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Optimal design of Sewer network using Cellular Automata

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Abstract.

In this paper, the General Cellular Automata (GCA) method is proposed for the optimal design of sewer network problems with the fixed layout. The network nodes and upstream and downstream pipe cover depths are considered as CA cells and cell states, respectively, and the links around each cell are taken into account as neighborhoods. The updating rule is derived mathematically from the original objective function of the problem. The proposed method is a general and flexible method for optimization of sewer networks as it can be used to optimally design both gravity and pumped network due to the use of pipe nodal cover depths as decision variables. The proposed method is tested against three gravitational sewer networks with different sizes and the comparison of results with other methods such as Cellular Automata, and Ant Colony Optimization Algorithm show the efficiency and effectiveness of the proposed method.

Keywords: Pumped Sewer Network, Cellular Automata, Optimization methods.

Introduction

The solution of sewer network optimization problems requires determination of pipe diameters and average pipe cover depths, minimizing the total cost of sewer network subject to operational constraints. Different numerical optimization approaches have been introduced and applied to the optimal design of sewer networks such as Linear Programming (LP) (Dajani and Gemmell 1971, Froise and Burges 1978), Non-Linear Programming (NLP) (Price 1978), Dynamic Programming (DP) (Yen et al. 1984, and Kulkarni and Khanna 1985), and Evolutionary Algorithms.

In the past decades, evolutionary algorithms have been widely applied for the optimal design of sewer systems due to their simplicity and flexibility. Pan and Kao (2009) used Quadratic Programming (QP) with Genetic Algorithm (GA) to solve the sewer network optimization problem for gravity and pumped alternatives within an acceptable computational time. Afshar (2010) applied the Continuous Ant Colony Optimization Algorithm (CACOA) for the optimal design of gravity sewer networks. Yeh et al. (2011) applied Tabu Search (TS) and Simulated Annealing (SA) for the optimization of sewer network problems. Haghighi and Bakhshipour (2012) developed an adaptive GA for the optimal design of gravity and pumped sewer networks. Palumbo et al. (2014) proposed a general method based on a standard GA for the optimal design of urban drainage networks.

Recently, Cellular Automata (CA) has been introduced to optimization problem. CA has four basic components, cell, cell state, neighborhood, and transition (updating) rule. Each cell has a finite possible value called cell state. The new states of all cells are defined simultaneously using an updating rule, which is a function of previous state of the cell itself and its neighborhoods.

In the early applications in water resource problems, CA was used to produce good initial populations for a GA leading to improved performance of the GA (Keedwell and khu 2005, and Guo et al. 2007b). Then CA was applied as a stand-alone optimizer with the transition rules derived by engineering judgment (Keedwell and Khu 2006a, 2006b; Guo et al. 2007a). Afshar et al. (2011) proposed a single stage CA for the optimal design of sewer networks in which the network nodes were considered as the CA cells and the corresponding nodal excavation depths as cell states. Afshar and Rohani (2012) extended the single stage CA method of Afshar et al. (2011) into a two-stage CA method, called Hybrid CA (HCA), with the pipe diameters and network nodal cover depths as decision variables. However, these methods were unable to design pumped sewer networks due to the restive choice of nodal excavation depths as decision variables.

In this paper, General Cellular Automata (GCA) method is proposed for design of pumped or gravity sewer network with fixed layout in which, pipe nodal cover depths are considered as decision variables. The nodes considered as the CA cells and upstream and downstream pipe cover depths as cell states and the links around each cell are taken into account as neighborhoods. The CA updating rule is derived by requiring that the network cost is minimized in the neighborhood of each cell. The proposed method is a general and flexible method for optimization of sewer networks as it can be used to optimally design both gravity and pumped network due to the use of pipe nodal cover depths as decision variables. The GCA method is used to design three benchmark examples and comparison the results with the existing ones shows the efficiency and effectiveness of the method to solve the sewer design optimization problems.

