LAYOUT AND COMPONENT SIZE OPTIMIZATION OF SEWER NETWORK USING SPANNING TREE AND MODIFIED PSO ALGORITHM

Ph.D. THESIS

by

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CERTIFICATE

This is to certify that the thesis entitled "**Layout and Component size Optimization of Sewer Network using Spanning tree and Modified PSO Algorithm**" which is being submitted by **Praveen Kumar Navin (ID: 2012RCE9012)** to the Malaviya National Institute of Technology Jaipur for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirement for the submission of this thesis, which has reached the requisite standard.

(Prof. Y. P. Mathur)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled "**Layout and Component size optimization of sewer network using Spanning tree and Modified PSO Algorithm**" in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted to the Department of Civil Engineering, Malaviya National Institute of Technology Jaipur, is an authentic record of my own work carried out at Department of Civil Engineering during a period from July 20, 2012 to April 15, 2016 under the supervision of Dr. Y. P. Mathur, Professor, Department of Civil Engineering, Malaviya National Institute of Technology Jaipur, Jaipur - 302017, Rajasthan (India).

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Date: (**Praveen Kumar Navin**)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Abstract

The optimal design of a sewerage system requires layout and component size optimization simultaneously. Layout and component size optimization of sewer network problem consists of many hydraulic constraints which are generally nonlinear and discrete; which creates a challenge even to the modern heuristic search methods. This study aims to introduce a method to solve the problem of layout and component size optimization of a sewer network.

An algorithm 'generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*' is introduced to generate a predefined number of sewer layouts of a base sewer network in order of increasing length and these generated layouts are sorted in ascending order of total cumulative flow *CQ*. Each layout is optimized for component size optimization in this sequence. It has been found that the optimal sewer layout for total system optimization is one where the total cumulative flow has the minimal value.

The modified particle swarm optimization (MPSO) algorithm has been used to optimally determine the component sizes of the selected layouts. The proposed method for optimal layout and component size optimization is applied on three sewer networks (Sudarshanpura, Bajaran and Laxmangarh) design. The results are presented for optimal cost vs cumulative flow of the layouts. Further, results of MPSO have been compared with the original PSO algorithm. The results indicated that the layout having minimum CQ has the minimum total cost and the total cost of sewer layout generally increases with the CQ of a layout. It is also found that the proposed MPSO algorithm solution is better than the original PSO algorithm in all the layouts regarding minimum cost of the sewer network.

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a	The cross section area while running partially full
A	Area of flow in m^2
C	Cost function of sewer network
CC	Concrete cover (m)
CD_{max}	Maximum permissible cover depth
CD_{min}	Minimum cover depth
CQ_j	Sum of cumulative flows in all links of the j^{th} layout
d	Depth of flow
D	Diameter of sewer pipe in m
DEPTH_DS	Downstream Depth in m
DEPTH_US	Upstream Depth in m
d_p	Particle size in mm
D_p	preceding sewers
GRLDS	Downstream ground level (m)
GRLUS	Upstream ground level (m)
ILDS	Downstream invert level (m)
ILUS	Upstream invert level (m)
K	constant
K_S	Dimensionless constant
n	Manning's co-efficient of roughness
N	Total number of edges or links in the layout
P	Wetted perimeter (m)
PC	Total penalty cost

PD	penalty due to depth
PF	Penalty factor
PV_{max}	Penalty due to maximum velocity
PV_{min}	Penalty due to minimum velocity
Q	Discharge in m^3/s
q	Discharge while running partially full
q_{ij}	Flow in the i^{th} link of the j^{th} layout
q_{min}	Minimum discharge in the link
r	Hydraulic mean depth while running partially full
R	Hydraulic mean depth in m
S	Slope of sewer in m/m
S_S	Specific gravity of particle
t	Pipe thickness
TC	Total cost of a sewer network
v	Velocity of flow while running partially full
V	Velocity of flow in m/s
V_{max}	Maximum permissible velocity
V_{min}	Minimum permissible velocity
θ	Central angle from the center of the section to the water surface

Abbreviations

ACO	Ant Colony Optimization
ACOA	Ant colony optimization algorithm
BIE	Bounded implicit enumeration
CA	Cellular automata
CACOA	Continuous Ant Colony Optimization Algorithm
CA-GASiNO	Cellular Automata and Genetic Algorithm for Sewer in Network Optimization
CASiNO	Cellular Automata for Sewers in Network Optimization
CCACOA	constrained Continuous Ant Colony Optimization Algorithms
DDDP	Discrete differential dynamic programming
DP	Dynamic Programming
EPA	Environmental Protection Agency
ERW	Earthworks
GA	Genetic Algorithms
LGA	Layout generation algorithm
LP	Linear Programming
MIP	Mixed integer programming
MST	Minimum spanning tree
NLP	Non-linear Programming
NSGAII	Non-dominated sorting genetic algorithm
OGSDP	Optimal Gravity Sewer Design Program
PCACOA	Partially constrained ant colony optimization algorithm
PSO	Particle Swarm Optimization

QP	Quadratic programing
RCC	Reinforced Cement Concrete
SA	Simulated annealing
SSD	Sanitary Sewer Design
SSOM	Sewer System Optimization Model
TGA	Tree growing algorithm
TS	Tabu search
UCACOA	Unconstrained continuous ant colony optimization algorithm
WWCS	Wastewater collection system

CHAPTER 1
Introduction

1.1 General

Sewer network has played a significant role in the development of human society by collecting wastewater for treatment and disposal. A sewer network collects wastewater from industrial, commercial and residential areas and transports to wastewater treatment plant. Sewerage systems have been used in urban environments since long time, and they are considered as an important part of the urban wastewater infrastructure. The earliest existence of sewerage system can be found in many ancient civilizations: 4000 BC in Mesopotamia (at present in Iraq) and 3000-2000 BC in Mohenjo-Daro (Presently in Pakistan). The Cloaca Maxima, the ancient drainage, built in the 6th century BC, to drain the ‘Forum Romanum’ is still in use (Butler and Davies, 2004). The modern concept of sewerage system evolved in the 19th century due to hygienic reasons. To avoid the hygienic problems, the sewerage system was constructed underground. The main issues of the urban sewerage system are to ensure a better public health, to protect natural water bodies from pollution and to provide a significant level of protection against urban flooding.

The cost of the sewerage system is a major fraction of the overall cost of wastewater disposal. Huge investment is required for construction and maintenance of these large scale sewer networks, and reduction of cost even by a few percent of the cost of these networks may result in substantial saving. Many researchers have focused on applying optimization techniques for obtaining cost effective designs of such networks in recent years. The optimization of sewer system design includes two sub problems:

(i) Optimal sewer network layout determination and,
(ii) Optimal design of sewer network components.

These two sub problems are strongly coupled and should be solved simultaneously for an optimal solution to the whole problem. Simultaneous sewer network layout and its component size optimization problem consist of many constraints which are non-linear, discrete and sequential. The construction cost of a sewerage system can be considerably reduced if the sewer layout, pipe diameters, and pipe slopes are optimized.

Determination of the optimal layout among a large number of alternatives is the first step in designing of a new sewer network. The sewer layout configuration is mainly dependent on the network size, location of the sewage treatment plant (i.e., outlet) and the topography of the area.

Sewer lines generally collect wastewater discharges gravitationally but sometimes depending on topography sewage pumping may be required. The designer depends on the topography of the area and follows natural ground slopes toward the outlet for sewer network layout. In steep areas, based on designer judgment, it is possible to select and design an economic sewer layout. In flat areas, there is no significant change in ground levels. As such many alternatives are there for the connectivity of the sewers and for the outlet position of the sewer network. The number of feasible layouts increases with the number of sewers. In such areas, designer judgment and experience are not sufficient to select and design the most economical sewer layout. For this reason, in such areas, it is necessary and cost effective to apply optimization techniques.

The design of a sewerage system involves the selection of an appropriate combination of sewer pipe diameters and slopes to ensure adequate capacity for peak flows and adequate self-cleansing velocity in the sewer.

In a conventional design process, designers typically use charts and thumb rules to select the diameter and calculate slope of sewers while designing sewer networks. Appropriate diameter and slope combinations are selected for all sewers (i.e., pipes) between manholes. Since there is a large range of sewer slopes, diameters and pipe material, designers can usually only evaluate a small number of alternative feasible solutions. The outcome of such a process depends to a large extent on the designer experience and efforts. It is practically almost impossible to incorporate all feasible design alternatives, and an optimal solution is not necessarily reached. Only using a computer oriented optimal designing procedure, may be a solution.

1.2 Need of the Study

Many researchers have applied optimization techniques to the sewer network design problem. Due to the complication of the problem, most of them have done either sewer layout determination or component sizing. Some researchers have focused on the optimization of component sizing and have ignored the impact of the layout on the component sizing. On the other hand, others have focused on the optimal layout determination and ignored the impact of the component sizing on the final solution. From the study of literature, it was observed that most of the researchers have focused on the problem of optimal component sizing while only a few researchers have focused on the problem of layout optimization and very few on the combined problem of layout and component size optimization of the sewer network.

1.3 Objectives of the Present Study

The present study has been taken keeping in mind the acknowledged gaps as discussed above. The objectives of this study are: sequenced

(i) to develop a method for the generation of potential optimal alternative layouts,

(ii) to develop a method of sequencing of these alternatives. This sequencing is to be used for optimising alternative layouts., and

(iii) to optimize these alternative layouts in the order of their sequencing to get the most optimal solution.

1.4 Thesis Organization

This thesis is organized into several chapters. Chapter 1 discusses the background and objectives of the present study.

In Chapter 2, a comprehensive review of the literature on studies on the different methods used for the sewer network optimization problem is presented.

Chapter 3, provides a general description of the sewerage system components, introduction to sewer hydraulics and design considerations.

In Chapter 4, the methodology used for simultaneous determination of the layout and component size optimization of sewer network problem is presented.

In Chapter 5, results and discussions have been presented.

In Chapter 6, conclusions drawn based on the study have been presented.

CHAPTER 2
Literature Review

2.1 General

The optimization of sewerage system has been a subject of considerable research since late 1960's. Numerous optimization techniques have been applied for sewer network optimization. A brief review of methods available in the literature related to sewer network optimization is presented in this chapter.

2.2 Optimization Methods for Sewer System

Optimal sewer design aims to minimize the network construction cost while ensuring a good system performance (Guo et al., 2008). Numerous optimization methods have been proposed to solve the sewer network problem. Due to the complexity of the problem, most of the existing researches are restricted to considering some simplified form of the problem. The literature survey has been divided in three sub sections. In the first one the papers which have considered only sewer system component size optimization without layout optimization have been reviewed. In the second one the papers which have considered only sewer layout optimization without sewer system component size optimization have been reviewed. In the third one the papers which have considered both sewer layout and component size optimization have been reviewed.

2.2.1 Sewer component optimization

Dajani and Hasit (1974) introduced mathematical programming models for the optimization of drainage networks. These mathematical models were based on two extensions of linear programming (i) separable-convex and (ii) mixed integer programming. The first model produced a continuous range of diameter and assumed full pipe flow, and the second model produced discrete pipe sizes and assumed partial flow. The minimum cost of the drainage system can be achieved by using both of these techniques with partially-full flow and commercially available diameters. The proposed methods were applied to design a seven-link drainage network. The result showed that, this solution required less computer time than those based on mixed-integer programming. However, the requirement of long CPU (central processing unit) time and large memory hinders the method from the application to large scale network.

Mays and Yen (1975) developed a methodology for the optimal design of large storm sewer systems using dynamic programing (DP) and Discrete Differential Dynamic Programing (DDDP) approach. The sewer pipes were sized by using the Manning formula for gravity driven open channel flow. Full pipe flow was assumed at the design flow rate. A feasible solution or an initial trajectory was found by assuming an average slope for every link in the network. The sewer network was divided into equivalent serial subsystems, which were then solved in sequence. They applied the proposed methodology to a hypothetical storm sewer system and found that DDDP requires less computer time than DP, although it cannot guarantee global optimization.

Mays and Wenzel (1976) have updated the search algorithm previously proposed by Mays and Yen (1975). They presented two models for the optimal design of storm sewer systems, using DDDP. The first model considered the sewer network as a non-serial optimization problem in which the basic strategy was to decompose the converging branched system into equivalent serial subsystems for a solution. The second model considered the sewer network as a serial optimization problem. Results of an example using the serial approach were compared with those achieved by using an earlier non-serial DDDP approach. The comparison showed that serial DDDP approach was superior to the non-serial approach because of the ease of handling large systems with many levels of branching.

Gupta et al. (1976) developed a methodology to deal with depth and diameter optimization. The problem was to minimize a non-linear cost function subject to a set of non-linear constraints. They developed a non-linear algorithm based on Powell's method to optimize the design of wastewater collection systems. Each link was considered in sequence, and the objective function was minimized subject to six constraints. The algorithm required small computer memory and small time duration during optimization of a wastewater collection system.

Gupta et al. (1983) developed an optimization approach for the selection of optimal diameter and depth combinations for all links of a wastewater collection system (WWCS) by using DP. They used a modified Hazen-Williams hydraulic model under partial-flow conditions. They considered a 10.7 km long wastewater collection system at Indian Institute of Technology, Bombay for optimal sewer design. The wastewater collection system considered 52 lines, 245 links, 224 ordinary manholes and 21 junction manholes. The proposed approach was applied to the WWCS, and the results were compared with conventional design. The cost of WWCS at IIT Bombay with proposed algorithm and conventional designs were estimated as Rs. 1.6×10^5 and Rs. 2.3×10^5 respectively. This optimization approach used a modified dynamic programming method that is only suitable for medium-sized networks and does not guarantee global optimality.

Nzewi et al. (1985) introduced an Optimal Gravity Sewer Design Program (OGSDP) to design a least-cost gravity sanitary sewer system. The OGSDP model obtained the least-cost design for gravity, non-looping sanitary sewerage system for a given set of design parameters, costs, and layout. The OGSDP determined an initial sewer system design using a heuristic procedure (called the Initial Solution Algorithm) and then improved the design using discrete dynamic programming (DDP) with successive approximations to obtain the final least-cost design. The proposed model was tested on a sample problem with 20 pipes. The design cost by using the Initial Solution Algorithm was \$ 3.5×10^5. By using optimization algorithm, the cost of this design was reduced to \$ 3.3×10^5.

Kulkarni and Khanna (1985) developed a Dynamic Programming optimization algorithm to find a global optimal solution for gravity-cum-pumped wastewater collection system (WWCS). A modified Hazen-William's hydraulic equation has been used in this DP-based approach. Application of DP to WWCS design has been plagued with problems of dimensionality. They tried to solve this problem with the concept of cost-effective feasible groups at junction manholes and a subdivision of the optimal design process. The proposed algorithm was applied to the design of two case studies. Results showed that, Internalization of intermediate pumping in WWCS has saved 7.75 - 28 % cost over complete gravity optimal systems in these case studies. In designing a WWCS consisting of 607 links and 291 junctions, the authors had to divide the network into three zones, which is an implicit indication of the computational difficulties in terms of time and storage encountered in DP-based sewer design approaches.

Walters (1985) applied DP for the least cost design of sewer network in which the positions of sewer junctions, slopes, and diameters of the sewers were considered as variables. The main restriction was that the general configuration of the sewer layout must be predetermined, i.e., the trunk sewer and its branches must first be defined. The method optimized the position of those manholes in plan that the designer selects as having some freedom of movement. It simultaneously optimized the pipe gradients and diameters. The proposed method was applied for the design of three storm sewer networks. The result showed that the construction cost of such networks was reduced by 4 % to 14 % on adaptation of this methodology, the cost would further reduced if more freedom of position for manhole is given in a network with higher flow rates.

The method proposed by Mays and Yen (1975), Mays and Wenzel (1976), Gupta et al. (1976), Gupta et al. (1983), Nzewi et al. (1985), Kulkarni and Khanna (1985), and Walters (1985) require long CPU (central processing unit) time and large memory requirement hinders these method from the application to large scale networks.

Desher and Davis (1986) introduced a heuristic program called Sanitary Sewer Design (SSD) to find the least cost design of a sanitary sewer network. The objective of SSD was to find the least cost design of a sewer network. The SSD program calculated pipe slopes, velocities, water depths, and invert elevations corresponding to input parameters (such as pipe lengths, diameters, ground elevations, flows, and design criteria). They applied SSD program to find the optimal design of a 3.25 mile sewer trunk line in Chapel Hill, N.C, USA. The results indicated that the cost can be reduced approximately 20-25% by maintaining a uniform progression of pipe sizes.

Elimam et al. (1989) developed a combined linear programming, diameter discretization and heuristic approach for the optimum design of large gravity sewer networks. It contained a non-linear convex function concerning pipe diameters and slopes, which was approached by piecewise linear sections. This approach used a modified Hazen-Williams hydraulic model at part-full flow conditions, along with a newly developed universal expression to determine the coefficient of roughness. The methodology was applied to the design of domestic wastewater network in the Wafra district of Kuwait. They concluded that the proposed method was able to design different hydraulic or structural factors for large sewer networks within a less CPU time.

Liang et al. (2000) introduced a procedure for designing a wastewater collection system. The purpose of the study was to minimize the overall cost of wastewater collection system. Many hydraulic constraints were incorporated within the modelling procedures. Genetic algorithm was applied to find good feasible pipeline networks. They applied their proposed procedure to the Changbin Coastal Industrial Park wastewater collection system in taiwan which resulted in cost savings of about 9 % as compared to traditional method.

Liang et al. (2004) implemented tabu search (TS) and genetic algorithms techniques to solve the sewer network optimization problem. The objective was to determine the optimal cost design for a given sewer network. In order to produce feasible solutions efficiently, an adaptive rule was generated for the GA and a dynamic strategy was developed for the TS technique. The proposed TS and GA techniques were tested against a case study and results were compared with the conventional methodology. They found that the optimal design using both GA and TS technique achieved a significant reduction in sewer network construction costs. Overall, the best GA and TS designs attained cost savings of 9 and 16 percent, respectively.

Guo et al. (2007) introduced an approach for sewer network design based on cellular automata (CA) principles, known as Cellular Automata for Sewers in Network Optimization (CASiNO). The objective was to minimize the capital cost and flooding within a sewer network. The pipe diameters of the storm sewer network were considered as the decision variables in the optimization problem. This approach is heuristic and generally relies on the main properties of CA: homogeneity, parallelism, and locality. They combined the CA optimizer with a sewer hydraulic simulator, the EPA Stormwater Management Model. At every optimization step the optimizer updates all decision variables simultaneously based on the hydraulic situation within every neighbourhood. The proposed CASiNO approach was tested against two case studies. They found that CASiNO approach obtained a near optimal solution in a less number of computational steps as compared to that of a genetic algorithm.

Weng and Liaw (2007) developed a Sewer System Optimization Model (SSOM) for optimal hydraulic designs of the urban sewer system. They used 0-1 mixed integer programming (MIP) for branched gravity sewer system hydraulic designs and the bounded implicit enumeration (BIE) algorithm for sewerage system optimization model (SSOM) development. The proposed model was tested against a case study, and the results were compared with the existing traditional design approach. It was found that the total construction cost for the Sewer System Optimization Model program was 6.9×10^7 NT$ and 7.8×10^7 NT$ for the traditional design approach.

Izquierdo et al. (2008) proposed PSO for optimal design of wastewater collection networks. The pipe diameters and slopes of the wastewater collection network were considered as the decision variables of the optimization problem. They considered slopes and depth of excavation as continuous variables, and pipe diameters as discrete variables. The proposed PSO technique was able to tackle simultaneously continuous and discrete variables. They applied PSO techniques on the cost function. The proposed technique was tested against a benchmark example, and the results were compared with those obtained by using dynamic programing (DP) to solve the same problem under the same conditions. The result showed that PSO techniques gave better result than dynamic programming.

Guo et al. (2008) proposed a hybrid optimization method GA-CASiNO (genetic algorithm and cellular automata for sewers in network optimization), which combined the genetic algorithm (GA) and cellular automata for sewers in network optimization (CASiNO). The objective of study was to minimization of flooding within a sewer network and of its capital cost. They combined CASiNO and the NSGA-II (non-dominated sorting genetic algorithm) together and executed them in two consecutive stages during the optimization. A localized approach CASiNO was applied in the first stage to obtain a set of preliminary solutions, which were then used to seed NSGA-II in the second stage. The proposed GA-CASiNO approach was tested against two case studies. They found that GA-CASiNO demonstrated better performance than traditional constrained NSGA-II with no extra computational cost.

Afshar (2010) introduced a Continuous Ant Colony Optimization Algorithm (CACOA) to optimal design of a sewer network. In this algorithm two alternative approaches (Continuous Ant Colony Optimization Algorithms, viz., CCACOA1 & CCACOA2) were implemented and applied to a storm sewer network. The nodal elevations of the sewer network were taken as the decision variables of the optimization problem. In the first algorithm (CCACOA1) which used an unconstrained approach, a Gaussian probability density function was used to represent the pheromone concentration over the allowable range of each decision variable. In the second algorithm (CCACOA2) which used a constrained approach, known value of the elevation at a downstream node of a pipe was used to define new bounds on the elevation of the upstream node satisfying the explicit constraints on the pipe slopes. The applicability of the proposed approaches was tested against a benchmark text example, and the results were compared with the original unconstrained continuous ant colony optimization algorithm (UCACOA). The results showed considerable improvements in the performance of the CACOA regarding both quality and convergence characteristics of the final solutions.

Afshar et al. (2011) applied CA approach for the optimal design of sewer networks, with a fixed layout, in which both slopes and pipe diameter were determined optimally. The nodes of the sewer network were considered as the CA cells, with their elevations as the corresponding cell states. The neighbourhood of the cells was defined by the set of pipes connected to the cell under consideration. The CA updating rule was received by requiring that the network cost is minimized over the cell and neighbourhood. They applied the proposed approach against two benchmark problems, and the results were compared with other methods. They found that the CA approach results in a near optimal solution compared to the existing methods, with less computational effort.

Yeh et al. (2011) applied simulated annealing (SA) and tabu search (TS) approach for the optimization of sewer network designs. They applied their proposed approach to sewer network design of a central Taiwan township, which contains significantly diverse elevations. The result of optimal sewer designs form SA and TS approaches were compared with the original official design. The results indicated that original official design was found to violate the minimum flow-velocity requirements. TS and SA approaches achieved least-cost designs that also satisfied all the constraints of the design, but construction costs were slightly higher (by 3.2 % and 3.4 %, respectively) than the construction costs of the original design. They found that optimization performance of SA optimization approach was much more efficient and reliable than TS approach for sewer network problem.

Haghighi and Bakhshipour (2012) introduced an optimization model for sewer networks design. This model specially focused on handling the non-linear and discrete constraints of the problem. For this reason, they proposed an adaptive genetic algorithm for the optimal design of each chromosome, containing sewer diameters, slopes and pump indicators. The binary chromosomes were freely produced and then decoded to feasible design alternatives following a sequential design-analysis algorithm. The adaptive decoding strategy was set up based on the open channel hydraulics and sewer design criteria. All design criteria were systematically satisfied using the proposed method. A benchmark sewer network was designed using the proposed method. The results showed that this method aids the GA to perform the optimization more proficiently in terms of speed and accuracy.

Karovic and Mays (2014) developed a new optimization procedure for the minimum cost design of sewer systems for a pre-determined layout. The optimization procedure was developed within Microsoft Excel using simulated annealing techniques. The total cost of the sewer system that was determined with their proposed optimal design procedure was compared with the total cost of the system as determined from the conventional design approach. They applied simulated annealing optimizer to the design of the storm sewer network which resulted in a cost savings of about 7 %.

2.2.2 Sewer layout optimization

Liebman (1967) presented a heuristic method for sewer layout optimization, assuming the pipe diameters to be fixed. They obtained the best layout by a search procedure. At every step, one branch of the network was changed. The change was reserved if it resulted in a decrease in the total cost. The method suffered from several limitations, the most important one being that the network was never designed hydraulically. Liebman's heuristic model in designing the sewer network for a town (Pinarkent) with 312 nodes and 514 links indicated excessive computation time requirements. Therefore, the heuristic search method may prove useful only in small networks.

Tekeli and Belkaya (1986) developed a Layout Generation Algorithm (LGA) for generation of sanitary sewer layouts, using a standard shortest path algorithm. The optimal layout, in terms of least cost, required minimization of total excavation, for evaluating the shortest path from each manhole to the predetermined outlet. From the data available, three shortest path measures were formulated using the ground slopes and the horizontal portion of sewer lengths for every sewer. The hypothetical excavation measure, which requires every sewer to be laid at minimum cover depth and slope, yielded the minimum invert depths and excavations when the generated layouts were hydraulically designed. The result showed that the proposed algorithm generates optimal layout for networks with up to 70 manholes. The propoesd algorithm required excessive computer memory or execution time. Hence, the algorithm can only be used with small networks.

Walters and Lohbeck (1993) applied GA for the optimal layout selection of a dendritic pipe network. The method assumed that the layout was generated from a directed base graph. This algorithm needed only limited memory requirement and computer facilities to design the layout of large non-linear flow networks. Results showed that, for small test networks, in comparison to an existing DP formulation, the GA has the advantage of significantly reduced memory requirements, but cannot guarantee to reach the optimal solution achieved by DP. Moreover, for big networks, no algorithm will guarantee to determine the global optimum; however, the GA gave near optimal solutions. They exhibited that the directed base graph considerably reduces the number of possible trees; nevertheless, it required great consideration when specifying the initial directions for satisfying the problem constraints.

Walters and Smith (1995) described a model for the optimal layout selection for a network with a tree structure. The model was based on genetic algorithm and tree growing algorithm. Unlike the previous work (Walters and Lohbeck 1993), this method was excerpted the optimum layout from an undirected base network.

Afshar and Mariño (2006) applied an ant colony optimization algorithm to the optimal layout determination of tree networks. Two different formulations were applied to represent the layout optimization problem of tree networks. In the first formulation, every link of the base graph was considered as the decision point of the problem. The ants were then required to choose from two options (viz., one and zero) at every decision point, where the zero option denoted the no pipe available for the link. The first formulation required a huge search space by the infeasible solutions. In the second formulation, the network nodes were taken as the decision points of the problem. In which the ants were required to choose any of the available links which were provided by a tree-growing algorithm. The second formulation required a very less search space compared to the first algorithm. The performances of the proposed approaches were tested against three benchmark examples. The results showed that the second formulation gives a better solution in comparison to other global optimization methods.

Haghighi (2013) developed a loop-by-loop cutting algorithm to generate feasible sewer layouts from the base graph. All constraints of the sewer layout sub-problem were systematically handled by using this algorithm. They defined a non-linear objective function to find the optimum layout by using genetic algorithm. After the determination of optimal layout, a discrete differential dynamic programming model was applied to optimize the network components. The proposed approach was applied to a case study from the literature. They found that the loop-by-loop cutting algorithm was more useful for the design of urban drainage systems in flat areas.

Haghighi and Bakhshipour (2015) introduced a procedure for designing the layout of sewer networks considering their reliability. They proposed a reliability criterion, in which loop-by-loop cutting algorithm used for the layout generation and then optimized using simulated annealing approach. The best sewer layout with the maximum reliability signifies an optimum layout in which clogging in a sewer has the least effect on its upstream lines. A case study was solved using the proposed procedure. Then, sewer specifications of the obtained layout were optimally designed by applying the discrete differential dynamic programming (DDDP) method. It was concluded that more reliable layouts lead to more expensive designs.

2.2.3 Sewer layout and component size optimization

Argaman et al. (1973) addressed the simultaneous optimization of layout and design of sewerage network. They developed a technique for the selection of the least cost combination of layout pipes, diameters, and slopes. The optimal solution was obtained by using dynamic programming. The major simplifying assumption was that for each pipe of the network the direction of flow was fixed in advance. Therefore, the method was only suitable where the natural topology is inclined in the direction to the outlet only. The main shortcoming of the method is the need for large computer space and long computation time, as the dimensions of the network increase. These restrictive requirements are inherent in the dynamic programming technique, and cannot be avoided unless a different approach is adopted.

Li and Matthew (1990) used the searching direction method for optimal layout determination and a DDDP for the optimal diameters, slopes and on-line pumps determination of a given layout. The result showed that the proposed method produced a satisfactory optimal layout as compared to shortest path spanning tree method or the existing design, although there was still no guarantee that the optimum layout was the global optimal layout.

Botrous et al. (2000) developed a computer program for the design of wastewater collection network. The program was divided into two subprograms (i) searches for the optimal layout of the network considering the excavation volume and (ii) optimal hydraulic design of all links in the layout. They applied DP technique to optimally compute pipe slopes, velocities, and invert elevations. It was applied to a real case 850 m link; the result showed capital cost savings up to 10 % as compared to the manual design. The problem with this methodology was only minimum excavation volume which may not optimal layout for total problem. Further DP technique was used which requires large computer space and long CPU time.

Diogo and Graveto (2006) exploited the specific restrictions of the layout design problem and introduced a deterministic model for small to medium systems. Deterministic model determined the optimal layout of a sewer network with respect to objective (i.e., cost) function. In this work infeasible trees were systematically evaded, and the optimal network is finally determined by means of a simple cost-effective comparison of all solutions having optimized design. For large dimension networks, where it was clearly impossible to achieve an optimal solution with full enumeration, they used a simulated annealing (SA) optimization model.

Moeini and Afshar (2012) used the ant algorithm to solve the layout and size optimization problem of a sewer network. Tree growing algorithm (TGA) was applied to find feasible tree-like layouts out of the base network, and an ant colony optimization algorithm (ACOA) was applied to optimally find the pipe diameters of the selected layout. They proposed two different approaches and their performances were checked against a hypothetical problem. In the first approach, ACOA was applied in a conventional manner for find optimal pipe sizes determination and an adhoc engineering concept for the feasible layout determination. In the second approach, ACOA equipped with TGA was applied to simultaneously find the layout and pipe sizes of the network. The proposed approaches were applied to solve three test examples of different scales. They found that the ACOA–TGA approach produced better results for the problem of layout and size determination of sewer networks. This method is only suitable to a very ideal case where the ground elevation is inclined in only one way to the wastewater treatment plant. Furthermore, this method would have trouble, when applied to practical cases.

The topic of optimal sewer network design has been studied since the concept was first proposed in the mid-1960s. Due to the complication of the problem, most of the existing researches in the field are carried out on either sewer layout optimization or optimal component sizing.

During literature survey, it was observed that for the optimal design of sewer network as a whole, the first step is to generate alternate layouts and then sewerage system components need to be optimized for such layouts. As the number of alternate layouts is very large a methodology needs to be developed to sequence them, and sewerage system components are then to be optimized for these alternate layouts as per their sequencing. This was the missing link in the literature and was the motivation for the present study.

CHAPTER 3

Sewerage System

3.1 General

A general description of the system, its components, and design considerations are presented in the following paragraphs.

3.2 Prominence of sewer systems

The sewer system is required because of the interaction between human activity and the natural water cycle (Butler and Davies 2004). These interactions are:

(i) the abstraction of water from natural cycle to provide water supply for human life, and

(ii) the covering of land with impermeable surfaces that divert rainwater away from the local natural system of drainage.

The earliest existence and use of sewerage systems can be traced back; some archaeological discovering proves that underground sewers existed since ancient civilizations such as Indus Valley civilization etc. In Rome, the first sewers were built between 800 BC to 735 BC.

Sewerage systems at that time were mainly used to drain water from the streets during rainfall. The importance of sewerage system for disposal of human waste and other domestic wastes was not recognised until the mid-19th century. In Europe and the Americas, this recognition came after a series of deadly cholera epidemics (such as the one in early 1800s in London and Paris) due to filthy water (such as water used in flushing toilets and kitchen water) flowing from houses and building into the streets and surrounding areas that polluted sources of freshwater. This led to the awareness of the importance of carrying filthy water away from houses and buildings, treating it before discharging it into the point of disposal (i.e., rivers, streams). A detailed historical description of the use and development of sewer systems since the ancient times has been presented by Schladweiler (2015).

Wastewater, if not drained suitably, can cause water pollution and create health risks. Meanwhile, stormwater, if not drained suitably, has the potential of causing flooding leading to potentially disastrous damages and further health risks. Therefore, sewer systems are considered as an important part of the urban infrastructure.

3.3 Appurtenances of a sewer system

The structures and devices, which are constructed at suitable intervals along the sewer line to help its efficient operation and maintenance, are called sewer appurtenances. In the present work, cost of manholes has been included in the Cost function, and a brief description of the same is presented in section 3.3.1.

3.3.1 Manholes

The manhole is a masonry or R.C.C. (Reinforced Cement Concrete) chamber constructed at suitable intervals along the sewer lines for providing access to the sewer for the purpose of inspection, testing, cleaning and maintenance of sewer. These are provided at every bend, junction, changing the direction or alignment, change of gradient or change of the diameter of the sewer. The sewer line between the two manholes is laid straight with uniform gradient. For straight sewer line manholes are provided at regular intervals depending upon the diameter of the sewer. For sewers which are to be cleaned manually or sewers which cannot be entered for cleaning or inspection, the maximum spacing between the manholes recommended is 30 m (Manual on sewerage and sewage treatment Systems, 2013). In trunk or main gravity sewers with no house service connections, the manual on sewerage and sewage treatment systems (2013) specifies manhole spacing as given in table 3.1.

Table 3.1 Spacing of Manholes

Sewer Diameter (mm)	600 or less	1000 or less	1500 or less	1650 or more
Maximum Manhole Space (m)	75	100	150	200

Source: Manual on sewerage and sewage treatment Systems (2013)

3.4 Design Considerations

Many design and construction factors need to be considered in the design of sewerage system. The manual on sewerage and sewage treatment systems (2013) gives recommendations and guidelines on these factors based on practical considerations. Some of the basic factors used in the present work are briefly discussed below.

3.4.1 Estimation of Design Flow

3.4.1.1 Design Period

The length of time up to which the capacity of a sewerage system will be adequate is referred to as its design period. A design period of 30 years (excluding the construction period) is normally considered for sewers.

3.4.1.2 Population Forecast

The design of the sewer system is based on the projected population of the city or town at the end of the design period. The appropriate method of population forecast, consistent with the growth pattern of the town is to be used for population forecast.

3.4.1.3 Per Capita Sewage Flow

Although the whole spent water of a community should normally contribute to the total flow in a sanitary sewer, a small portion may be lost through evaporation, seepage into the ground, leakage, etc. In arid regions, mean sewage flows may be as low as 40% of water consumption while for an intensely developed area, flows may be as high as 90% (Manual on Sewerage and Sewage Treatment Systems 2013). Generally, 80% of the water supply may be expected to reach the sewers unless there is data available to the contrary.

The flow in sewers varies considerably from hour to hour and seasonally. For the purpose of hydraulic design estimated peak flows are adopted. The peak factor or the ratio of maximum to average flows depends upon the contributory population as given in Table 3.2.

Table 3.2 Values of Peak Factors

Contributory Population	Peak Factors
Up to 20,000	3
20,001 to 50,000	2.5
50,001 to 7,50,000	2.25
Above 7,50,001	2

Source: Manual On Sewerage And Sewage Treatment Systems (2013)

3.4.2 Minimum Size of Circular Sewers

The minimum diameter may be adopted as 200 mm for cities having a present population of over 1 lakh. Nevertheless, depending on growth potential in certain areas, even 150 mm diameter can also be considered. However, in towns having a present population of less than 1 lakh, the minimum diameter of 150 mm shall be adopted.

3.4.3 Flow in Circular Sewers

3.4.3.1 Minimum Velocity for Avoiding Sedimentation

The flow velocity in the sewers should be such that the suspended solid materials in sewage do not get deposited at the bottom of the sewer. In the design of sewerage system it is ensure that the self-cleansing velocity is achieved at least ones in a day so that any suspended solid settled during low velocity in the sewers are washed away when this velocity is achieved. To ensure that the deposition of suspended solids does not take place, self-cleansing velocities using Shield's formula is considered in the design of sewers.

$$V = \frac{1}{n}\left[R^{\frac{1}{6}}\sqrt{K_S\left(S_S - 1\right)d_p}\right] \tag{3.1}$$

Where, n = Manning's co-efficient, R = Hydraulic mean radius in m, K_S = Dimensionless constant with a value of about 0.04 to start motion of granular particles and about 0.8 for adequate self-cleansing of sewers, S_S is Specific gravity of particle and d_p is Particle size in mm. The Shield's formula indicates that the velocity required to transport material in sewers is generally dependent on the particle size and specific gravity and slightly dependent on the shape of the sewer and depth of flow. The specific gravity of grit is usually in the range of 2.4 to 2.65. Gravity sewers shall be designed for the velocities, as given in the Table 3.3.

