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Layout and Component Size Optimization of Sewer Network Using Spanning Tree and Modified PSO Algorithm

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Abstract In the paper, a new method is introduced for optimally solve the problem of the layout and component size determination of sewer network. 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. An algorithm generation of a predefined number of spanning trees is introduced to generate a predefined number of sewer layouts of a base sewer network in order of increasing length. These generated layouts are sorted in ascending order of total cumulative flow and sorted layouts are individually optimized for sewer components sizing. 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 is applied to the Sudarshanpura sewer network (situated in Jaipur, India) design problem. The results are presented for optimal cost vs cumulative flow of the layouts. Further results of MPSO has been compared with the original PSO algorithm.

Keywords Sewer network · Optimization · Spanning tree · Modified PSO · Cumulative flow

1 Introduction

A sewer network has a tree-like structure which collects wastewater from industrial, commercial and residential areas and transports to wastewater treatment plant. A Huge amount of investment is required for construction and maintenance of large scale sewerage networks. Thus, reduction by a few percent of the cost of a network may result in substantial reduction in the project cost. Design optimization of sewer network problem includes two sub problems (i)

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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 generally non-linear, discrete and sequential. Due to the complex nature of the problem, most of the researchers have focused on only the component size optimization of sewer network (Walsh and Brown 1973; Dajani and Hasit 1974; Price 1978; Walters and Templeman 1979; Kulkarni and Khanna 1985; Elimam et al. 1989; Swamee 2001; Afshar 2006, 2007, 2010; Guo et al. 2007, 2008; Izquierdo et al. 2008; Pan and Kao 2009; Haghighi and Bakhshipour 2012; Karovic and Mays 2014). Only a few researchers have addressed the problem of layout and the combined layout and component size optimization of sewer network (Argaman et al. 1973; Tekeli and Belkaya 1986; Li and Matthew 1990; Walters and Lohbeck 1993; Walters and Smith 1995; Diogo and Graveto 2006; Moeini and Afshar 2012; Haghighi 2013; Steele et al. 2016).

The present work describes a method to optimally solve the problem of the layout and component size determination of sewer networks. The optimization has been done in four steps: (1) An algorithm is applied to find a predetermined number of sewer layouts of a base sewer network in order of increasing length of sewer line; (2) For all layouts total cumulative flow (CQ) is obtained by adding flows in each sewer; (3) These layouts are sequenced in ascending order of total cumulative flow; (4) The modified PSO is then applied to get optimal sewer component sizes of each of these sequenced sewer layout. The optimal cost of the sewer system with modified PSO is compared with original PSO.

2 Optimal Sewer Layout Selection Method

The sewer network 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):

- 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.
- Tree: A graph G is called a tree if it is a connected acyclic graph. In acyclic graph, one and only one path between any pair of vertices.
- 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 e.
- Spanning Tree: A spanning tree of a graph G is a tree containing all vertices of a graph G.
- Minimum spanning tree (MST): A spanning tree with the minimum weight in a weighted graph is called a minimum spanning tree.

The layout of the sewer system is a sub graph extracted from a predefined base graph of city or town drainage system. In a base graph, 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 to be satisfied are: (i) graph should be acyclic and (ii) all manholes (vertices) must be included in the layout (spanning tree).

There are number of greedy algorithms for finding the minimum spanning tree (MST) of an undirected weighted graph G, Kruskal's and Prim's algorithms are well known (Clark and Holton 1995). Each sewer line constitutes the edge with weight equal to its length. MST represents minimum length layout of a base sewer network (graph). The MST does not guarantee an optimal solution of the sewer system.

2.1 Algorithm – Generation of a Predefined Number of Spanning Trees

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. The flow chart shown in Fig. 1 presents the simplified representation of the 'generation of a predetermined spanning trees' algorithm:

2.2 Optimal Layout Selection

All constraints of the layout problem are systematically satisfied during the generation of layouts. A large number of alternative layouts are available, and it is very difficult to identify which layout should be selected first for component size optimization. Therefore, a strategy to sequence these alternatives needs to be developed. The Eq. 1 is used to calculate total cumulative flow (CQ_j) of ith layout.

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

Where, N = the total number of links (edges) in the layout, q_{ij} = flow in the ith link of the jth layout, and CQ_j is the sum of cumulative flows in all links of the jth layout.

The total cumulative flow (CQ) is calculated for all generated layouts, and then these layouts are sequenced in ascending order of CQ. Each layout is optimized for component size optimization in this sequence.

The applicability of the proposed algorithm is tested against a benchmark example in the literature. The first example (network 1) to be considered is a simple network illustrated in Fig. 2. The network 1 consists of 9 manholes (vertices), 12 links (edges) and an outlet located at manhole number 9. This example has been considered as a test example by Afshar and Mariño (2006) to test the performance of ant algorithms for layout optimization of tree network. The wastewater contribution at each node of the network is given in table 1.

By applying the proposed approach, all alternative layouts are sequenced in ascending order of CQ. The top 4 solutions (minimum CQ) of the network 1 are shown in Fig. 3.