Sewer network Size Optimization

Optimal sewer network design with a fixed layout aims to find a cost-effective solution by determining the pipes diameters and slopes which minimizes the capital investment whilst ensuring a good system performance under specific design criteria. The problem of sewer network design for a fixed network layout can be formulated as:

$$\begin{aligned} Min C_{network} = \sum_{l=1}^{NL} Cp_l + \sum_{k=1}^{NN} Cm_k + \sum_{k=1}^{NN} Cd_k + \sum_{k=1}^{NN} Cpump_k = \sum_{l=1}^{NL} L_l Kp\left(D_l, H_l^i, H_l^j\right) \\ + \sum_{k=1}^{NN} Km\left(hm_k\right) + \sum_{k=1}^{NN} Kd\left(hd_k\right) + \sum_{k=1}^{NN} Kpp\left(Q_k, hp_k\right) \end{aligned} \tag{1}$$

Subject to:

$$V_{\min} \le V_l \le V_{\max} \qquad l = 1,\ldots,NL \tag{2}$$

$$\beta_{\min} \le \beta_l \le \beta_{\max} \qquad l = 1,\ldots,NL \tag{3}$$

$$H_{\min} \leq H_l^i, H_l^j \leq H_{\max} \qquad l = 1, \ldots, NL \tag{4}$$

$$S_{\min} \leq S_l \leq S_{\max} \qquad l = 1, \ldots, NL \tag{5}$$

$$D_l \in \mathbf{D} \qquad l = 1, \ldots, NL \tag{6}$$

$$D_l \leq D_{l'} \qquad l = 1, \ldots, NL \tag{7}$$

Where, $C_{network}$ is the total cost of the network, Cp_l is the installation cost of l^{th} pipe, Cm_k is the cost of k^{th} manhole, Cd_k is the cost of drop installed at the k^{th} node if required, $Cpump_k$ represents the installation and/or operation cost of the pump at the k^{th} node, *NL* is the number of pipes in the network, *NN* is the number of nodes in the network, L_l is the length of l^{th} pipe, Kp is the unit cost of l^{th} pipe defined as a function of its diameter (D_l) and upstream and downstream nodal cover depths of l^{th} pipe (H_l^i, H_l^j), Km is the cost of manhole construction as a function of manhole depth (hm), Kd is the cost of drop construction as a function of drop height (hd), and Kpp is the coefficient of pumping installation and/or operation cost as a function of pumping discharge (Q) and pumping height (hp)

Eqs. (2) to (7) represents the constraints of velocity, water-depth ratio, pipe nodal cover depth, pipe slope, commercially available pipe diameter, and progressive diameter for the sewer network problem, respectively, where, V_l is the velocity of l^{th} pipe, $\beta_l = {y_l}/{D_l}$, y_l is the flow depth of l^{th} pipe, S_l is the slope of l^{th} pipe, $\boldsymbol{D}$ is the set of commercially available pipe diameters, l' refers to the set of pipe located downstream of pipe *l*, and min, max are the allowable minimum and maximum parameters, respectively.

General Cellular Automata (GCA)

As it is mentioned before, CA has four basic components, cell, cell state, neighborhood, and updating rule, and application of CA to any problem requires that these parameters are properly defined. In optimization problems, generally, cell states are decision variables and depend on the defined cells.

In General Cellular Automata (GCA) method, each node of the sewer network is regarded as a cell and pipe nodal cover depths are considered as the cell states (decision variables). Choosing the pipe nodal cover depths as decision variables results in considering pumping station in the nodes that nodal cover depth of connected pipes are not coincident. The set of the pipes connected to each node of the network is considered as the cell neighborhood. The convergence criterion is met when the solution is fixed or repeated in the successive iteration.

Decision variables are updated through the updating rule. This rule is achieved by considering objective function on the cell and its neighborhoods. The objective function (Eq. 1), in the absence of drop cost and applying a penalty method for the satisfaction of velocity and pipe slope constraints defined by Eqs. (2) and (5), can be written as:

$$MinC = \sum_{l=1}^{NL} Cp_l + \sum_{k=1}^{NN} Cm_k + \sum_{l=1}^{NL} \left(\alpha\, CSVv_l + \alpha\, CSVs_l\right) + \sum_{k=1}^{NN} Cpump_k \tag{8}$$

Where, α is the penalty parameters with large enough positive value, and $CSVv, CSVs$ represent the violation from the constraints of velocity and slope for each pipe, respectively, $CSVv_l = \left(1 - \frac{V_l}{V_{min}}\right)^2 + \left(\frac{V_l}{V_{max}} - 1\right)^2$, $CSVs_l = \left(1 - \frac{S_l}{S_{min}}\right)^2 + \left(\frac{S_l}{S_{max}} - 1\right)^2$, $Cp_l = L_l Kp\left(D_l, H_l^i, H_l^j\right)$, $Cm_i = Km\left(hm_i\right)$, $Cpump_k = Kpp\left(Q_k, hp_k\right)$.