Table 3.3 Design Velocities in Gravity Sewers

No	Criteria	Value
I	Minimum velocity at initial peak flow	0.6 m/s
2	Minimum velocity at ultimate peak flow	0.8 m/s
3	Maximum velocity	3 m/s

Source: Manual On Sewerage And Sewage Treatment Systems (2013)

In India the sewerage system is design for 30 years. Initial peak flow refers to the peak flow corresponding to the start of the design period, whereas the ultimate peak flow refers to the peak flow at the end of the design period.

3.4.3.2 Maximum Velocity

Just as it is essential to provide a minimum velocity of flow of sewage (self-cleansing velocity) in sewers to avoid its clogging, it is also essential that the velocity of flow of sewage in sewers should not be excessive to cause erosion or scouring of its inner surface. At higher flow velocities beyond permissible limit erosion or scouring will be caused due to the abrasive action of harder materials such as sand, gravel and other gritty, present in sewage and this will damage the inner surface of the sewer. Therefore, the maximum velocity shall be limited to 3 m/s.

3.4.4 Slope of sewer

Pipe slope must be sufficient to provide the required minimum velocity and depth of cover on the pipe. The minimum slopes recommended for adoption are given in table 3.4.

Table 3.4 Minimum Slopes in sewers

Sewer Size (mm)	Minimum Slope		Sewer Size (mm)	Minimum Slope	
	As percent	As 1 in		As percent	As 1 in
150	0.60	170	375	0.15	670
200	0.40	250	450	0.12	830
250	0.28	360	≥ 525	0.10	1000
300	0.22	450			

Source: Manual on sewerage and sewage treatment Systems (2013)

3.4.5 Cover

In the case of sewerage system, standard design practice is to provide a minimum cover of 1m at the starting point. The minimum cover depth for sewers is provided to protect against imposed loads mainly vehicle loads, and to allow sufficient fall on house connections.

3.4.6 Hydraulics of Sewers

The circular sewers may run either full or partially full conditions. When sewers run full, the hydraulic elements are as described below:

i. Area

$$A = \frac{\pi D^2}{4} \tag{3.2}$$

Where, A = area of flow in m^2

D = diameter of sewer pipe in m

ii. Hydraulic Mean Radius

$$R = \frac{A}{P} = \frac{D}{4} \tag{3.3}$$

Where, P is wetted perimeter (m).

$$P = \pi D \tag{3.4}$$

iii. Velocity of Flow (Manning's equation)

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{3.5}$$

Where,

V = velocity of flow in m/s, S = slope of sewer in m/m,

n = Manning's coefficient of roughness

iv. Discharge

$$Q = AV \tag{3.6}$$

Where, Q = discharge in m^3/s

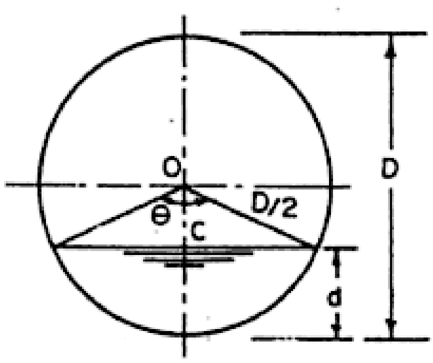


Figure 3.1 Partially filled circular sewer

Figure 3.1 shows a circular sewer running partially full. Let D be the internal diameter of the sewer, d be the depth of flow, and θ be the central angle in degrees.

v. Theta (θ)

Saatci (1990) gave an expression for computing the value of θ directly by using the values of D, Q, and S.

$$\theta = \frac{3\pi}{2}\sqrt{1-\sqrt{1-\sqrt{\pi K}}} \tag{3.7}$$

Where, K is a constant, and calculated values of θ as in radian.

This expression based on regression analysis is valid for θ within the range of 0 to 265 degrees.

The value of K is calculated by following equation:

$$K = Q.n.D^{-8/3}S^{-1/2} \tag{3.8}$$

Equation 3.7 should be applied for K values less than $1/\pi = 0.318$ (which corresponds to $\theta = 265°$, $d/D = 0.838$).

vi. Depth Ratio

$$\frac{d}{D} = \frac{1}{2} \times \left(1 - \cos\frac{\theta}{2}\right) \tag{3.9}$$

Where, d is the depth of flow.

vii. Hydraulic Mean Radius (HMR)

$$r = \frac{D}{4}\left(\frac{\theta - \sin\theta}{\theta}\right) \tag{3.10}$$

viii. Area of Cross Section

$$a = \frac{D^2}{8}(\theta - \sin\theta) \tag{3.11}$$

Where, a = flow area while running partially full.

3.4.7 Invert Levels

The invert level is the interior bottom level of a sewer pipe. The upstream and downstream invert levels are calculated by following equations:

$$\mathrm{ILUS} = \mathrm{GRLUS} - \mathrm{cover} - \mathrm{D} - \mathrm{t} \tag{3.12}$$

$$\mathrm{ILDS} = \mathrm{ILUS} - \left\{\mathrm{Pipe\ length} \times \left(1/\mathrm{slope} \right)\right\} \tag{3.13}$$

Where,

ILUS = upstream invert level (m),

ILDS = downstream invert level (m),

GRLUS = upstream ground level (m),

t = pipe thickness, and slope is expressed as 1 in n.

3.4.8 Earthwork

Earthwork (ERW) for the trench is calculated by the following equation:

$$\mathrm{ERW} = \mathrm{Length} \times \mathrm{Width} \times \mathrm{Depth} \tag{3.14}$$

Where, Width = Pipe Diameter (m) + (2 × 0.25 m)

3.4.9 Depth of Excavation

Depth of excavation (DEP_EX) is calculated by the following formula:

$$\mathrm{DEP\_EX} = \left(\frac{\mathrm{DEPTH\_US} + \mathrm{DEPTH\_DS}}{2} \right) + \mathrm{CC} \tag{3.15}$$

Where,

Upstream Depth in m (DEPTH_US) = GRLUS – ILUS,

Downstream Depth in m (DEPTH_DS) = GRLDS – ILDS,

GRLDS = downstream ground level (m),

CC = Concrete bedding (m).

CHAPTER 4
Methodology

4.1 General

As discussed in the previous chapter, sewer network design, and its optimization problem is divided into two sub-problems:

(i) Selection of optimal sewer layout, and

(ii) The design of optimal size of sewer network components.

The sewer layout is mainly dependent on the location of the sewage treatment plant (outlet), the topography of the area and the network size. Selection of the good layouts among a large number of alternatives is the initial step in designing a new sewerage system.

4.1.1 Basics of Graph Theory

The sewer layout is a graph with specific properties. Therefore, it is necessary to review some basic definitions and principles of the graphs (Clark and Holton 1995; Deo 2005; Sörensen and Janssens 2005; Fournier 2009; Biswas et al. 2012):

i. Graph: An undirected graph G = (V, E) consists of a set of vertices V (V = v_1, v_2, . ., v_n) and another set of edges E (E = e_1, e_2, . ., e_m), such that each edge e_{ij} is identified with an unordered pair (v_i, v_j) of vertices.
ii. Tree: A graph G is called a tree if it is a connected acyclic graph. In acyclic graph there is one and only one path between any pair of vertices.
iii. Weighted Graph: A weighted graph is a graph G in which each edge e is assigned a real number w(e) called the weight of the edge.
iv. Spanning Tree: A spanning tree of a graph *G* is a tree containing all vertices of a graph G.
v. Minimum spanning tree (MST): A spanning tree with the minimum total weight in a weighted graph is called a minimum spanning tree.

The layout of a sewer system is a sub graph extracted from a predefined base graph of city or town drainage system. In a base graph (network), all possible locations of manholes (vertices) and sewer lines (edges or links) are identified and this graph is a connected cyclic graph. With respect to the urban street configurations, topology, barriers, locations of the outlets, an undirected base graph can be drawn. Nevertheless, for generating a feasible layout from a base graph two basic constraints must be met are: (i) no cycle is accepted in layout in other words, it should be tree and (ii) all manholes (vertices) must be involved in the layout (spanning tree).

There are number of greedy algorithms for finding a minimum spanning tree (MST) of an undirected, weighted graph G and Kruskal's algorithm is well known among them.

4.1.2 Kruskal's algorithm

Kruskal's algorithm is one of the optimized ways to determine the minimum spanning tree in a connected graph. The basic steps to determine the minimum spanning tree in this process are as follows (Clark and Holton 1995).

Step1: Choose e_1 an edge of graph G, Such that w (e_1) is minimum, and e_1 is not a loop.

Step 2: If edge e_1, e_2, . . ., e_i have been chosen, then choose an edge e_{i+1} not already chosen, such that:

i. The induced sub graph G[{e_1, . . ., e_{i+1}}] is acyclic and

ii. w(e_{i+1}) is minimum (Subject to Condition (i))

Step 3: If G has n vertices, stop after n-1 edges have been chosen else Repeat Step2.

Each sewer line constitutes the edge with weight equal to it's length. Minimum spanning tree represents the minimum length layout of a base sewer network (graph). The minimum length sewer layout (MST) does not guarantee to give an optimal solution of the sewer system. Therefore, sewer layout optimization problem needs to generate many sewer layouts from a predetermined base network. Hence, an algorithm 'Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*' is proposed to find a predefined number of spanning trees of a graph (base sewer network) in order of increasing total cumulative discharge *CQ* (Kapoor and Ramesh, 1995; Kapoor and Ramesh, 2000; Yamada et al., 2010; Naskar et al., 2010).

4.1.3 Algorithm: Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*

The algorithm is based on the assumption that a base sewer network (graph) including all possible edges of the network is given i.e., locations of manholes have been identified. In this algorithm, initially a predefined number of spanning trees of a graph are generated in order of increasing total weight (length). Total cumulative flow (*CQ*) is then calculated for all generated layouts (spanning tree), and finally these layouts are sequenced in ascending order of *CQ*. The equation 4.1 is used to calculate total cumulative flow (CQ_j) of j^{th} layout:

$$CQ_j = \sum_{i=1}^{i=N} q_{ij} \tag{4.1}$$

Where, N = the total number of links in the j^{th} layout, q_{ij}= flow in the i^{th} link of the j^{th} layout, and CQ_j is the sum of cumulative flows in all links of the j^{th} layout.

The 'Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*' algorithm is formulated by using the following steps:

1. Feeding input, number of spanning trees to be generated (NST), number of nodes (i.e., manholes) m, number of links n, nodal connectivity, link lengths (i.e., weight), nodal flow contribution, and sink node number.
2. Finding the MST from a given graph (base network) using Kruskal's algorithm
3. Calculating the remaining (NST-1) number of spanning trees in order of increasing weight by elementary tree transformation technique.
4. Calculating discharges (flows) in the links for each spanning tree.
5. Calculating the total cumulative flow *CQ* for each spanning tree.

6. Arranging the spanning trees in order of increasing *CQ*.

7. Getting output, Generated spanning trees in ascending order of *CQ*.

The detail programming of the above algorithm is given in Appendix A. The proposed algorithm is tested against a test example (Network 1). The first example that has been considered is a simple network, which is shown in Figure 4.1. The Network 1 consists of 6 manholes (nodes or vertices) and 10 links (edges), the outlet is located at the Manhole Number 3. Input details; link number, nodal connectivity and the edge length of the Network 1 are given in Table 4.1; and nodal wastewater contributions are given in Table 4.2.

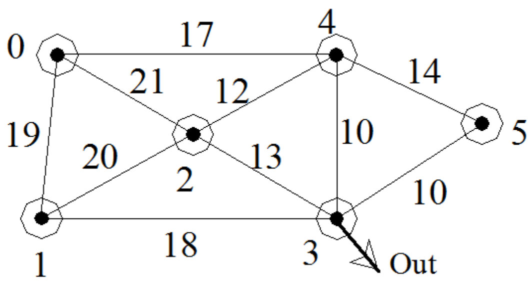


Figure 4.1 Base graph of Network 1

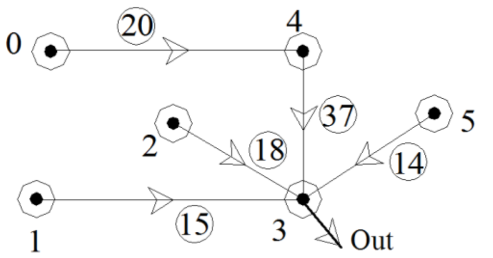
Table 4.1 Input Details for Network 1

Link No.	Nodal Connectivity		Length
1	0	1	19
2	1	2	20
3	1	3	18
4	2	3	13
5	2	0	21
6	2	4	12
7	3	4	10
8	4	5	14
9	4	0	17
10	5	3	10

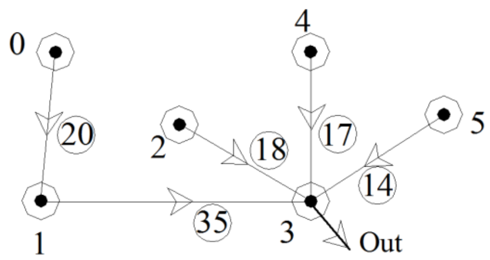
Table 4.2 Nodal Wastewater Contribution for Network 1

Node No.	0	1	2	3	4	5
Flow Contribution (l/s)	20	15	18	0	17	14

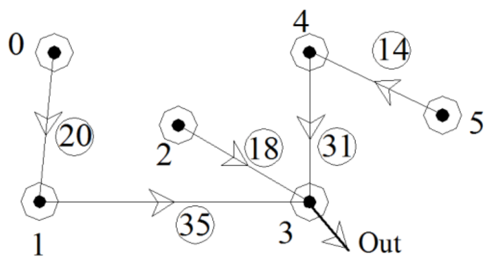
The algorithm 'Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*' is applied to Network 1. The sequenced six layouts of the Network 1 in order of increasing *CQ* are shown in Figure 4.2 (a to f). Flow in each pipe is mentioned in Figure 4.2 (a to f). *CQ* is calculated by using equation 4.1 for all layouts.



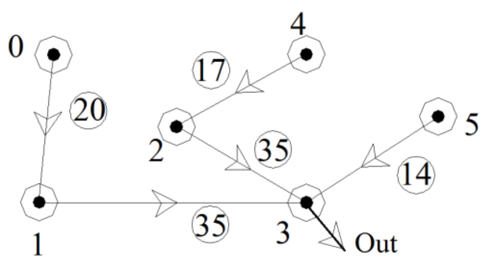
(a) *CQ* = 104 = (20+37+18+14+15)



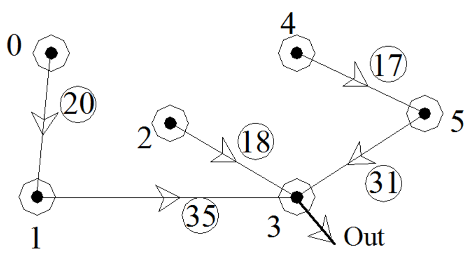
(b) *CQ* = 104 = (20+35+18+14+17)



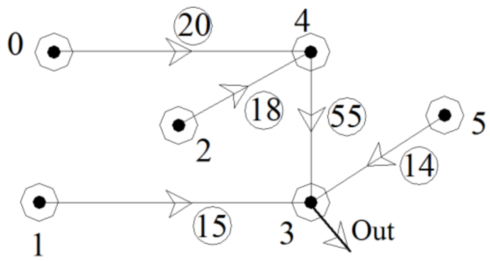
(c) *CQ* =118 = (20+35+18+14+31)



(d) *CQ* = 121= (20+35+17+35+14)



(e) *CQ* = 121 = (20+35+18+17+31)



(f) *CQ* = 122 = (15+20+18+55+14)

Figure 4.2 Sequenced six layouts according to ascending order of *CQ* for Network 1

4.2 Formulation of optimal sewer design problem

The cost of the sewer system without pumping mainly depends upon sewer diameters, excavation depths, and manhole construction.

(i) **The cost of sewer:** It includes the cost of their transportation, lowering & laying in trenches, aligning & jointing of pipes. Table 4.3 gives the cost of RCC NP4 class sewer pipes.

Table 4.3 Cost of Different Diameter Sewer Pipes

Diameter (mm)	Cost (Rs.) per m
200	518
250	724
300	973
350	1600
400	1850
450	2150
500	2520
600	3400

Source: RUIDP Schedule of Rates (2013)

(ii) **The cost of Earthwork:** The cost of earthwork for sewer line includes the cost of trench excavation, dressing of sides, ramming of bottoms, getting out the excavated material, refilling after laying pipe and disposal of surplus excavated material. Table 4.4 gives the cost of earthwork for the sewer line at different depths.

Table 4.4 Earthwork Cost at Different Depths

Depth (m)	Cost (Rs.) per m^3
< 1.5	203.00
1.5 to 3.0	233.50
3.0 to 4.5	299.00
4.5 to 6.0	405.00

Source: RUIDP Schedule of Rates (2013)

(iii) **The cost of Manhole:** The cost of a manhole depends on its depth and the diameter of the manhole and material of construction.Table 4.5 gives the cost of the manholes at different depths.

Table 4.5 Manhole Cost Detail

Depth (m)	Internal Diameter (m)	Cost (Rs.)
< 0.90	0.90	11800
0.90 to 1.70	1.20	23100
1.70 to 2.60	1.50	40000
2.60 to 3.60	1.50	54600
3.60 to 4.60	1.50	69200
4.60 to 5.10	1.50	77500
5.10 to 6.10	1.50	95800

Source: RUIDP Schedule of Rates (2013)

Total Cost: The total cost (TC_i) of i^{th} link is,

$$TC_i = (\text{cost of sewer})_i + (\text{cost of manhole})_i + (\text{cost of earthwork})_i \tag{4.2}$$

4.2.1 Design constraints:

For a given layout, a feasible sewer design is defined as a set of pipe diameters, slopes and excavation depths which satisfies all the constraints. Constraints of sewer network design are:

(i) Sewer cover depth: It is necessary to provide a minimum cover depth (CD_{min}) for protection of sewer from vehicular load to avoid damage to the sewer line and providing adequate fall for house sewer connections. Further, in order to reduce the cost of the sewer line laying and overburden load, cover depth should be less than maximum permissible cover depth (CD_{max}).

$$CD_{min} \le CD_i \le CD_{max} \qquad \forall\ i = 1, 2,\ \ldots, N \tag{4.3}$$

Where, CD_i = average cover depth of the i^{th} sewer link. The minimum cover depth of 0.9 m and maximum cover depth of 5.0 m has been adopted in the present study.

(ii) Sewer flow velocity: In each sewer flow velocity must be greater than the minimum permissible velocity (V_{min}) to prevent the deposit of solids in the sewers and less than the maximum permissible velocity (V_{max}) to prevent sewer scouring.

$$V_{min} \le V_i \le V_{max} \qquad \forall\ i = 1, 2,\ \ldots, N \tag{4.4}$$

Where, V_i = flow velocity in the i^{th} sewer link. The minimum permissible velocity of 0.6 m/s and maximum permissible velocity of 3.0 m/s has been adopted in the present study.

(iii) Flow depth ratio: wastewater depth ratio of the sewer should be less than 0.8.

$$\frac{d_i}{D_i} \le 0.8 \qquad \forall\ i = 1, 2,\ \ldots, N \tag{4.5}$$

Where, D_i = diameter of i^{th} sewer and d_i = sewage flow depth in i^{th} sewer at peak flow.

(iv) Sewer diameters: The diameter of a sewer should not be less than the minimum prescribed size (D_{min}). The minimum diameter of 0.2 m has been adopted in the present study.

$$D_{min} - D_i \le 0 \qquad \forall\ i = 1, 2,\ \ldots, N \tag{4.6}$$

(v) Progressive sewer diameters: The diameter of i^{th} sewer (D_i) should not be less than the maximum diameter of immediately preceding sewers (D_p)

$$D_p - D_i \le 0 \qquad \forall\ i = 1, 2,\ \ldots, N \tag{4.7}$$

4.2.2 Penalty Function

The Penalty function technique is used for converting the constrained optimization problem to an unconstrained optimization problem. The penalty function has some penalty factor (PF), which puts the relative weight on the penalty when a constraint is violated. In present study penalty cost (PC) is imposed on violation of maximum cover depth constraint, minimum and maximum velocity constraints. Other constraints are satisfied while selecting the sewer components.

(i) **Penalty due to depth of sewer:** If the average cover depth in a particular link is greater than the maximum permissible cover depth, the penalty is imposed.

If $CD_{max} - CD_i < 0$

Penalty factor ($PFCD_{max}$) = 1×10^8

Else $PFCD_{max} = 0$

$$PD_i = PFCD_{max} \times (CD_i - CD_{max}) \quad (4.8)$$

Where, PD_i = penalty due to depth for i^{th} link.

(ii) **Penalty due to minimum velocity in sewer:** If in a particular sewer velocity is less than minimum permissible velocity and discharge is more Q_{min}, penalty cost needs to be added.

If $Q_i \geq Q_{min}$ and $V_i - V_{min} < 0$

Penalty factor (PFV_{min}) = 1×10^8

Else $PFV_{min} = 0$

$$(PV_{min})_i = PFV_{min} \times (V_{min} - V_i) \quad (4.9)$$

Where, $(PV_{min})_i$ = penalty due to minimum velocity for i^{th} link; Q_i = discharge at partial flow condition at peak flow in the i^{th} sewer link; and Q_{min} = minimum discharge below which penalty for minimum velocity would not be imposed. In the present study Q_{min} has been taken as 0.0014 m^3/s.

The minimum velocity criteria have been checked only if the discharge in the link is greater than the 0.0014 m^3/s. For a 200 mm diameter pipe (the minimum diameter used in the problem) with a discharge of 0.0014 m^3/s self-cleansing velocity of 0.6 m/s can only be achieved at a slope of 1 in 60. It is obvious that for discharge less than the 0.0014 m^3/s, a slope steeper than 1 in 60 would be required to get the self-cleansing velocity. Since in field condition it is very difficult to provide a slope steeper than 1 in 60 from the sewer depth considerations, the penalty has not been imposed for violation of minimum velocity constraints if the discharge is less than the 0.0014 m^3/s. Necessary flushing arrangements need to be provided in this condition.

(iii) **Penalty due to maximum velocity:** If in a particular sewer, the velocity is more than the maximum permissible velocity, penalty cost needs to be added.

If $V_{max} - V_i < 0$

Penalty factor (PFV_{max}) = 1×10^8

Else $PFV_{max} = 0$

$$(PV_{\max})_i = PFV_{\max} \times (V_i - V_{\max}) \tag{4.10}$$

Where $(PV_{max})_i$ = penalty due to maximum velocity for i^{th} link.

Total penalty cost: The total penalty cost (PC_i) of i^{th} link would be,

$$PC_i = (PD)_i + (PV_{\min})_i + (PV_{\max})_i \tag{4.11}$$

The objective function of the present problem: The problem of optimization of a sewer network with N number of links, without any pumping station may be expressed as:

$$\text{Minimize } C = \sum_{i=1}^{N} (TC_i + PC_i) \tag{4.12}$$

Where,

C = cost function of sewer network,

N = total number of sewer pipes (links),

TC_i = total cost of a sewer network for the i^{th} link, and

PC_i = penalty cost for the i^{th} link.

4.3 Modified Particle Swarm Optimization

An evolutionary algorithm, Particle Swarm Optimization was introduced by Kennedy and Eberhart (1995). In PSO, each problem solution is a bird of the flock and is referred to as a particle. In PSO algorithm, the birds having individual and social behaviour and mutually coordinate their movement towards a destination (Izquierdo et al., 2008; Shi and Russell, 1998; Montalvo et al., 2008).

PSO has some common evolutionary computational features, such as (a) initialization with a population (swarm) of random solutions, (b) updating positions in search of optima and (c) with some specific strategy particles evolution through the problem space (Izquierdo et al., 2008; Jin et al., 2007).

Particles start their movement in the first iteration randomly. Then they try to find the optimum solutions through a method that can be described as follows (Ostadrahimi et al., 2012; Mu et al., 2009; Al-kazemi and Mohan, 2002; Voss, 2003; Montalvo et al., 2010).

The current position of the i^{th} particle in the d-dimension at t^{th} iteration is denoted as:

$$x_i(t) = \{x_{i1}(t),\ x_{i2}(t),\ \ldots,\ x_{id}(t)\} \tag{4.13}$$

Best position reached so far by the particle is where best value of the fitness function has been achieved by the particle and is denoted by,

$$x_{i\_best}(t) = \{x_{i1\_best}(t),\ x_{i2\_best}(t),\ \ldots,\ x_{id\_best}(t)\} \tag{4.14}$$

Its current velocity is given by,

$$v_i(t) = \{v_{i1}(t),\ v_{i2}(t),\ \ldots,\ v_{id}(t)\} \tag{4.15}$$

The velocity updates of the particles are given by the following equation:

$$v_i(t+1) = \omega(t).v_i(t) + c_1(t).r_1\{x_{i\_best}(t) - x_i(t)\} + c_2(t).r_2\{x_{g\_best}(t) - x_i(t)\} \tag{4.16}$$

The location updates of the particles are given by the following equation:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{4.17}$$

Where, i = 1, 2, . . ., P (P = total number of particles in the swarm); t = 1, 2,. ., T (T = total number of iterations or time intervals). In each time interval, the particle's velocity $v_i(t)$ changes the position of the particle. The best position of each particle up to time t is $x_{i\_best}(t)$ and the best position of a particle among all particles (from 1 to P) up to time t is $x_{g\_best}(t)$. The previous velocity $v_i(t)$ is biased with inertia ω(t), and the other parts are biased with two acceleration coefficients $c_1(t)$ and $c_2(t)$. Random numbers r_1 and r_2 are uniformly distributed between 0 to 1 (Ostadrahimi et al., 2012).

The inertia weights at each time interval ω(t) and acceleration coefficients at each time interval $c_1(t)$ & $c_2(t)$ are updated with the following equations:

$$\omega(t) = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{T} \times t \tag{4.18}$$

$$c_1(t) = c_{1m\mathrm{ax}} - \frac{c_{1\max} - c_{1\min}}{T} \times t \tag{4.19}$$

$$c_2(t) = c_{2m\mathrm{ax}} - \frac{c_{2\max} - c_{2\min}}{T} \times t \tag{4.20}$$

Where, ω_{max} and ω_{min} are the maximum and minimum inertia weights, and their values have been taken as 0.7 and 0.2, respectively in the present problem; c_{1max} and $c_{2\,max}$ are the maximum accelerations, and their values have been taken as 2. c_{1min} and c_{2min} are the minimum accelerations, and their values have been taken as 0.5.

Particle's velocity in each dimension is limited to minimum and maximum velocities (Montalvo et al., 2010):

$$v_{\min} \le v_i \le v_{\max} \tag{4.21}$$

Particle's velocity is a very important parameter. The value of v_{max} and v_{min} must be selected so that the search space is explored fully. v_{max} is generally set to about 10-20% of the range of the variable in each dimension (Eberhart and Shi 1998). v_{min} is generally considered to avoid stagnancy of the particles exploration of a new solution space.

These adjustable parameters (v_{max}, v_{min}, ω_{max}, ω_{min}, c_1, *and* c_2) need to be adjusted by trial and error, according to the sensitivity of the problem. These parameters, number of iteration and number of particles affects the final solution. Generally, the searching process is terminated after a specified number of iterations or when the best result of the objective function remains unchanged for a specific number of consecutive iterations. In the modified PSO methodology adjustable parameters change in each time interval, whereas in original PSO they remain fixed throughout the optimization process. The modified PSO methodology is as follows:

1. Initialize the particle swarm by randomly assigning initial velocity and position to each particle.
2. Calculate the fitness function for each particle.
3. For each particle, update its best position reached so far $x_{i\_best}(t)$**,** if its current position is better than its earlier best one.
4. Update the globally best particle position of the swarm that has the best fitness value among the particles and set its index as g and its position at $x_{g\_best}(t)$.
5. Calculate velocities of all the particles for new time interval using equation (4.16).
6. Update the new positions of each particle using equation (4.17).
7. If the problem involves discrete variables, the new position needs to be changed to discrete position in each dimension by selecting the nearest discrete position in that dimension.
8. If the stopping criterion is met output the result given by the x_{g_best} and stop else repeat steps 2–7.

The modified PSO methodology deals with both continuous and discrete variables, as required for the optimal design of sewer networks.

4.4 Case studies for Optimization of Sewer System

In India rainfall days are very limited and rainfall mainly takes place in Monsoon season (June to September). There are few rainy days during winter (December and January). As such the drainage system adopted in India is Separate system consisting of Stormwater drainage and Sewerage network. In the present work only Sewerage network optimization has been considered.

Three sewer networks (two elongated, and one clustered type network) have been considered for implementation of the algorithm 'Generation of a predefined number of spanning tree in order of increasing weights and sequencing them in ascending order of total cumulative flow *CQ*' and modified PSO. All three networks collect only domestic wastewater from the residential colony through gravity.

4.4.1 Case Study 1: Elongated type Network

The Base Network 2 (Sudarshanpura sewer network, Jaipur, India) as shown in Figure 4.3 consists of 105 nodes (i.e., manholes), 116 links (i.e., sewer pipes), and STP is located at Node Number 0. Details of Network 2 like link number, nodal connectivity and their lengths are given in Table 4.6. Nodal wastewater flow contribution and ground level of Network 2 are given in Table 4.7.

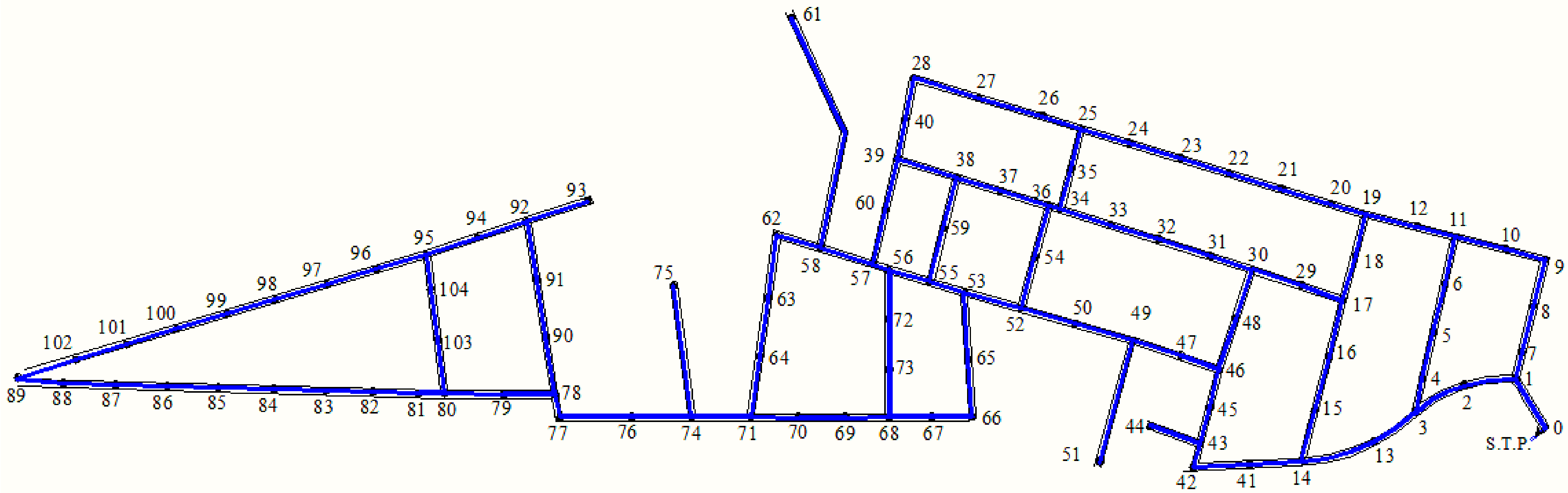


Figure 4.3 Base sewer network of Sudarshanpura (Network 2)

Table 4.6 Base Network Data for Network 2

Pipe/ Link No.	Nodal Connectivity		Length (m)	Pipe/ Link No..	Nodal Connectivity		Length (m)	Pipe/ Link No.	Nodal Connectivity		Length (m)
1	0	1	30	40	36	37	16	79	72	73	30
2	1	2	23	41	37	38	30	80	73	68	30
3	2	3	23	42	38	39	30	81	68	69	26
4	3	4	10	43	39	40	14	82	69	70	26
5	4	5	30	44	40	28	30	83	70	71	26
6	5	6	30	45	14	41	30	84	71	74	34
7	6	11	30	46	41	42	30	85	74	75	76
8	1	7	9	47	42	43	11	86	74	76	38
9	7	8	30	48	43	44	30	87	76	77	38
10	8	9	30	49	43	45	20	88	77	78	13
11	9	10	20	50	45	46	20	89	78	79	31
12	10	11	30	51	46	48	30	90	79	80	31
13	11	12	20	52	48	30	24	91	80	81	10
14	12	19	30	53	46	47	26	92	81	82	30
15	3	13	30	54	47	49	26	93	82	83	30
16	13	14	30	55	49	51	72	94	83	84	30
17	14	15	30	56	49	50	30	95	84	85	30
18	15	16	30	57	50	52	30	96	85	86	30
19	16	17	30	58	52	54	30	97	86	87	30
20	17	18	30	59	54	36	24	98	87	88	30
21	18	19	12	60	52	53	30	99	88	89	30
22	19	20	18	61	53	55	20	100	78	90	33
23	20	21	30	62	55	59	30	101	90	91	33
24	21	22	30	63	59	38	30	102	91	92	33
25	22	23	30	64	55	56	25	103	92	93	36
26	23	24	30	65	56	57	8	104	92	94	30
27	24	25	30	66	57	60	32	105	94	95	26
28	25	26	27	67	60	39	32	106	95	96	30
29	26	27	30	68	57	58	33	107	96	97	30
30	27	28	30	69	58	61	143	108	97	98	30
31	17	29	30	70	58	62	24	109	98	99	30
32	29	30	22	71	62	63	33	110	99	100	30
33	30	31	30	72	63	64	33	111	100	101	30
34	31	32	30	73	64	71	33	112	101	102	30
35	32	33	30	74	53	65	30	113	102	89	30
36	33	34	18	75	65	66	30	114	80	103	27
37	34	35	30	76	66	67	22	115	103	104	27
38	35	25	12	77	67	68	22	116	104	95	27
39	34	36	7	78	56	72	21				

Table 4.7 Nodal Wastewater Flow Contribution and Ground Levels of Network 2

Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)
0	0.000	90.745	35	0.38	95.540	70	0.33	97.525
1	0.380	91.085	36	0.09	95.555	71	0.51	97.610
2	0.292	92.455	37	0.20	95.650	72	0.57	96.925
3	0.292	93.120	38	0.57	96.030	73	0.57	97.050
4	0.127	93.185	39	0.18	96.335	74	0.43	97.775
5	0.380	93.245	40	0.38	96.105	75	0.96	97.970
6	0.380	93.340	41	0.38	94.550	76	0.48	97.820
7	0.114	91.350	42	0.38	95.635	77	0.48	97.885
8	0.380	92.435	43	0.14	95.775	78	0.17	97.820
9	0.254	93.135	44	0.38	96.265	79	0.39	98.115
10	0.444	93.185	45	0.25	95.530	80	0.39	98.205
11	0.570	93.345	46	0.44	95.255	81	0.13	98.270
12	0.254	94.135	47	0.33	95.625	82	0.38	98.385
13	0.380	93.425	48	0.51	95.250	83	0.38	98.435
14	0.380	93.795	49	0.33	96.040	84	0.38	98.610
15	0.380	93.820	50	0.38	96.115	85	0.38	98.680
16	0.380	93.855	51	0.91	96.445	86	0.38	99.045
17	0.570	93.990	52	0.57	96.340	87	0.38	99.225
18	0.342	94.050	53	0.38	96.625	88	0.38	99.240
19	0.380	94.245	54	0.51	95.950	89	50.38	99.305
20	0.228	94.310	55	0.44	96.555	90	0.42	98.125
21	0.380	94.425	56	0.32	96.790	91	0.84	98.235
22	0.380	94.550	57	0.32	96.885	92	0.38	98.450
23	0.380	94.625	58	0.42	96.970	93	0.46	98.475
24	0.380	94.815	59	0.57	96.435	94	0.33	98.400
25	0.380	94.955	60	0.61	96.565	95	0.34	98.395
26	0.342	94.450	61	51.80	95.865	96	0.38	98.430
27	0.380	94.125	62	0.30	97.240	97	0.38	98.545
28	0.380	94.855	63	0.42	97.345	98	0.38	98.685
29	0.380	94.150	64	0.67	97.605	99	0.38	98.750
30	0.279	94.400	65	0.38	96.765	100	0.38	98.810
31	0.380	94.750	66	0.38	96.915	101	0.38	98.875
32	0.380	95.115	67	0.28	96.955	102	0.76	98.980
33	0.380	95.350	68	0.28	97.100	103	0.34	98.260
34	0.418	95.500	69	0.36	97.320	104	0.34	98.325

4.4.2 Case Study II: Elongated type Network

The Base Network 3 (Banjaran sewer network, Laxmangarh, Rajasthan, India) as shown in Figure 4.4 consists of 105 nodes, 128 links, and STP is located at Node Number 0. Details of Network 3 like link number, nodal connectivity and their lengths are given in Table 4.8. Nodal wastewater flow contribution and ground level of Network 3 are given in Table 4.9.