3 Formulation of Optimal Sewer Design Problem for Component Sizing

3.1 Sewer Hydraulics

In circular sewer Steady-state flow is described by the continuity principle ($Q = VA$) and Manning's equation which is:
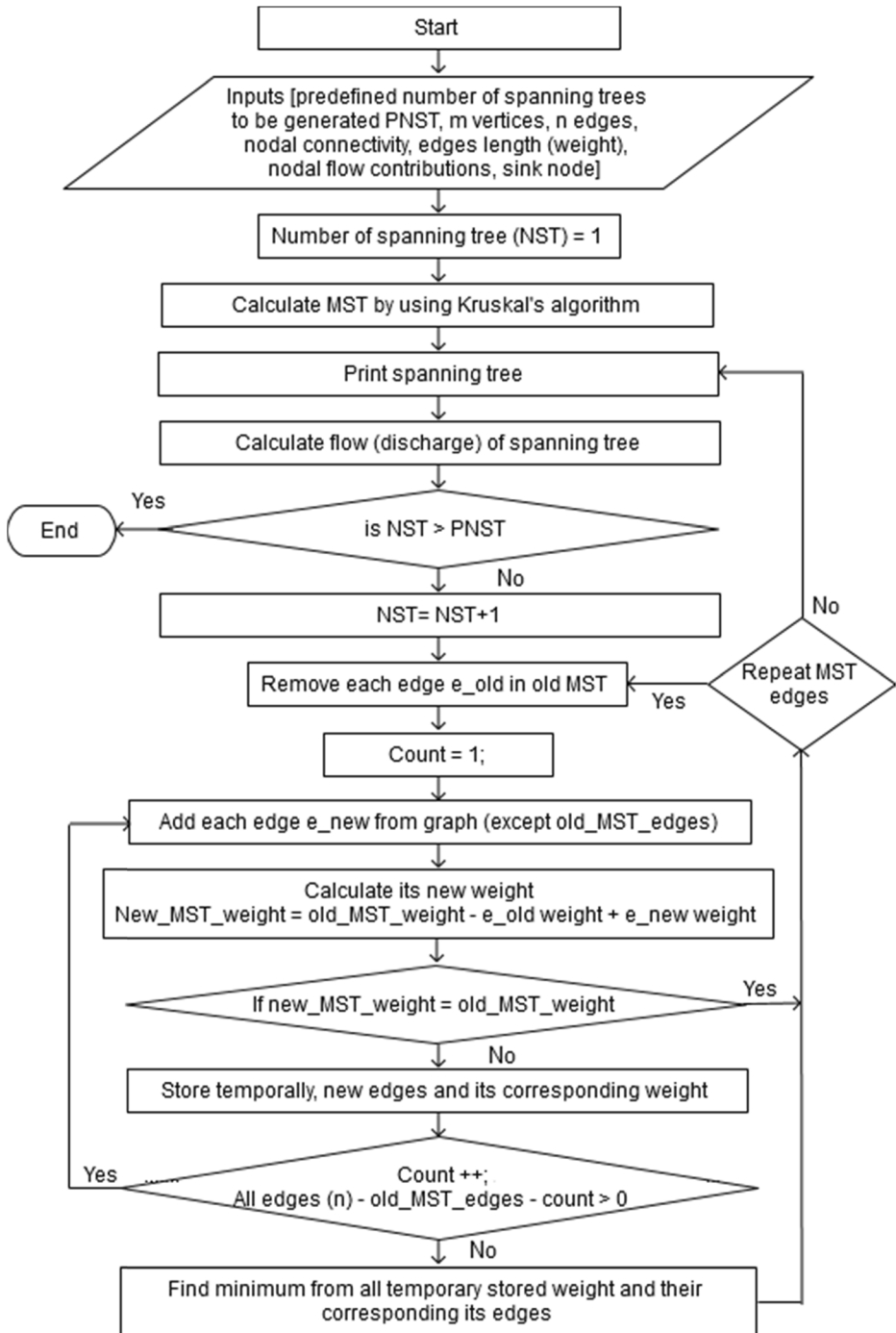
$$V = \frac{1}{n} R^{2/3} S^{1/2} \tag{2}$$

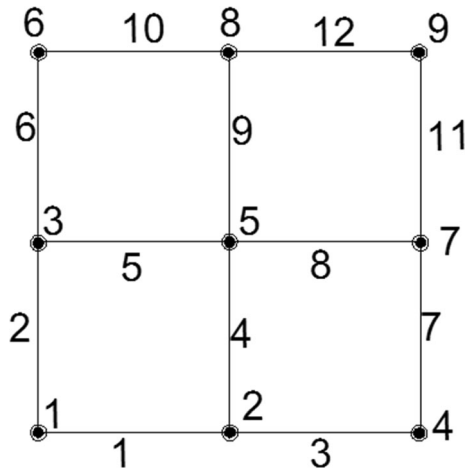**Fig. 1** Generation of a predefined number of spanning trees algorithm

Fig. 2 Base layout of network 1

where Q = discharge in sewer, V = velocity of sewage flow, A = flow cross-sectional area, n = Manning's coefficient, R = hydraulic mean depth and S = sewer slope.

Common partially full parameters for circular sewer sections are also determined from the following equations:

$$K = QnD^{-8/3}S^{-1/2} \tag{3}$$

$$\theta = \frac{3\pi}{2}\sqrt{1-\sqrt{1-\sqrt{\pi K}}} \tag{4}$$

$$\left(\frac{d}{D}\right) = \frac{1}{2} \times \left(1-\cos\frac{\theta}{2}\right) \tag{5}$$

$$r = \frac{D}{4}\left(\frac{\theta-\sin\theta}{\theta}\right) \tag{6}$$

where K = constant, D = sewer diameter, (d/D) = proportional sewage depth, r = hydraulic mean depth, and θ = the central angle from the center of the section to the sewage