Subject to:

$$H_{\min} \le H_l^i, H_l^j \le H_{\max} \qquad l = 1, \ldots, NL \tag{9}$$

The pipe nodal cover depths are calculated in a manner that the objective function over the cell neighborhood (Ω_k) is minimized. Since the constraint of water-depth ratio is considered in calculation of pipe diameters when the optimization process is finished, this constraint is automatically satisfied. Pipe slopes are obtained using the optimal values of upstream and downstream pipe nodal cover depths calculated with CA and then for getting the pipe diameters, starting from the smallest diameter, and increased the pipe diameter until the water-depth ratio attains its maximum value, which does not violate the constraint of maximum water-depth ratio. The resulting diameter is then considered as the optimal diameter for the corresponding pipe. Therefore, all the constraints of optimization problem are automatically satisfied.

The objective function over the cell neighborhood is defined as:

$$C_k = \sum_{l \in \Omega_k} \left(Cp_l + \alpha\, CSVv_l + \alpha\, CSVs_l \right) + Cm_k + Cpump_k \tag{10}$$

Minimization of the local objective function of Eq. (10) with respect to pipe nodal cover depths ($H_l^i, H_l^j \quad l = 1,\ldots,NL$) leads to the nonlinear system of equations to be solved with the Newton-Raphson method which results in the updated pipe nodal cover depths:

$$\mathbf{K}\big|^{kk} \Delta X = \mathbf{F}\big|^{kk} \qquad \Delta X = \Delta\left(H_1^k, H_2^k, H_3^k, \ldots\right) = \Delta\left(H_{l \in \Omega_k}\right) \qquad \mathit{\Delta} X_k = \mathit{\Delta} X_k^{kk+1} - \mathit{\Delta} X_k^{kk} \tag{11}$$

Where, **K** is the stiffness matrix, **F** is the right-hand side vector, *kk* is the nonlinear iteration index, $\mathbf{F}^{kk} = F\left(H_{l \in \Omega_k}^{kk}\right)$, and $\Delta H_{l \in \Omega_k}$ is the change in the value of the cell state. **F** and **K** are both implicit functions of the $\Delta H_{l \in \Omega_k}$ which can be calculated using the chain rule of differentiation and Manning equation. This procedure is repeated for the cell under consideration until the convergence is met and the process of updating is repeated for all cells of the network.

Test examples

In this section, the performance of GCA method is investigated by applying the model to three hypothetical design problems with different sizes previously proposed and used by Moeini and Afshar (2012 a,b) for the simultaneous layout and size optimization of sewer network using ACOA based methods. The optimal layouts obtained by Moeini and Afshar (2012 b), shown in Figure 1, is used here to assess the efficiency and effectiveness of GCA method. More details and constraints of the sewer networks can be found in the work of Moeini and Afshar (2012 a,b) and Rohani and Afshar (2014).

The terms of pipe and manhole construction costs are defined as (Moeini and Afshar, 2012 a,b):

$$\begin{aligned} K_p &= 10.93 e^{3.43D} + 0.012 X^{1.53} + 0.437 X^{1.47} D \\ K_h &= 41.46 h_m \end{aligned} \tag{12}$$

Where, *D* is the pipe diameter (m), *X* is the buried depth (m), and h_m is the depth of manhole (m).

These test problems are here solved using GCA method and the results are presented in Table 1 and compared with CA (Rohani and Afshar, 2014), HCA (Rohani and Afshar, 2014), and those of ACOA-TGA (Moeini and Afshar, 2012 a) and CACOA-TGA (Moeini and Afshar, 2012 b) methods using a 2 MHz Pentium 4. It can be seen that the cost of the GCA method is near the optimal solution obtained by other methods, while requiring comparable computational effort. Since GCA method requires an initial guess for decision variables of the problem, pipe nodal cover depths, to start off the solution procedure, a sensitivity analysis is carried out here to assess the sensitivity of the final solution to the initial guess. Table 2 represents the maximum, minimum and average solution costs over 10 runs using different initial designs along with the scaled standard deviation of the solutions defined as the ratio of the standard deviation to the average solution. This table emphasizes on the insensitivity of the CA methods to the initial population. Details of the optimal solution obtained by the GCA method for three sewer networks are also shown in Table 3, 4, and 5, respectively.