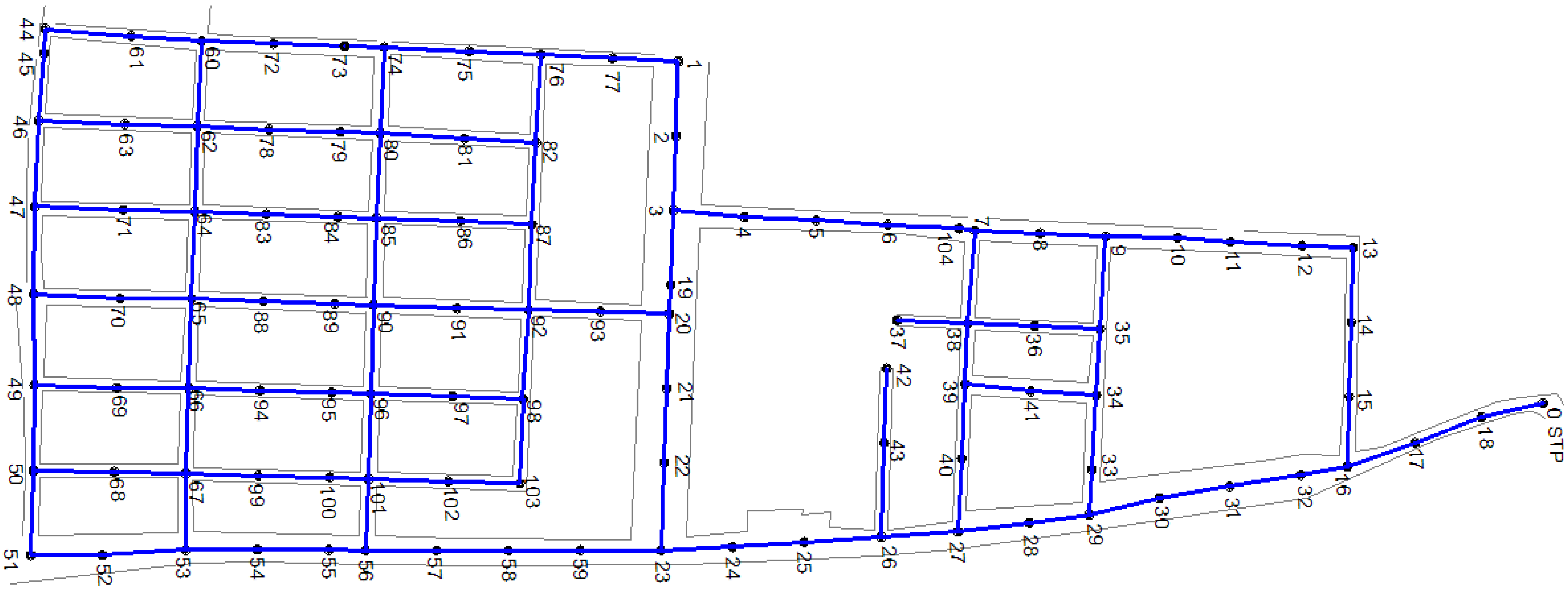


Figure 4.4 Base sewer network of Banjaran (Network 3)

Table 4.8 Base Network Data for Network 3

Pipe/ Link No.	Nodal Connectivity		Length (m)	Pipe/ Link No.	Nodal Connectivity		Length (m)	Pipe/ Link No	Nodal Connectivity		Length (m)
1	1	2	30	44	39	41	28	87	70	48	36
2	2	3	30	45	40	27	29	88	71	47	36
3	3	4	30	46	41	34	28	89	72	73	30
4	3	19	30	47	42	43	30	90	73	74	17
5	4	5	30	48	43	26	38	91	74	75	35
6	5	6	30	49	44	45	10	92	74	80	35
7	6	104	30	50	45	46	27	93	75	76	30
8	7	8	28	51	46	47	35	94	76	77	30
9	7	38	38	52	47	48	35	95	76	82	35
10	8	9	28	53	48	49	37	96	77	1	28
11	9	10	30	54	49	50	35	97	78	79	30
12	9	35	37	55	50	51	34	98	79	80	17
13	10	11	22	56	51	52	30	99	80	81	35
14	11	12	30	57	52	53	35	100	80	85	34
15	12	13	21	58	53	54	30	101	81	82	30
16	13	14	30	59	54	55	30	102	82	87	33
17	14	15	30	60	55	56	15	103	83	84	30
18	15	16	28	61	56	57	30	104	84	85	17
19	16	17	30	62	57	58	30	105	85	86	35
20	17	18	30	63	58	59	30	106	85	90	35
21	18	0	26	64	59	23	34	107	86	87	30
22	19	20	12	65	60	61	30	108	87	92	34
23	20	21	30	66	60	62	34	109	88	89	30
24	21	22	30	67	60	72	30	110	89	90	18
25	22	23	35	68	61	44	36	111	90	91	35
26	23	24	30	69	62	63	30	112	90	96	36
27	24	25	30	70	62	64	34	113	91	92	30
28	25	26	32	71	62	78	30	114	92	93	30
29	26	27	32	72	63	46	36	115	93	20	29
30	27	28	30	73	64	65	35	116	94	95	30
31	28	29	25	74	64	71	30	117	95	96	16
32	29	30	30	75	64	83	30	118	96	97	34
33	30	31	30	76	65	66	36	119	96	101	34
34	31	32	30	77	65	70	30	120	97	98	30
35	32	16	20	78	65	88	30	121	98	92	36
36	35	34	27	79	66	67	34	122	99	100	30
37	34	33	30	80	66	69	30	123	100	101	26
38	33	29	18	81	66	94	30	124	101	102	33
39	36	35	28	82	67	53	24	125	101	56	29
40	36	38	28	83	67	68	30	126	102	103	30
41	37	38	20	84	67	99	30	127	103	98	34
42	38	39	24	85	68	50	36	128	104	7	7
43	39	40	30	86	69	49	36				

Table 4.9 Nodal Wastewater Flow Contribution and Ground Levels of Network 3

Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)
0	0.000	329.345	35	0.054	330.003	70	0.108	331.407
1	6.102	331.608	36	0.165	330.421	71	0.108	331.958
2	0.090	331.670	37	0.059	330.005	72	0.090	332.134
3	0.180	331.205	38	0.073	329.735	73	0.049	332.064
4	0.090	330.812	39	0.172	329.325	74	0.850	331.325
5	0.090	330.705	40	0.088	329.151	75	0.090	331.625
6	0.090	330.036	41	0.082	334.580	76	0.195	332.503
7	1.246	330.003	42	0.090	330.074	77	0.083	332.870
8	0.082	330.327	43	0.113	329.638	78	0.090	332.075
9	0.202	329.563	44	5.208	331.775	79	0.050	331.556
10	0.067	329.605	45	0.794	331.726	80	0.207	331.634
11	7.055	328.796	46	0.103	331.624	81	0.090	331.721
12	0.064	328.370	47	0.105	331.421	82	0.099	332.775
13	0.090	328.125	48	0.110	331.192	83	0.090	332.096
14	0.090	327.825	49	0.103	330.655	84	0.049	331.250
15	0.084	328.007	50	0.102	330.510	85	0.210	331.300
16	0.090	328.457	51	61.881	330.597	86	0.090	331.166
17	0.090	328.991	52	0.105	330.885	87	0.102	331.341
18	0.079	329.216	53	0.090	330.898	88	0.090	331.617
19	0.035	331.178	54	0.090	330.637	89	0.054	330.972
20	0.090	331.134	55	0.046	330.600	90	0.212	330.717
21	0.090	330.975	56	0.090	330.467	91	0.090	330.721
22	0.105	330.793	57	0.090	330.196	92	0.090	330.882
23	0.090	330.704	58	0.090	330.511	93	0.087	331.159
24	0.090	330.714	59	0.102	330.659	94	0.090	331.068
25	0.097	330.500	60	0.282	332.214	95	0.049	331.144
26	0.097	329.840	61	0.108	332.352	96	0.204	330.735
27	0.090	329.253	62	0.282	332.365	97	0.090	330.804
28	0.076	329.354	63	0.108	332.064	98	0.108	330.897
29	0.090	330.077	64	0.284	331.882	99	0.090	330.532
30	0.090	330.086	65	0.287	331.540	100	0.079	330.592
31	0.090	329.513	66	0.283	331.166	101	0.187	330.550
32	0.059	328.669	67	0.252	330.736	102	0.090	330.620
33	0.080	330.294	68	0.108	330.880	103	0.102	330.725
34	0.090	330.163	69	0.108	331.147	104	0.019	330.004

4.4.3 Case Study III: Cluster Type Network

The Base Network 4 (Nawalgarh sewer network, Nawalgarh, Rajasthan, India) as shown in Figure 4.5 consists of 166 nodes, 181 links, and STP is located at Node Number 0. Details of Network 4 like link number, nodal connectivity and their lengths are given in Table 4.10. Nodal wastewater flow contribution and ground level of Network 4 are given in Table 4.11.

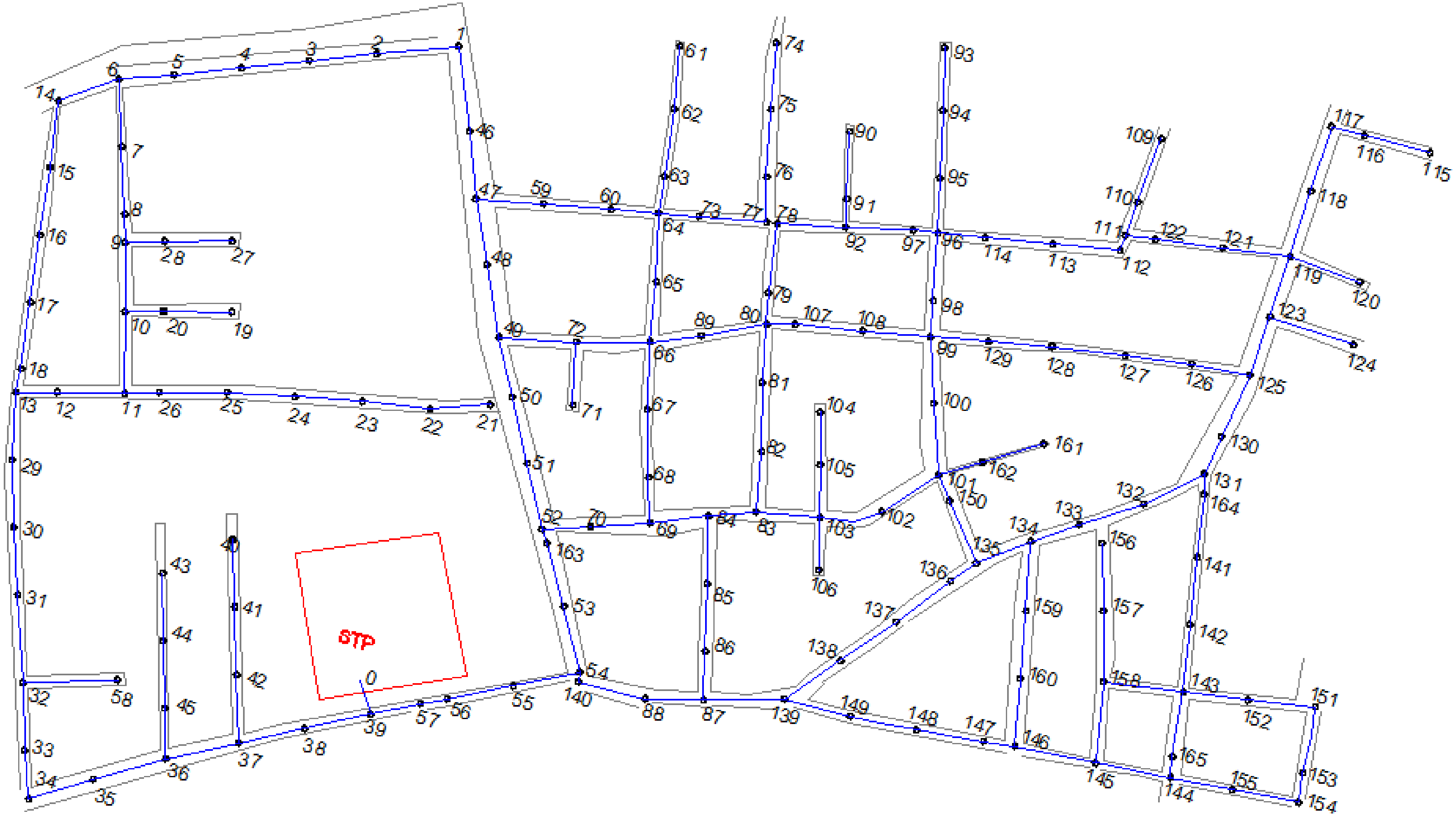


Figure 4.5 Base sewer network of Nawalgarh (Network 4)

Table 4.10 Base Network Data for Network 4

Pipe/ Link No.	Nodal Connectivity		Length (m)	Pipe/ Link No	Nodal Connectivity		Length (m)	Pipe/ Link No	Nodal Connectivity		Length (m)
1	1	2	35	62	58	32	44	123	113	114	30
2	1	46	35	63	59	60	30	124	114	96	21
3	2	3	30	64	60	64	21	125	115	116	30
4	3	4	30	65	61	62	30	126	116	117	15
5	4	5	30	66	62	63	30	127	117	118	30
6	5	6	30	67	63	64	17	128	118	119	30
7	6	7	30	68	64	65	30	129	119	121	30
8	6	14	29	69	64	73	18	130	119	123	28
9	7	8	30	70	65	66	27	131	120	119	37
10	8	9	13	71	66	67	30	132	121	122	30
11	9	10	30	72	66	89	23	133	122	111	13
12	10	11	30	73	67	68	30	134	123	125	27
13	11	12	30	74	68	69	20	135	124	123	39
14	12	13	18	75	69	70	30	136	125	126	30
15	13	29	30	76	69	84	26	137	125	130	30
16	14	15	30	77	70	52	17	138	126	127	30
17	15	16	30	78	71	72	30	139	127	128	30
18	16	17	30	79	72	66	33	140	128	129	30
19	17	18	30	80	73	77	30	141	129	99	22
20	18	13	11	81	74	75	30	142	130	131	18
21	19	20	30	82	75	76	30	143	131	132	30
22	20	10	17	83	76	77	20	144	131	164	8
23	21	22	30	84	77	78	5	145	132	133	30
24	22	23	30	85	78	79	30	146	133	134	23
25	23	24	30	86	78	92	30	147	134	135	26
26	24	25	30	87	79	80	13	148	134	159	30
27	25	26	30	88	80	81	29	149	135	136	14
28	26	11	15	89	80	107	12	150	136	137	30
29	27	28	30	90	81	82	30	151	137	138	30
30	28	9	17	91	82	83	26	152	138	139	30
31	29	30	30	92	83	84	22	153	139	87	30
32	30	31	30	93	84	85	30	154	140	54	3
33	31	32	30	94	85	86	30	155	141	142	30
34	32	33	30	95	86	87	22	156	142	143	30
35	33	34	21	96	87	88	26	157	143	165	30
36	34	35	30	97	88	140	30	158	143	158	35
37	35	36	33	98	89	80	30	159	144	145	34
38	36	37	33	99	90	91	30	160	145	146	34
39	37	38	30	100	91	92	13	161	146	147	14
40	38	39	30	101	92	97	30	162	147	148	30
41	39	0	15	102	93	94	30	163	148	149	30

Table 4.10 (Continued)

Pipe/ Link No	Nodal Connectivity		Length (m)	Pipe/ Link No	Nodal Connectivity		Length (m)	Pipe/ Link No	Nodal Connectivity		Length (m)
42	40	41	30	103	94	95	30	164	149	139	30
43	41	42	30	104	95	96	25	165	150	135	31
44	42	37	30	105	96	98	30	166	151	152	30
45	43	44	30	106	97	96	11	167	151	153	30
46	44	45	30	107	98	99	16	168	152	143	19
47	45	36	22	108	99	100	30	169	153	154	13
48	46	47	30	109	100	101	30	170	154	155	30
49	47	48	30	110	101	102	30	171	155	144	28
50	47	59	30	111	101	150	12	172	156	157	30
51	48	49	30	112	102	103	28	173	157	158	31
52	49	50	30	113	103	83	27	174	158	145	35
53	49	72	34	114	104	105	30	175	159	160	30
54	50	51	30	115	105	103	20	176	160	146	30
55	51	52	30	116	106	103	26	177	161	162	30
56	52	163	6	117	107	108	30	178	162	101	20
57	53	54	30	118	108	99	30	179	163	53	30
58	54	55	30	119	109	110	30	180	164	141	30
59	55	56	30	120	110	111	16	181	165	144	8
60	56	57	12	121	111	112	7				
61	57	39	22	122	112	113	30				

Table 4.11 Nodal Wastewater Flow Contribution and Ground Levels of Network 4

Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)
0	0.000	421.610	56	0.061	421.930	112	0.154	422.568
1	0.358	424.400	57	0.527	421.608	113	0.154	422.425
2	0.154	424.393	58	0.227	421.308	114	0.108	422.325
3	0.154	424.105	59	0.154	425.502	115	0.154	424.420
4	0.154	423.900	60	0.108	424.922	116	0.078	423.954
5	0.154	423.250	61	0.154	425.536	117	3.615	423.572
6	0.299	423.115	62	0.154	424.920	118	0.155	423.452
7	0.154	423.100	63	0.086	424.567	119	0.298	423.398
8	0.064	423.005	64	0.244	424.206	120	0.192	423.599
9	0.154	422.951	65	0.138	423.170	121	0.154	422.985
10	0.154	422.617	66	0.271	423.004	122	0.068	422.820
11	0.154	422.238	67	0.154	422.189	123	0.139	423.388
12	0.093	422.150	68	0.104	421.525	124	2.873	423.757
13	0.154	422.083	69	0.288	421.242	125	0.333	423.278

Table 4.11 (Continued)

Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)	Node No.	Flow contribution (l/s)	Ground Level (m)
14	0.154	423.321	70	0.089	421.442	126	0.154	422.900
15	0.154	422.968	71	0.156	423.355	127	0.154	422.670
16	0.154	422.598	72	0.167	423.198	128	0.154	422.549
17	0.154	422.263	73	0.154	424.060	129	0.115	422.270
18	0.054	422.100	74	0.154	423.625	130	0.093	423.310
19	0.154	422.967	75	0.154	423.325	131	0.195	423.249
20	0.087	422.725	76	0.100	423.055	132	0.154	423.390
21	0.154	424.423	77	0.026	422.841	133	0.116	422.477
22	0.154	423.915	78	0.307	422.841	134	0.287	422.125
23	0.154	423.500	79	0.064	422.316	135	0.072	422.077
24	0.154	422.995	80	0.210	422.316	136	0.154	422.100
25	0.154	422.760	81	0.154	421.995	137	0.154	422.264
26	0.079	422.370	82	0.133	421.625	138	0.072	423.006
27	0.154	423.351	83	0.113	421.329	139	0.507	423.260
28	0.088	423.125	84	0.154	421.394	140	1.701	422.130
29	0.154	421.825	85	0.154	421.998	141	0.154	423.703
30	0.154	421.670	86	0.111	422.005	142	0.154	423.750
31	0.154	421.420	87	0.132	423.038	143	0.335	423.812
32	0.154	421.233	88	1.260	422.528	144	0.172	423.228
33	0.108	420.980	89	0.154	422.670	145	0.187	423.172
34	10.560	420.702	90	0.154	423.614	146	8.368	422.686
35	0.171	421.115	91	0.064	422.930	147	0.154	422.730
36	0.169	421.757	92	0.154	422.549	148	0.154	422.931
37	0.154	421.618	93	0.154	424.013	149	0.154	423.160
38	0.154	421.610	94	0.154	423.500	150	0.154	421.640
39	0.077	421.610	95	0.126	422.870	151	0.307	423.519
40	0.154	421.749	96	0.154	422.223	152	0.096	423.615
41	0.154	421.625	97	0.055	422.442	153	0.067	423.150
42	0.154	421.568	98	0.081	422.295	154	4.036	423.100
43	0.154	421.295	99	0.152	422.195	155	0.143	423.190
44	0.154	421.805	100	0.162	421.652	156	0.154	423.370
45	0.114	421.778	101	0.217	421.456	157	0.161	423.310
46	0.154	424.300	102	0.143	421.452	158	0.179	423.278
47	0.307	423.980	103	0.140	421.449	159	0.154	422.530
48	0.154	423.570	104	0.154	422.532	160	0.154	422.610
49	0.328	423.235	105	0.104	421.995	161	0.154	421.710
50	0.154	423.070	106	0.132	421.515	162	0.104	421.670
51	0.151	422.740	107	0.154	422.316	163	0.154	421.647
52	0.032	421.647	108	0.154	422.390	164	0.154	423.249
53	0.154	421.930	109	0.154	422.999	165	0.041	423.320
54	0.154	422.022	110	0.079	422.832			
55	0.154	421.804	111	0.036	422.67			

The Networks 2, 3 & 4 are solved in two steps. In the first step, 'Generation of a predefined number of spanning tree in the order of increasing weights and sequencing them in ascending order of total cumulative flow *CQ*' algorithm is applied. In the second step, the modified PSO is applied to the sequenced sewer layouts for component size optimization. The best optimal solution among these layouts is likely to give global optima. The process of sewer component optimization with Modified PSO Algorithm is shown in Figure 4.6.

The process of Sewer components optimization using modified PSO algorithm is described briefly here. Firstly feeding inputs (Maximum number of particles i_{max}, Maximum number of iteration ITN_{max}, total number of links in the sewer layout, Manning's coefficient, minimum permissible velocity, maximum permissible velocity, minimum prescribed cover, maximum permissible depth, minimum discharge Q_{min}, commercially available diameters, pre-specified slopes, sewer layout details which includes Link no, upstream node, downstream node, the length of each link, discharge in each link, and ground level of each node). Start with first iteration (ITN = 1), particle number i = 1 (consisting of all sewer links diameter and slopes). Calculate sewer hydraulics (i.e., hydraulic mean depth, velocity, depth of flow, discharge, etc.) for complete sewer network. In the next step, calculate invert levels of upstream and downstream node; calculate no of manholes, depth of excavation and earthwork; calculate the cost of sewer, cost of manholes and cost of earthwork; and finally calculate the total cost (TC) of the sewer network. Add the respective penalty cost in total cost where constraints are violated. Calculate the fitness value of the particle. Calculate particle best position reached so far (p_{best}) and repeat for i = i+1 till i is less than or equal to i_{max} . Calculate globally best particle position of the swarm that has the best fitness value among the particles (g_{best}). Repeat this or ITN = ITN +1 till ITN is less than or equal to ITN_{max}. Finally, take solution given by the g_{best} particle and stop.

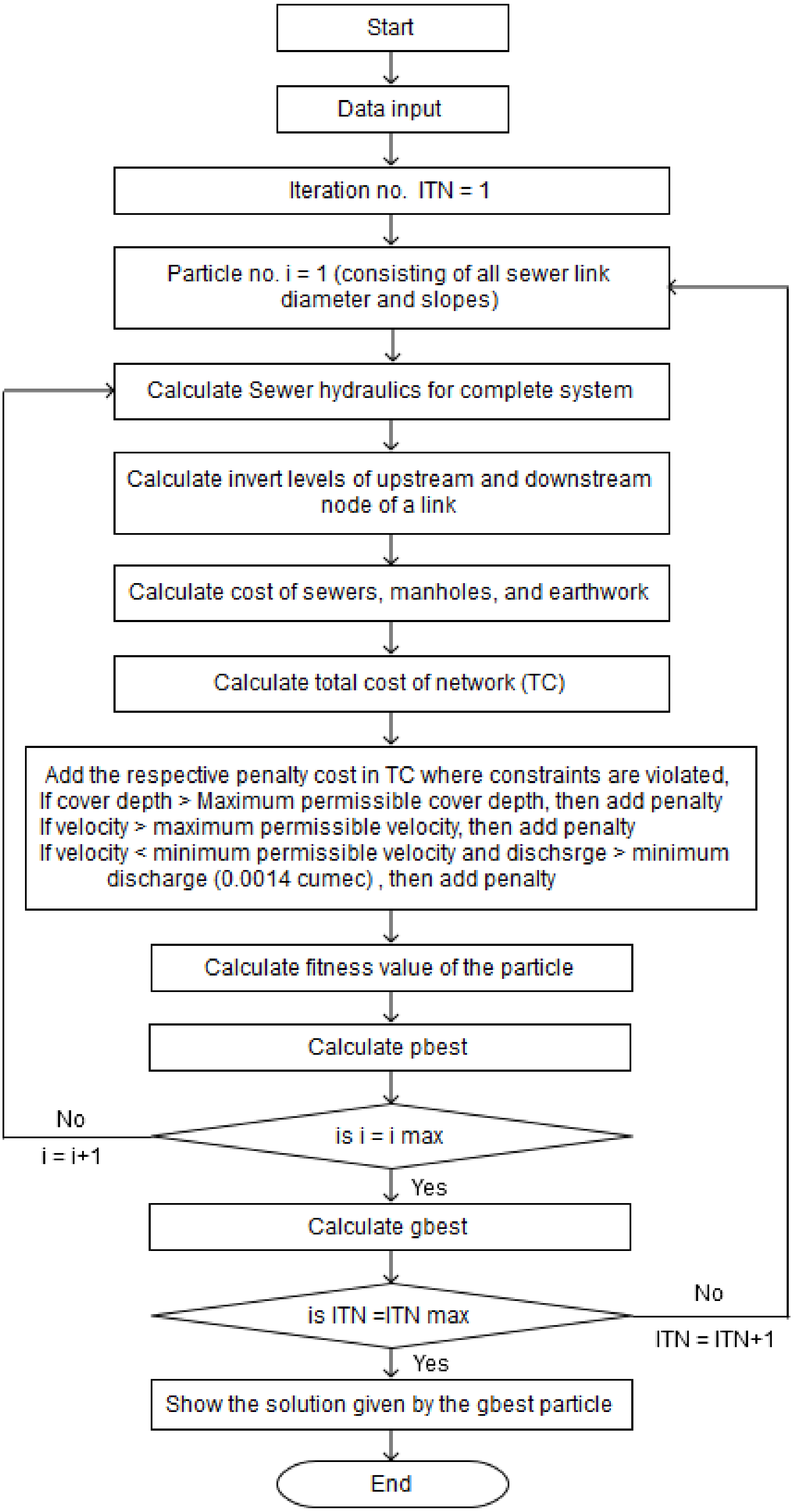


Figure 4.6 Sewer components optimization procedure using modified PSO algorithm

4.4.4 Input data of Program

The program requires the following inputs:

(i) Total number of links in the selected sewer layout

(ii) Manning's coefficient = 0.013

(iii) Minimum permissible velocity = 0.6 m/s

(iv) Maximum permissible velocity = 3.0 m/s

(v) Minimum prescribed cover = 0.9 m

(vi) Maximum permissible depth = 5 m

(vii) Minimum discharge (Q_{min}) = 0.0014 m^3/s

(viii) Total number of commercially available diameters is given in Table 4.12 and pre-specified slopes are given in Table 4.13.

(ix) Link no, upstream node, downstream node, the length of each link, discharge in each link, and ground level of each node.

Table 4.12 Commercially Available Diameters

S. No.	Diameter (mm)	S. No.	Diameter (mm)
1	200	7	500
2	250	8	600
3	300	9	700
4	350	10	800
5	400	11	900
6	450	12	1000

Table 4.13 Pre-specified Slopes

S. No.	Slope (1 in)	S. No.	Slope (1 in)
1	60	11	400
2	70	12	450
3	80	13	500
4	100	14	550
5	125	15	600
6	150	16	700
7	200	17	830
8	250	18	950
9	300	19	1000
10	350		

CHAPTER 5

Results and Discussion

The application of the ‘Generation of a predefined number of spanning tree in the order of increasing weights and sequencing them in ascending order of total cumulative flow *CQ*’ and the modified PSO algorithm is presented in this section by applying both algorithms to solve the Networks 2, 3 & 4. Results with modified PSO are compared with original PSO. The original PSO parameter values of c_1 and c_2 have been taken as 2 and ω has been taken as 0.8.

5.1 Results of case Study I

The results of Network 2 (Sudarshanpura) were obtained using swarm size of 1000. The maximum numbers of iterations were kept as 30, 60 & 90 for each sewer layout. Table 5.1 shows the variation in total optimal cost with total cumulative discharges of the layout.

Table 5.1 Total Cumulative Discharge vs. Total Optimal Cost for Different Iterations for Network 2

S. No.	Total cumulative discharge *CQ* (l/s)	Total cost (Rs.)					
		30 Iterations		60 Iterations		90 Iterations	
		Modified PSO	Standard PSO	Modified PSO	Standard PSO	Modified PSO	Standard PSO
1	3639.13	8409804	8473401	8387754	8473401	8371539	8473401
2	3642.34	8531554	8547602	8494772	8547330	8477464	8547330
3	3644.56	8575012	8632550	8575012	8632550	8561420	8632550
4	3692.80	9005505	9064954	8930532	9064954	8984307	9064954
5	3724.24	9356613	9412557	9314713	9410543	9336448	9410543
6	4027.95	11432085	11492097	11412199	11492097	11414562	11492097
7	4252.10	11456577	11494326	11465393	11494326	11465363	11494326
8	4480.85	11528582	11627095	11505595	11618001	11526601	11618001
9	4676.69	11668743	11825881	11625467	11825881	11671505	11825881
10	4774.97	11786525	11910006	11789190	11910006	11769816	11910006
11	5130.95	13327064	13770609	13315939	13770609	13311153	13770609
12	5521.53	13584318	14126408	13569519	14126408	13569977	14126408

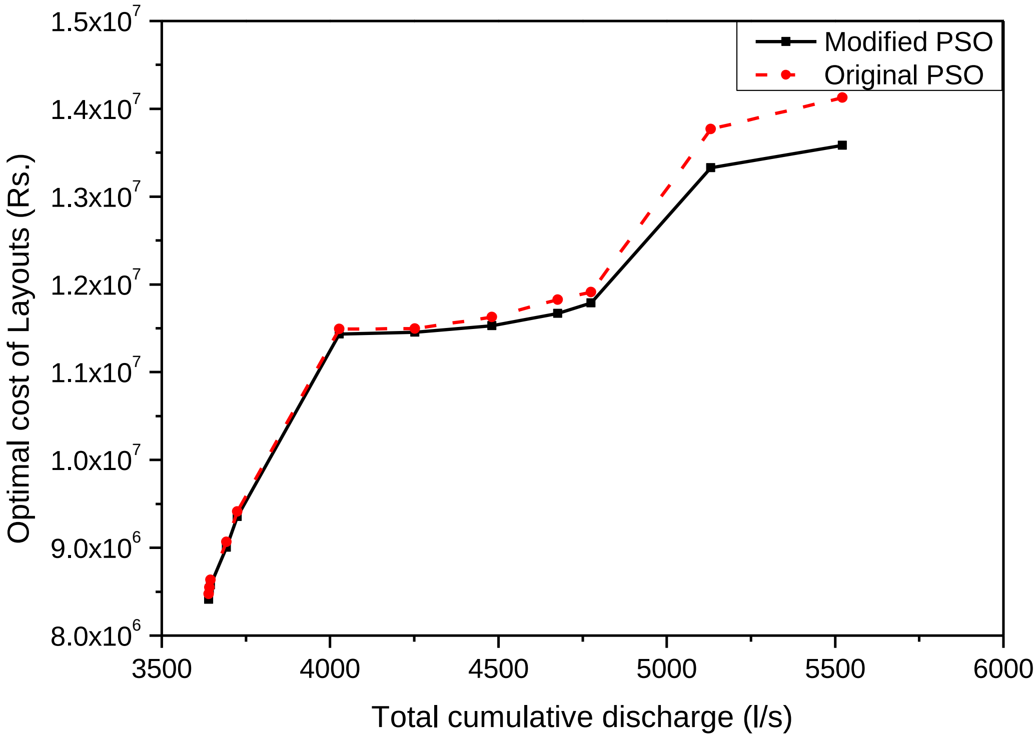


Figure 5.1 Total cumulative discharge vs. Optimal cost of layouts at 30 iterations for Network 2

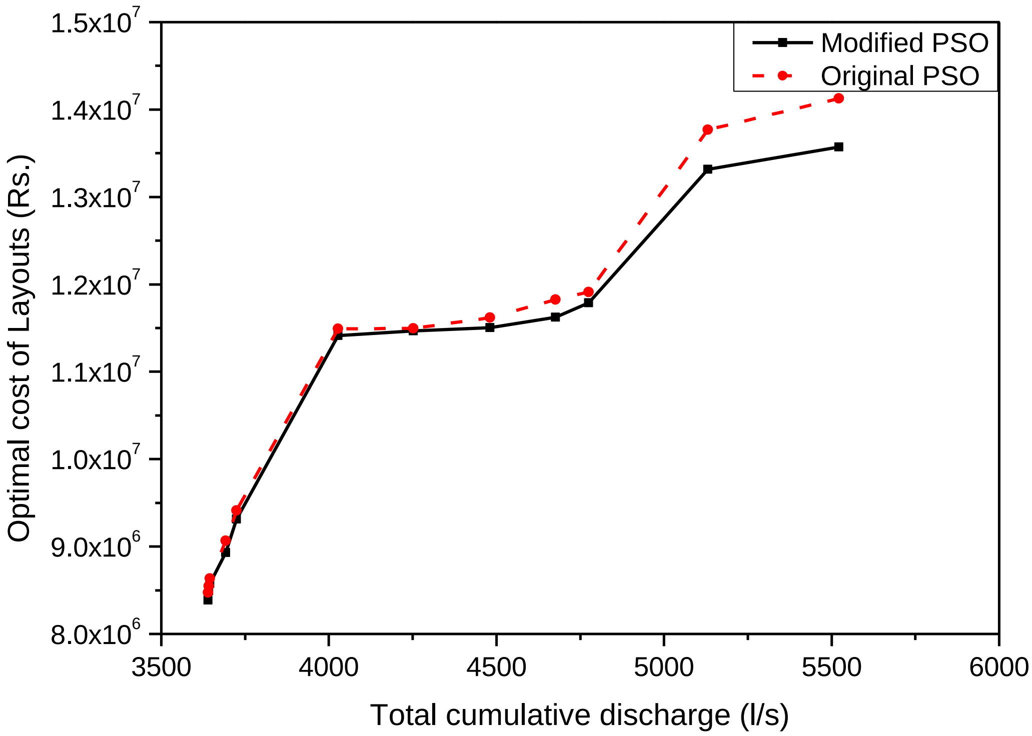


Figure 5.2 Total cumulative discharges vs. Optimal cost of layouts at 60 iterations for Network 2

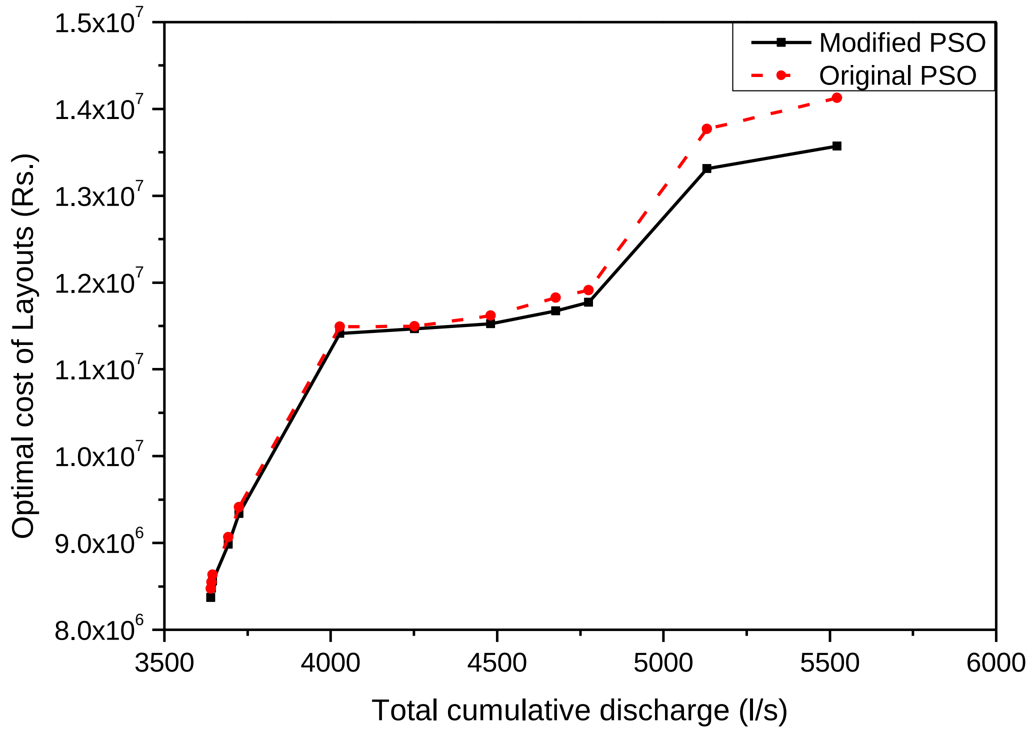


Figure 5.3 Total cumulative discharges vs. Optimal cost of layouts at 90 iterations for Network 2

Table 5.2 Sewer Layout Cost Details for Network 2

S. No.	Total cumulative discharge (l/s)	Cost of Earthwork (Rs.)	Cost of Manholes (Rs.)	Cost of Sewer Pipe (Rs.)	Total Cost (Rs.)
1	3639.13	1248959	4569200	2553380	8371539
2	3642.34	1306484	4617600	2553380	8477464
3	3644.56	1237880	4619900	2703640	8561420
4	3692.80	1437117	4937600	2609590	8984307
5	3724.24	1508448	5226400	2601600	9336448
6	4027.95	1894832	6439700	3080030	11414562
7	4252.10	1923163	6532900	3009300	11465363
8	4480.85	1848781	6677000	3000820	11526601
9	4676.69	1917195	6815500	2938810	11671505
10	4774.97	2020866	6680400	3068550	11769816
11	5130.95	2432103	7613500	3265550	13311153
12	5521.53	2384407	7764700	3420870	13569977

Table 5.1 clearly shows that the layout having minimum *CQ* has the minimum total cost. The total cost of sewer layout is generally increasing with the *CQ* of a layout. The cost of optimal layout (*CQ* = 3639.13 l/s) is Rs. 8.371×10^6 with modified PSO as compared to the cost of original PSO Rs. 8.473×10^6. Further the 2nd alternative layout (*CQ* = 3642.34 l/s) these cost are Rs. 8.477×10^6 and Rs. 8.547×10^6 respectively, for 90 iterations.