Table 1 Nodal wastewater contribution for network 1

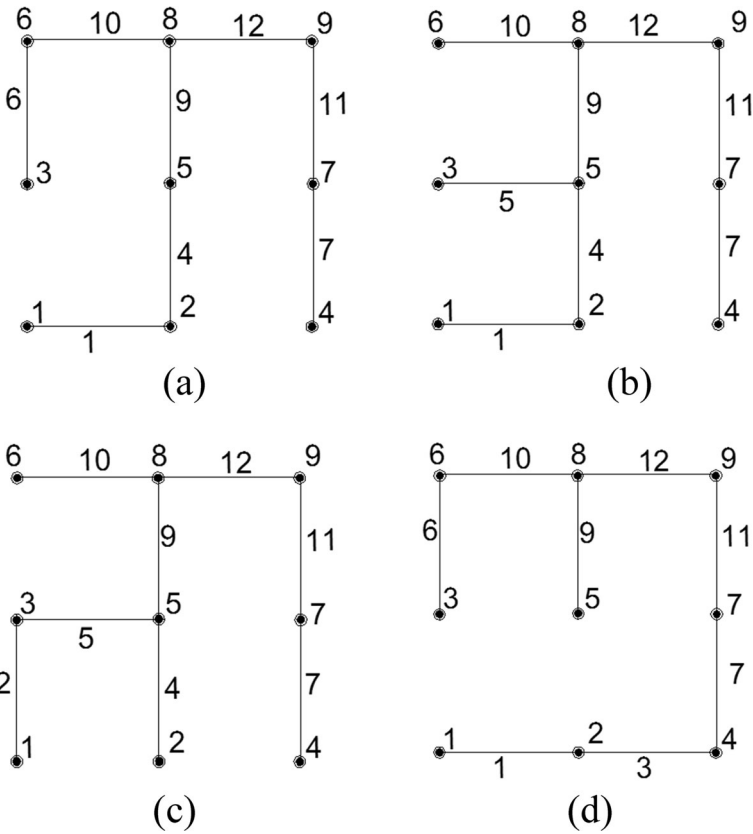| Node	1	2	3	4	5	6	7	8	9
Nodal wastewater contribution (l/s)	10	20	10	20	10	20	10	20	−120

Fig. 3 Top four layout alternatives with CQ = 260 l/s

surface (in radian). Equation 4 is applicable for K values less than $(1/\pi) = 0.318$ (Saatci 1990).

3.2 Design Constraints

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

(1) Sewer cover depth: It is necessary to provide minimum cover depth (CD$_{min}$) to avoid damage to the sewer line and also to provide adequate fall for house sewer connections. Further in order to reduce the excavation, manhole cost and pumping cost, cover depth should be less than prescribed maximum cover depth (CD$_{max}$).

$$CD_{min} \leq CD_i \leq CD_{max} \quad i = 1, \ldots, N \tag{7}$$

Where CD_i = average cover depth of the ith sewer link, and N = total number of links. The minimum cover depth of 0.9 m and maximum cover depth of 5.0 m has been adopted in the present paper.

(2) Sewer flow velocity: For 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.

$$V_{min} \leq V_i \leq V_{max} \quad i = 1, ..., N \tag{8}$$

Minimum permissible velocity of 0.6 m/s and maximum velocity of 3.0 m/s has been adopted in the present paper.

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

$$\frac{d_i}{D_i} \leq 0.8 \quad i = 1, ..., N \tag{9}$$

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

(4) 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 paper.

$$D_{min} - D_i \leq 0 \quad i = 1, ..., N \tag{10}$$

(5) Progressive sewer diameters: The diameter of ith sewer (D_i) should not be less than diameter of immediately preceding sewer (D_p)

$$D_p - D_i \leq 0 \quad i = 1, ..., N \tag{11}$$

Constraints (Eqs. 9, 10 & 11) are satisfied while selecting pipe diameters and as such not included for penalty cost.

The optimal design of a sewer system for a given layout is to determine the feasible sewer diameters, excavation depths and sewer slopes in order to minimize the total cost of the sewerage system. The cost of the sewerage systems mainly depends upon sewer diameters, excavation depths, and manhole construction.

Total Cost: The total cost (TC_i) of ith link would be

$$TC_i = (\text{Cost of sewer})_i + (\text{Cost of manhole})_i + (\text{Cost of earthwork})_i \tag{12}$$

The problem of optimization of a sewer network with N number of links may be expressed as

$$\text{Minimize } C = \sum_{i=1}^{N} (TC_i + PC_i) \tag{13}$$

where C = cost function of sewer network, TC_i = total cost of a sewer network for the ith link, and PC_i = penalty cost for the ith link.

$$PC_i = (PD)_i + (PV_{min})_i + (PV_{max})_i \tag{14}$$

Where $(PD)_i$ is penalty due to maximum depth, $(PV_{min})_i$ is penalty due to minimum velocity, and $(PV_{max})_i$ is penalty due to maximum depth for the ith link. Penalty for violation of minimum velocity constraints has not been applied for discharge less than 0.0014 m^3/s.

These penalties are applied by multiplying a very large number (such as Rs. 10^8) to the violated constraint and are added to the total cost (TC) if the maximum cover depth constraint, minimum, and maximum velocity constraints are violated.

4 Modified Particle Swarm Optimization (MPSO)

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 Eberhart 1998). PSO has some common evolutionary computation 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).

An initial group of particles starts their movement in the first iteration randomly. Then they try to determine the optimum solutions through the method described below.

The current position of the ith particle in the d-dimensional space at tth iteration is denoted as:

$$x_i(t) = \{x_{i1}(t), x_{i2}(t), \ldots, x_{id}(t)\} \tag{15}$$

Its best position reached so far,

$$x_{i\_best}(t) = \{x_{i1\_best}(t), x_{i2\_best}(t), \ldots, x_{id\_best}(t)\} \tag{16}$$

Its velocity,

$$v_i(t) = \{(v_{i1}(t), v_{i2}(t), \ldots, v_{id}(t)\} \tag{17}$$

Individual particle's position in the search space is updated by

$$x_i(t+1) = x_i + v_i(t+1) \tag{18}$$

Where the new velocity

$$v_i(t+1) = \omega(t).v_i(t) + c_1 r_1 \{x_{i\_best}(t) - x_i(t)\} + c_2 r_2 \{x_{g\_best}(t) - x_i(t)\} \tag{19}$$

Where, I = 1, 2, . . ., P (P = total number of particles in a 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), and the other parts are biased with two acceleration coefficients c_1 and c_2, with the random numbers (r_1 and r_2) which are uniformly distributed between 0 to 1 (Ostadrahimi et al. 2012).