Concluding remarks

In this paper, General Cellular Automata approach was used for the optimal solution of sewer network design problems. Considering the pipe nodal cover depths as decision variables in the proposed method resulted in flexibility of the method for optimization of both gravity and pumped sewer networks. The network nodes and upstream and downstream pipe cover depths were considered as CA cells and cell states, respectively, and the links around each cell were taken into account as neighborhoods. The GCA method was used to solve three benchmark examples in the literature and the comparison of the results with other CA methods and two versions of Ant Colony Optimization Algorithm indicated the ability and efficiency of the GCA method to produce near optimal results.

Figures and Tables

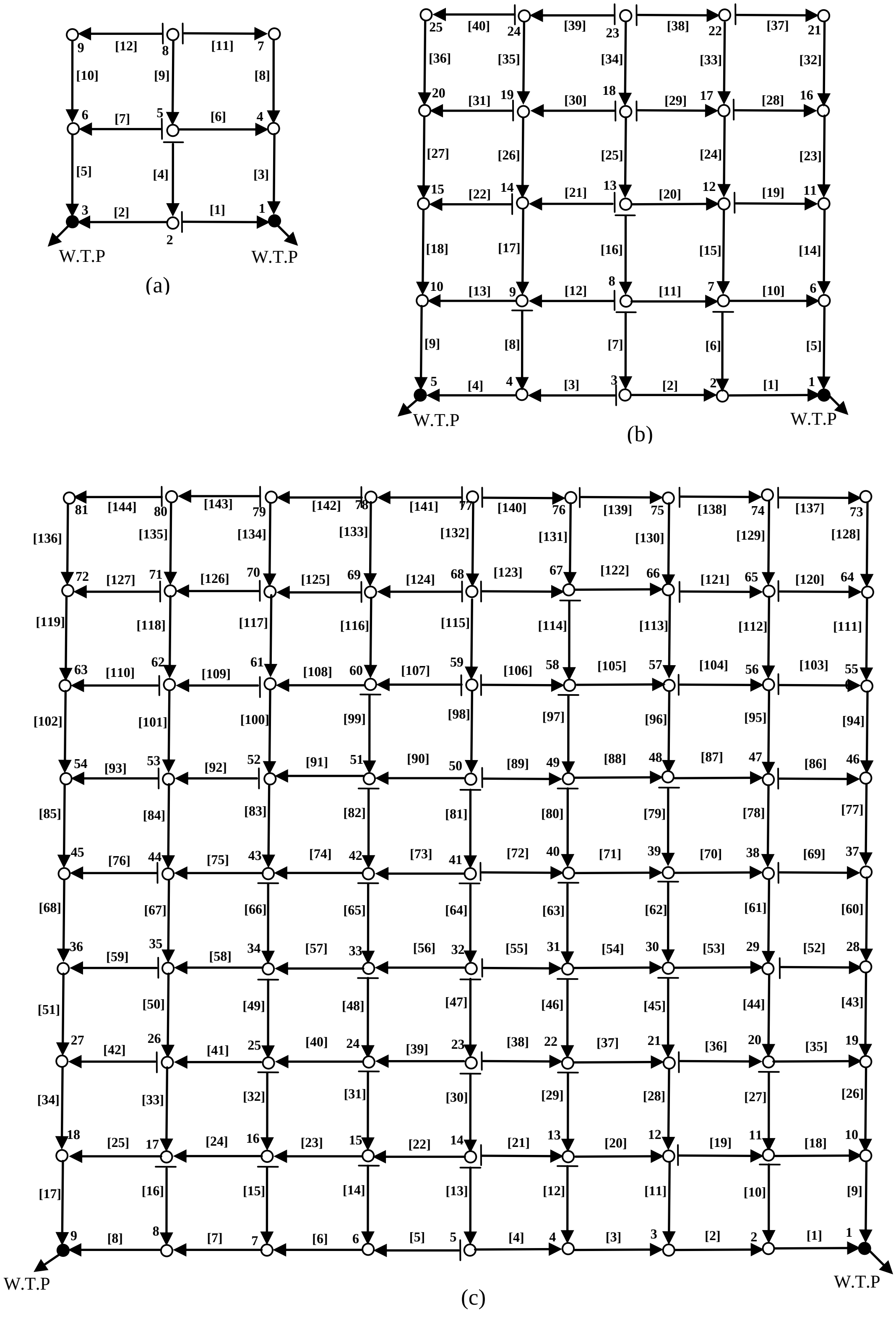

Figure 1: Network layouts for three examples: a) small scale sewer network, b) medium scale sewer network, c) large scale sewer network.