Figures 5.1, 5.2 and 5.3 show the optimal cost obtained by the modified and original PSO algorithm against the total cumulative discharges of the layouts for 30, 60 and 90 iterations, respectively. It is clearly seen that the proposed modified PSO algorithm was able to obtain a better solution as compared to an original PSO algorithm in all the layouts.

Table 5.2 shows the sewer component costs (cost of earthwork, manhole and sewer) against the total cost of layouts.

The Optimal sewer layout and 11 other alternative layouts of the base network 2 are shown in Figures 5.4 to Figure 5.15 respectively.

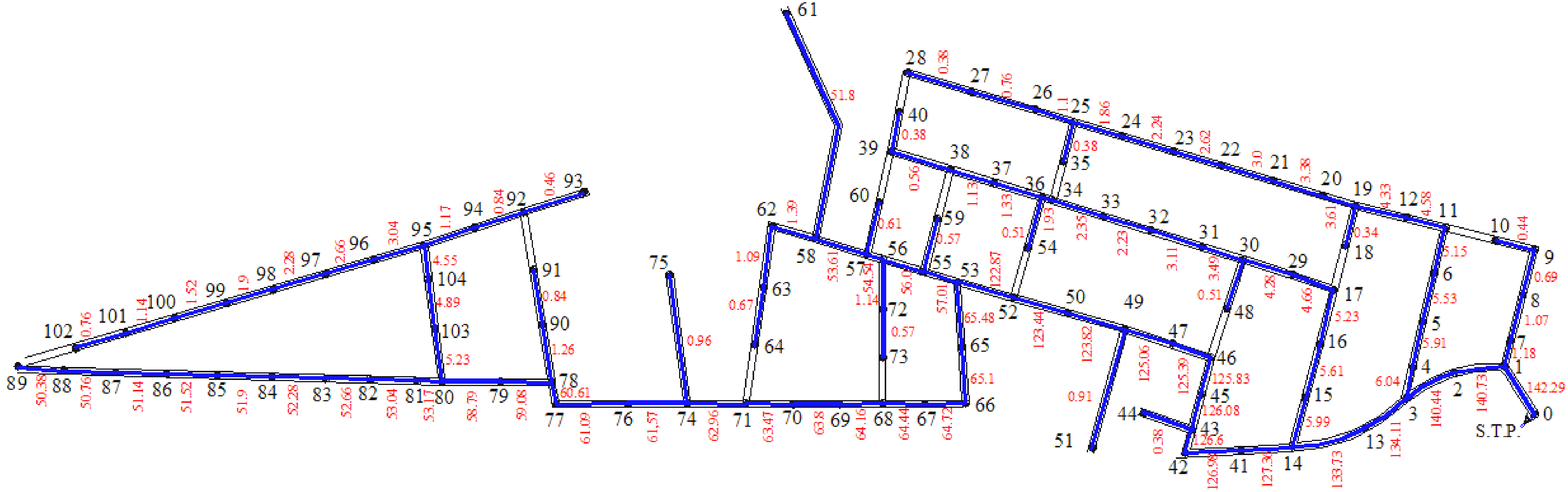


Figure 5.4 Optimal sewer layout of Network 2, CQ = 3639.13 l/s

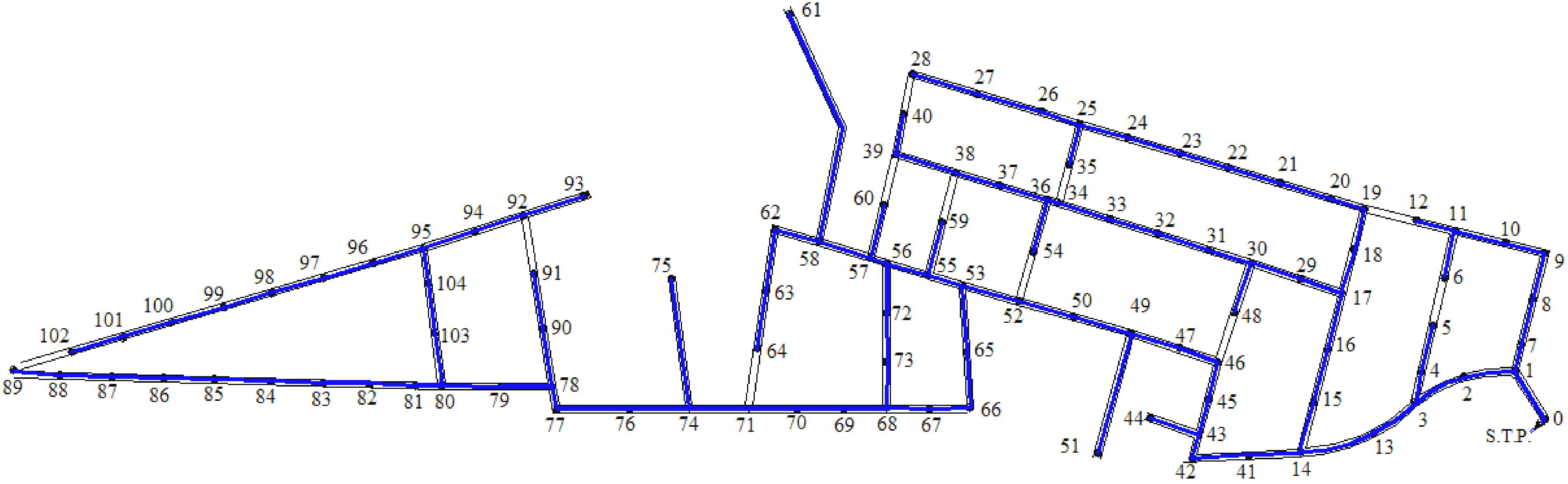


Figure 5.5 Alternative layout 1 of Network 2, CQ = 3642.34 l/s

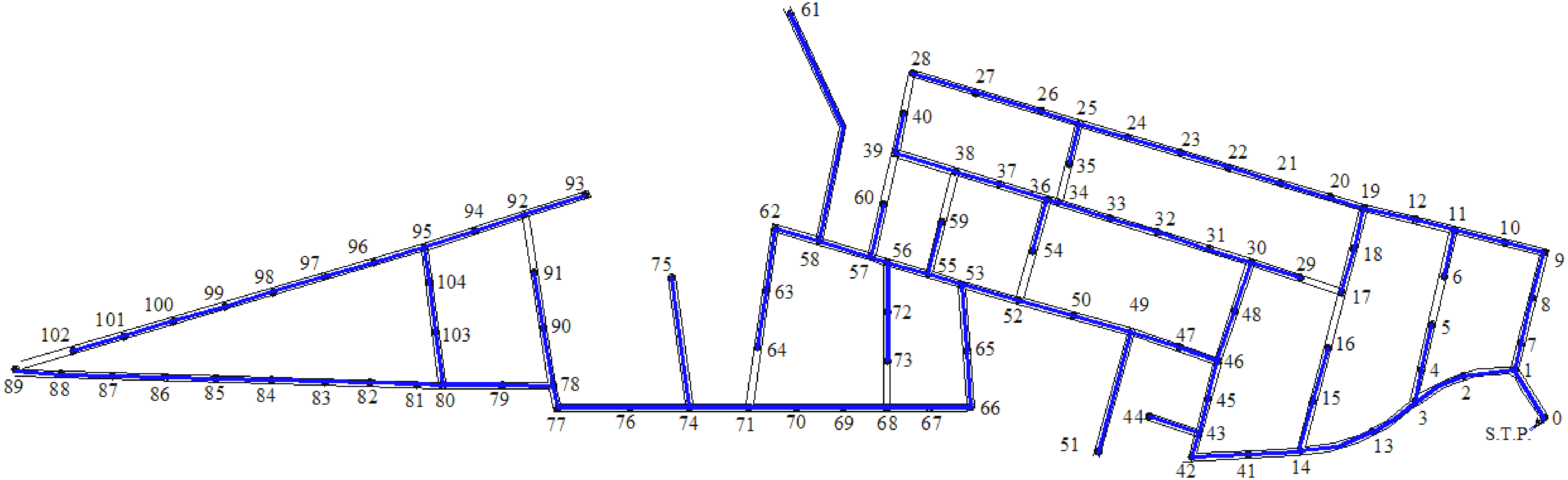


Figure 5.6 Alternative layout 2 of Network 2, CQ = 3644.56 l/s

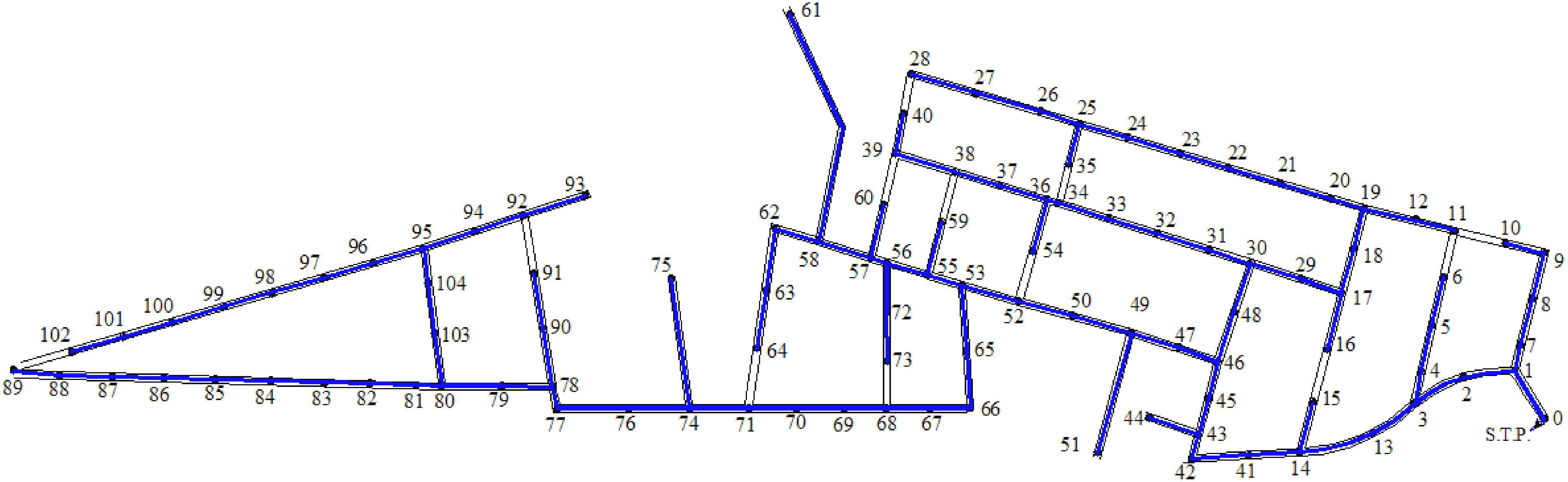


Figure 5.7 Alternative layout 3 of Network 2, CQ = 3692.80 l/s

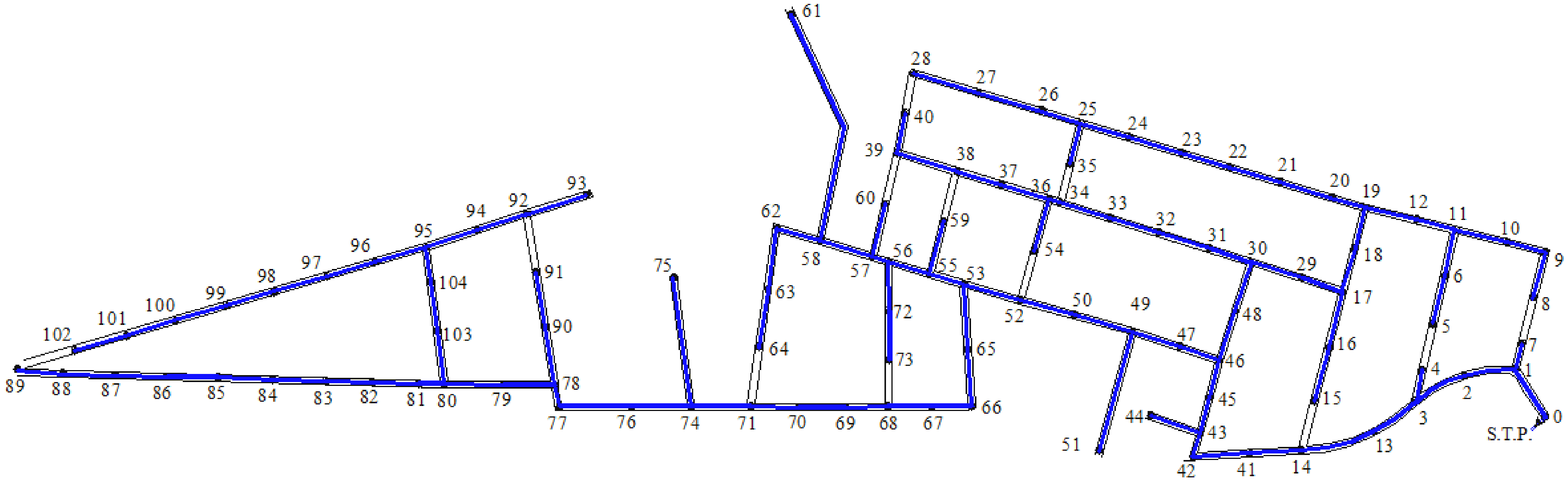


Figure 5.8 Alternative layout 4 of Network 2, CQ = 3724.24 l/s

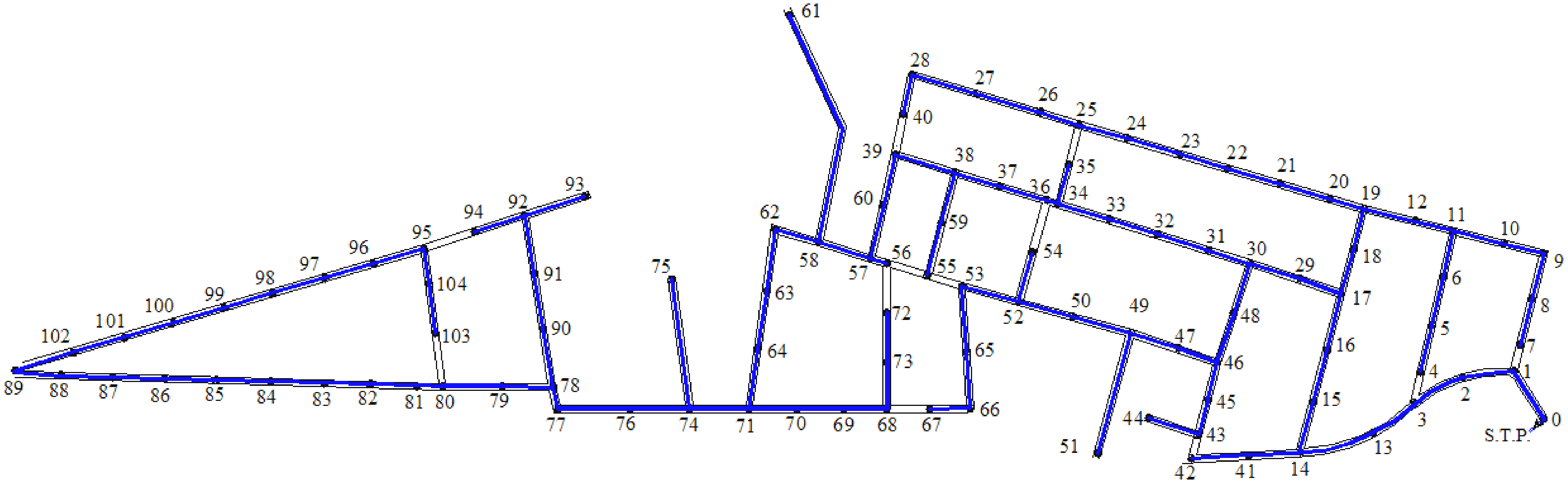


Figure 5.9 Alternative layout 5 of Network 2, CQ = 4027.95 l/s

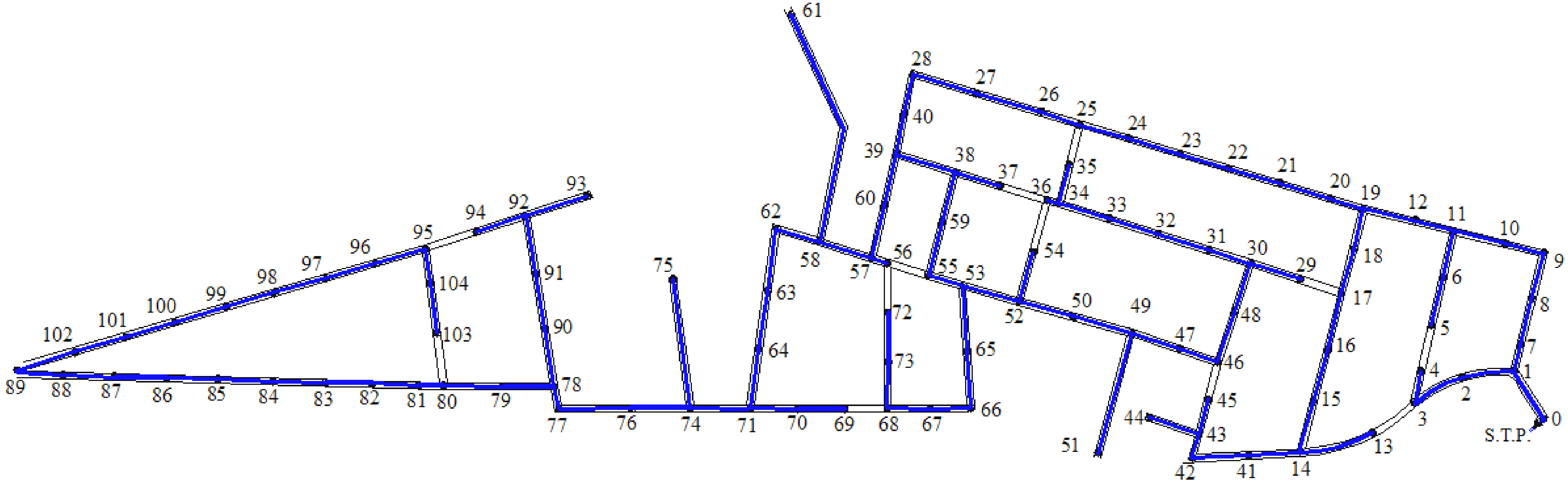


Figure 5.10 Alternative layout 6 of Network 2, CQ = 4252.10 l/s

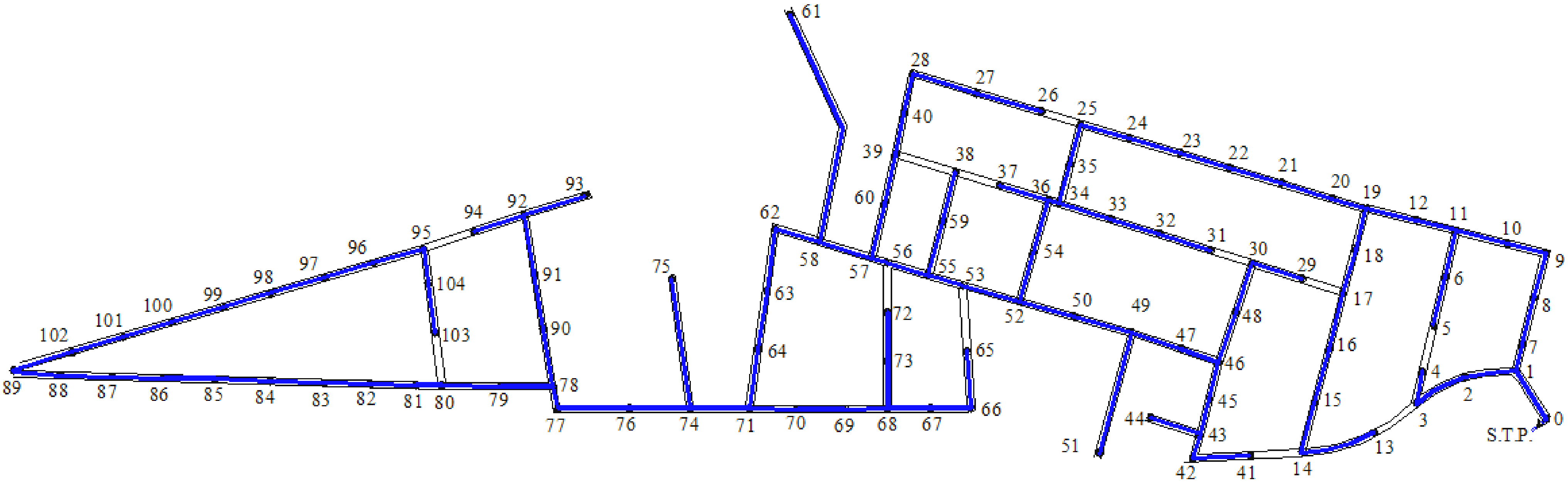


Figure 5.11 Alternative layout 7 of Network 2, CQ = 4480.85 l/s

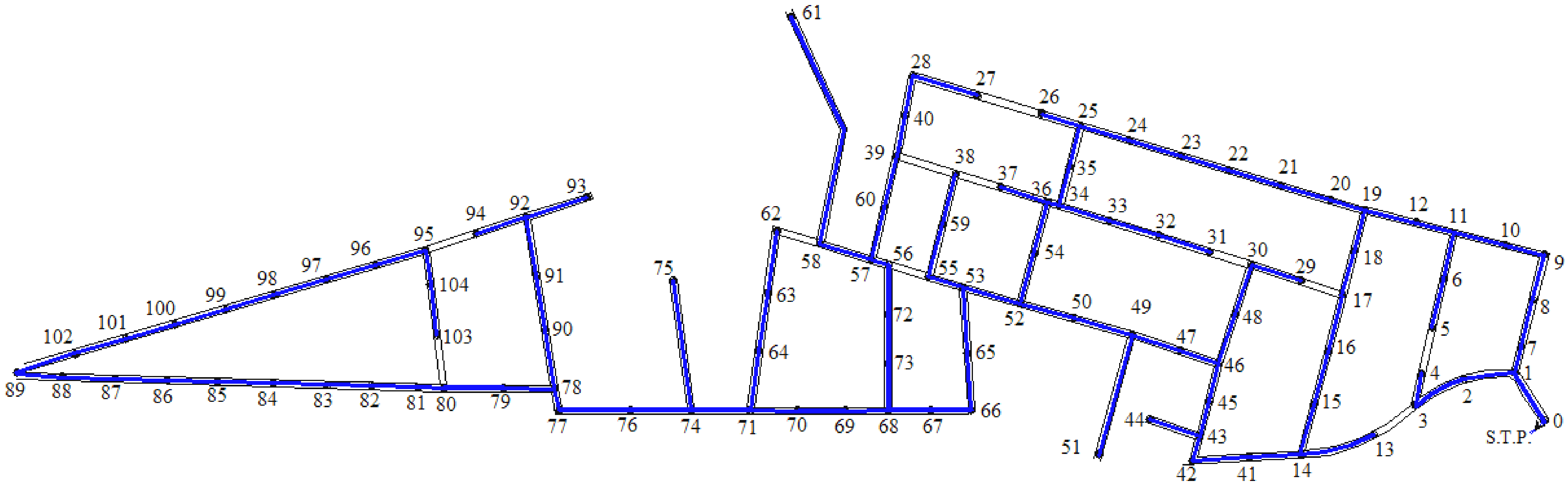


Figure 5.12 Alternative layout 8 of Network 2, CQ = 4676.69 l/s

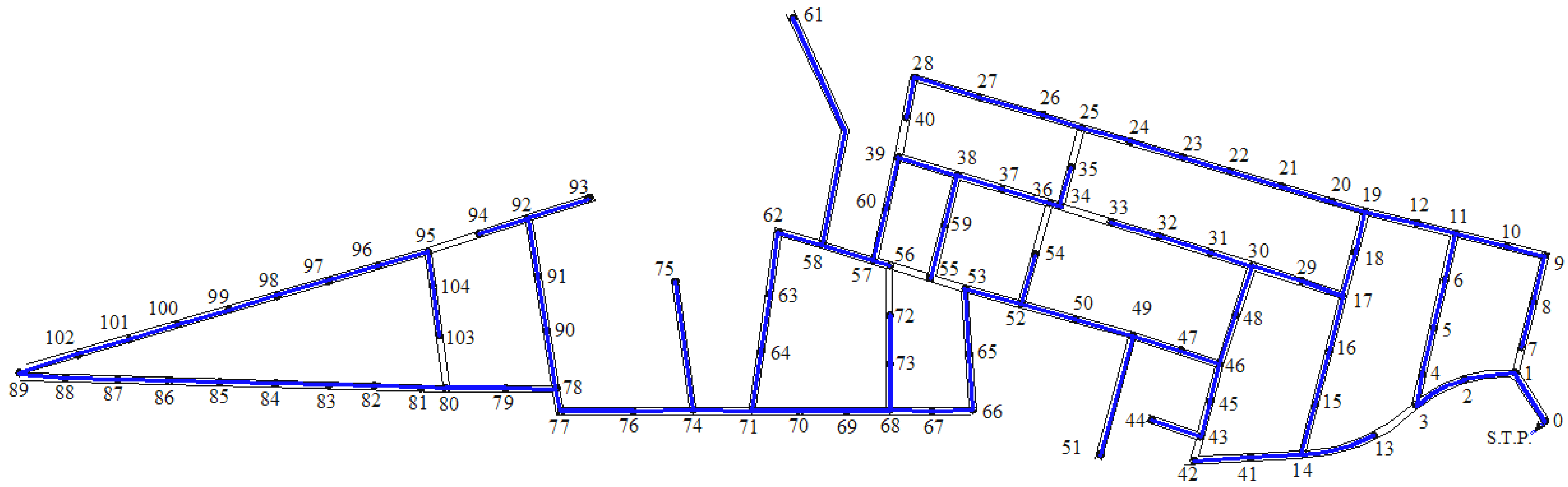


Figure 5.13 Alternative layout 9 of Network 2, CQ = 4774.97 l/s

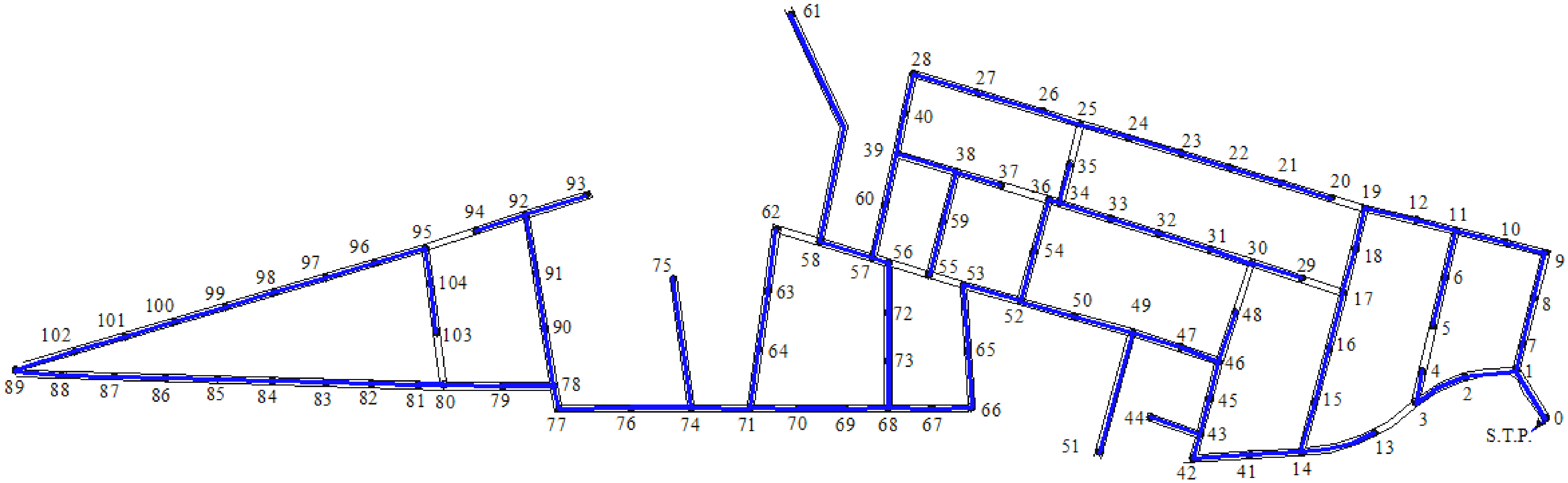


Figure 5.14 Alternative layout 10 of Network 2, CQ = 5130.95 l/s

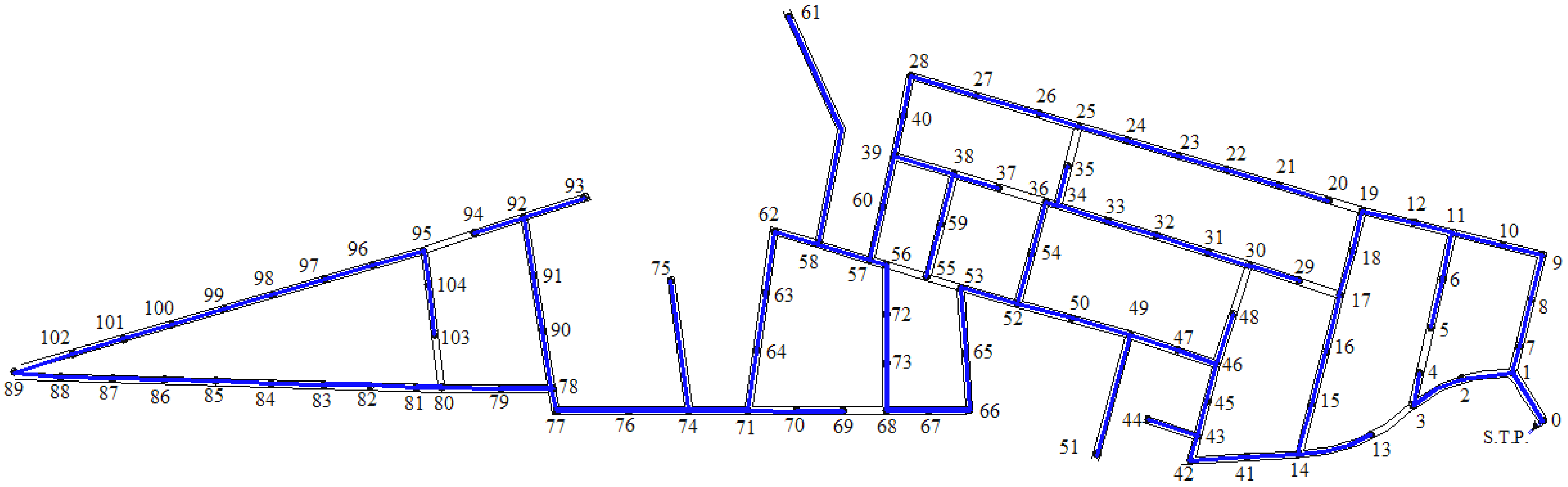


Figure 5.15 Alternative layout 11 of Network 2, CQ = 5521.53 l/s

Optimal sewer layout of Base Network 2 as shown in Figure 5.4 is selected for the detailed design. This layout is solved using different swarm sizes of 200, 400, 600, 800, 1000 and 1200 to assess the effect of the swarm size on the performance of the proposed modified and original PSO algorithm.

Figures 5.16, 5.17, 5.18 and 5.19 show the minimum total cost obtained by the modified and original PSO algorithm against the swarm sizes for different iterations. From the Figures 5.16 to 5.19 following observation can be made:

(i) In original PSO the minima is obtained with swarm size 600 with $c_1 = 2$, $c_2 = 2$ and $\omega = 0.8$.

(ii) In modified PSO the minima is obtained with swarm size 1000 with c_1, c_2 and ω are modified as per equations 4.19, 4.20 and 4.18 respectively.

(iii) It can further be observed the minima of modified PSO is better as compare to minima of original PSO.

The optimal cost obtained by the original PSO in 90 iterations for 1000 swarm size is Rs. 8.473×10^6, whereas the solution cost obtained by the modified PSO is reduced to Rs. 8.371×10^6.