The inertia weights $\omega(t)$ and acceleration coefficients (c_1 and c_2) are updated in each time interval with the following equations:

$$\omega(t) = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{T} \times t \qquad (20)$$

$$c_1(t) = c_{1,max} - \frac{c_{1,max} - c_{1,min}}{T} \times t \qquad (21)$$

$$c_2(t) = c_{2,max} - \frac{c_{2,max} - c_{2,min}}{T} \times t \qquad (22)$$

where ω_{max} is the maximum and ω_{min} is the minimum inertia weight and their values have been taken as 0.7 and 0.2, respectively in the present problem. $c_{1,\ max}$ and $c_{2,\ max}$ are the maximum accelerations, and their values have been taken as 2. $c_{1,min}$ and $c_{2,min}$ 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:

$$v_{min} \leq v_i \leq v_{max} \qquad (23)$$

Particle velocity is a very important parameter. The value of v_{max} and v_{min} must be in limit otherwise the search space may not be 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 in exploration of a new solution space. The above adjustable parameters (v_{max}, ω_{max}, ω_{min}, c_1, and c_2) must be fixed. These adjustable parameters should be adjusted by trial and error, according to the sensitivity of the problem and the model performance. Moreover, these adjustable parameters, the number of iteration and number of particles affect 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:

Step 1   Initialize the particle swarm by randomly assigning initial velocity and position of each particle.
Step 2   Calculate the fitness function for each particle.
Step 3   For each particle, update its best position so far $x_{i\_best}(t)$, if its current position is better than its earlier best one.
Step 4   Update the globally best particle of the swarm that has the swarm's best fitness value and set its index as g and its position at $x_{g\_best}(t)$.
Step 5   Calculate velocities of all the particles using equation (19).
Step 6   Update the new position of each particle using equation (18).
Step 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

Step 8 If the stopping criterion is met stop else repeat steps 2–7
Step 9 Show the result given by the best particle (x_{g_best})

Above mentioned modified PSO methodology deals with both continuous and discrete variables, as requisite for the design of sewer networks.

5 Optimization of Sewer System

The second example network 2 (Sudarshanpura sewer network) as shown in Fig. 4 has been considered to for application of the proposed 'generation of a predefined number of spanning trees', their sequencing and MPSO algorithm. The Sudarshanpura sewer network (network 2) collects only domestic wastewater from the Sudarshanpura residential colony, Jaipur, India through gravity. It consists of 105 nodes (manholes), 116 links (sewer pipes), and STP is located at node number 0. The Link number, nodal connectivity, link length and nodal wastewater contribution are given as input.

The network 2 is solved in two phases. In the first phase, the 'generation of a predefined number of spanning trees' algorithm is applied to finds a predetermined number of layouts of the network in order of increasing length of sewer line; after this, by using Eq. 1 these alternative layouts are sequenced in ascending order of CQ. In the second phase, the proposed MPSO methodology is applied to the sequenced sewer layouts for component size optimization. The following steps have been followed to optimize the sewer system for component sizing:

1. Start with the first iteration (t = 1).
2. Select particle i = 1 (consisting of all sewer link diameters and slopes)
3. Calculate sewer hydraulis for complete sewer system.
4. Calculate invert levels of upstream and downstream node of a link
5. Calculate cost of sewers, cost of manholes and cost of earthwork
6. Calculate total cost of sewer network (TC)
7. Add the respective penalty costs in TC where contraints (maximum depth, maximum velocity, and minimum velocity) are violated.
8. Calculate fitness value of the particle and update pbest.
9. Increase the value of i by one. If it exceeds maximum number of particles go to step 10 else go to step 3
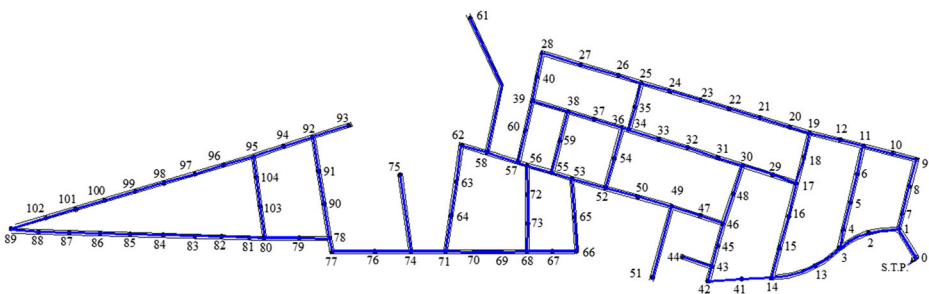

Fig. 4 Base network of Sudarshanpura (network 2)

Table 2 Sewer network cost details

Sewer Pipe cost		Manhole Cost		Cost of Earth work	
Diameter (mm)	(Rs./m)	Depth (m)	(Rs.)	Depth (m)	(Rs./m3)
200	518	<1	11,800	<1.5	203.00
250	724	1 to 2	23,100	1.5 to 3.0	233.50
300	973	2 to 3	40,000	3.0 to 4.5	299.00
350	1600	3 to 4	54,600	4.5 to 6.0	405.00
400	1850	4 to 5	69,200		
450	2150	5 to 6	77,500		
500	2520				

10. Calculate gbest among all particles for all time steps.
11. Calulate new particle velocities and their positions. Increase t by one. If t value exceeds maximum number of iterations go to step 12 else set i =1 and go to step 3.
12. Output the gbest and stop.

Table 2 shows the cost of NP4 class RCC sewer pipes (including the cost of their transportation, lowering & laying in trenches, aligning & jointing of pipes), cost of manholes (it depends on the depth of excavation and the diameter of the manhole and material of construction), and cost of earthworks (it 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). The cost of pipe (RCC NP4 class), manhole and earth work have been taken from Schedule of Rates (2013).