Table 1: Optimal network cost obtained by different methods.

Test Example	Model	Cost	Time (milli second)
Small Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	23467	-
	CACOA-TGA (Moeini and Afshar, 2012 b)	23467	-
	CA (Rohani and Afshar 2014)	23811	1.6
	HCA-Discrete (Rohani and Afshar 2014)	23460	4.7
	HCA-Continuous (Rohani and Afshar 2014)	23513	3.1
	GCA	23747	9.4
Medium Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	86204	-
	CACOA-TGA (Moeini and Afshar, 2012 b)	85990	-
	CA (Rohani and Afshar 2014)	88096	14.1
	HCA-Discrete (Rohani and Afshar 2014)	85873	46.9
	HCA- Continuous (Rohani and Afshar 2014)	86678	15.6
	GCA	87484	42.2
Large Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	365600	-
	CACOA-TGA (Moeini and Afshar, 2012 b)	363922	-
	CA (Rohani and Afshar 2014)	370486	103.1
	HCA-Discrete (Rohani and Afshar 2014)	361685	200.0
	HCA- Continuous (Rohani and Afshar 2014)	367436	54.6
	GCA	368142	240.6

Table 2: Maximum, Minimum and Average solution costs over 10 runs.

		Cost			
Test Example	Model	Minimum	Maximum	Average	Scaled Standard Deviation
Small Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	23467	23467	23467	0.0000
	CACOA-TGA (Moeini and Afshar, 2012 b)	23467	23467	23467	0.0000
	CA (Rohani and Afshar 2014)	23811	23811	23811	0.0000
	HCA-Discrete (Rohani and Afshar 2014)	23460	23747	23546	0.0059
	HCA-Continuous (Rohani and Afshar 2014)	23513	34064	25798	0.1683
	GCA	23747	23747	23747	0.0000
Medium Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	86204	87127	86642	0.0037
	CACOA-TGA (Moeini and Afshar, 2012 b)	85990	86591	86187	0.0020
	CA (Rohani and Afshar 2014)	88096	88096	88096	0.0000
	HCA-Discrete (Rohani and Afshar 2014)	85873	86953	86410	0.0052
	HCA- Continuous (Rohani and Afshar 2014)	86678	87786	87397	0.0038
	GCA	87484	87484	87484	0.0000
Large Scale Network	ACOA-TGA (Moeini and Afshar, 2012 a)	365600	381484	372605	0.0127
	CACOA-TGA (Moeini and Afshar, 2012 b)	363922	367174	365606	0.0030
	CA (Rohani and Afshar 2014)	370486	370489	370488	0.0000
	HCA-Discrete (Rohani and Afshar 2014)	361685	367131	363894	0.0040
	HCA- Continuous (Rohani and Afshar 2014)	367436	371350	369661	0.0031
	GCA	368142	368142	368142	0.0000

Table 3: Results obtained from GCA method for the small scale sewer network.

		Cover Depth (m)			
Pipe	D (mm)	Upstream	Downstream	V (m/s)	y/d
1	100	2.5	4.5	1.39	0.57
2	150	2.5	4.5	1.83	0.58
3	200	2.5	4.5	2.25	0.61
4	150	2.5	2.5	1.27	0.56
5	200	2.5	4.5	2.08	0.50
6	200	2.5	2.5	1.52	0.53
7	150	2.5	2.5	1.27	0.56
8	150	2.5	2.5	1.27	0.56
9	150	2.5	2.5	1.27	0.56
10	150	2.5	2.5	1.27	0.56
11	100	2.5	2.5	1.05	0.73
12	100	2.5	2.5	1.05	0.73

Table 4: Results obtained from GCA method for the medium scale sewer network.