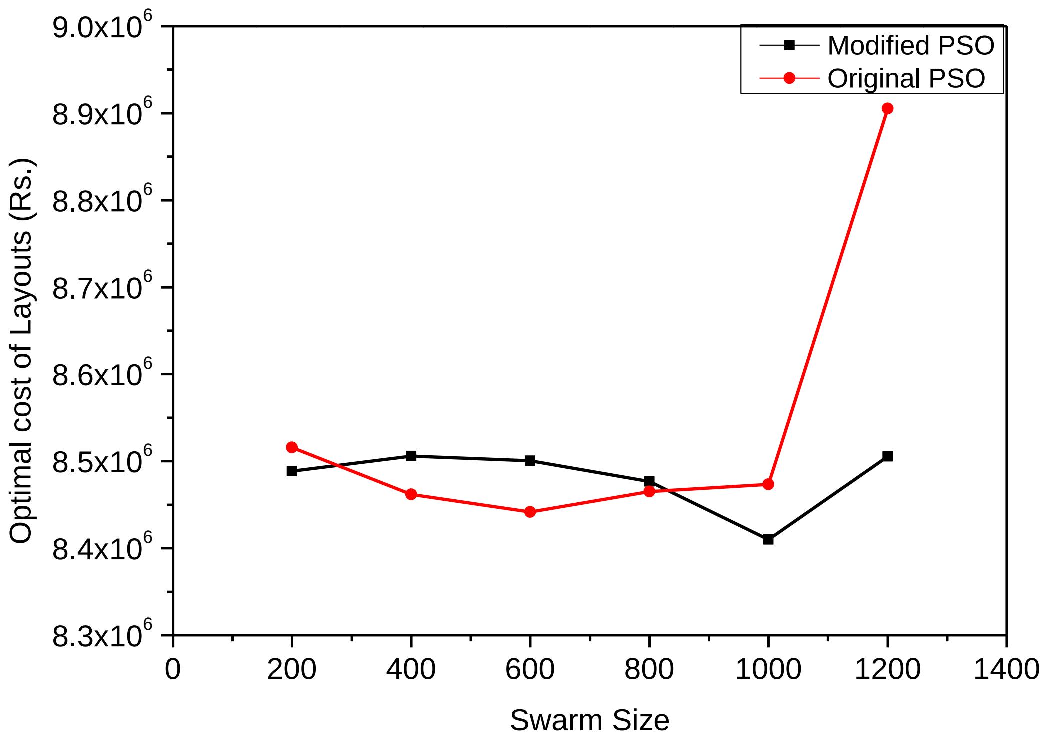


Figure 5.16 Variation of the optimal cost with swarm sizes (at 30 iterations) for Network 2

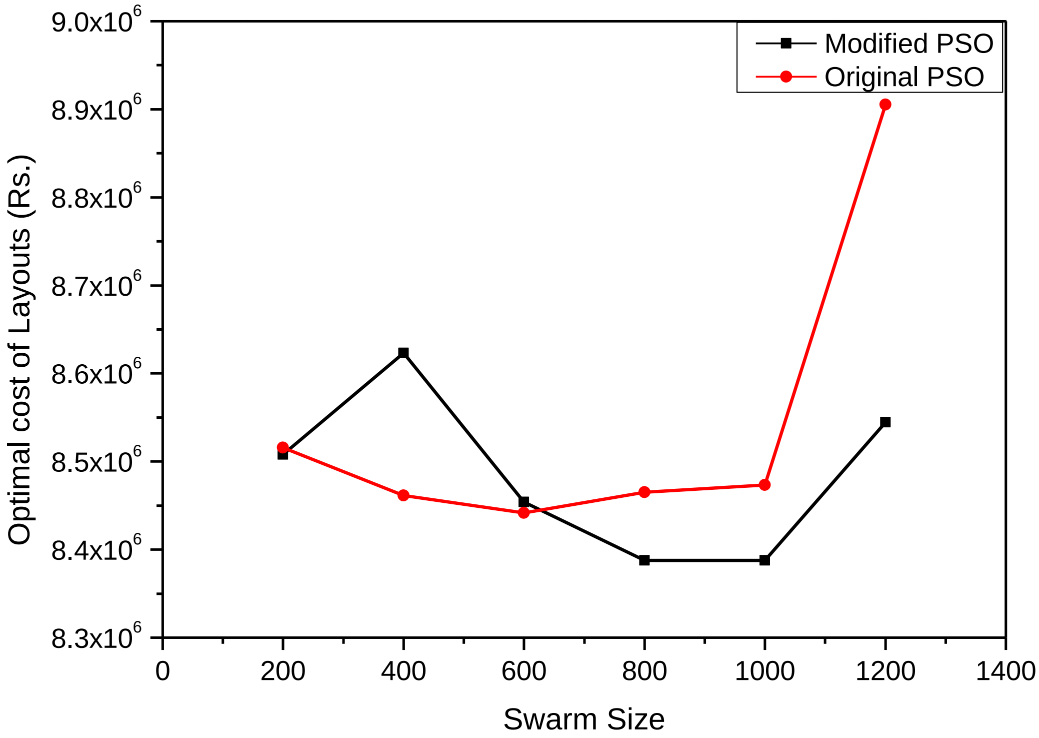


Figure 5.17 Variation of the optimal cost with swarm sizes (at 60 iterations) for Network 2

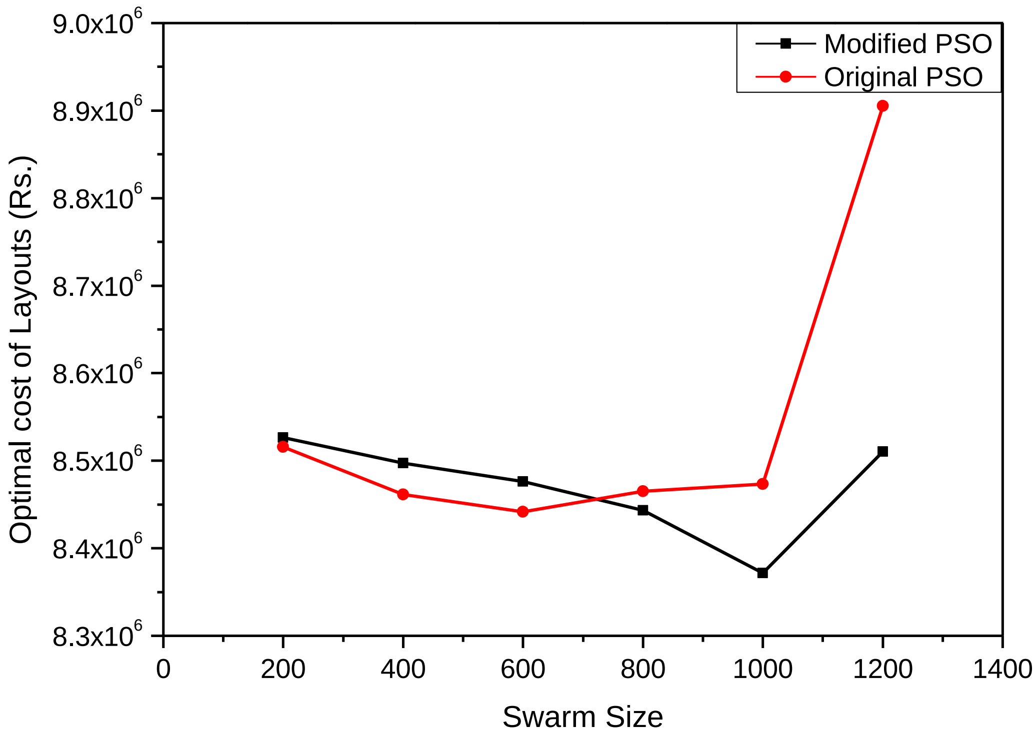


Figure 5.18 Variation of the optimal cost with swarm sizes (at 90 iterations) for Network 2

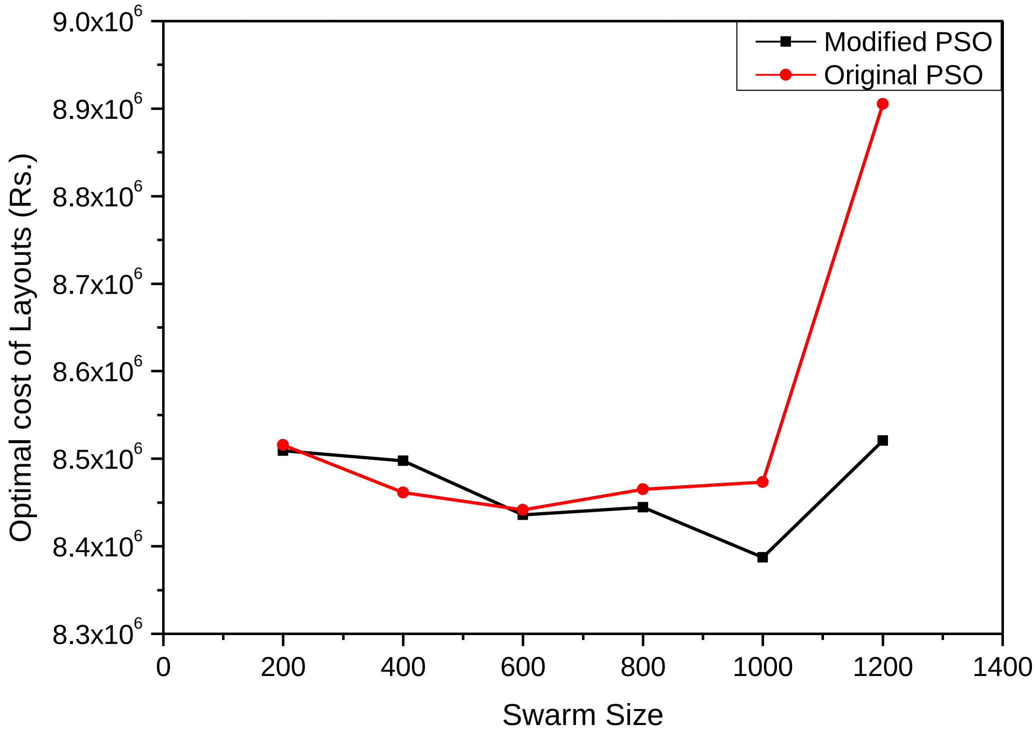


Figure 5.19 Variation of the optimal cost with swarm sizes (at 120 iterations) for Network 2

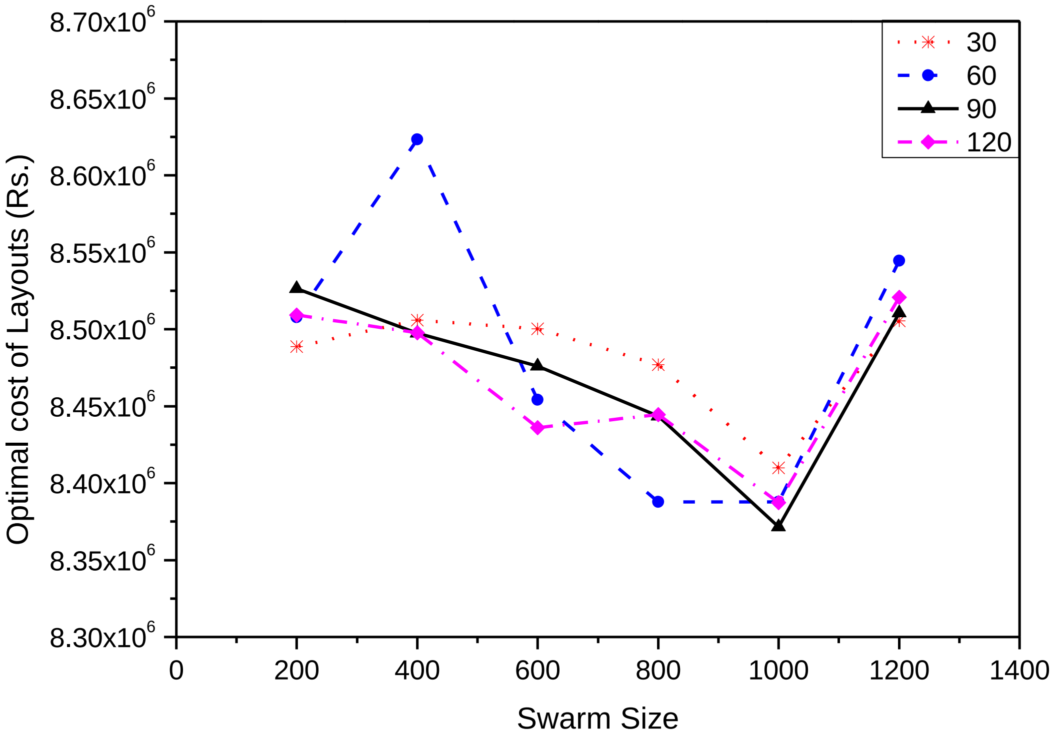


Figure 5.20 Variation of the optimal cost with swarm sizes at different iterations, modified PSO for Network 2

It is seen that the solution obtained by the Modified PSO algorithm is much better than the solution of the Original PSO algorithm. Figure 5.20 shows the optimal cost obtained with modified particle swarm optimization; the best solution produced when the swarm size is 1000. Table 5.3 presents the details of the optimal design of sewer component sizing of an optimal layout (Figure 5.4) with 1000 swarm size and 90 iterations. The Comparison of the Modified PSO with the Original PSO for the optimal layout of Network 2 is given in Appendix B.

Table 5.3 Characteristics of the Optimal Sewer Network Obtained by the Modified PSO for Network 2

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
11	10	9	20	0.0004	200	250	0.27	0.10	93.185	93.135	92.065	91.985	1.120	1.150
21	18	19	12	0.0003	200	250	0.25	0.09	94.050	94.245	92.930	92.882	1.120	1.363
30	28	27	30	0.0004	200	250	0.25	0.09	94.855	94.125	93.125	93.005	1.730	1.120
38	35	25	12	0.0004	200	250	0.25	0.09	95.540	94.955	93.883	93.835	1.657	1.120
43	40	39	14	0.0004	200	250	0.25	0.09	96.105	96.335	94.985	94.929	1.120	1.406
48	44	43	30	0.0004	200	250	0.25	0.09	96.265	95.775	94.775	94.655	1.490	1.120
52	48	30	24	0.0005	200	60	0.45	0.08	95.250	94.400	93.680	93.280	1.570	1.120
55	51	49	72	0.0009	200	250	0.33	0.14	96.445	96.040	95.208	94.920	1.237	1.120
59	54	36	24	0.0005	200	250	0.28	0.11	95.950	95.555	94.531	94.435	1.419	1.120
62	59	55	30	0.0006	200	250	0.29	0.11	96.435	96.555	95.315	95.195	1.120	1.360
66	60	57	32	0.0006	200	250	0.30	0.12	96.565	96.885	95.445	95.317	1.120	1.568
69	61	58	143	0.0518	300	250	0.97	0.70	95.865	96.970	94.645	94.073	1.220	2.897
72	64	63	33	0.0007	200	250	0.30	0.12	97.605	97.345	96.357	96.225	1.248	1.120
79	73	72	30	0.0006	200	250	0.29	0.11	97.050	96.925	95.925	95.805	1.125	1.120
85	75	74	76	0.0010	200	250	0.34	0.15	97.970	97.775	96.850	96.546	1.120	1.229
99	89	88	30	0.0504	300	250	0.96	0.68	99.305	99.240	98.085	97.965	1.220	1.275
101	91	90	33	0.0008	200	250	0.33	0.14	98.235	98.125	97.115	96.983	1.120	1.142
103	93	92	36	0.0005	200	250	0.27	0.10	98.475	98.450	97.355	97.211	1.120	1.239
112	102	101	30	0.0008	200	250	0.32	0.13	98.980	98.875	97.860	97.740	1.120	1.135
10	9	8	30	0.0007	200	60	0.50	0.09	93.135	92.435	91.815	91.315	1.320	1.120
29	27	26	30	0.0008	200	250	0.32	0.13	94.125	94.450	93.005	92.885	1.120	1.565
42	39	38	30	0.0006	200	250	0.29	0.11	96.335	96.030	94.929	94.809	1.406	1.221
71	63	62	33	0.0011	200	250	0.35	0.16	97.345	97.240	96.225	96.093	1.120	1.147

Table 5.3 (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
78	72	56	21	0.0011	200	250	0.36	0.16	96.925	96.790	95.754	95.670	1.171	1.120
98	88	87	30	0.0508	300	250	0.97	0.69	99.240	99.225	97.965	97.845	1.275	1.380
100	90	78	33	0.0013	200	60	0.60	0.12	98.125	97.820	96.983	96.433	1.142	1.387
104	92	94	30	0.0008	200	250	0.33	0.14	98.450	98.400	97.211	97.091	1.239	1.309
105	94	95	26	0.0012	200	250	0.36	0.16	98.400	98.395	97.091	96.987	1.309	1.408
111	101	100	30	0.0011	200	250	0.36	0.16	98.875	98.810	97.740	97.620	1.135	1.190
9	8	7	30	0.0011	200	60	0.57	0.11	92.435	91.350	90.730	90.230	1.705	1.120
28	26	25	27	0.0011	200	250	0.35	0.16	94.450	94.955	92.885	92.777	1.565	2.178
41	38	37	30	0.0011	200	100	0.49	0.13	96.030	95.650	94.809	94.509	1.221	1.141
70	62	58	24	0.0014	200	70	0.59	0.13	97.240	96.970	96.093	95.750	1.147	1.220
97	87	86	30	0.0511	300	250	0.97	0.69	99.225	99.045	97.845	97.725	1.380	1.320
110	100	99	30	0.0015	200	70	0.61	0.14	98.810	98.750	97.620	97.191	1.190	1.559
8	7	1	9	0.0012	200	60	0.59	0.12	91.350	91.085	90.115	89.965	1.235	1.120
27	25	24	30	0.0019	200	80	0.62	0.16	94.955	94.815	92.777	92.402	2.178	2.413
40	37	36	16	0.0013	200	250	0.38	0.18	95.650	95.555	94.499	94.435	1.151	1.120
68	58	57	33	0.0536	300	250	0.97	0.71	96.970	96.885	94.073	93.941	2.897	2.944
96	86	85	30	0.0515	300	250	0.97	0.69	99.045	98.680	97.580	97.460	1.465	1.220
109	99	98	30	0.0019	200	80	0.62	0.16	98.750	98.685	97.191	96.816	1.559	1.869
26	24	23	30	0.0022	200	100	0.61	0.18	94.815	94.625	92.402	92.102	2.413	2.523
39	36	34	7	0.0019	200	80	0.63	0.16	95.555	95.500	94.435	94.348	1.120	1.153
65	57	56	8	0.0545	300	250	0.98	0.72	96.885	96.790	93.941	93.909	2.944	2.881
95	85	84	30	0.0519	300	250	0.97	0.70	98.680	98.610	97.460	97.340	1.220	1.270
108	98	97	30	0.0023	200	100	0.61	0.18	98.685	98.545	96.816	96.516	1.869	2.029

Table 5.3 (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
25	23	22	30	0.0026	200	100	0.64	0.20	94.625	94.550	92.102	91.802	2.523	2.748
36	34	33	18	0.0023	200	60	0.73	0.16	95.500	95.350	94.348	94.048	1.153	1.303
64	56	55	25	0.0560	300	250	0.98	0.74	96.790	96.555	93.909	93.809	2.881	2.746
94	84	83	30	0.0523	300	250	0.97	0.70	98.610	98.435	97.335	97.215	1.275	1.220
107	97	96	30	0.0027	200	100	0.64	0.20	98.545	98.430	96.516	96.216	2.029	2.214
24	22	21	30	0.0030	200	125	0.61	0.22	94.550	94.425	91.802	91.562	2.748	2.863
35	33	32	30	0.0027	200	100	0.64	0.20	95.350	95.115	94.048	93.748	1.303	1.368
61	55	53	20	0.0570	300	250	0.98	0.75	96.555	96.625	93.809	93.729	2.746	2.896
93	83	82	30	0.0527	300	250	0.97	0.70	98.435	98.385	97.215	97.095	1.220	1.290
106	96	95	30	0.0030	200	125	0.61	0.22	98.430	98.395	96.216	95.976	2.214	2.419
23	21	20	30	0.0034	200	125	0.63	0.24	94.425	94.310	91.562	91.322	2.863	2.988
34	32	31	30	0.0031	200	125	0.62	0.23	95.115	94.750	93.748	93.508	1.368	1.243
92	82	81	30	0.0530	300	250	0.97	0.71	98.385	98.270	97.095	96.975	1.290	1.295
116	95	104	27	0.0046	200	150	0.65	0.29	98.395	98.325	95.976	95.796	2.419	2.529
115	104	103	27	0.0049	200	150	0.66	0.30	98.325	98.260	95.796	95.616	2.529	2.644
22	20	19	18	0.0036	200	150	0.61	0.26	94.310	94.245	91.322	91.202	2.988	3.043
33	31	30	30	0.0035	200	125	0.64	0.24	94.750	94.400	93.508	93.268	1.243	1.133
91	81	80	10	0.0532	300	250	0.97	0.71	98.270	98.205	96.975	96.935	1.295	1.270
114	103	80	27	0.0052	200	200	0.61	0.33	98.260	98.205	95.616	95.481	2.644	2.724
14	19	12	30	0.0043	200	150	0.64	0.28	94.245	94.135	91.202	91.002	3.043	3.133
32	30	29	22	0.0043	200	150	0.64	0.28	94.400	94.150	93.177	93.030	1.223	1.120
90	80	79	31	0.0588	300	250	0.99	0.77	98.205	98.115	95.481	95.357	2.724	2.758
13	12	11	20	0.0046	200	150	0.65	0.29	94.135	93.345	91.002	90.869	3.133	2.476

Table 5.3 (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
31	29	17	30	0.0047	200	150	0.65	0.29	94.150	93.990	93.030	92.830	1.120	1.160
89	79	78	31	0.0592	300	250	0.99	0.78	98.115	97.820	95.357	95.233	2.758	2.587
7	11	6	30	0.0052	200	200	0.60	0.33	93.345	93.340	90.869	90.719	2.476	2.621
19	17	16	30	0.0052	200	200	0.61	0.33	93.990	93.855	92.830	92.680	1.160	1.175
88	78	77	13	0.0606	300	200	1.09	0.72	97.820	97.885	95.233	95.168	2.587	2.717
6	6	5	30	0.0055	200	200	0.62	0.34	93.340	93.245	90.719	90.569	2.621	2.676
18	16	15	30	0.0056	200	200	0.62	0.34	93.855	93.820	92.680	92.530	1.175	1.290
87	77	76	38	0.0611	300	200	1.09	0.72	97.885	97.820	95.168	94.978	2.717	2.842
5	5	4	30	0.0059	200	200	0.63	0.35	93.245	93.185	90.569	90.419	2.676	2.766
17	15	14	30	0.0060	200	200	0.63	0.36	93.820	93.795	92.530	92.380	1.290	1.415
86	76	74	38	0.0616	300	200	1.09	0.73	97.820	97.775	94.978	94.788	2.842	2.987
4	4	3	10	0.0060	200	60	0.97	0.26	93.185	93.120	90.419	90.252	2.766	2.868
84	74	71	34	0.0630	300	200	1.10	0.74	97.775	97.610	94.788	94.618	2.987	2.992
83	71	70	26	0.0635	300	200	1.10	0.75	97.610	97.525	94.618	94.488	2.992	3.037
82	70	69	26	0.0638	300	200	1.10	0.75	97.525	97.320	94.488	94.358	3.037	2.962
81	69	68	26	0.0642	300	200	1.10	0.75	97.320	97.100	94.358	94.228	2.962	2.872
77	68	67	22	0.0644	300	200	1.10	0.76	97.100	96.955	94.228	94.118	2.872	2.837
76	67	66	22	0.0647	300	200	1.10	0.76	96.955	96.915	94.118	94.008	2.837	2.907
75	66	65	30	0.0651	300	200	1.10	0.76	96.915	96.765	94.008	93.858	2.907	2.907
74	65	53	30	0.0655	300	200	1.10	0.77	96.765	96.625	93.858	93.708	2.907	2.917
60	53	52	30	0.1229	400	250	1.19	0.75	96.625	96.340	93.708	93.588	2.917	2.752
57	52	50	30	0.1234	450	450	0.96	0.74	96.340	96.115	93.588	93.522	2.752	2.593
56	50	49	30	0.1238	450	450	0.96	0.74	96.115	96.040	93.522	93.455	2.593	2.585

Table 5.3 (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
54	49	47	26	0.1251	450	450	0.96	0.75	96.040	95.625	93.455	93.397	2.585	2.228
53	47	46	26	0.1254	450	450	0.96	0.75	95.625	95.255	93.397	93.340	2.228	1.916
50	46	45	20	0.1258	450	450	0.96	0.75	95.255	95.530	93.340	93.295	1.916	2.235
49	45	43	20	0.1261	450	450	0.96	0.75	95.530	95.775	93.295	93.251	2.235	2.524
47	43	42	11	0.1266	450	450	0.96	0.76	95.775	95.635	93.251	93.226	2.524	2.409
46	42	41	30	0.1270	450	450	0.96	0.76	95.635	94.550	93.226	93.160	2.409	1.391
45	41	14	30	0.1274	450	60	2.13	0.42	94.550	93.795	92.925	92.425	1.625	1.370
16	14	13	30	0.1337	450	100	1.78	0.49	93.795	93.425	92.355	92.055	1.440	1.370
15	13	3	30	0.1341	450	100	1.78	0.49	93.425	93.120	92.050	91.750	1.375	1.370
3	3	2	23	0.1404	450	350	1.09	0.74	93.120	92.455	90.252	90.186	2.868	2.269
2	2	1	23	0.1407	450	60	2.18	0.44	92.455	91.085	90.098	89.715	2.357	1.370
1	1	0	30	0.1423	450	70	2.07	0.46	91.085	90.745	89.715	89.286	1.370	1.459

5.2 Result of Case Study II

The results of Network 3 (Banjaran) were obtained using swarm size of 1000. The maximum numbers of iterations were kept as 30, 60 & 90 for each sewer layout. Table 5.4 shows the variation in total optimal cost with total cumulative discharges of the layout.

Table 5.4 Total Cumulative Discharge vs. Total optimal Cost at Different Iterations for network 3

S. No.	Total cumulative discharge (l/s)	Total cost (Rs.)					
		30 Iterations		60 Iterations		90 Iterations	
		Modified PSO	Standard PSO	Modified PSO	Standard PSO	Modified PSO	Standard PSO
1	1936.62	8481572	8592942	8461514	8592742	8455746	8592742
2	1936.80	8524050	8692557	8557276	8692557	8515448	8692557
3	1937.95	8557831	8709819	8543633	8709819	8595790	8709819
4	1939.34	9123060	9213455	9045062	9213119	9028524	9213119
5	1950.18	9234746	9381940	9215594	9381940	9236219	9381940
6	2074.10	9437854	10635704	9421560	10635704	9416131	10635704
7	2221.65	10960246	14387497	10993204	14387497	10807841	14387497

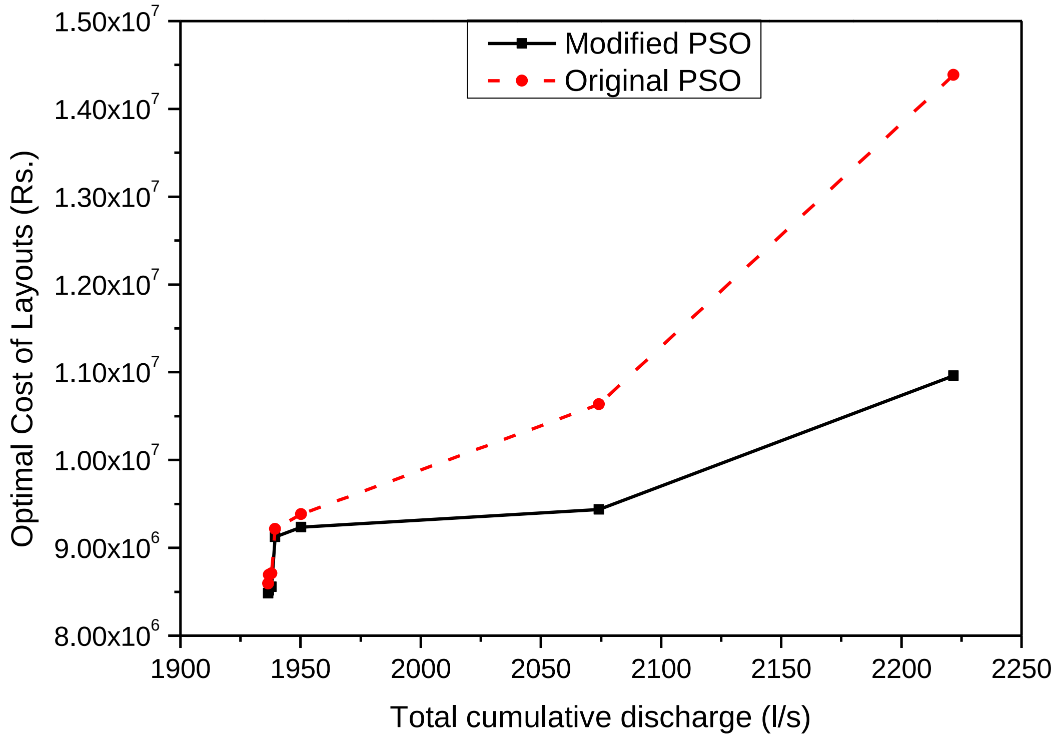


Figure 5.21 Total cumulative discharges vs. Optimal cost of layouts at 30 iterations for Network 3

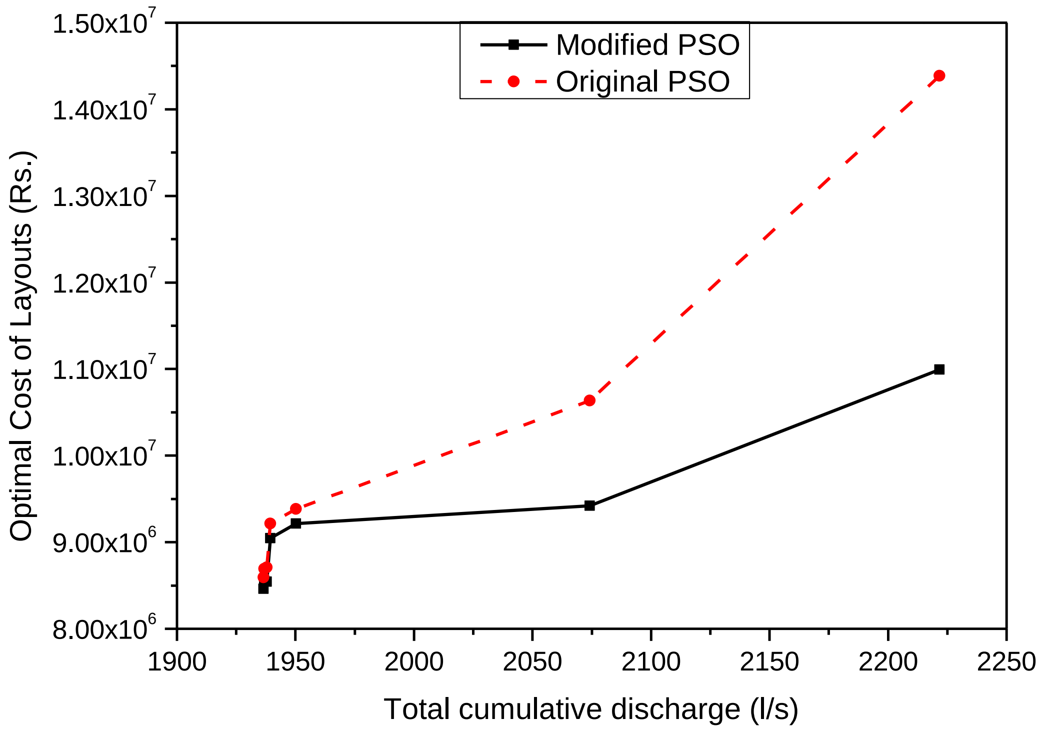


Figure 5.22 Total cumulative discharges vs. Optimal cost of layouts at 60 iterations for Network 3

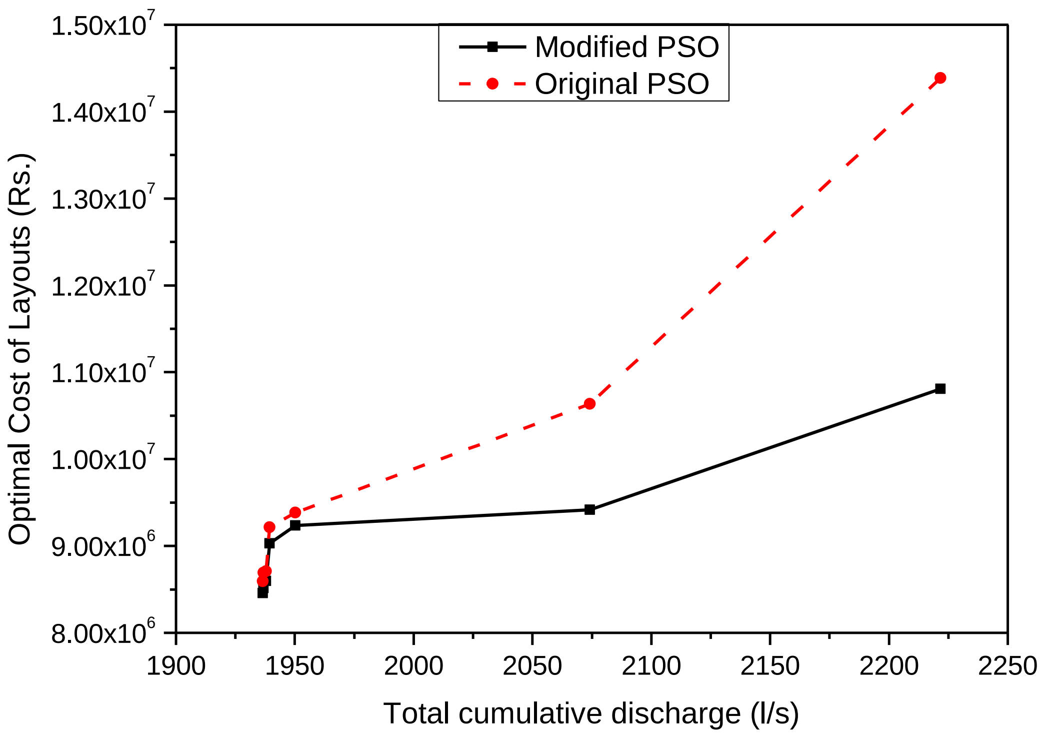


Figure 5.23 Total cumulative discharges vs. Optimal cost of layouts at 90 iterations for Network 3

Table 5.5 Sewer Layout Cost Details for Network 3

S. No.	Total cumulative discharge (l/s)	Cost of Earthwork (Rs.)	Cost of Manholes (Rs.)	Cost of Sewer Pipe (Rs.)	Total Cost (Rs.)
1	1936.62	1396710	5077166	1981870	8455746
2	1936.80	1333070	5004608	2177770	8515448
3	1937.95	1369970	5029720	2196100	8595790
4	1939.34	1523720	5310174	2194630	9028524
5	1950.18	1474720	5564699	2196800	9236219
6	2074.10	1509080	5669421	2237630	9416131
7	2221.65	1761010	6746076	2300756	10807841

Table 5.4 clearly shows that the layout having minimum *CQ* has the minimum total cost. The total cost of sewer layout is generally increasing with the *CQ* of a layout. The cost of optimal layout (CQ = 1936.62 l/s) is Rs. 8.455×10^6 with modified PSO

as compared to the cost of original PSO Rs. 8.592×10^6. Further the 2^{nd} alternative layout (CQ = 1936.8 l/s) these costs is Rs. 8.515×10^6 and Rs. 8.692×10^6 respectively, for 90 iterations.

Figures 5.21, 5.22 and 5.23 show the optimal cost obtained by the modified and original PSO algorithm against the total cumulative discharges of the layouts for 30, 60 and 90 iterations, respectively. It is clearly seen that the proposed modified PSO algorithm was able to obtain a better solution as compared to an original PSO algorithm in all the layouts.

Table 5.5 shows the sewer component costs (cost of earthwork, manhole and sewer) against the total cost of layouts.

The Optimal sewer layout and 2^{nd} alternative layout of a Base Network 3 are shown in Figures 5.24 and 5.25 respectively.