Table 3 Total cumulative discharge vs. Total cost at different iterations

Layout 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	3639.13	8,409,804	8,473,401	8,387,754	8,473,401	8,371,539	8,473,401
2	3642.34	8,531,554	8,547,602	8,494,772	8,547,330	8,477,464	8,547,330
3	3644.56	8,575,012	8,632,550	8,575,012	8,632,550	8,561,420	8,632,550
4	3692.80	9,005,505	9,064,954	8,930,532	9,064,954	8,984,307	9,064,954
5	3724.24	9,356,613	9,412,557	9,314,713	9,410,543	9,336,448	9,410,543
6	4027.95	11,432,085	11,492,097	11,412,199	11,492,097	11,414,562	11,492,097
7	4252.10	11,456,577	11,494,326	11,465,393	11,494,326	11,465,363	11,494,326
8	4480.85	11,528,582	11,627,095	11,505,595	11,618,001	11,526,601	11,618,001
9	4676.69	11,668,743	11,825,881	11,625,467	11,825,881	11,671,505	11,825,881
10	4774.97	11,786,525	11,910,006	11,789,190	11,910,006	11,769,816	11,910,006
11	5130.95	13,327,064	13,770,609	13,315,939	13,770,609	13,311,153	13,770,609
12	5521.53	13,584,318	14,126,408	13,569,519	14,126,408	13,569,977	14,126,408

6 Results

The performance of the proposed generation of a predefined number of spanning tree and MPSO algorithm is tested in this section by applying the both algorithms to find optimal design of network 2.

Table 3 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) thses cost are Rs. 8.477×10^6 and Rs. 8.547×10^6 respectively, for 90 iterations. Figure 5 shows the Optimal sewer layouts of a base network 2.

Results of MPSO are compared with original PSO in order to compare the efficiency of the proposed algorithm. The original PSO parameter values of c_1 and c_2 have been taken as 2 and ω has been taken as 0.8. The results are obtained using swarm size 1000 and 30, 60 and 90 iterations respectively for each sewer layout. Table 3 compares the results of the proposed MPSO with original PSO. It is clearly seen that the proposed MPSO algorithm was able to obtain a better solution as compared to an original PSO algorithm in all the layouts.

Optimal sewer layout of a base network 2 as shown in Fig. 5a is selected for the detailed design. Figure 6 a, b, c and d show that the minimum solution 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. 8.473×10^6, whereas the cost obtained by the MPSO is reduced to Rs. 8.371×10^6.

(a)

(b)
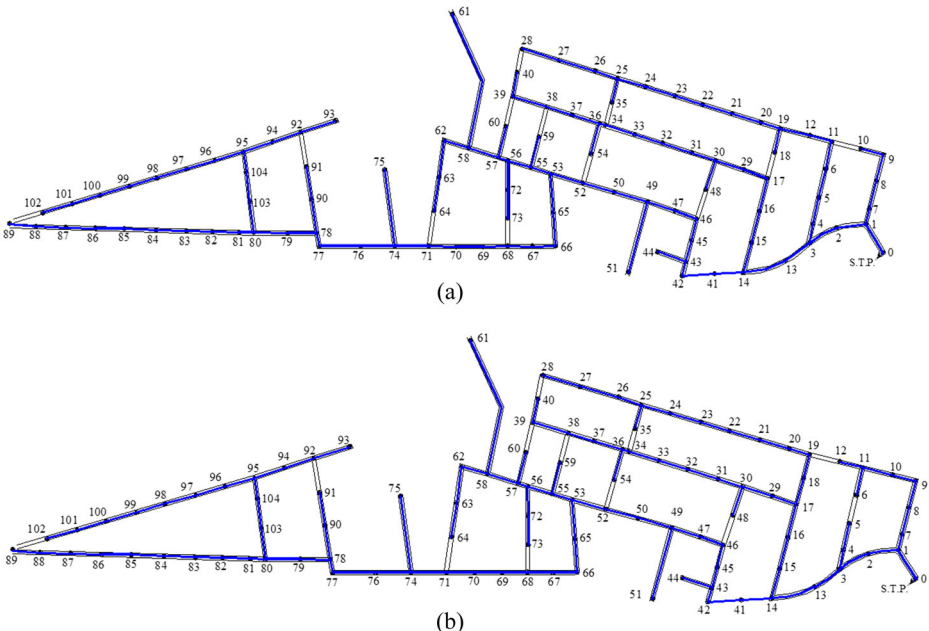
Fig. 5 Optimal sewer layouts of network 2 (**a**) $CQ = 3639.13$ l/s (**b**) $CQ = 3642.34$ l/s
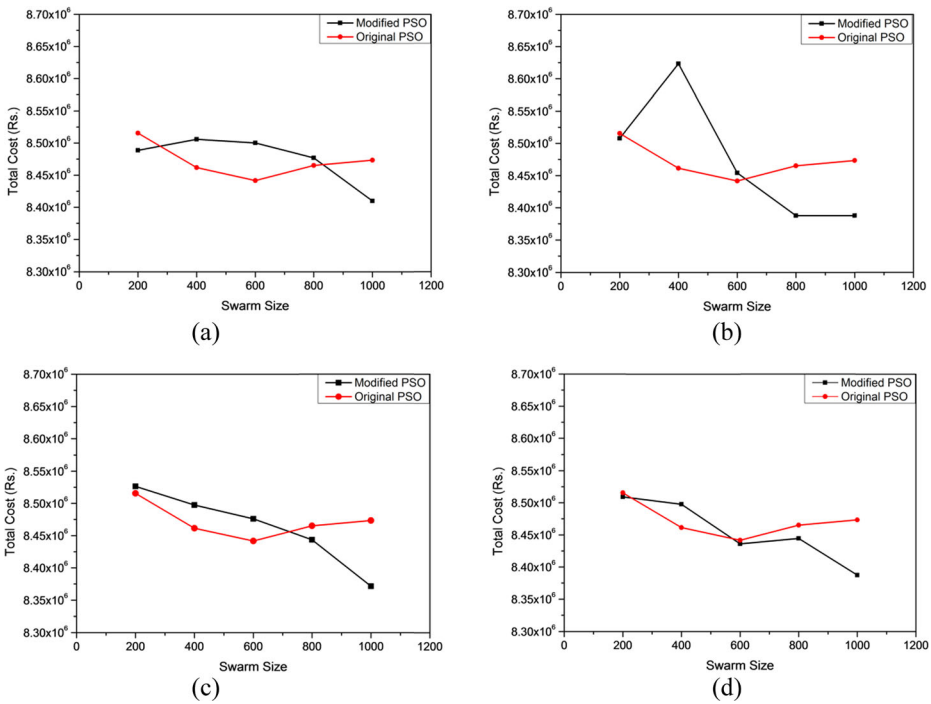
Fig. 6 Variations of the minimum cost with swarm sizes at (**a**) 30 iterations (**b**) 60 iterations (**c**) 90 iterations (**d**) 120 iterations

