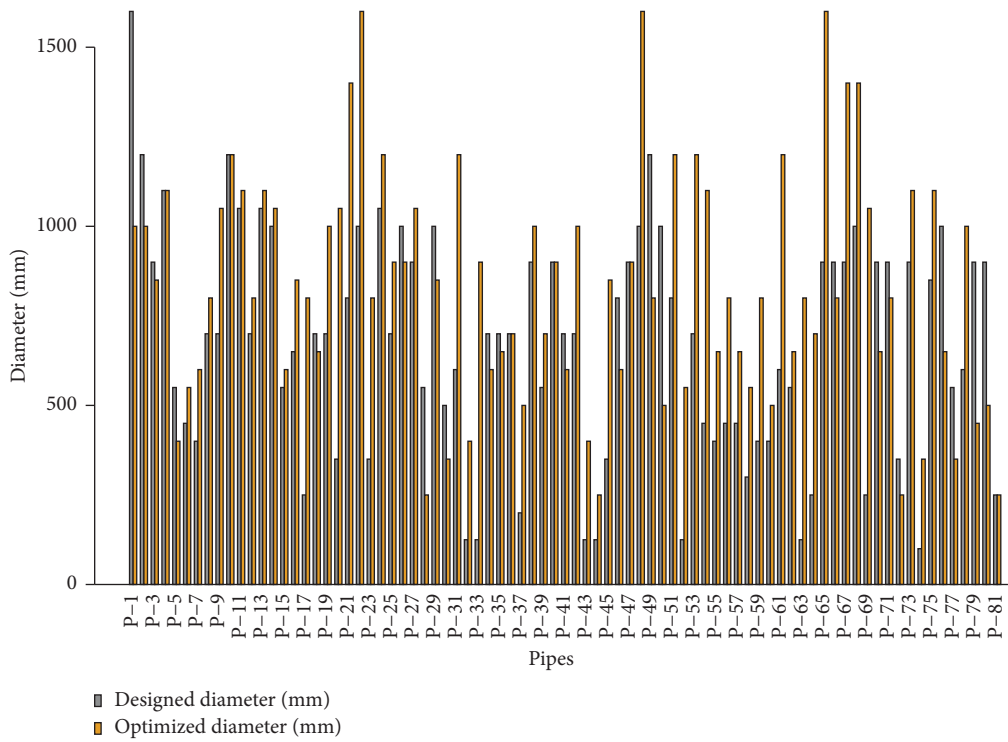Figure 7: Pressure variation at each junction of looped network.

Figure 8: Designed diameter versus optimized diameter of initial Steiner tree network.
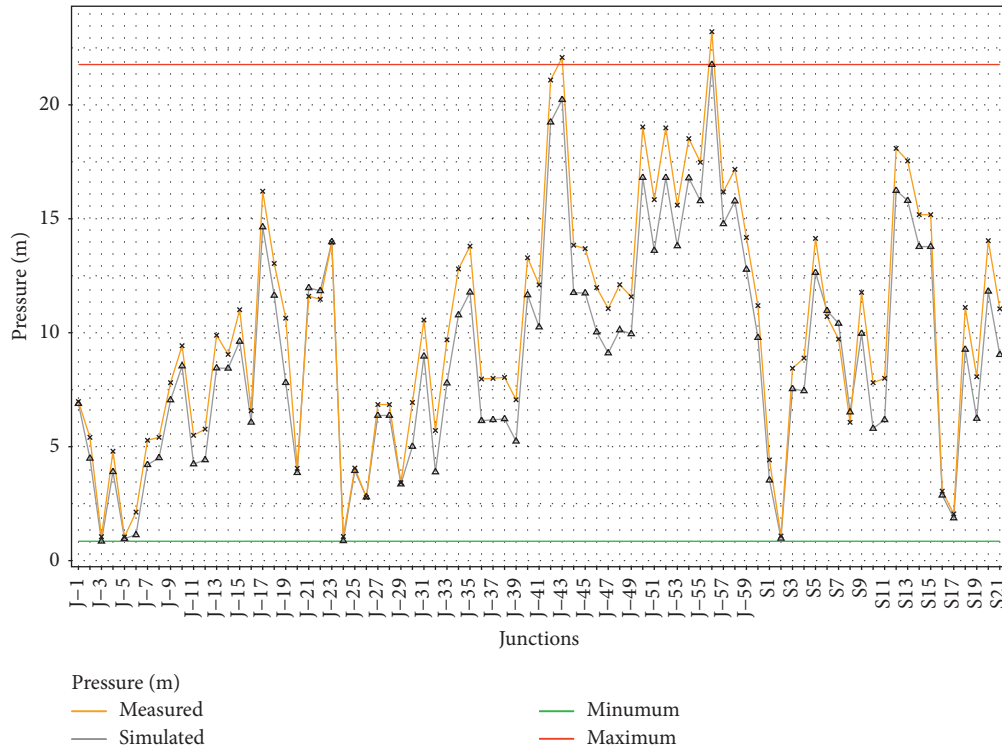
Figure 9: Pressure variation at each node for initial Steiner tree.

Table 4: Comparison between looped network and initial Steiner tree network.

Parameter	Looped network		IST network	
Length (km)	59.17		25.151	
Area (km^2)	2057.17		2057.17	
Material	PVC		PVC	
Source reservoir	1		1	
Node	60		81 (60 + 21 Steiner points)	
Pipe	87		81	
Discharge capacity (cumecs)	1.578		1.578	
Total cost (rs.)	25.86 crores		24.76 crores	
Cost per km length (rs./km)	0.437 crores		0.984 crores	
	Minimum	Maximum	Minimum	Maximum
Designed diameters (mm)	50	1200	250	1600
Optimized diameter (mm)	50	1200	250	1600
Pressures (m)	0.17	20	0.65	23
Simulated pressures (m)	0.28	19.3	0.85	21.72

designed and optimized diameters and pressures and simulated pressures of both the networks is also presented.

5. Conclusion

As the network is buried underground, therefore the location of the nodes does not create any hindrance to on-land farming. Moreover, the increment in the number of nodes also has little effect on the functionality of the network. In the present study, initially, a looped network is analyzed and design is carried out for the total length of 59.17 Km. The total cost of looped PIN is found to be 25.86 crores, that is, 0.45 crores per Km length. After converting the looped network to a branch network (MST) using PA, it is observed

that number of links reduced to 60 from the 87 for the same nodal demand. The length of the looped network decreases to 28.65 Km from 59.17 Km, that is, 51.58%. The final step in which the MST is converted to IST using the Steiner concept shows the reduction in network length from 28.65 to 25.151 Km, that is, 12.21% although the number of links and nodes were increased to 81 and 81 (60 already existing nodes and 21 Steiner points), respectively. The total cost of the Steiner network is 24.76 crores, that is, 0.987 crores per km length. The total reduction in the cost of the Steiner tree is found to be 4.25% compared to the looped network. Results highlight that though the per meter cost of the ST is higher than the initial looped network, but the two-step optimization of layout reduced the total cost of the network. Hence,

the method proposed in the present study can be certainly utilized for the layout and pipe size optimization. As the pipes are underground, the Steiner point junctions are feasible, as no on-field problems are faced. The present work can be extended for further cost reduction, which may be possible if different pipe materials are used for different lengths of the network.

Data Availability

Data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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