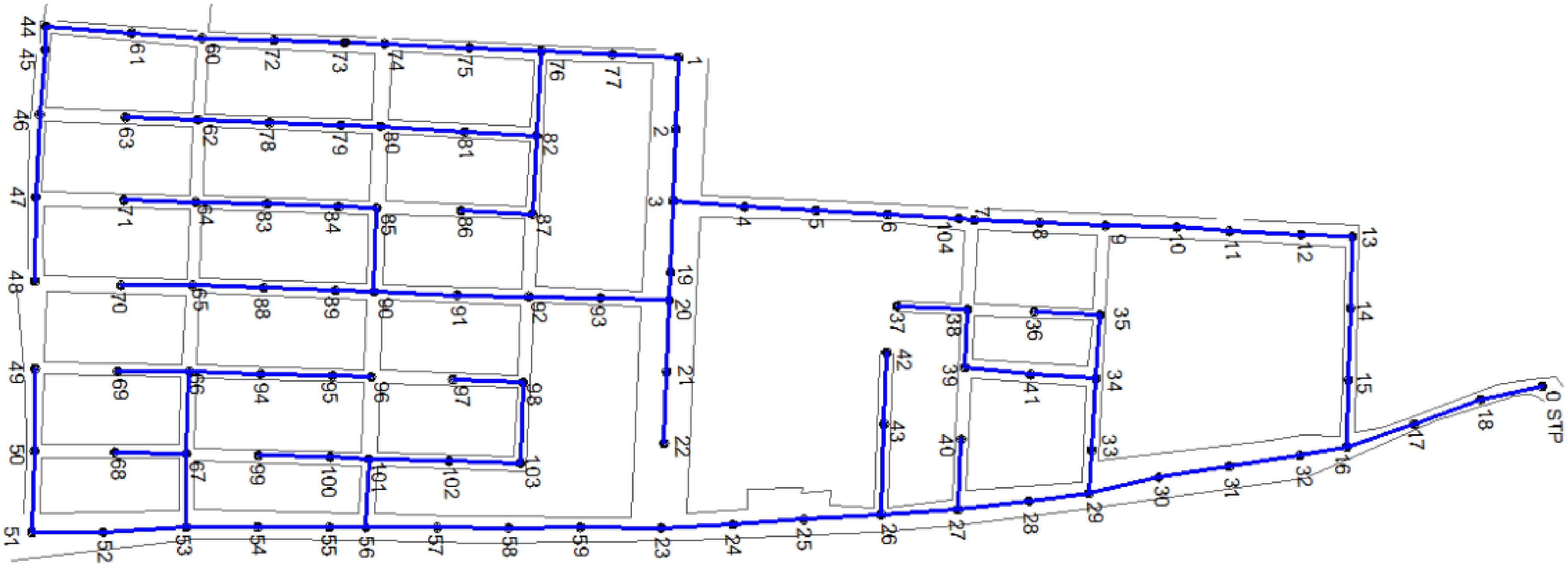


Figure 5.24 Optimal sewer layout of Network 3, CQ = 1936.62 l/s

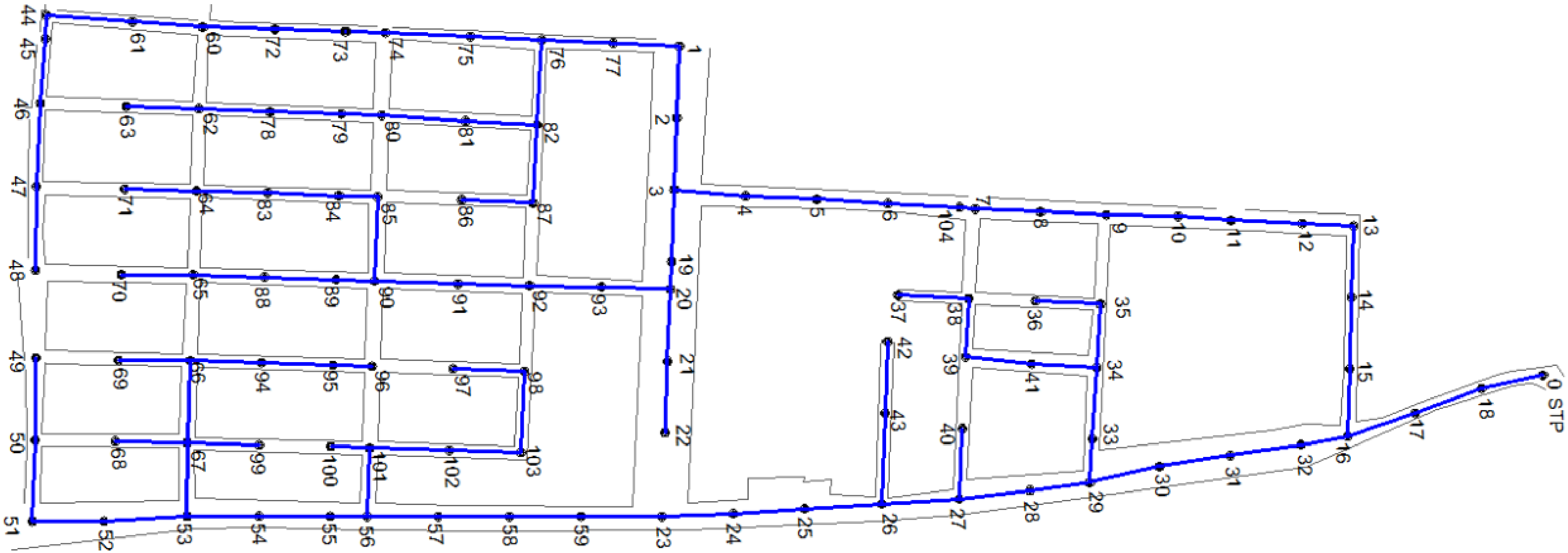


Figure 5.25 Alternative layout 1 of Network 3, CQ = 1936.80 l/s

Optimal sewer layout of Base Network 3 as shown in Figure 5.24 is selected for the detailed design. This layout is solved using different swarm sizes of 200, 400, 600, 800, 1000 and 1200 to assess the effect of the swarm size on the performance of the proposed modified and original PSO algorithm.

Figures 5.26, 5.27, 5.28 and 5.29 show the minimum total cost obtained by the modified and original PSO algorithm against the swarm sizes for different iterations. The optimal cost obtained by the original PSO in 90 iterations for 1000 swarm size is Rs. 8.592×10^6, whereas the solution cost obtained by the modified PSO is reduced to Rs. 8.455×10^6.

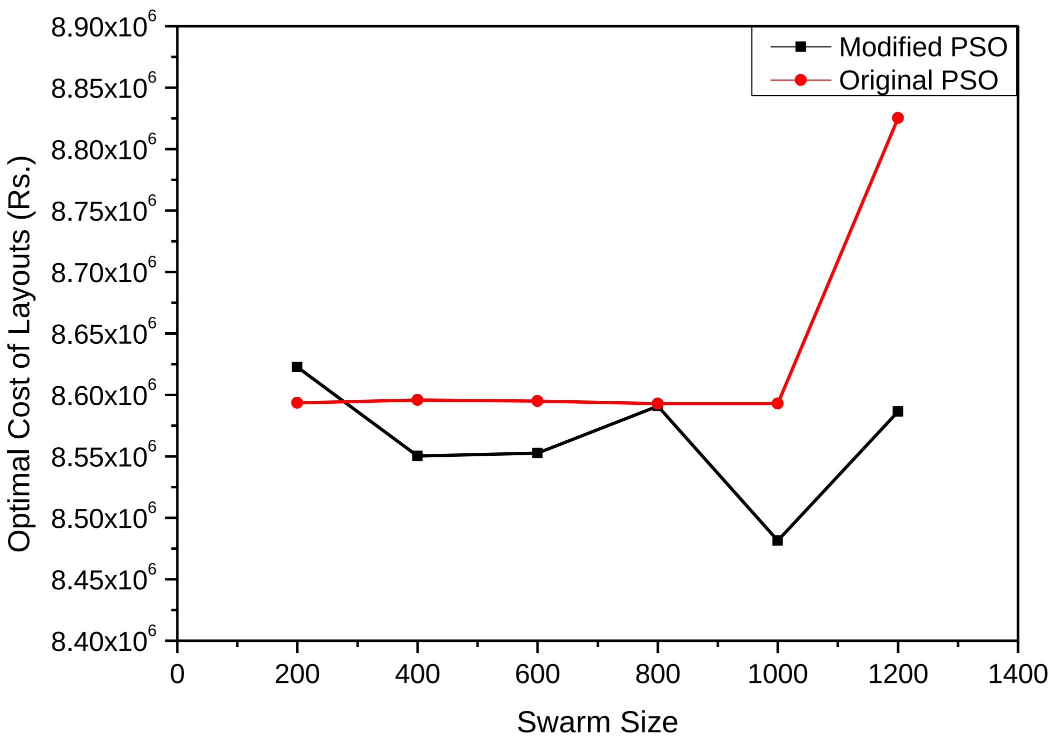


Figure 5.26 Variation of the optimal cost with swarm sizes (at 30 iterations) for Network 3

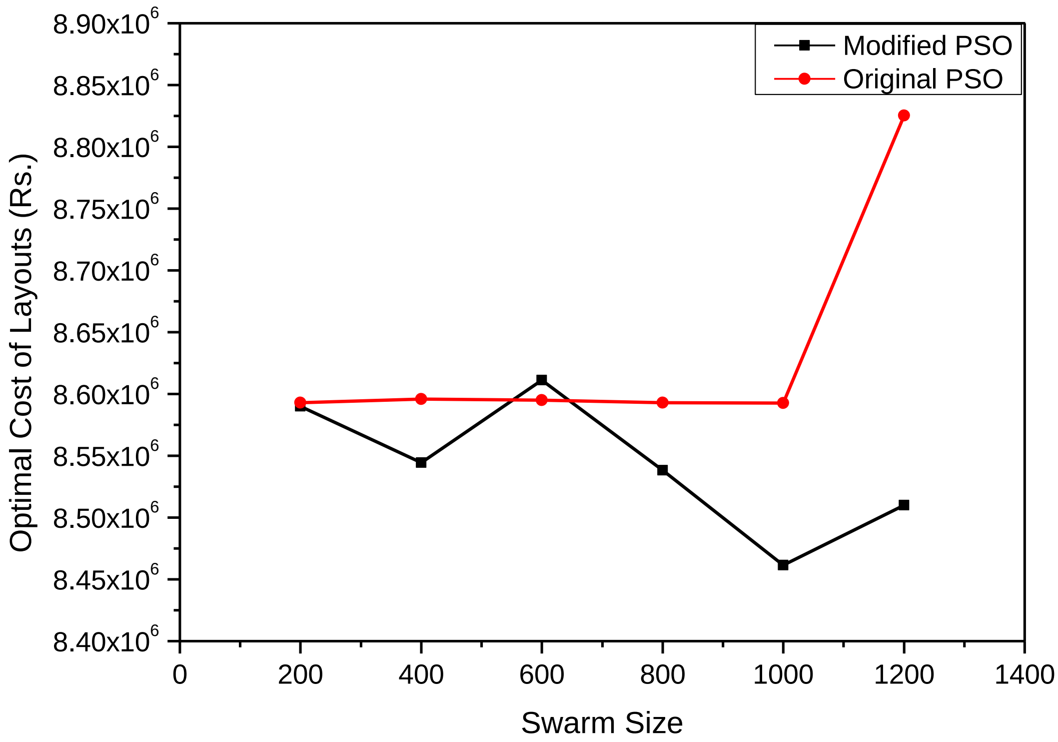


Figure 5.27 Variation of the optimal cost with swarm sizes (at 60 iterations) for Network 3

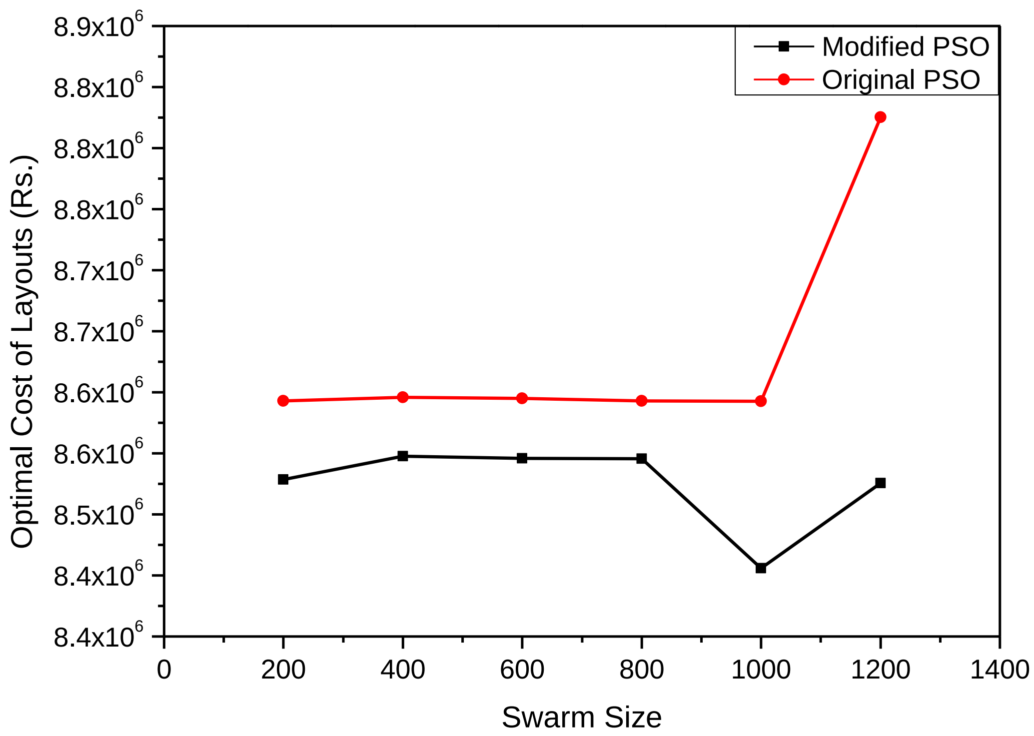


Figure 5.28 Variation of the optimal cost with swarm sizes (at 90 iterations) for Network 3

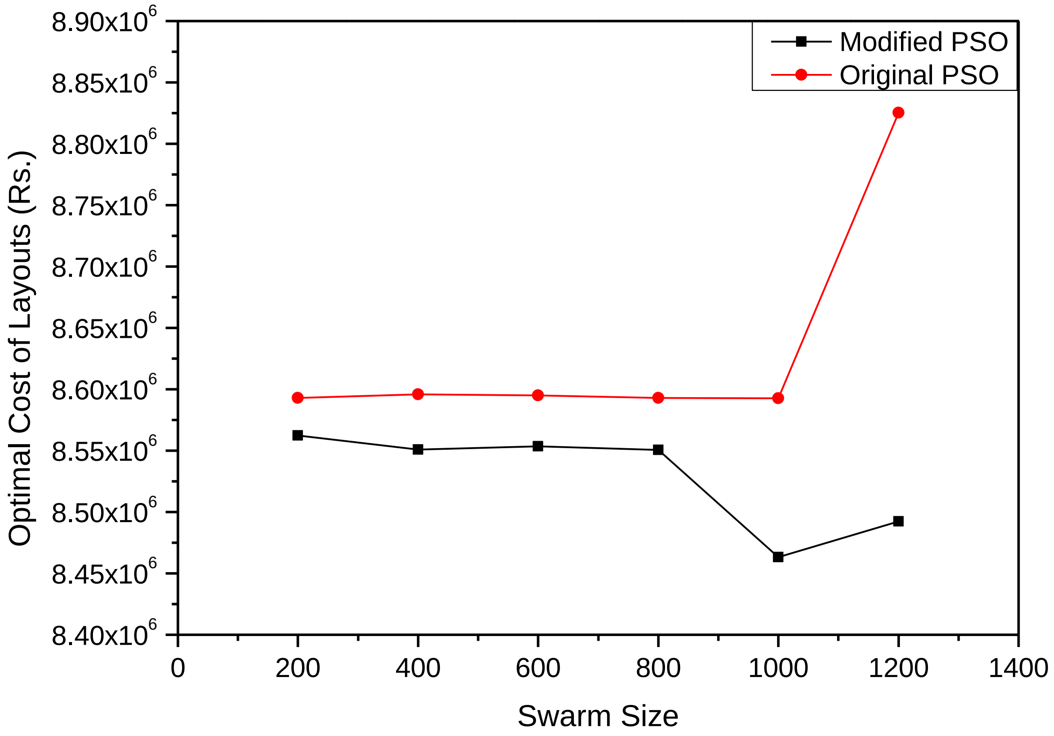


Figure 5.29 Variation of the optimal cost with swarm sizes (at 120 iterations) for Network 3

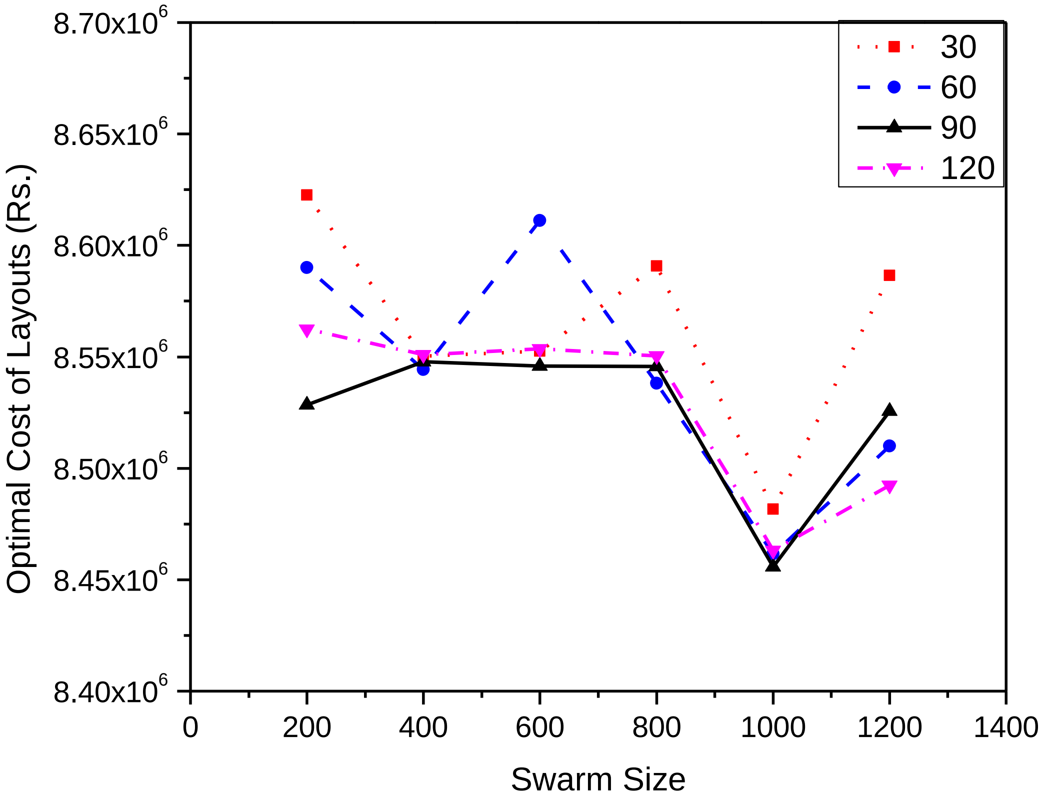


Figure 5.30 Variation of the minimum total cost with swarm sizes at different iterations, modified PSO for network 3

It is seen that the solution obtained by the modified PSO algorithm is much better than the solution of the original PSO algorithm. Figure 5.30 shows the optimal cost obtained with modified particle swarm optimization; the best solution produced when the swarm size is 1000. Table 5.6 presents the details of the optimal design of sewer component sizing of an optimal layout (Figure 5.24) with 1000 swarm size and 90 iterations.

Table 5.6 Characteristics of the Optimal Sewer Network Obtained by the Modified PSO for Network 3

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
24	23	22	30	0.0001	200	250	0.17	0.05	330.793	330.975	329.673	329.553	1.120	1.422
39	37	36	28	0.0002	200	250	0.19	0.06	330.421	330.003	328.995	328.883	1.426	1.120
41	38	39	20	0.0001	200	80	0.20	0.03	330.005	329.735	328.865	328.615	1.140	1.120
42	39	40	24	0.0001	200	250	0.18	0.05	329.735	329.325	328.301	328.205	1.434	1.120
44	40	42	28	0.0003	200	250	0.24	0.08	329.325	334.580	328.205	328.093	1.120	6.487
45	41	28	29	0.0001	200	250	0.16	0.04	329.151	329.253	328.031	327.915	1.120	1.338
46	42	35	28	0.0004	200	250	0.26	0.09	334.580	330.163	328.093	327.981	6.487	2.182
47	43	44	30	0.0001	200	60	0.26	0.03	330.074	329.638	328.954	328.454	1.120	1.184
48	44	27	38	0.0002	200	250	0.21	0.07	329.638	329.840	328.454	328.302	1.184	1.538
52	49	48	35	0.0001	200	250	0.17	0.05	331.192	331.421	330.072	329.932	1.120	1.489
54	50	51	35	0.0001	200	250	0.17	0.05	330.655	330.510	329.530	329.390	1.125	1.120
55	51	52	34	0.0002	200	250	0.21	0.07	330.510	330.597	329.390	329.254	1.120	1.343
56	52	53	30	0.0621	300	200	1.09	0.73	330.597	330.885	329.254	329.104	1.343	1.781
57	53	54	35	0.0622	300	200	1.09	0.73	330.885	330.898	329.104	328.929	1.781	1.969
69	64	63	30	0.0001	200	250	0.17	0.05	332.064	332.365	330.944	330.824	1.120	1.541
83	69	68	30	0.0001	200	200	0.18	0.05	330.880	330.736	329.760	329.610	1.120	1.126
80	70	67	30	0.0001	200	250	0.17	0.05	331.147	331.166	330.027	329.907	1.120	1.259
77	71	66	30	0.0001	200	250	0.17	0.05	331.407	331.540	330.287	330.167	1.120	1.373
74	72	65	30	0.0001	200	250	0.17	0.05	331.958	331.882	330.838	330.718	1.120	1.164
107	87	88	30	0.0001	200	250	0.16	0.05	331.166	331.341	330.046	329.926	1.120	1.415
102	88	83	33	0.0002	200	250	0.20	0.07	331.341	332.775	329.926	329.794	1.415	2.981
117	97	96	16	0.0002	200	250	0.21	0.07	330.735	331.144	329.615	329.551	1.120	1.593

Table 5.6 (continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
120	98	99	30	0.0001	200	250	0.16	0.05	330.804	330.897	329.684	329.564	1.120	1.333
127	99	104	34	0.0002	200	250	0.21	0.07	330.897	330.725	329.564	329.428	1.333	1.297
122	100	101	30	0.0001	200	250	0.16	0.05	330.532	330.592	329.412	329.292	1.120	1.300
123	101	102	26	0.0002	200	250	0.20	0.06	330.592	330.550	329.292	329.188	1.300	1.362
126	104	103	30	0.0003	200	250	0.24	0.08	330.725	330.620	329.428	329.308	1.297	1.312
23	22	21	30	0.0002	200	250	0.21	0.07	330.975	331.134	329.553	329.433	1.422	1.701
36	36	35	27	0.0002	200	250	0.21	0.07	330.003	330.163	328.883	328.775	1.120	1.388
51	48	47	35	0.0002	200	250	0.21	0.07	331.421	331.624	329.932	329.792	1.489	1.832
71	63	79	30	0.0004	200	250	0.26	0.09	332.365	332.075	330.824	330.704	1.541	1.371
75	65	84	30	0.0004	200	250	0.26	0.09	331.882	332.096	330.718	330.598	1.164	1.498
78	66	89	30	0.0004	200	250	0.26	0.10	331.540	331.617	330.167	330.047	1.373	1.570
97	79	80	30	0.0005	200	250	0.27	0.10	332.075	331.556	330.556	330.436	1.519	1.120
98	80	81	17	0.0005	200	250	0.28	0.11	331.556	331.634	330.436	330.368	1.120	1.266
99	81	82	35	0.0007	200	250	0.31	0.13	331.634	331.721	330.368	330.228	1.266	1.493
101	82	83	30	0.0008	200	250	0.32	0.14	331.721	332.775	330.228	330.108	1.493	2.667
95	83	77	35	0.0011	200	250	0.36	0.16	332.775	332.503	329.794	329.654	2.981	2.849
103	84	85	30	0.0005	200	250	0.27	0.11	332.096	331.250	330.250	330.130	1.846	1.120
104	85	86	17	0.0005	200	250	0.28	0.11	331.250	331.300	330.130	330.062	1.120	1.238
106	86	91	35	0.0007	200	80	0.46	0.10	331.300	330.717	330.035	329.597	1.266	1.120
109	89	90	30	0.0005	200	80	0.40	0.08	331.617	330.972	330.047	329.672	1.570	1.300
110	90	91	18	0.0005	200	250	0.28	0.11	330.972	330.717	329.669	329.597	1.303	1.120
111	91	92	35	0.0015	200	70	0.60	0.13	330.717	330.721	329.597	329.097	1.120	1.624
113	92	93	30	0.0016	200	70	0.62	0.14	330.721	330.882	329.097	328.669	1.624	2.214

Table 5.6 (continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
114	93	94	30	0.0017	200	70	0.63	0.14	330.882	331.159	328.669	328.240	2.214	2.919
115	94	21	29	0.0018	200	80	0.61	0.15	331.159	331.134	328.240	327.877	2.919	3.257
116	96	95	30	0.0003	200	250	0.22	0.08	331.144	331.068	329.551	329.431	1.593	1.637
124	103	102	33	0.0004	200	250	0.26	0.09	330.620	330.550	329.308	329.176	1.312	1.374
22	21	20	12	0.0020	200	80	0.64	0.16	331.134	331.178	327.877	327.727	3.257	3.451
37	35	34	30	0.0007	200	250	0.31	0.13	330.163	330.294	327.981	327.861	2.182	2.433
50	47	46	27	0.0003	200	250	0.24	0.09	331.624	331.726	329.792	329.684	1.832	2.042
81	95	67	30	0.0003	200	250	0.25	0.09	331.068	331.166	329.431	329.311	1.637	1.855
125	102	57	29	0.0007	200	250	0.31	0.13	330.550	330.467	329.176	329.060	1.374	1.407
4	20	4	30	0.0021	200	80	0.64	0.16	331.178	331.205	327.727	327.352	3.451	3.853
38	34	30	18	0.0008	200	250	0.32	0.13	330.294	330.077	327.861	327.789	2.433	2.288
49	46	45	10	0.0011	200	250	0.36	0.16	331.726	331.775	329.684	329.644	2.042	2.131
79	67	68	34	0.0007	200	250	0.31	0.13	331.166	330.736	329.311	329.175	1.855	1.561
82	68	54	24	0.0011	200	250	0.35	0.16	330.736	330.898	329.175	329.079	1.561	1.819
68	45	62	36	0.0063	200	200	0.64	0.37	331.775	332.352	329.644	329.464	2.131	2.888
58	54	55	30	0.0634	300	200	1.10	0.75	330.898	330.637	328.929	328.779	1.969	1.858
59	55	56	30	0.0635	300	200	1.10	0.75	330.637	330.600	328.779	328.629	1.858	1.971
60	56	57	15	0.0635	300	200	1.10	0.75	330.600	330.467	328.629	328.554	1.971	1.913
61	57	58	30	0.0643	300	200	1.10	0.76	330.467	330.196	328.554	328.404	1.913	1.792
62	58	59	30	0.0644	300	200	1.10	0.76	330.196	330.511	328.404	328.254	1.792	2.257
63	59	60	30	0.0645	300	200	1.10	0.76	330.511	330.659	328.254	328.104	2.257	2.555
64	60	24	34	0.0646	300	200	1.10	0.76	330.659	330.704	328.104	327.934	2.555	2.770
65	62	61	30	0.0064	200	200	0.64	0.37	332.352	332.214	329.464	329.314	2.888	2.900

Table 5.6 (continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
26	24	25	30	0.0647	300	200	1.10	0.76	330.704	330.714	327.934	327.784	2.770	2.930
27	25	26	30	0.0648	300	200	1.10	0.76	330.714	330.500	327.784	327.634	2.930	2.866
28	26	27	32	0.0649	300	200	1.10	0.76	330.500	329.840	327.634	327.474	2.866	2.366
29	27	28	32	0.0652	300	200	1.10	0.76	329.840	329.253	327.474	327.314	2.366	1.939
30	28	29	30	0.0654	300	200	1.10	0.77	329.253	329.354	327.314	327.164	1.939	2.190
31	29	30	25	0.0655	300	200	1.10	0.77	329.354	330.077	327.164	327.039	2.190	3.038
32	30	31	30	0.0663	300	200	1.10	0.78	330.077	330.086	327.039	326.889	3.038	3.197
33	31	32	30	0.0664	350	250	1.04	0.63	330.086	329.513	326.889	326.769	3.197	2.744
34	32	33	30	0.0665	350	250	1.04	0.63	329.513	328.669	326.769	326.649	2.744	2.020
35	33	17	20	0.0666	350	250	1.04	0.63	328.669	328.457	326.649	326.569	2.020	1.888
67	61	73	30	0.0067	200	200	0.65	0.38	332.214	332.134	329.314	329.164	2.900	2.970
89	73	74	30	0.0068	200	200	0.65	0.38	332.134	332.064	329.164	329.014	2.970	3.050
90	74	75	17	0.0068	200	250	0.60	0.41	332.064	331.325	329.014	328.946	3.050	2.379
91	75	76	35	0.0077	200	250	0.62	0.43	331.325	331.625	328.946	328.806	2.379	2.819
93	76	77	30	0.0078	200	250	0.62	0.43	331.625	332.503	328.806	328.686	2.819	3.817
94	77	78	30	0.0091	200	250	0.65	0.47	332.503	332.870	328.686	328.566	3.817	4.304
96	78	2	28	0.0092	200	250	0.65	0.47	332.870	331.608	328.566	328.454	4.304	3.154
1	2	3	30	0.0153	200	250	0.72	0.63	331.608	331.670	328.454	328.334	3.154	3.336
2	3	4	30	0.0154	200	250	0.72	0.64	331.670	331.205	328.334	328.214	3.336	2.991
3	4	5	30	0.0176	200	250	0.74	0.70	331.205	330.812	327.352	327.232	3.853	3.580
5	5	6	30	0.0177	200	250	0.74	0.70	330.812	330.705	327.232	327.112	3.580	3.593
6	6	7	30	0.0178	200	250	0.74	0.70	330.705	330.036	327.112	326.992	3.593	3.044
7	7	105	30	0.0179	200	250	0.74	0.71	330.036	330.004	326.992	326.872	3.044	3.132

Table 5.6 (continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
128	105	8	7	0.0179	200	250	0.74	0.71	330.004	330.003	326.872	326.844	3.132	3.159
8	8	9	28	0.0192	200	250	0.75	0.74	330.003	330.327	326.844	326.732	3.159	3.595
10	9	10	28	0.0193	200	250	0.75	0.75	330.327	329.563	326.732	326.620	3.595	2.943
11	10	11	30	0.0195	200	250	0.75	0.75	329.563	329.605	326.620	326.500	2.943	3.105
13	11	12	22	0.0195	200	250	0.75	0.76	329.605	328.796	326.500	326.412	3.105	2.384
14	12	13	30	0.0266	250	250	0.83	0.62	328.796	328.370	326.412	326.292	2.384	2.078
15	13	14	21	0.0266	250	250	0.83	0.62	328.370	328.125	326.292	326.208	2.078	1.917
16	14	15	30	0.0267	250	250	0.83	0.62	328.125	327.825	326.208	326.088	1.917	1.737
17	15	16	30	0.0268	250	250	0.83	0.62	327.825	328.007	326.088	325.968	1.737	2.039
18	16	17	28	0.0269	250	250	0.83	0.62	328.007	328.457	325.968	325.856	2.039	2.601
19	17	18	30	0.0936	400	350	0.99	0.69	328.457	328.991	325.856	325.771	2.601	3.220
20	18	19	30	0.0936	400	350	0.99	0.69	328.991	329.216	325.771	325.685	3.220	3.531
21	19	1	26	0.0937	400	350	0.99	0.69	329.216	329.345	325.685	325.611	3.531	3.734

5.3 Result of Case study III

The results of Network 4 (Nawalgarh) were obtained using swarm size of 1000. The maximum numbers of iterations were kept as 30, 60 & 90 for each sewer layout. Table 5.7 shows the variation in total optimal cost with total cumulative discharges of the layout.

Table 5.7 Total Cumulative Discharge vs. Total Optimal Cost at Different Iterations for network 4

S. No.	Total cumulative discharge (l/s)	Total cost (Rs.)					
		30 Iterations		60 Iterations		90 Iterations	
		Modified PSO	Standard PSO	Modified PSO	Standard PSO	Modified PSO	Standard PSO
1	782.305	8832960	8956858	8826437	8956858	8825648	8956858
2	783.575	8866182	9325498	8866486	9325498	8865631	9325498
3	784.52	9267493	9369972	9281602	9369499	9238069	9369499
4	785.62	9493587	10656747	9464435	10656747	9464435	10656747
5	792.04	9946074	9956157	9941329	9956157	9943422	9956157
6	796.27	10234896	11217101	10160188	11217101	10162921	11217101
7	808.39	10769615	10998840	10766192	10998840	10780661	10998840

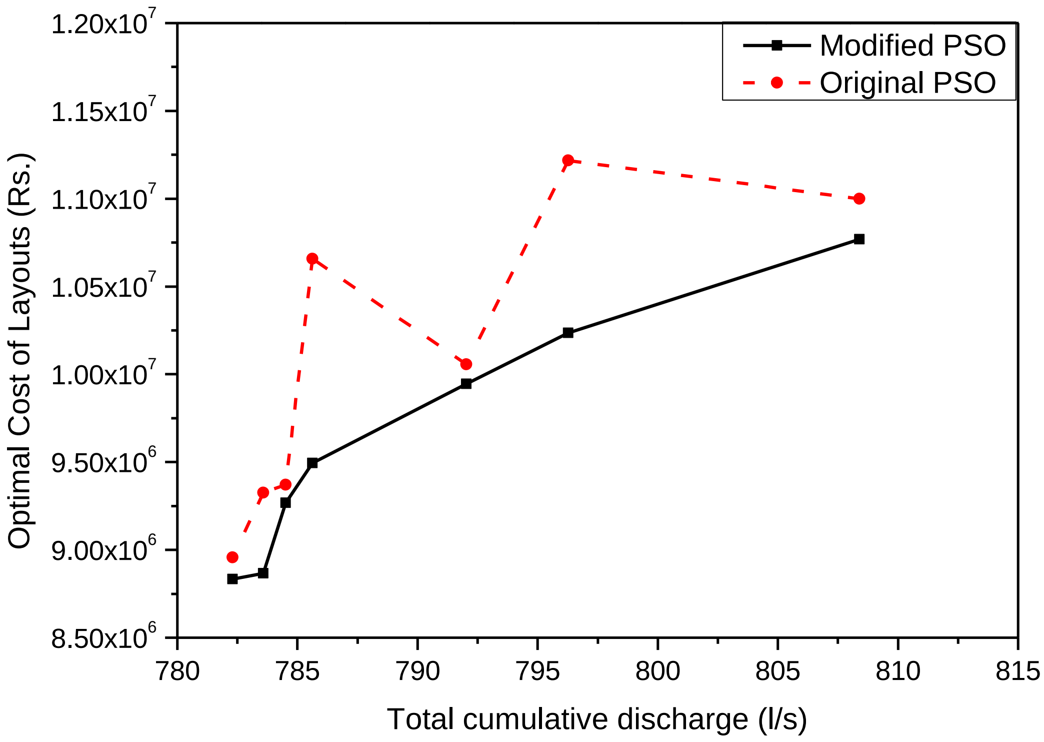


Figure 5.31 Total cumulative discharges vs. Optimal cost of layouts at 30 iterations for Network 4

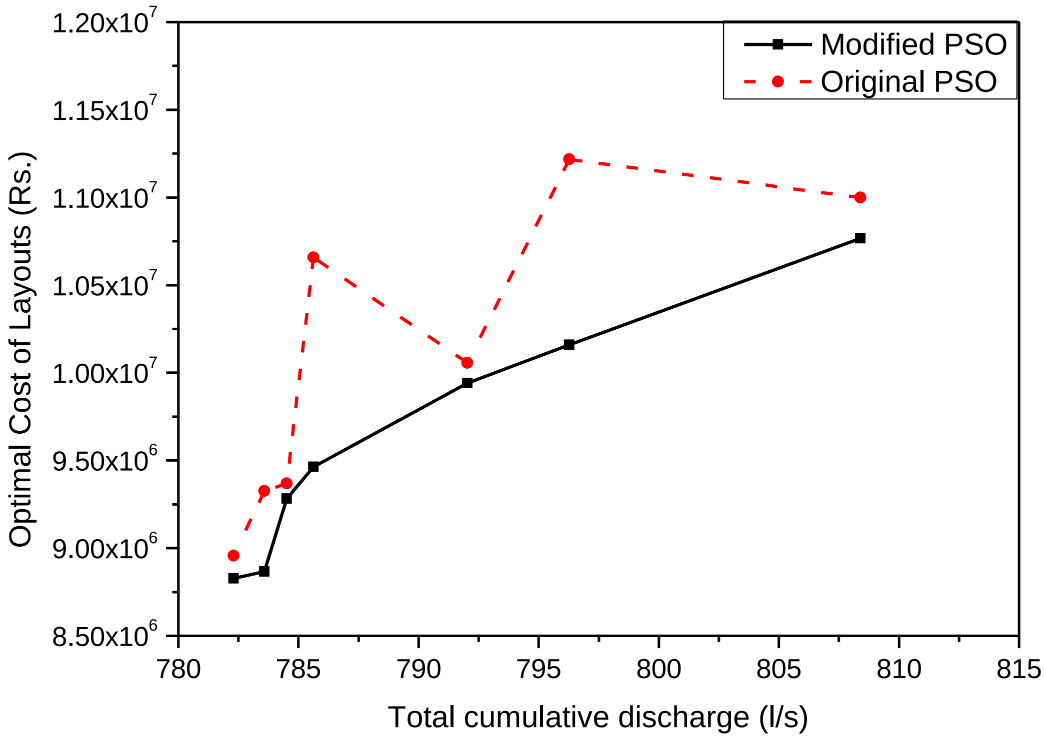


Figure 5.32 Total cumulative discharges vs. Optimal cost of layouts at 60 iterations for Network 4

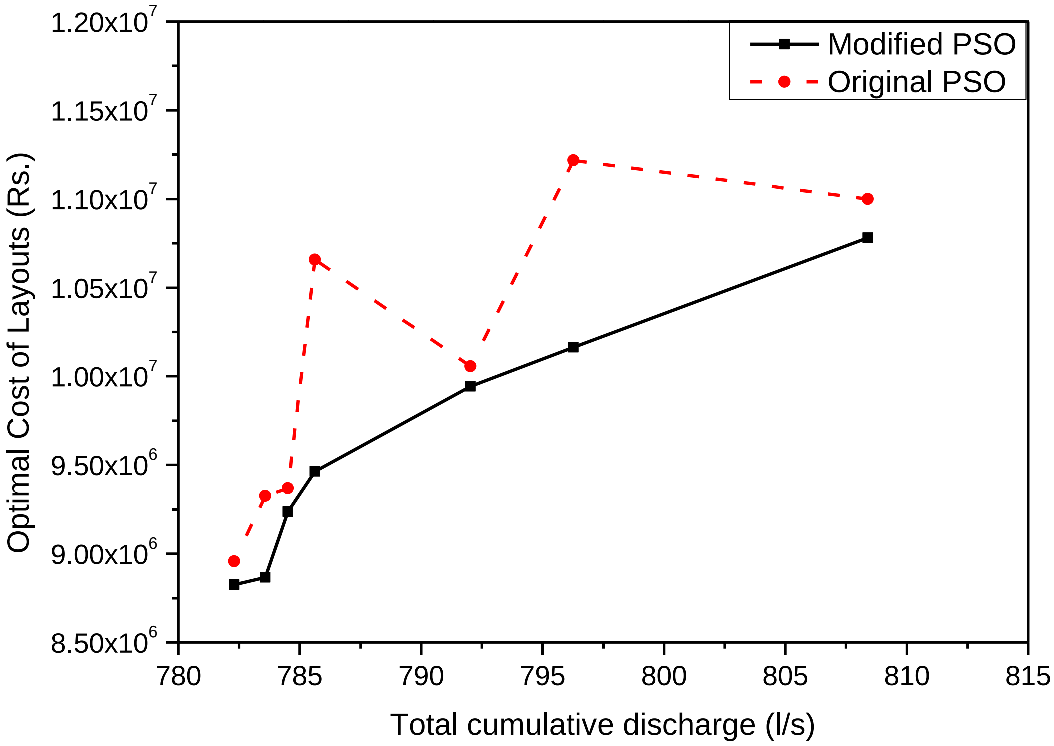


Figure 5.33 Total cumulative discharges vs. Optimal cost of layouts at 90 iterations for Network 4

Table 5.8 Sewer Layout Cost Details for Network 4

S No.	Total cumulative discharge (l/s)	Cost of Earthwork (Rs.)	Cost of Manholes (Rs.)	Cost of Sewer Pipe (Rs.)	Total Cost (Rs.)
1	782.305	1225650	5325908	2274090	8825648
2	783.575	1231240	5349231	2285160	8865631
3	784.52	1315660	5659979	2262430	9238069
4	785.62	1365810	5813465	2285160	9464435
5	792.04	1561290	6119702	2262430	9943422
6	796.27	1604500	6265781	2292640	10162921
7	808.39	1758780	6747171	2274710	10780661

Table 5.7 clearly shows that the layout having minimum *CQ* has the minimum total cost. The total cost of sewer layout is generally increasing with the *CQ* of a layout. The cost of optimal layout (*CQ* = 782.305 l/s) is Rs. 8.825 × 10^6 with modified PSO as compared to the cost of original PSO Rs. 8.956 × 10^6 for 90 iterations.