It is seen that the solution obtained by MPSO algorithm is better than the solution of the original PSO algorithm when the swarm size is 1000. Figure 7 shows the solution cost obtained with modified particle swarm optimization, the best solution produced when the swarm size is 1000. Table 4 shows the details of the optimal design of sewer component sizing of a layout Fig. 5a with 1000 swarm size and 90 iterations.

Fig. 7 Variations of the minimum cost with swarm sizes at different iterations, MPSO

Table 4 Daimeters & slopes of the optimal sewer network obtained by MPSO

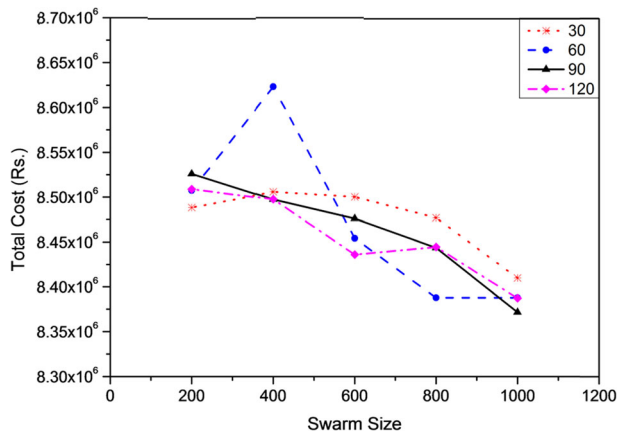| Pipe no.	Node no.		Length (m)	Diameter (mm)	Slope (1 in)	Design flow (m/s)	v_p (m/s)	d/D	cover depths (m)	
	Up	down							up	down
11	10	9	20	200	250	0.0004	0.27	0.10	1.120	1.150
21	18	19	12	200	250	0.0003	0.25	0.09	1.120	1.363
30	28	27	30	200	250	0.0004	0.25	0.09	1.730	1.120
38	35	25	12	200	250	0.0004	0.25	0.09	1.657	1.120
43	40	39	14	200	250	0.0004	0.25	0.09	1.120	1.406
48	44	43	30	200	250	0.0004	0.25	0.09	1.490	1.120
52	48	30	24	200	60	0.0005	0.45	0.08	1.570	1.120
55	51	49	72	200	250	0.0009	0.33	0.14	1.237	1.120
59	54	36	24	200	250	0.0005	0.28	0.11	1.419	1.120
62	59	55	30	200	250	0.0006	0.29	0.11	1.120	1.360
66	60	57	32	200	250	0.0006	0.30	0.12	1.120	1.568
69	61	58	143	300	250	0.0518	0.97	0.70	1.220	2.897
72	64	63	33	200	125	0.0007	0.39	0.10	1.120	1.124
79	73	72	30	200	250	0.0006	0.29	0.11	1.125	1.120
85	75	74	76	200	250	0.0010	0.34	0.15	1.120	1.229
99	89	88	30	300	250	0.0504	0.96	0.68	1.220	1.275
101	91	90	33	200	250	0.0008	0.33	0.14	1.120	1.142
103	93	92	36	200	250	0.0005	0.27	0.10	1.120	1.239
112	102	101	30	200	250	0.0008	0.32	0.13	1.120	1.135
10	9	8	30	200	60	0.0007	0.50	0.09	1.320	1.120
29	27	26	30	200	250	0.0008	0.32	0.13	1.120	1.565
42	39	38	30	200	250	0.0006	0.29	0.11	1.406	1.221
71	63	62	33	200	250	0.0011	0.35	0.16	1.124	1.151
78	72	56	21	200	150	0.0011	0.43	0.14	1.120	1.125
98	88	87	30	300	250	0.0508	0.97	0.69	1.275	1.380
100	90	78	33	200	60	0.0013	0.60	0.12	1.142	1.387
104	92	94	30	200	250	0.0008	0.33	0.14	1.239	1.309
105	94	95	26	200	250	0.0012	0.36	0.16	1.309	1.408
111	101	100	30	200	250	0.0011	0.36	0.16	1.135	1.190
9	8	7	30	200	60	0.0011	0.57	0.11	1.705	1.120
28	26	25	27	200	250	0.0011	0.35	0.16	1.565	2.178
41	38	37	30	200	100	0.0011	0.49	0.13	1.221	1.141
70	62	58	24	200	60	0.0014	0.62	0.13	1.151	1.281
97	87	86	30	300	250	0.0511	0.97	0.69	1.380	1.320
110	100	99	30	200	70	0.0015	0.61	0.14	1.190	1.559
8	7	1	9	200	250	0.0012	0.36	0.16	1.349	1.120
27	25	24	30	200	80	0.0019	0.62	0.16	2.178	2.413
40	37	36	16	200	250	0.0013	0.38	0.18	1.151	1.120
68	58	57	33	300	250	0.0536	0.97	0.71	2.897	2.944
96	86	85	30	300	250	0.0515	0.97	0.69	1.465	1.220
109	99	98	30	200	80	0.0019	0.62	0.16	1.559	1.869
26	24	23	30	200	100	0.0022	0.61	0.18	2.413	2.523