Figures 5.31, 5.32 and 5.33 show the optimal cost obtained by the modified and original PSO algorithm against the total cumulative discharges of the layouts for 30, 60 and 90 iterations, respectively. It is clearly seen that the proposed modified PSO algorithm was able to obtain a better solution as compared to an original PSO algorithm in all the layouts.

Table 5.8 shows the sewer component costs (cost of earthwork, manhole and sewer) against the total cost of layouts.

The Optimal Sewer Layout and an alternative layout of a Base Network 4 are shown in Figures 5.34 and 5.35 respectively.

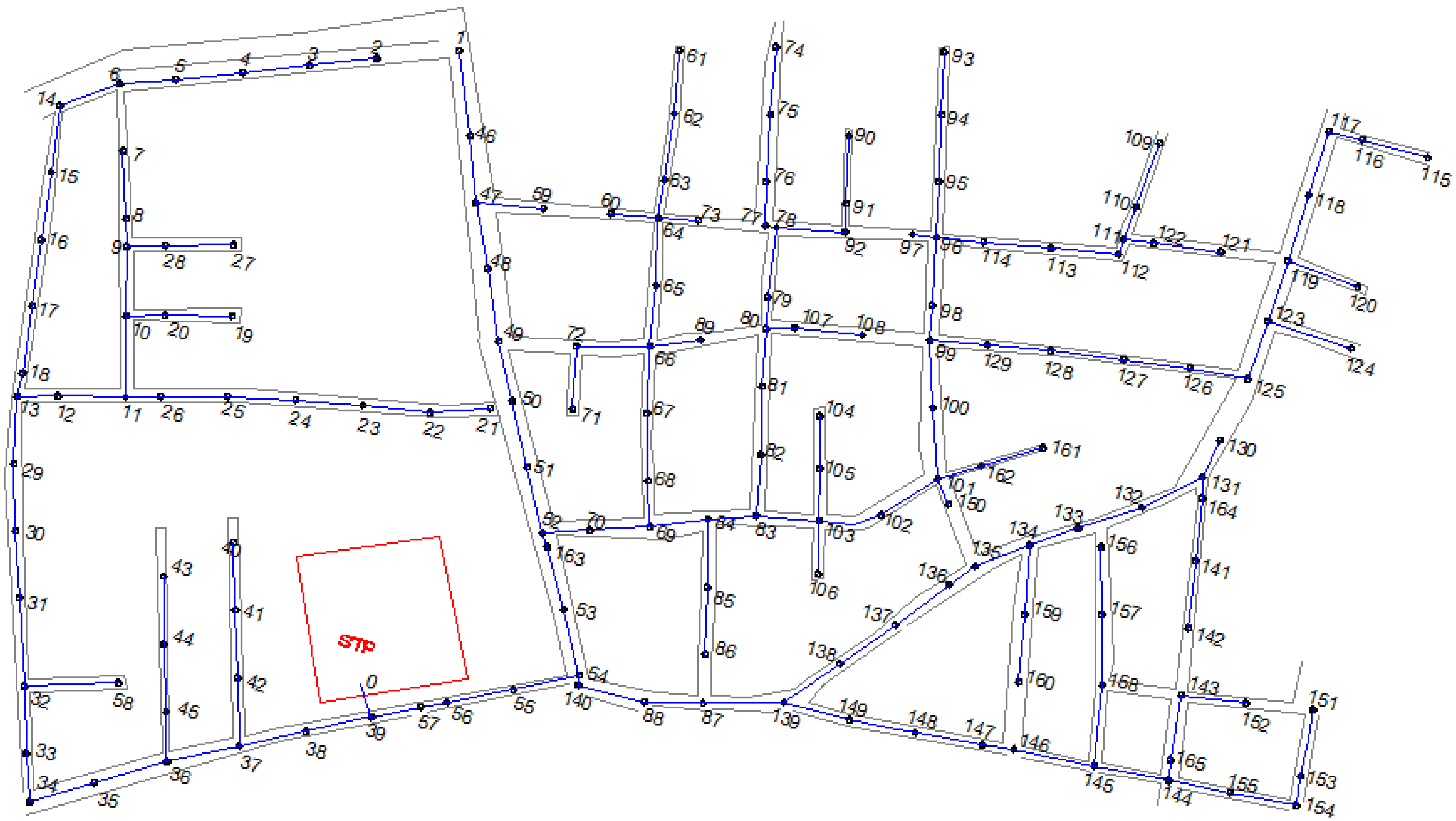


Figure 5.34 Optimal sewer layout of Network 4, CQ = 782.305 l/s

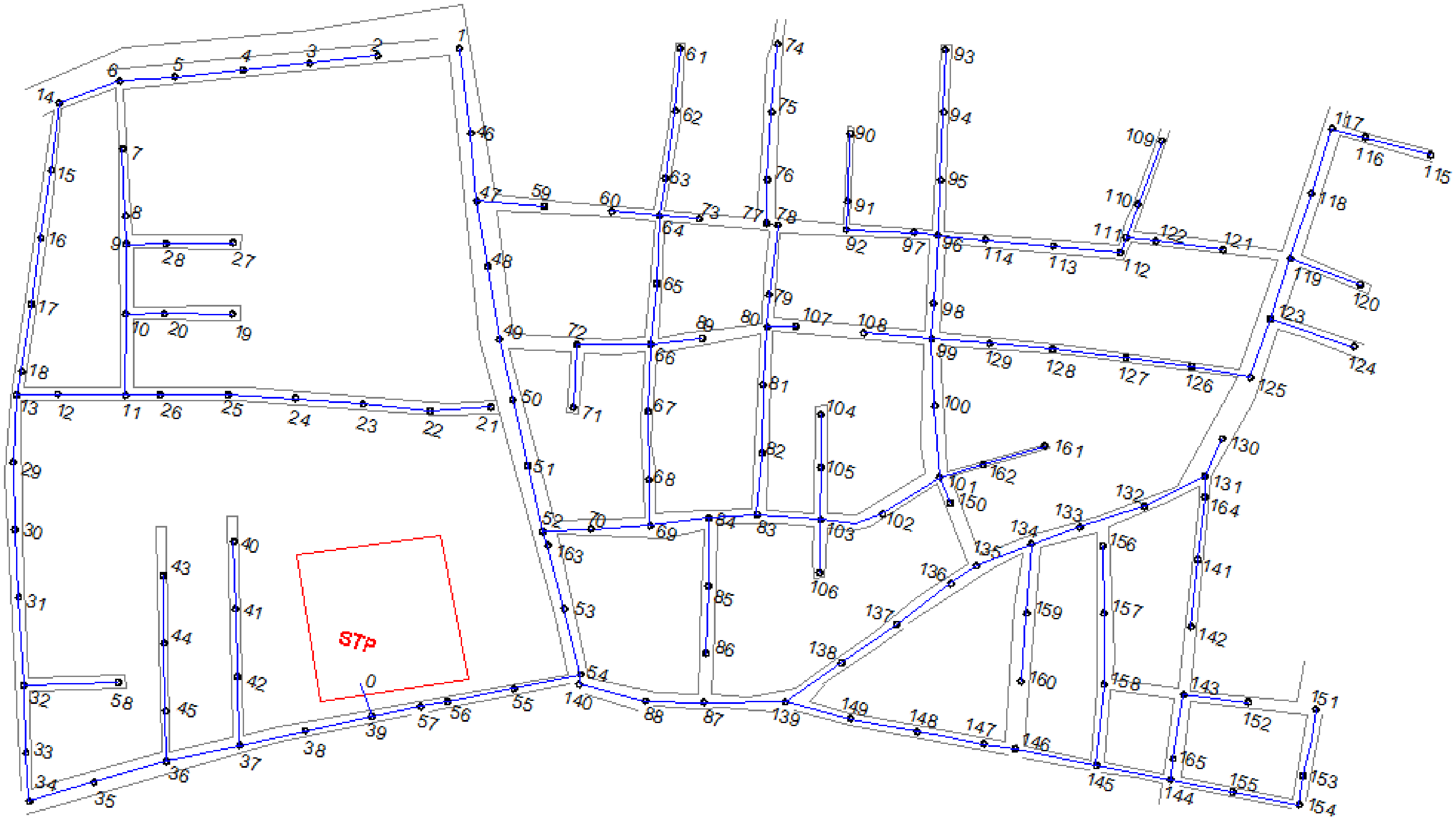


Figure 5.35 Alternative layout 1 of Network 4, CQ = 783.575 l/s

Optimal sewer layout of Base Network 4 as shown in Figure 5.34 is selected for the detailed design. This layout is solved using different swarm sizes of 200, 400, 600, 800, 1000 and 1200 to assess the effect of the swarm size on the performance of the proposed modified and original PSO algorithm.

Figures 5.36, 5.37, 5.38 and 5.39 show the minimum total cost obtained by the modified and original PSO algorithm against the swarm sizes for different iterations. The minimum cost obtained by the Original PSO in 90 iterations for 1000 swarm size is Rs. 8.956×10^6, whereas the solution cost obtained by the Modified PSO is reduced to Rs. 8.825×10^6.

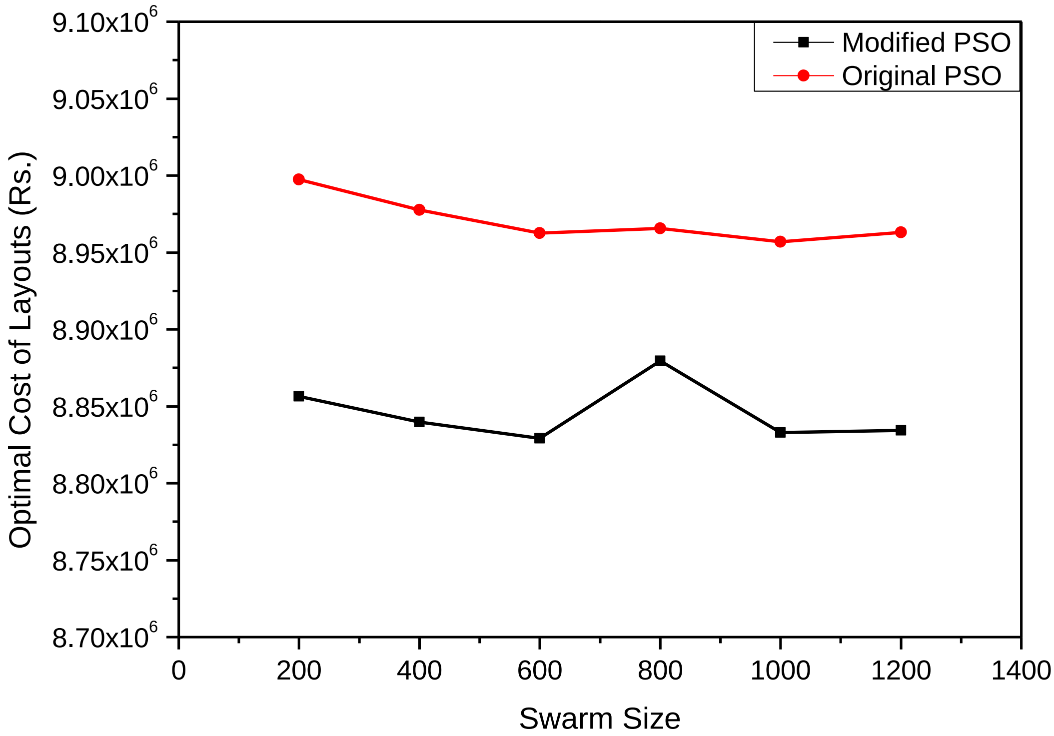


Figure 5.36 Variation of the optimal cost with swarm sizes (at 30 iterations) for Network 4

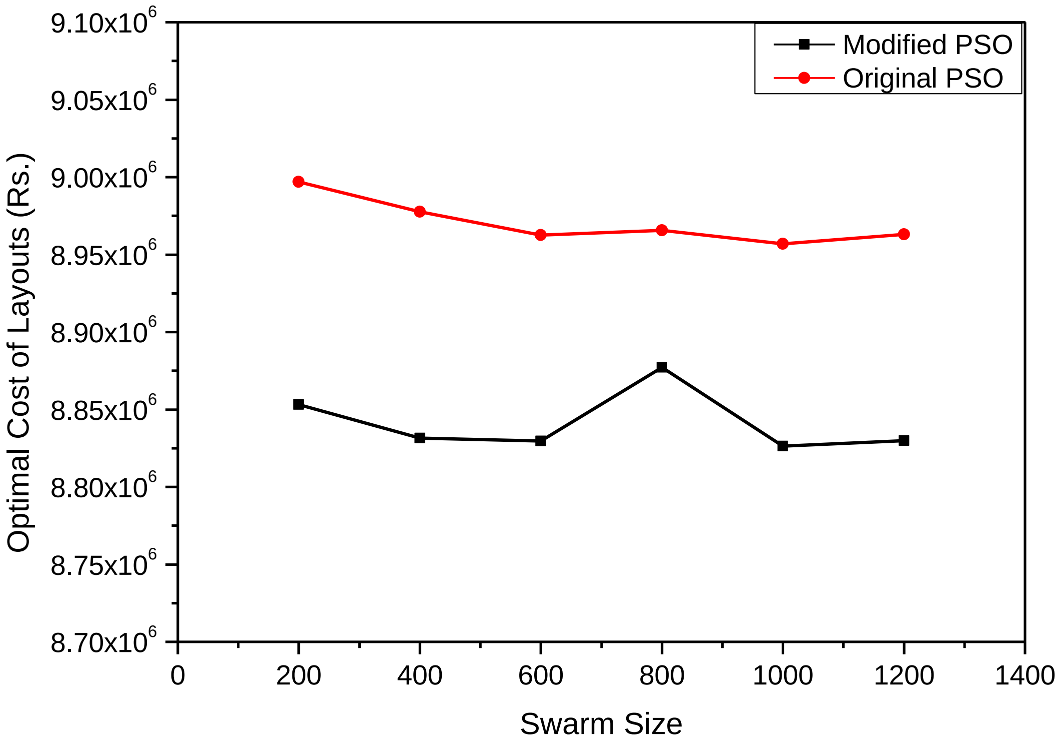


Figure 5.37 Variation of the optimal cost with swarm sizes (at 60 iterations) for Network 4

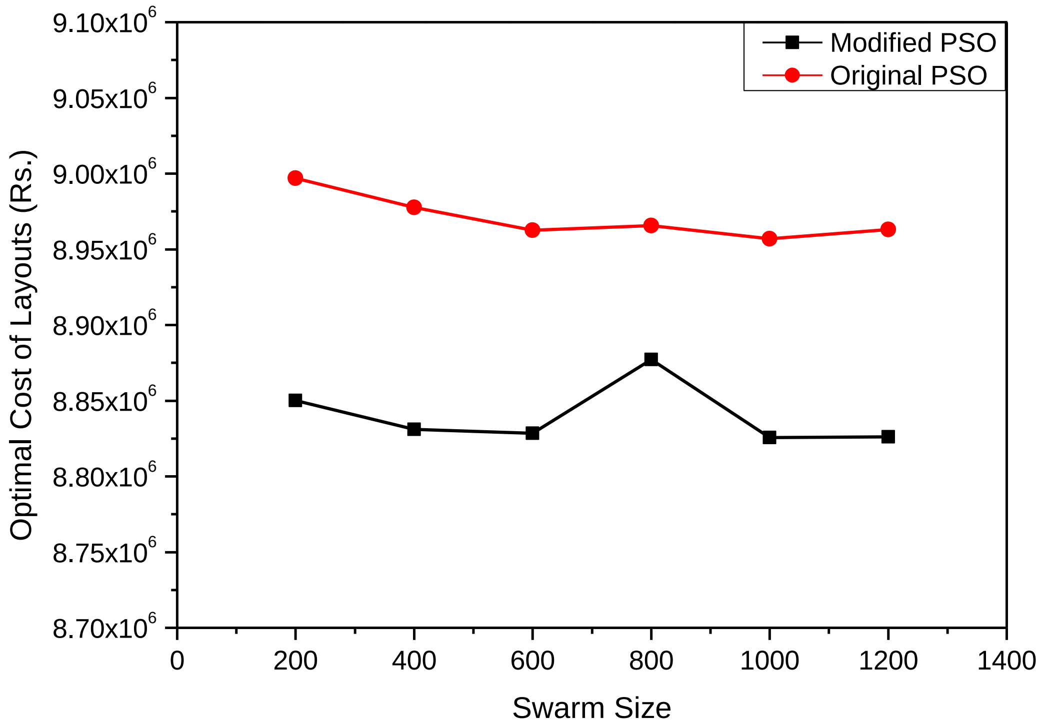


Figure 5.38 Variation of the optimal cost with swarm sizes (at 90 iterations) for Network 4

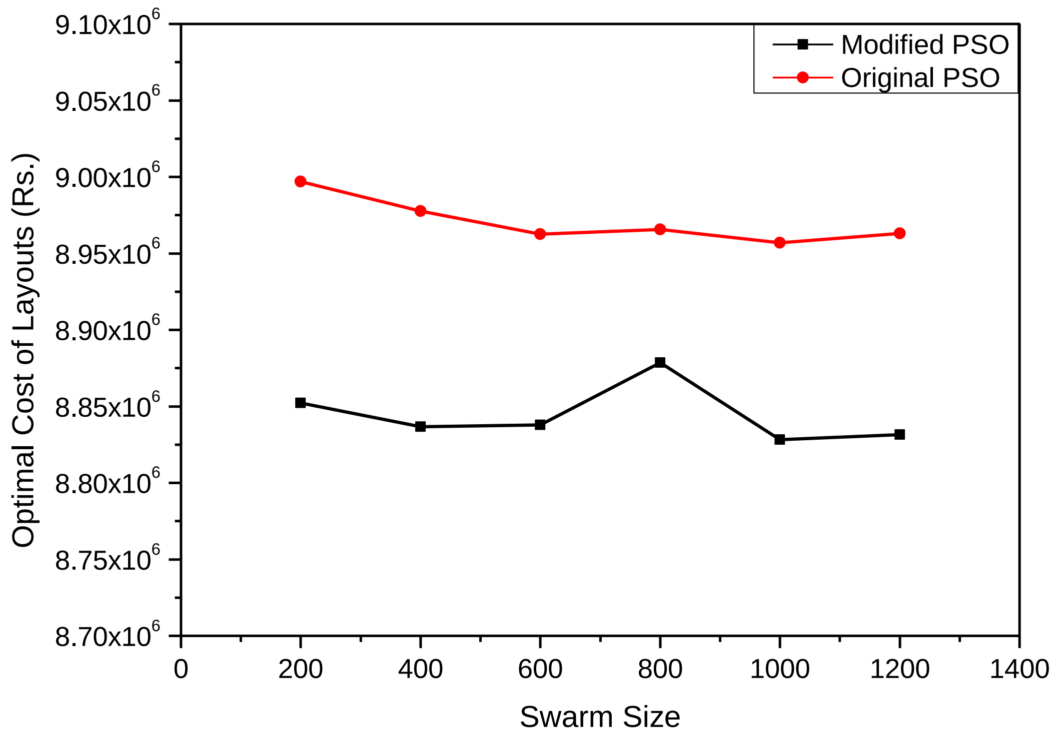


Figure 5.39 Variation of the optimal cost with swarm sizes (at 120 iterations) for Network 4

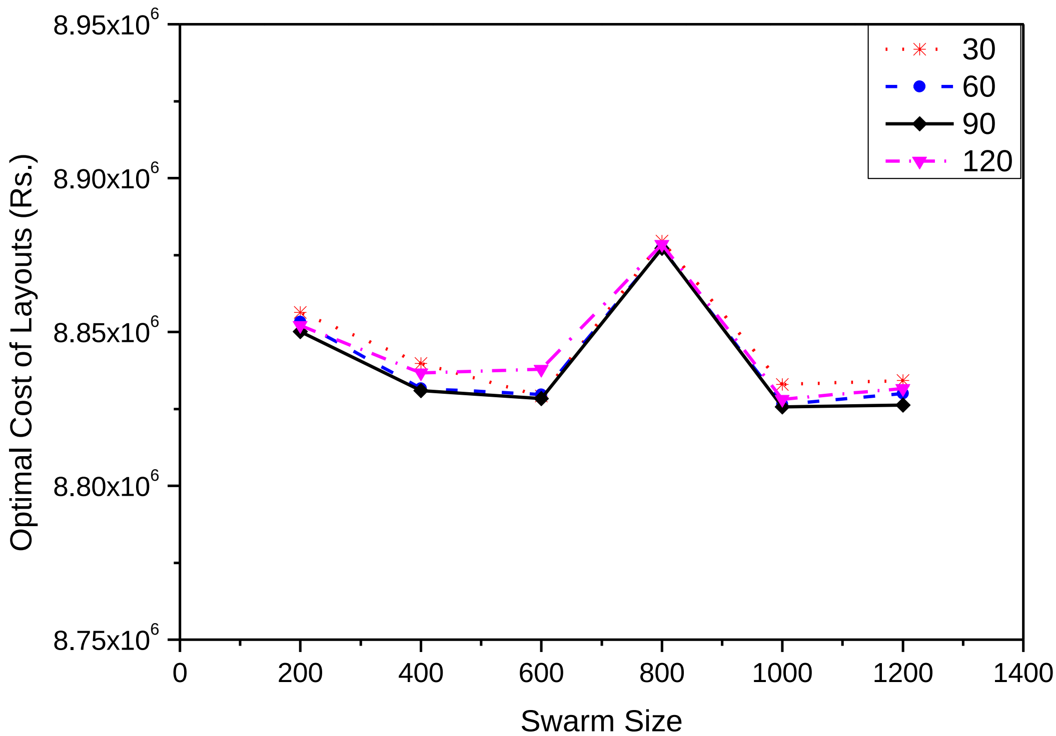


Figure 5.40 Variation of the minimum total cost with swarm sizes at different iterations, modified PSO for Network 4

It is seen that the solution obtained by the modified PSO algorithm is much better than the solution of the original PSO algorithm. Figure 5.40 shows the optimal cost obtained with modified particle swarm optimization; the best solution produced when the swarm size is 1000. Table 5.9 presents the details of the optimal design of sewer component sizing of an optimal layout (Figure 5.34) with 1000 swarm size and 90 iterations.

Table 5.9 Characteristics of the Optimal Sewer Network Obtained by the Modified PSO for Network 4

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
2	1	46	35	0.0004	200	250	0.25	0.09	424.400	424.300	423.280	423.140	1.120	1.160
3	2	3	30	0.0002	200	250	0.19	0.06	424.393	424.105	423.105	422.985	1.288	1.120
4	3	4	30	0.0003	200	250	0.24	0.08	424.105	423.900	422.900	422.780	1.205	1.120
5	4	5	30	0.0005	200	250	0.27	0.10	423.900	423.250	422.250	422.130	1.650	1.120
6	5	6	30	0.0006	200	250	0.30	0.12	423.250	423.115	422.115	421.995	1.135	1.120
8	6	14	29	0.0009	200	250	0.34	0.15	423.115	423.321	421.995	421.879	1.120	1.442
9	7	8	30	0.0002	200	250	0.19	0.06	423.100	423.005	421.980	421.860	1.120	1.145
10	8	9	13	0.0002	200	250	0.21	0.07	423.005	422.951	421.860	421.808	1.145	1.143
16	14	15	30	0.0011	200	250	0.35	0.16	423.321	422.968	421.879	421.759	1.442	1.209
17	15	16	30	0.0012	200	250	0.37	0.17	422.968	422.598	421.598	421.478	1.370	1.120
18	16	17	30	0.0014	200	80	0.56	0.13	422.598	422.263	421.478	421.103	1.120	1.160
19	17	18	30	0.0015	200	70	0.61	0.14	422.263	422.100	421.103	420.674	1.160	1.426
20	18	13	11	0.0016	200	70	0.62	0.14	422.100	422.083	420.674	420.517	1.426	1.566
21	19	20	30	0.0002	200	250	0.19	0.06	422.967	422.725	421.725	421.605	1.242	1.120
22	20	10	17	0.0002	200	250	0.22	0.07	422.725	422.617	421.565	421.497	1.160	1.120
23	21	22	30	0.0002	200	250	0.19	0.06	424.423	423.915	422.915	422.795	1.508	1.120
24	22	23	30	0.0003	200	60	0.39	0.06	423.915	423.500	422.795	422.295	1.120	1.205
25	23	24	30	0.0005	200	250	0.27	0.10	423.500	422.995	421.995	421.875	1.505	1.120
26	24	25	30	0.0006	200	250	0.30	0.12	422.995	422.760	421.760	421.640	1.235	1.120
27	25	26	30	0.0008	200	70	0.49	0.10	422.760	422.370	421.640	421.212	1.120	1.159
28	26	11	15	0.0008	200	250	0.33	0.14	422.370	422.238	421.178	421.118	1.192	1.120
29	27	28	30	0.0002	200	250	0.19	0.06	423.351	423.125	422.125	422.005	1.226	1.120
30	28	9	17	0.0002	200	60	0.36	0.05	423.125	422.951	422.005	421.722	1.120	1.229

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
42	40	41	30	0.0002	200	250	0.19	0.06	421.749	421.625	420.625	420.505	1.124	1.120
43	41	42	30	0.0003	200	250	0.24	0.08	421.625	421.568	420.505	420.385	1.120	1.183
44	42	37	30	0.0005	200	250	0.27	0.10	421.568	421.618	420.385	420.265	1.183	1.353
45	43	44	30	0.0002	200	250	0.19	0.06	421.295	421.805	420.175	420.055	1.120	1.750
46	44	45	30	0.0003	200	250	0.24	0.08	421.805	421.778	420.055	419.935	1.750	1.843
47	45	36	22	0.0004	200	250	0.26	0.10	421.778	421.757	419.935	419.847	1.843	1.910
48	46	47	30	0.0005	200	250	0.28	0.11	424.300	423.980	422.980	422.860	1.320	1.120
62	58	32	44	0.0002	200	250	0.22	0.07	421.308	421.233	420.188	420.012	1.120	1.221
50	59	47	30	0.0002	200	60	0.31	0.04	425.502	423.980	423.360	422.860	2.142	1.120
64	60	64	21	0.0001	200	60	0.27	0.03	424.922	424.206	423.436	423.086	1.486	1.120
65	61	62	30	0.0002	200	250	0.19	0.06	425.536	424.920	423.920	423.800	1.616	1.120
66	62	63	30	0.0003	200	60	0.39	0.06	424.920	424.567	423.800	423.300	1.120	1.267
67	63	64	17	0.0004	200	250	0.26	0.09	424.567	424.206	423.154	423.086	1.413	1.120
78	71	72	30	0.0002	200	250	0.19	0.06	423.355	423.198	422.198	422.078	1.157	1.120
79	72	66	33	0.0003	200	250	0.24	0.09	423.198	423.004	422.016	421.884	1.182	1.120
69	73	64	18	0.0002	200	250	0.19	0.06	424.060	424.206	422.940	422.868	1.120	1.338
81	74	75	30	0.0002	200	250	0.19	0.06	423.625	423.325	422.325	422.205	1.300	1.120
82	75	76	30	0.0003	200	60	0.39	0.06	423.325	423.055	422.205	421.705	1.120	1.350
83	76	77	20	0.0004	200	250	0.26	0.10	423.055	422.841	421.705	421.625	1.350	1.216
84	77	78	5	0.0004	200	250	0.27	0.10	422.841	422.841	421.625	421.605	1.216	1.236
94	86	85	30	0.0001	200	250	0.17	0.05	422.005	421.998	420.885	420.765	1.120	1.233
72	89	66	23	0.0002	200	250	0.19	0.06	422.670	423.004	421.550	421.458	1.120	1.546
99	90	91	30	0.0002	200	60	0.31	0.04	423.614	422.930	422.310	421.810	1.304	1.120

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
100	91	92	13	0.0002	200	250	0.21	0.07	422.930	422.549	421.481	421.429	1.449	1.120
86	92	78	30	0.0004	200	250	0.25	0.09	422.549	422.841	421.429	421.309	1.120	1.532
102	93	94	30	0.0002	200	60	0.31	0.04	424.013	423.500	422.880	422.380	1.133	1.120
103	94	95	30	0.0003	200	150	0.28	0.07	423.500	422.870	421.950	421.750	1.550	1.120
104	95	96	25	0.0004	200	250	0.27	0.10	422.870	422.223	421.203	421.103	1.667	1.120
106	97	96	11	0.0001	200	250	0.14	0.04	422.442	422.223	421.147	421.103	1.295	1.120
114	104	105	30	0.0002	200	250	0.19	0.06	422.532	421.995	420.995	420.875	1.537	1.120
115	105	103	20	0.0003	200	250	0.22	0.08	421.995	421.449	420.409	420.329	1.586	1.120
116	106	103	26	0.0001	200	250	0.18	0.05	421.515	421.449	420.395	420.291	1.120	1.158
117	108	107	30	0.0002	200	250	0.19	0.06	422.390	422.316	421.270	421.150	1.120	1.166
119	109	110	30	0.0002	200	250	0.19	0.06	422.999	422.832	421.832	421.712	1.167	1.120
120	110	111	16	0.0002	200	250	0.22	0.07	422.832	422.670	421.614	421.550	1.218	1.120
125	115	116	30	0.0002	200	250	0.19	0.06	424.420	423.954	422.954	422.834	1.466	1.120
126	116	117	15	0.0002	200	250	0.22	0.07	423.954	423.572	422.512	422.452	1.442	1.120
127	117	118	30	0.0038	200	150	0.62	0.26	423.572	423.452	422.452	422.252	1.120	1.200
128	118	119	30	0.0040	200	150	0.62	0.27	423.452	423.398	422.252	422.052	1.200	1.346
131	120	119	37	0.0002	200	250	0.20	0.07	423.599	423.398	422.426	422.278	1.173	1.120
132	121	122	30	0.0002	200	250	0.19	0.06	422.985	422.820	421.820	421.700	1.165	1.120
133	122	111	13	0.0002	200	250	0.21	0.07	422.820	422.670	421.602	421.550	1.218	1.120
135	124	123	39	0.0029	200	60	0.78	0.18	423.757	423.388	422.637	421.987	1.120	1.401
142	130	131	18	0.0001	200	250	0.16	0.05	423.310	423.249	422.190	422.118	1.120	1.131
155	142	141	30	0.0002	200	250	0.19	0.06	423.750	423.703	422.630	422.510	1.120	1.193
111	150	101	12	0.0002	200	250	0.19	0.06	421.640	421.456	420.384	420.336	1.256	1.120

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
167	151	153	30	0.0003	200	100	0.32	0.07	423.519	423.150	422.330	422.030	1.189	1.120
168	152	143	19	0.0001	200	250	0.16	0.05	423.615	423.812	422.495	422.419	1.120	1.393
169	153	154	13	0.0004	200	250	0.25	0.09	423.150	423.100	422.030	421.978	1.120	1.122
170	154	155	30	0.0044	200	150	0.64	0.28	423.100	423.190	421.978	421.778	1.122	1.412
171	155	144	28	0.0046	200	150	0.65	0.29	423.190	423.228	421.778	421.591	1.412	1.637
172	156	157	30	0.0002	200	250	0.19	0.06	423.370	423.310	422.250	422.130	1.120	1.180
173	157	158	31	0.0003	200	250	0.24	0.08	423.310	423.278	422.130	422.006	1.180	1.272
174	158	145	35	0.0005	200	200	0.30	0.10	423.278	423.172	422.006	421.831	1.272	1.341
175	160	159	30	0.0002	200	250	0.19	0.06	422.610	422.530	421.490	421.370	1.120	1.160
177	161	162	30	0.0002	200	250	0.19	0.06	421.710	421.670	420.590	420.470	1.120	1.200
178	162	101	20	0.0003	200	250	0.22	0.08	421.670	421.456	420.416	420.336	1.254	1.120
11	9	10	30	0.0006	200	250	0.30	0.12	422.951	422.617	421.617	421.497	1.334	1.120
12	10	11	30	0.0010	200	250	0.35	0.15	422.617	422.238	421.238	421.118	1.379	1.120
13	11	12	30	0.0020	200	80	0.63	0.16	422.238	422.150	421.118	420.743	1.120	1.407
14	12	13	18	0.0021	200	80	0.64	0.17	422.150	422.083	420.743	420.518	1.407	1.565
15	13	29	30	0.0038	200	150	0.62	0.26	422.083	421.825	420.517	420.317	1.566	1.508
31	29	30	30	0.0040	200	150	0.62	0.27	421.825	421.670	420.317	420.117	1.508	1.553
32	30	31	30	0.0042	200	150	0.63	0.27	421.670	421.420	420.117	419.917	1.553	1.503
33	31	32	30	0.0043	200	150	0.64	0.28	421.420	421.233	419.917	419.717	1.503	1.516
34	32	33	30	0.0047	200	150	0.65	0.29	421.233	420.980	419.717	419.517	1.516	1.463
35	33	34	21	0.0048	200	150	0.66	0.30	420.980	420.702	419.517	419.377	1.463	1.325
36	34	35	30	0.0154	200	250	0.72	0.64	420.702	421.115	419.377	419.257	1.325	1.858
37	35	36	33	0.0155	200	250	0.72	0.64	421.115	421.757	419.257	419.125	1.858	2.632