Table 4 (continued)

Pipe no.	Node no.		Length (m)	Diameter (mm)	Slope (1 in)	Design flow (m/s)	v_p (m/s)	d/D	cover depths (m)	
	Up	down							up	down
39	36	34	7	200	80	0.0019	0.63	0.16	1.120	1.153
65	57	56	8	300	250	0.0545	0.98	0.72	2.944	2.881
95	85	84	30	300	250	0.0519	0.97	0.70	1.220	1.270
108	98	97	30	200	100	0.0023	0.61	0.18	1.869	2.029
25	23	22	30	200	100	0.0026	0.64	0.20	2.523	2.748
36	34	33	18	200	100	0.0023	0.61	0.19	1.153	1.183
64	56	55	25	300	250	0.0560	0.98	0.74	2.881	2.746
94	84	83	30	300	250	0.0523	0.97	0.70	1.275	1.220
107	97	96	30	200	100	0.0027	0.64	0.20	2.029	2.214
24	22	21	30	200	125	0.0030	0.61	0.22	2.748	2.863
35	33	32	30	200	100	0.0027	0.64	0.20	1.183	1.248
61	55	53	20	300	250	0.0570	0.98	0.75	2.746	2.896
93	83	82	30	300	250	0.0527	0.97	0.70	1.220	1.290
106	96	95	30	200	125	0.0030	0.61	0.22	2.214	2.419
23	21	20	30	200	125	0.0034	0.63	0.24	2.863	2.988
34	32	31	30	200	125	0.0031	0.62	0.23	1.248	1.123
92	82	81	30	300	250	0.0530	0.97	0.71	1.290	1.295
116	95	104	27	200	150	0.0046	0.65	0.29	2.419	2.529
115	104	103	27	200	150	0.0049	0.66	0.30	2.529	2.644
22	20	19	18	200	150	0.0036	0.61	0.26	2.988	3.043
33	31	30	30	200	125	0.0035	0.64	0.24	1.230	1.120
91	81	80	10	300	250	0.0532	0.97	0.71	1.295	1.270
114	103	80	27	200	200	0.0052	0.61	0.33	2.644	2.724
14	19	12	30	200	150	0.0043	0.64	0.28	3.043	3.133
32	30	29	22	200	150	0.0043	0.64	0.28	1.223	1.120
90	80	79	31	300	250	0.0588	0.99	0.77	2.724	2.758
13	12	11	20	200	150	0.0046	0.65	0.29	3.133	2.476
31	29	17	30	200	150	0.0047	0.65	0.29	1.120	1.160
89	79	78	31	300	250	0.0592	0.99	0.78	2.758	2.587
7	11	6	30	200	200	0.0052	0.60	0.33	2.476	2.621
19	17	16	30	200	200	0.0052	0.61	0.33	1.160	1.175
88	78	77	13	300	200	0.0606	1.09	0.72	2.587	2.717
6	6	5	30	200	200	0.0055	0.62	0.34	2.621	2.676
18	16	15	30	200	200	0.0056	0.62	0.34	1.175	1.290
87	77	76	38	300	200	0.0611	1.09	0.72	2.717	2.842
5	5	4	30	200	200	0.0059	0.63	0.35	2.676	2.766
17	15	14	30	200	200	0.0060	0.63	0.36	1.290	1.415
86	76	74	38	300	200	0.0616	1.09	0.73	2.842	2.987
4	4	3	10	200	60	0.0060	0.97	0.26	2.766	2.868
84	74	71	34	300	200	0.0630	1.10	0.74	2.987	2.992
83	71	70	26	300	200	0.0635	1.10	0.75	2.992	3.037
82	70	69	26	300	200	0.0638	1.10	0.75	3.037	2.962

Table 4 (continued)

Pipe no.	Node no.		Length (m)	Diameter (mm)	Slope (1 in)	Design flow (m/s)	v_p (m/s)	d/D	cover depths (m)	
	Up	down							up	down
81	69	68	26	300	200	0.0642	1.10	0.75	2.962	2.872
77	68	67	22	300	200	0.0644	1.10	0.76	2.872	2.837
76	67	66	22	300	200	0.0647	1.10	0.76	2.837	2.907
75	66	65	30	300	200	0.0651	1.10	0.76	2.907	2.907
74	65	53	30	300	200	0.0655	1.10	0.77	2.907	2.917
60	53	52	30	400	250	0.1229	1.19	0.75	2.917	2.752
57	52	50	30	400	250	0.1234	1.19	0.75	2.752	2.647
56	50	49	30	450	450	0.1238	0.96	0.74	2.647	2.638
54	49	47	26	450	450	0.1251	0.96	0.75	2.638	2.281
53	47	46	26	450	450	0.1254	0.96	0.75	2.281	1.969
50	46	45	20	450	450	0.1258	0.96	0.75	1.969	2.288
49	45	43	20	450	450	0.1261	0.96	0.75	2.288	2.578
47	43	42	11	450	450	0.1266	0.96	0.76	2.578	2.462
46	42	41	30	450	450	0.1270	0.96	0.76	2.462	1.444
45	41	14	30	450	60	0.1274	2.13	0.42	1.625	1.370
16	14	13	30	450	100	0.1337	1.78	0.49	1.440	1.370
15	13	3	30	450	100	0.1341	1.78	0.49	1.375	1.370
3	3	2	23	450	350	0.1404	1.09	0.74	2.868	2.269
2	2	1	23	450	60	0.1407	2.18	0.44	2.357	1.370
1	1	0	30	450	70	0.1423	2.07	0.46	1.370	1.459

7 Conclusions

This paper presents the generation of a predefined number of spanning trees with their sequencing and modified PSO algorithm to optimally solve the problem of the layout and component size determination of sewer networks. An algorithm 'generation of a predefined number of spanning tree' is applied to generate a predetermined number of alternative layouts of a base network in order of increasing length. These layouts are sequenced in ascending order of total cumulative flows. After the layouts are sequenced, a modified PSO algorithm is applied to optimaly size sewer components of the sewer system. The proposed methods for optimal layout and component size determination were applied to a problem of Sudarshanpura sewer network design.