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
38	36	37	33	0.0161	200	250	0.73	0.66	421.757	421.618	419.125	418.993	2.632	2.625
39	37	38	30	0.0167	200	250	0.73	0.67	421.618	421.610	418.993	418.873	2.625	2.737
40	38	39	30	0.0169	200	250	0.74	0.68	421.610	421.610	418.873	418.753	2.737	2.857
49	47	48	30	0.0010	200	60	0.56	0.10	423.980	423.570	422.860	422.360	1.120	1.210
51	48	49	30	0.0011	200	250	0.36	0.16	423.570	423.235	422.235	422.115	1.335	1.120
52	49	50	30	0.0015	200	70	0.60	0.13	423.235	423.070	422.115	421.686	1.120	1.384
54	50	51	30	0.0016	200	70	0.62	0.14	423.070	422.740	421.686	421.258	1.384	1.482
55	51	52	30	0.0018	200	80	0.61	0.15	422.740	421.647	420.902	420.527	1.838	1.120
68	64	65	30	0.0009	200	250	0.33	0.14	424.206	423.170	422.170	422.050	2.036	1.120
70	65	66	27	0.0010	200	250	0.35	0.15	423.170	423.004	421.992	421.884	1.178	1.120
71	66	67	30	0.0018	200	80	0.61	0.15	423.004	422.189	421.444	421.069	1.560	1.120
73	67	68	30	0.0019	200	80	0.63	0.16	422.189	421.525	420.780	420.405	1.409	1.120
74	68	69	20	0.0020	200	80	0.64	0.16	421.525	421.242	420.372	420.122	1.153	1.120
85	78	79	30	0.0011	200	250	0.36	0.16	422.841	422.316	421.309	421.189	1.532	1.127
87	79	80	13	0.0012	200	250	0.36	0.16	422.316	422.316	421.189	421.137	1.127	1.179
93	85	84	30	0.0003	200	250	0.23	0.08	421.998	421.394	420.394	420.274	1.604	1.120
89	107	80	12	0.0003	200	250	0.24	0.08	422.316	422.316	421.150	421.102	1.166	1.214
121	111	112	7	0.0005	200	250	0.28	0.11	422.670	422.568	421.476	421.448	1.194	1.120
122	112	113	30	0.0006	200	250	0.30	0.12	422.568	422.425	421.425	421.305	1.143	1.120
123	113	114	30	0.0008	200	250	0.32	0.14	422.425	422.325	421.305	421.185	1.120	1.140
124	114	96	21	0.0009	200	250	0.33	0.14	422.325	422.223	421.185	421.101	1.140	1.122
130	119	123	28	0.0045	200	150	0.65	0.29	423.398	423.388	422.052	421.865	1.346	1.523
134	123	125	27	0.0075	200	250	0.62	0.43	423.388	423.278	421.865	421.757	1.523	1.521

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
136	125	126	30	0.0078	200	250	0.62	0.44	423.278	422.900	421.757	421.637	1.521	1.263
138	126	127	30	0.0080	200	250	0.62	0.44	422.900	422.670	421.637	421.517	1.263	1.153
139	127	128	30	0.0081	200	250	0.63	0.44	422.670	422.549	421.517	421.397	1.153	1.152
140	128	129	30	0.0083	200	60	1.07	0.31	422.549	422.270	421.397	420.897	1.152	1.373
141	129	99	22	0.0084	200	250	0.63	0.45	422.270	422.195	420.897	420.809	1.373	1.386
180	141	164	30	0.0003	200	250	0.24	0.08	423.703	423.249	422.249	422.129	1.454	1.120
157	143	165	30	0.0004	200	60	0.43	0.07	423.812	423.320	422.419	421.919	1.393	1.401
148	159	134	30	0.0003	200	150	0.28	0.07	422.530	422.125	421.205	421.005	1.325	1.120
144	164	131	8	0.0005	200	250	0.27	0.10	423.249	423.249	422.129	422.097	1.120	1.152
181	165	144	8	0.0005	200	250	0.27	0.10	423.320	423.228	421.919	421.887	1.401	1.341
88	80	81	29	0.0017	200	80	0.60	0.15	422.316	421.995	421.102	420.740	1.214	1.256
90	81	82	30	0.0018	200	80	0.62	0.16	421.995	421.625	420.740	420.365	1.256	1.261
91	82	83	26	0.0020	200	80	0.63	0.16	421.625	421.329	420.365	420.040	1.261	1.290
105	96	98	30	0.0015	200	70	0.61	0.14	422.223	422.295	421.101	420.672	1.122	1.623
107	98	99	16	0.0016	200	70	0.62	0.14	422.295	422.195	420.672	420.444	1.623	1.751
108	99	100	30	0.0102	200	250	0.66	0.50	422.195	421.652	420.444	420.324	1.751	1.328
109	100	101	30	0.0104	200	250	0.67	0.51	421.652	421.456	420.324	420.204	1.328	1.252
110	101	102	30	0.0110	200	250	0.67	0.52	421.456	421.452	420.204	420.084	1.252	1.368
112	102	103	28	0.0111	200	250	0.68	0.53	421.452	421.449	420.084	419.972	1.368	1.477
113	103	83	27	0.0117	200	250	0.68	0.54	421.449	421.329	419.972	419.864	1.477	1.465
143	131	132	30	0.0008	200	250	0.32	0.13	423.249	423.390	422.097	421.977	1.152	1.413
145	132	133	30	0.0009	200	250	0.33	0.14	423.390	422.477	421.477	421.357	1.913	1.120
146	133	134	23	0.0010	200	250	0.35	0.15	422.477	422.125	421.097	421.005	1.380	1.120

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
147	134	135	26	0.0016	200	70	0.62	0.14	422.125	422.077	421.005	420.634	1.120	1.443
149	135	136	14	0.0017	200	80	0.60	0.15	422.077	422.100	420.634	420.459	1.443	1.641
150	136	137	30	0.0018	200	80	0.62	0.15	422.100	422.264	420.459	420.084	1.641	2.180
151	137	138	30	0.0020	200	80	0.63	0.16	422.264	423.006	420.084	419.709	2.180	3.297
152	138	139	30	0.0021	200	80	0.64	0.16	423.006	423.260	419.709	419.334	3.297	3.926
159	144	145	34	0.0052	200	200	0.61	0.33	423.228	423.172	421.591	421.421	1.637	1.751
160	145	146	34	0.0059	200	200	0.63	0.35	423.172	422.686	421.421	421.251	1.751	1.435
161	146	147	14	0.0142	200	250	0.71	0.61	422.686	422.730	421.251	421.195	1.435	1.535
162	147	148	30	0.0144	200	250	0.71	0.61	422.730	422.931	421.195	421.075	1.535	1.856
163	148	149	30	0.0146	200	250	0.72	0.62	422.931	423.160	421.075	420.955	1.856	2.205
164	149	139	30	0.0147	200	250	0.72	0.62	423.160	423.260	420.955	420.835	2.205	2.425
92	83	84	22	0.0138	200	250	0.71	0.60	421.329	421.394	419.864	419.776	1.465	1.618
76	84	69	26	0.0142	200	250	0.71	0.61	421.394	421.242	419.776	419.672	1.618	1.570
153	139	87	30	0.0173	200	250	0.74	0.69	423.260	423.038	419.334	419.214	3.926	3.824
75	69	70	30	0.0165	200	250	0.73	0.67	421.242	421.442	419.672	419.552	1.570	1.890
77	70	52	17	0.0166	200	250	0.73	0.67	421.442	421.647	419.552	419.484	1.890	2.163
96	87	88	26	0.0174	200	250	0.74	0.69	423.038	422.528	419.214	419.110	3.824	3.418
97	88	140	30	0.0187	200	250	0.75	0.73	422.528	422.130	419.110	418.990	3.418	3.140
154	140	54	3	0.0204	200	150	0.94	0.65	422.130	422.022	418.990	418.970	3.140	3.052
56	52	163	6	0.0184	200	250	0.74	0.72	421.647	421.647	419.484	419.460	2.163	2.187
179	163	53	30	0.0185	200	250	0.75	0.72	421.647	421.930	419.460	419.340	2.187	2.590
57	53	54	30	0.0187	200	250	0.75	0.73	421.930	422.022	419.340	419.220	2.590	2.802
58	54	55	30	0.0392	250	200	0.97	0.75	422.022	421.804	418.970	418.820	3.052	2.984

Table 5.9 (continued)

Pipe No.	Node no.		Length (m)	Design flow (m/s)	Diameter (mm)	Slope (1 in)	v_p (m/s)	$\frac{d}{D}$	Ground Level		Invert Level		Cover depths (m)	
	Up	Down							Up	Down	Up	Down	Up	Down
59	55	56	30	0.0394	250	200	0.97	0.75	421.804	421.930	418.820	418.670	2.984	3.260
60	56	57	12	0.0394	250	200	0.97	0.75	421.930	421.608	418.670	418.610	3.260	2.998
61	57	39	22	0.0400	300	250	0.92	0.59	421.608	421.610	418.610	418.522	2.998	3.088
41	39	0	15	0.0569	300	250	0.98	0.75	421.610	421.610	418.522	418.462	3.088	3.148

CHAPTER 6

Conclusions

In this study, an optimization procedure has been introduced for the optimal layout and component size determination of a sewer network. An algorithm 'Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*' is introduced to find a predefined number of layouts of a base sewer network in order of increasing total cumulative discharge *CQ*.

After the layouts are sequenced, a modified PSO algorithm is applied to optimally size sewer components of the sewer system. The proposed methods for optimal layout and component size determination were applied on three sewer networks (Sudarshanpura, Bajaran and Laxmangarh) design.

The results indicated that the layout having minimum *CQ* has the minimum optimal cost and the optimal cost of sewer layout generally increases with the *CQ* of layout. Irrespective of the shape of the area, the layout which gives the least cumulative flow gives the optimal cost. It is also seen that the proposed Modified PSO algorithm optimal solution was better as compared to Original PSO algorithm in all the layouts.

The optimal cost of the Original PSO is Rs. 8.473×10^6, 8.592×10^6 and 8.956×10^6 whereas that of the Modified PSO is reduced to Rs. 8.371×10^6, 8.455×10^6 and 8.825×10^6, respectively for Sudarshanpura, Bajaran and Laxmangarh sewer networks.

By applying an optimization procedure during the design of a sewer system substantial cost savings can be realized. The results showed the ability of the proposed methods to optimally solve the problem of the layout and component size determination of sewer networks.

Future Scope of Work

Based on the investigations carried out in this thesis, the following suggestions are made for future research work in this area:

i. This problem can also be done using different optimization techniques such as Ant Colony Optimization (ACO), Genetic Algorithm (GA), Tabu search, etc. and results can be compared.
ii. Optimization of sewerage system with or without intermediate pumping station can be done and results can be compared.
iii. Selection of the optimal location of a sewage pumping station can be determined.

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Algorithm: Generation of a predefined number of spanning tree in order of increasing weight and sequencing them in ascending order of total cumulative flow *CQ*

```
#include<iostream>
#include<set>
#include<algorithm>
#include<fstream>
#include<vector>
#include<queue>
#include<stack>
#include<map>
using namespace std;
#define N 1000
fstream fin;
fstream fout;
fstream flow;
struct edge{
        int x, y, w;
        edge(int xx, int yy, int ww){
                x = xx, y = yy, w = ww;
        }
        friend bool operator<(const struct edge& e1, const struct edge& e2){
      if( e1.w == e2.w)
      {
        return pair<int,int>(e1.x,e1.y) < pair<int,int>(e2.x,e2.y);
      }
                return e1.w < e2.w;
        }
};
set<set<edge> >  treesVisited;
double contribution[N];
```

```
int parent[N];
int height[N];
map<double,vector<vector<double> > > flowSortedMsts;
int fp(int x){
	if(parent[x] == x) return x;
	return parent[x] = fp(parent[x]);
}
edge replacement(set<edge>&E1, set<edge>E2, edge e){
	int  n = E1.size()+1;
	for(int i=0;i<n;i++) parent[i] = i, height[i] = 1;
	set<edge>::iterator it;
	for(it=E1.begin(); it!=E1.end(); it++){
		if(it->x == e.x && it->y == e.y) continue;
		int x=it->x, y=it->y;
		int px = fp(x), py = fp(y);
		if(px == py) continue;
		if(height[px] > height[py]){
			parent[py] = px;
			height[px]++;
		}
		else{
			parent[px] = py;
			height[py]++;
		}
	}
	edge tmp = edge(-1,-1,-1);
	int mn = (int)2e9;
	for(it=E2.begin();it!=E2.end();it++){
		if(it->x == e.x && it->y == e.y) continue;
		// Replacement shouldn't be of lesser weight
		if(it->w < e.w) continue;
		if(fp(it->x) != fp(it->y) && (it->w) < mn){
			mn = it->w;
			tmp = *it;
```

```
                }
        }
        return tmp;

}
pair<edge, edge> nextMST(set<edge>E1, set<edge>E2){
        int mstWeight = 0, n = E1.size()+1;
        set<edge>::iterator it;
        for(it=E1.begin(); it != E1.end(); it++) mstWeight += (it->w);

        int mn = (int)(2e9);
        edge prev = edge(-1,-1,-1), curr = edge(-1,-1,-1);
        for(it=E1.begin(); it!=E1.end(); it++){
                edge tmp  = replacement(E1, E2, *it);
                int delta = tmp.w - (it->w);
      if(delta == 0){
        set<edge> copyOfE1(E1);
        copyOfE1.erase(*it);
        copyOfE1.insert(tmp);
        if(treesVisited.find(copyOfE1) == treesVisited.end()){
           mn = delta;
           prev = *it; curr = tmp;
           break;
        }
      }
                if(delta > 0 && delta < mn){
                        mn = delta;
                        prev = *it; curr = tmp;
                }
        }
        if(prev.x>=0)
           fout<<"Weight of next spanning tree --> "<<mstWeight+mn<<endl;
//  If no spanning tree of same length found, clear set of spanning trees for previous length
```

```
    if(mn != 0 ){
        treesVisited.clear();
    }
//  Insert this spanning tree for current new length in the set
    set<edge> copyOfE1(E1);
    copyOfE1.erase(prev);
    copyOfE1.insert(curr);
    treesVisited.insert(copyOfE1);
            return pair<edge, edge>(prev, curr);
}
set<edge> genMST(set<edge>&E, int n){
            set<edge>MST;
            for(int i=0;i<n;i++) parent[i] = i, height[i]=1;
            set<edge>::iterator it;
            int cnt = 0;
            for(it=E.begin();it!=E.end();it++){
                        if(cnt == n-1) break;
                        int x = it->x, y = it->y;
                        int px=fp(x), py = fp(y);
                        if(px != py){
                                    cnt++;
                                    MST.insert(*it);
                                    if(height[px]>height[py]){
                                                parent[py] = px;
                                                height[px]++;
                                    }
                                    else{
                                                parent[px] = py;
                                                height[py]++;
                                    }
                        }
            }
            int mstWeight=0;
            for(it=MST.begin(); it != MST.end(); it++) mstWeight += (it->w);
```

```
    fout<<"MST Weight : "<<mstWeight<<endl;
        return MST;
}
void calculateFlow(set<edge> spanningTree, int sinkNode, int totalNodes) {
    vector<vector<int> > tree(totalNodes+1,vector<int>(totalNodes+1,-1));
    vector<vector<int> > dag(totalNodes+1,vector<int>(totalNodes+1,-1));
    vector<vector<double>                                              >
edgeFlow(totalNodes+1,vector<double>(totalNodes+1,0.));
    set<edge>::iterator it;
    for(it=spanningTree.begin(); it!=spanningTree.end();it++){
                tree[it->x][it->y] = it->w;
                tree[it->y][it->x] = it->w;
    }
    vector<bool> visitedBfs(totalNodes+1,false);

//  BFS Queue
    queue<int> q;
    q.push(sinkNode);

    int toNode;
//  BFS starts
    while(!q.empty())
    {
        toNode =  q.front();
        q.pop();
        visitedBfs[toNode] = true;

        for(int fromNode=0;fromNode<totalNodes;fromNode++){
            if(fromNode==toNode) continue;
            if(visitedBfs[fromNode]) continue;
            if(tree[fromNode][toNode] != -1){
                q.push(fromNode);
                dag[fromNode][toNode] = 1;
            }
```

```
        }
    }

    vector<double> finalContribution(N,0);
    for(int i=0;i<N;i++){
        finalContribution[i] = contribution[i];
    }

    vector<bool> visitedDfs(totalNodes+1,false);

//  DFS Stack
    stack<int> s;
    s.push(sinkNode);
    visitedDfs[sinkNode] = true;

//  DFS starts
    while(!s.empty()){
        toNode =  s.top();
        bool hasUnvisitedAdjacentNode = false;
        for(int fromNode=0;fromNode<totalNodes;fromNode++){
            if(fromNode==toNode) continue;
            if(dag[fromNode][toNode] == 1 && !visitedDfs[fromNode]){
                hasUnvisitedAdjacentNode = true;
                s.push(fromNode);
                visitedDfs[fromNode] = true;
                break;
            }
        }
        if(!hasUnvisitedAdjacentNode){
            int fromNode = s.top();
            s.pop();
            if(s.empty())
                break;
            toNode = s.top();
```

```
            for(int i=0;i<totalNodes;i++){
                if(i==fromNode) continue;
                finalContribution[fromNode] +=  edgeFlow[i][fromNode];
            }
            edgeFlow[fromNode][toNode] = finalContribution[fromNode];
        }
    }

    double totalFlowSum = 0;
    for(int from=0;from<totalNodes;from++){
        for(int to=0;to<totalNodes;to++){
            if(edgeFlow[from][to]>0.){
                        totalFlowSum+=edgeFlow[from][to];
                                    flow << from << " " << to << " " <<
edgeFlow[from][to] <<"\n";
            }
                        }
    }
    flowSortedMsts[totalFlowSum] = edgeFlow;
            return;
}

int main(){
    fin.open ("input.txt", std::fstream::in);
            int n, nE, k, x, y, w, sinkNode;
            fin >> n >> nE >> k;

            set<edge>E1, E2;
            for(int i=0;i<nE;i++){
                        fin >> x >> y >> w;
                        E2.insert(edge(x,y,w));
            }
            fin >> sinkNode;
```

```
        for(int i=0;i<n;i++){
            fin >> contribution[i];
        }

    flow.open ("flow.txt", std::fstream::out);
    fout.open ("output.txt", std::fstream::out);

        E1 = genMST(E2, n);
        fout<<"MST  follows : \n";
    set<edge>::iterator it;

    for(it=E1.begin(); it!=E1.end();it++){
                    fout << it->x << " " << it->y << "\n";
    }
    flow << "Discharge volume in MST \n";
    calculateFlow(E1,sinkNode,n);
    int cnt = 2;
        while(k--){

        pair<edge, edge>ret = nextMST(E1, E2);
        edge e1 = ret.first, e2 = ret.second;
        if(e1.x <0 || e1.y<0 || e2.x<0 || e2.y<0)
        {
            fout<<"No MORE Spanning trees left\n";
            break;
        }
        fout<<"To get next spanning tree which is number "<< cnt << ", REMOVE
EDEGE --> "<<e1.x << " " << e1.y << " and INSERT EDGE --> " << e2.x << " " <<
e2.y << " \n";
        E1.erase(e1);
        E1.insert(e2);
        fout<<"Edges in this Spanning Tree : \n";
        for(it=E1.begin(); it!=E1.end();it++){
                    fout << it->x << " " << it->y << "\n";
```

```
            }
            flow << "Discharge volume in Spanning Tree \n";
            calculateFlow(E1,sinkNode,n);
        cnt++;
        }
        int flowSortedNo = 1;
        fout<< "\nPrinting Sorted Spanning Trees in increasing order of Total Flow ---
------> \n";
        for (map<double,vector<vector<double> > >::iterator i =
flowSortedMsts.begin(); i != flowSortedMsts.end(); i++){
                fout<<"Spanning Tree Number "<<flowSortedNo<<" w.r.t Total
Flow\n";
                fout<<"Total Discharge Flow --> "<<i->first<<"\n";
                vector<vector<double> > sTree = i->second;
                for(int from=0;from<n;from++){
                        for(int to=0;to<n;to++){
                                if(sTree[from][to]>0.){
                                        fout << from << " " << to << " " <<
sTree[from][to] <<"\n";
                                }
                        }
                }
                flowSortedNo++;
        }
        return 0;
}
```

The Comparison of Results of the Modified PSO with the Original PSO for Network 2

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Modified PSO						Original PSO					
					Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)		Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down					Up	Down
11	10	9	20	0.0004	200	250	0.27	0.10	1.120	1.150	200	250	0.27	0.10	1.120	1.150
21	18	19	12	0.0003	200	250	0.25	0.09	1.120	1.363	200	250	0.25	0.09	1.120	1.363
30	28	27	30	0.0004	200	250	0.25	0.09	1.730	1.120	200	60	0.41	0.07	1.350	1.120
38	35	25	12	0.0004	200	250	0.25	0.09	1.657	1.120	200	250	0.25	0.09	1.657	1.120
43	40	39	14	0.0004	200	250	0.25	0.09	1.120	1.406	200	250	0.25	0.09	1.120	1.406
48	44	43	30	0.0004	200	250	0.25	0.09	1.490	1.120	200	250	0.25	0.09	1.490	1.120
52	48	30	24	0.0005	200	60	0.45	0.08	1.570	1.120	200	250	0.28	0.11	1.874	1.120
55	51	49	72	0.0009	200	250	0.33	0.14	1.237	1.120	200	250	0.33	0.14	1.237	1.120
59	54	36	24	0.0005	200	250	0.28	0.11	1.419	1.120	200	60	0.45	0.08	1.120	1.125
62	59	55	30	0.0006	200	250	0.29	0.11	1.120	1.360	200	250	0.29	0.11	1.120	1.360
66	60	57	32	0.0006	200	250	0.30	0.12	1.120	1.568	200	250	0.30	0.12	1.120	1.568
69	61	58	143	0.0518	300	250	0.97	0.70	1.220	2.897	300	250	0.97	0.70	1.220	2.897
72	64	63	33	0.0007	200	250	0.30	0.12	1.248	1.120	200	250	0.30	0.12	1.248	1.120
79	73	72	30	0.0006	200	250	0.29	0.11	1.125	1.120	200	250	0.29	0.11	1.125	1.120
85	75	74	76	0.0010	200	250	0.34	0.15	1.120	1.229	200	250	0.34	0.15	1.120	1.229
99	89	88	30	0.0504	300	250	0.96	0.68	1.220	1.275	300	250	0.96	0.68	1.220	1.275

Table (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Modified PSO						Original PSO					
					Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)		Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down					Up	Down
101	91	90	33	0.0008	200	250	0.33	0.14	1.120	1.142	200	250	0.33	0.14	1.120	1.142
103	93	92	36	0.0005	200	250	0.27	0.10	1.120	1.239	200	250	0.27	0.10	1.120	1.239
112	102	101	30	0.0008	200	250	0.32	0.13	1.120	1.135	200	250	0.32	0.13	1.120	1.135
10	9	8	30	0.0007	200	60	0.50	0.09	1.320	1.120	200	60	0.50	0.09	1.320	1.120
29	27	26	30	0.0008	200	250	0.32	0.13	1.120	1.565	200	250	0.32	0.13	1.120	1.565
42	39	38	30	0.0006	200	250	0.29	0.11	1.406	1.221	200	250	0.29	0.11	1.406	1.221
71	63	62	33	0.0011	200	250	0.35	0.16	1.120	1.147	200	250	0.35	0.16	1.120	1.147
78	72	56	21	0.0011	200	250	0.36	0.16	1.171	1.120	200	250	0.36	0.16	1.171	1.120
98	88	87	30	0.0508	300	250	0.97	0.69	1.275	1.380	300	250	0.97	0.69	1.275	1.380
100	90	78	33	0.0013	200	60	0.60	0.12	1.142	1.387	200	250	0.37	0.17	1.293	1.120
104	92	94	30	0.0008	200	250	0.33	0.14	1.239	1.309	200	250	0.33	0.14	1.239	1.309
105	94	95	26	0.0012	200	250	0.36	0.16	1.309	1.408	200	250	0.36	0.16	1.309	1.408
111	101	100	30	0.0011	200	250	0.36	0.16	1.135	1.190	200	250	0.36	0.16	1.135	1.190
9	8	7	30	0.0011	200	60	0.57	0.11	1.705	1.120	200	60	0.57	0.11	1.705	1.120
28	26	25	27	0.0011	200	250	0.35	0.16	1.565	2.178	200	250	0.35	0.16	1.565	2.178
41	38	37	30	0.0011	200	100	0.49	0.13	1.221	1.141	200	250	0.36	0.16	1.380	1.120
70	62	58	24	0.0014	200	70	0.59	0.13	1.147	1.220	200	60	0.62	0.13	1.147	1.277
97	87	86	30	0.0511	300	250	0.97	0.69	1.380	1.320	300	250	0.97	0.69	1.380	1.320
110	100	99	30	0.0015	200	70	0.61	0.14	1.190	1.559	200	70	0.61	0.14	1.190	1.559
8	7	1	9	0.0012	200	60	0.59	0.12	1.235	1.120	200	60	0.59	0.12	1.235	1.120
27	25	24	30	0.0019	200	80	0.62	0.16	2.178	2.413	200	80	0.62	0.16	2.178	2.413
40	37	36	16	0.0013	200	250	0.38	0.18	1.151	1.120	200	250	0.38	0.18	1.151	1.120

Table (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Modified PSO						Original PSO					
					Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)		Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down					Up	Down
68	58	57	33	0.0536	300	250	0.97	0.71	2.897	2.944	300	250	0.97	0.71	2.897	2.944
96	86	85	30	0.0515	300	250	0.97	0.69	1.465	1.220	300	250	0.97	0.69	1.465	1.220
109	99	98	30	0.0019	200	80	0.62	0.16	1.559	1.869	200	80	0.62	0.16	1.559	1.869
26	24	23	30	0.0022	200	100	0.61	0.18	2.413	2.523	200	100	0.61	0.18	2.413	2.523
39	36	34	7	0.0019	200	80	0.63	0.16	1.120	1.153	200	80	0.63	0.16	1.125	1.158
65	57	56	8	0.0545	300	250	0.98	0.72	2.944	2.881	300	250	0.98	0.72	2.944	2.881
95	85	84	30	0.0519	300	250	0.97	0.70	1.220	1.270	300	250	0.97	0.70	1.220	1.270
108	98	97	30	0.0023	200	100	0.61	0.18	1.869	2.029	200	100	0.61	0.18	1.869	2.029
25	23	22	30	0.0026	200	100	0.64	0.20	2.523	2.748	200	100	0.64	0.20	2.523	2.748
36	34	33	18	0.0023	200	60	0.73	0.16	1.153	1.303	200	100	0.61	0.19	1.158	1.188
64	56	55	25	0.0560	300	250	0.98	0.74	2.881	2.746	300	250	0.98	0.74	2.881	2.746
94	84	83	30	0.0523	300	250	0.97	0.70	1.275	1.220	300	250	0.97	0.70	1.275	1.220
107	97	96	30	0.0027	200	100	0.64	0.20	2.029	2.214	200	100	0.64	0.20	2.029	2.214
24	22	21	30	0.0030	200	125	0.61	0.22	2.748	2.863	200	125	0.61	0.22	2.748	2.863
35	33	32	30	0.0027	200	100	0.64	0.20	1.303	1.368	200	100	0.64	0.20	1.188	1.253
61	55	53	20	0.0570	300	250	0.98	0.75	2.746	2.896	300	250	0.98	0.75	2.746	2.896
93	83	82	30	0.0527	300	250	0.97	0.70	1.220	1.290	300	250	0.97	0.70	1.220	1.290
106	96	95	30	0.0030	200	125	0.61	0.22	2.214	2.419	200	125	0.61	0.22	2.214	2.419
23	21	20	30	0.0034	200	125	0.63	0.24	2.863	2.988	200	125	0.63	0.24	2.863	2.988
34	32	31	30	0.0031	200	125	0.62	0.23	1.368	1.243	200	125	0.62	0.23	1.253	1.128
92	82	81	30	0.0530	300	250	0.97	0.71	1.290	1.295	300	250	0.97	0.71	1.290	1.295
116	95	104	27	0.0046	200	150	0.65	0.29	2.419	2.529	200	150	0.65	0.29	2.419	2.529

Table (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Modified PSO						Original PSO					
					Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)		Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down					Up	Down
115	104	103	27	0.0049	200	150	0.66	0.30	2.529	2.644	200	150	0.66	0.30	2.529	2.644
22	20	19	18	0.0036	200	150	0.61	0.26	2.988	3.043	200	150	0.61	0.26	2.988	3.043
33	31	30	30	0.0035	200	125	0.64	0.24	1.243	1.133	200	125	0.64	0.24	1.230	1.120
91	81	80	10	0.0532	300	250	0.97	0.71	1.295	1.270	300	250	0.97	0.71	1.295	1.270
114	103	80	27	0.0052	200	200	0.61	0.33	2.644	2.724	200	200	0.61	0.33	2.644	2.724
14	19	12	30	0.0043	200	150	0.64	0.28	3.043	3.133	200	150	0.64	0.28	3.043	3.133
32	30	29	22	0.0043	200	150	0.64	0.28	1.223	1.120	200	150	0.64	0.28	1.223	1.120
90	80	79	31	0.0588	300	250	0.99	0.77	2.724	2.758	300	250	0.99	0.77	2.724	2.758
13	12	11	20	0.0046	200	150	0.65	0.29	3.133	2.476	200	150	0.65	0.29	3.133	2.476
31	29	17	30	0.0047	200	150	0.65	0.29	1.120	1.160	200	150	0.65	0.29	1.120	1.160
89	79	78	31	0.0592	300	250	0.99	0.78	2.758	2.587	300	250	0.99	0.78	2.758	2.587
7	11	6	30	0.0052	200	200	0.60	0.33	2.476	2.621	200	200	0.60	0.33	2.476	2.621
19	17	16	30	0.0052	200	200	0.61	0.33	1.160	1.175	200	200	0.61	0.33	1.160	1.175
88	78	77	13	0.0606	300	200	1.09	0.72	2.587	2.717	300	200	1.09	0.72	2.587	2.717
6	6	5	30	0.0055	200	200	0.62	0.34	2.621	2.676	200	200	0.62	0.34	2.621	2.676
18	16	15	30	0.0056	200	200	0.62	0.34	1.175	1.290	200	200	0.62	0.34	1.175	1.290
87	77	76	38	0.0611	300	200	1.09	0.72	2.717	2.842	350	250	1.03	0.59	2.717	2.804
5	5	4	30	0.0059	200	200	0.63	0.35	2.676	2.766	200	200	0.63	0.35	2.676	2.766
17	15	14	30	0.0060	200	200	0.63	0.36	1.290	1.415	200	200	0.63	0.36	1.290	1.415
86	76	74	38	0.0616	300	200	1.09	0.73	2.842	2.987	350	250	1.03	0.60	2.804	2.911
4	4	3	10	0.0060	200	60	0.97	0.26	2.766	2.868	200	200	0.63	0.36	2.766	2.751
84	74	71	34	0.0630	300	200	1.10	0.74	2.987	2.992	350	250	1.03	0.61	2.911	2.882

Table (Continued)

Pipe no.	Node no.		Length (m)	Design flow (m/s)	Modified PSO						Original PSO					
					Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)		Diameter (mm)	Slope (1 in)	v_p (m/s)	d/D	Cover depths (m)	
	Up	Down							Up	Down					Up	Down
83	71	70	26	0.0635	300	200	1.10	0.75	2.992	3.037	350	250	1.03	0.61	2.882	2.901
82	70	69	26	0.0638	300	200	1.10	0.75	3.037	2.962	350	250	1.04	0.61	2.901	2.800
81	69	68	26	0.0642	300	200	1.10	0.75	2.962	2.872	350	250	1.04	0.61	2.800	2.684
77	68	67	22	0.0644	300	200	1.10	0.76	2.872	2.837	350	250	1.04	0.61	2.684	2.627
76	67	66	22	0.0647	300	200	1.10	0.76	2.837	2.907	350	250	1.04	0.62	2.627	2.675
75	66	65	30	0.0651	300	200	1.10	0.76	2.907	2.907	350	250	1.04	0.62	2.675	2.645
74	65	53	30	0.0655	300	200	1.10	0.77	2.907	2.917	350	250	1.04	0.62	2.645	2.625
60	53	52	30	0.1229	400	250	1.19	0.75	2.917	2.752	400	250	1.19	0.75	2.896	2.731
57	52	50	30	0.1234	450	450	0.96	0.74	2.752	2.593	400	250	1.19	0.75	2.731	2.626
56	50	49	30	0.1238	450	450	0.96	0.74	2.593	2.585	400	250	1.19	0.75	2.626	2.671
54	49	47	26	0.1251	450	450	0.96	0.75	2.585	2.228	400	250	1.19	0.76	2.671	2.360
53	47	46	26	0.1254	450	450	0.96	0.75	2.228	1.916	400	250	1.19	0.76	2.360	2.094
50	46	45	20	0.1258	450	450	0.96	0.75	1.916	2.235	400	250	1.19	0.77	2.094	2.449
49	45	43	20	0.1261	450	450	0.96	0.75	2.235	2.524	400	250	1.19	0.77	2.449	2.774
47	43	42	11	0.1266	450	450	0.96	0.76	2.524	2.409	400	250	1.19	0.77	2.774	2.678
46	42	41	30	0.1270	450	450	0.96	0.76	2.409	1.391	400	250	1.19	0.77	2.678	1.713
45	41	14	30	0.1274	450	60	2.13	0.42	1.625	1.370	400	250	1.19	0.78	1.955	1.320
16	14	13	30	0.1337	450	100	1.78	0.49	1.440	1.370	400	150	1.50	0.66	1.490	1.320
15	13	3	30	0.1341	450	100	1.78	0.49	1.375	1.370	450	250	1.24	0.64	1.555	1.370
3	3	2	23	0.1404	450	350	1.09	0.74	2.868	2.269	450	60	2.18	0.44	2.751	2.470
2	2	1	23	0.1407	450	60	2.18	0.44	2.357	1.370	450	125	1.65	0.54	2.556	1.370
1	1	0	30	0.1423	450	70	2.07	0.46	1.370	1.459	450	100	1.80	0.51	1.410	1.370

List of Publications Out of Thesis Work

Papers that have been published / accepted for publication out of this thesis work:

International Journals:

Navin, P.K. and Mathur, Y.P., 2016. Layout and Component Size Optimization of Sewer Network Using Spanning Tree and Modified PSO Algorithm. *Water Resources Management*, 30 (10), 3627–3643.

International Conference:

Navin P.K. and Mathur Y.P., 2016. Design optimization of sewer system using particle swarm optimization. IN Proceedings of Fifth International Conference on Soft Computing for Problem Solving (pp. 173-182). Springer Singapore.

Navin P.K. and Mathur Y.P., 2016. Layout optimization of sewer network using minimum cumulative flow in the sewer network. In Proc. International conference on Waste Management (Recycle-2016), IIT Guwahati,Assam, India.

Navin P.K. and Mathur Y.P., 2015. Application of graph theory for optimal sewer layout generation. In Proceeding of International conference on GCCT pp. 151-157. Discovery Publication.

Navin P.K. and Mathur Y.P., 2013. Minimum spanning tree layout of sewerage system. In: International Conference on Advance Trends in Engineering & Technology (ICATET), Arya College of Engineering & IT, Jaipur, pp 272-276.

Bio Data of the Author

Praveen Kumar Navin received the B.Tech. degree in 2008 from Allahabad Agricultural Institute – DU, Allahabad, and the M.Tech. degree in Environmental Engineering in 2010 from Malaviya National Institute of Technology, Jaipur, Rajasthan, India. He worked for M/s Durha Construction Pvt. Ltd, Lucknow and Department of Civil Engineering, NIMS University for a short period of two years. He is currently a research scholar in the department of Civil Enginering, Malaviya National Institute of Technology Jaipur. His area of research is optimization of environmental systems. He is an associate member of the Institution of Engineers (India) and Indian Water Works Association (IWWA). He has wide experiences in the field of water supply and drainage systems. He has provided technical assistance in many consultancy works with Prof. Y. P. Mathur. He has authored around 10 papers in different journals and conferences.