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 seen that the proposed modified PSO algorithm solution was better as compared to an original PSO algorithm in all the layouts for swarm size 1000. The minimum cost obtained by the original PSO is Rs. 8.473×10^6, whereas the cost obtained by the Modified PSO is reduced to Rs. 8.371×10^6. The results showed that the ability of the proposed methods to optimally solve the problem of the layout and component size determination of sewer networks.

References

Afshar MH (2006) Application of a genetic algorithm to storm sewer network optimization. Sci Iran 13:234–244

Afshar MH (2007) Partially constrained ant colony optimization algorithm for the solution of constrained optimization problems: application to storm water network design. Adv Water Resour 30:954–965

Afshar MH (2010) A parameter free continuous ant colony optimization algorithm for the optimal design of storm sewer networks: constrained and unconstrained approach. Adv Eng Softw 41:188–195

Afshar MH, Mariño MA (2006) Application of an ant algorithm for layout optimization of tree networks. Eng Optim 38:353–369

Argaman Y, Shamir U, Spivak E (1973) Design of optimal sewerage systems. J Environ Eng Div 99:703–716

Clark J, Holton DA (1995) A first look at graph theory. Allied Publishers Ltd

Dajani JS, Hasit Y (1974) Capital cost minimization of drainage networks. J Environ Eng Div 100:325–337

Deo N (2005) Graph theory with applications to engineering and computer science. Prentice Hall of India Pvt. Ltd., New Delhi

Diogo AF, Graveto VM (2006) Optimal layout of sewer systems: a deterministic versus a stochastic model. J Hydraul Eng 132:927–943

Eberhart RC, Shi Y (1998) Comparison between genetic algorithms and particle swarm optimization. In Evolutionary Programming VII. Springer Berlin Heidelberg, pp 611–616

Elimam AA, Charalambous C, Ghobrial FH (1989) Optimum design of large sewer networks. J Environ Eng 115:1171–1190

Guo Y, Walters GA, Khu ST, Keedwell E (2007) A novel cellular automata based approach to storm sewer design. Eng Optim 39:345–364

Guo YF, Walters GA, Khu ST, Keedwell EC (2008) Efficient multiobjective storm sewer design using cellular automata and genetic algorithm hybrid. J Water Resour Plan Manag 134:511–515

Haghighi A (2013) Loop-by-loop cutting algorithm to generate layouts for urban drainage systems. J Water Resour Plan Manag 139:693–703

Haghighi A, Bakhshipour AE (2012) Optimization of sewer networks using an adaptive genetic algorithm. Water Resour Manag 26:3441–3456

Izquierdo J, Montalvo I, Pérez R, Fuertes VS (2008) Design optimization of wastewater collection networks by PSO. Comput Math Appl 56:777–784

Karovic O, Mays LW (2014) Sewer system design using simulated annealing in excel. Water Resour Manag 28: 4551–4565

Kennedy J, Eberhart R (1995) Particle swarm optimization. IEEE International Conference on Neural Networks (Perth, Australia), IEEE Service Center, Piscataway, NJ, IV. pp 1942–1948

Kulkarni VS, Khanna P (1985) Pumped wastewater collection systems optimization. J Environ Eng 111:589–601

Li G, Matthew RGS (1990) New approach for optimization of urban drainage systems. J Environ Eng 116:927–944

Moeini R, Afshar MH (2012) Layout and size optimization of sanitary sewer network using intelligent ants. Adv Eng Softw 51:49–62

Ostadrahimi L, Mariño MA, Afshar A (2012) Multi-reservoir operation rules: Multi-swarm PSO-based optimization approach. Water Resour Manag 26:407–427

Pan T-C, Kao J-J (2009) GA-QP model to optimize sewer system design. J Environ Eng 135:17–24

Price RK (1978) Design of storm water sewers for minimum construction cost. 1st International Conference on Urban Strom Drainage. Southampton, United Kingdom, pp 636–647

Saatci A (1990) Velocity and depth of flow calculations in partially filled pipes. J Environ Eng 116:1202–1208

Schedule of Rates (2013) Rajasthan Urban Infrastructure Development Project (RUIDP), Government of Rajasthan

Shi Y, Eberhart R (1998) A modified particle swarm optimizer. IEEE International Conference on Evolutionary Computation. IEEE, Anchorage, AK, pp 69–73

Steele JC, Mahoney K, Karovic O, Mays LW (2016) Heuristic optimization model for the optimal layout and pipe design of sewer systems. Water Resour Manag 30:1605–1620

Swamee PK (2001) Design of sewer line. J Environ Eng 127:776–781

Tekeli S, Belkaya H (1986) Computerized layout generation for sanitary sewers. J Water Resour Plan Manag 112:500–515

Walsh S, Brown LC (1973) Least cost method for sewer design. J Environ Eng Div 99:333–345

Walters GA, Lohbeck T (1993) Optimal layout of tree networks using genetic algorithms. Eng Optim 22:27–48

Walters GA, Smith DK (1995) Evolutionary design algorithm for optimal layout of tree networks. Eng Optim 24: 261–281

Walters GA, Templeman AB (1979) Non-optimal dynamic programming algorithms in the design of minimum cost drainage systems. Eng Optim 4:139–148