		Cover Depth (m)			
Pipe	D(mm)	Upstream	Downstream	V (m/s)	y/d
1	200	2.81	4.50	2.11	0.57
2	150	2.50	2.81	1.47	0.70
3	100	2.50	2.61	1.07	0.72
4	150	2.61	4.50	1.91	0.72
5	350	3.36	4.50	2.95	0.65
6	150	2.50	2.81	1.35	0.54
7	150	2.50	2.50	1.27	0.56
8	150	2.50	2.61	1.30	0.55
9	300	3.28	4.50	2.78	0.74
10	300	2.73	3.36	2.50	0.72
11	200	2.50	2.73	1.58	0.52
12	150	2.50	2.62	1.30	0.55
13	300	2.62	3.28	2.35	0.57
14	200	2.60	3.36	1.98	0.78
15	300	2.50	2.73	2.19	0.60
16	150	2.50	2.50	1.27	0.56
17	250	2.50	2.62	1.97	0.69
18	200	2.57	3.28	1.96	0.79
19	150	2.50	2.60	1.30	0.55
20	200	2.50	2.50	1.65	0.70
21	150	2.50	2.50	1.27	0.56
22	150	2.50	2.57	1.29	0.55
23	200	2.50	2.60	1.63	0.61
24	200	2.50	2.50	1.68	0.80
25	200	2.50	2.50	1.52	0.53
26	200	2.50	2.50	1.68	0.80
27	200	2.50	2.57	1.62	0.61
28	150	2.50	2.50	1.27	0.56
29	150	2.50	2.50	1.27	0.56
30	150	2.50	2.50	1.27	0.56
31	150	2.50	2.50	1.27	0.56
32	150	2.50	2.50	1.27	0.56
33	150	2.50	2.50	1.38	0.74
34	150	2.50	2.50	1.27	0.56
35	150	2.50	2.50	1.38	0.74
36	150	2.50	2.50	1.27	0.56
37	100	2.50	2.50	1.05	0.73
38	100	2.50	2.50	1.05	0.73
39	100	2.50	2.50	1.05	0.73
40	100	2.50	2.50	1.05	0.73

Table 5: Results obtained from GCA method for the large scale sewer network.

Pipe	D(mm)	Cover Depth (m)		V (m/s)	y/d
		Upstream	Downstream		
1	350	3.33	4.50	2.92	0.62
2	350	2.77	3.33	2.62	0.61
3	200	2.50	2.77	1.74	0.67
4	150	2.50	2.50	1.38	0.74
5	100	2.50	2.50	1.05	0.73
6	200	2.50	2.50	1.52	0.53
7	200	2.50	2.97	1.85	0.73
8	250	2.97	4.50	2.36	0.55
9	500	3.67	4.50	3.69	0.78
10	150	2.50	3.33	1.45	0.50
11	300	2.50	2.77	2.29	0.68
12	150	2.50	2.50	1.27	0.56
13	150	2.50	2.50	1.27	0.56
14	150	2.50	2.50	1.27	0.56
15	150	2.50	2.50	1.27	0.56
16	150	2.50	2.97	1.38	0.52
17	550	3.69	4.50	3.91	0.81
18	200	2.50	3.67	1.99	0.60
19	150	2.50	2.50	1.27	0.56
20	200	2.50	2.50	1.65	0.70
21	150	2.50	2.50	1.27	0.56
22	200	2.50	2.50	1.52	0.53
23	250	2.50	2.53	1.81	0.56
24	250	2.53	3.13	2.18	0.68
25	550	3.13	3.69	3.68	0.71
73	200	2.5	2.5	1.52	0.53
74	250	2.5	2.5	1.80	0.57
75	400	2.5	2.5	2.67	0.79
76	150	2.5	2.5	1.27	0.56
77	250	2.5	2.5	1.92	0.71
78	400	2.5	2.5	2.65	0.74
79	150	2.5	2.5	1.27	0.56
80	150	2.5	2.5	1.27	0.56
81	150	2.5	2.5	1.27	0.56
82	150	2.5	2.5	1.27	0.56
83	400	2.5	2.5	2.57	0.65
84	300	2.5	2.5	2.10	0.62
85	250	2.5	2.5	1.92	0.71
86	150	2.5	2.5	1.27	0.56
87	350	2.5	2.5	2.42	0.73
88	200	2.5	2.5	1.65	0.70
89	150	2.5	2.5	1.27	0.56
90	250	2.5	2.5	1.80	0.57
91	250	2.5	2.5	1.94	0.76
92	150	2.5	2.5	1.27	0.56
93	150	2.5	2.5	1.27	0.56
94	250	2.5	2.5	1.80	0.57
95	250	2.5	2.5	1.92	0.71
96	300	2.5	2.5	2.20	0.78
97	150	2.5	2.5	1.27	0.56

		Cover Depth (m)			
Pipe	D(mm)	Upstream	Downstream	V (m/s)	y/d
26	500	3.10	3.67	3.50	0.76
27	150	2.50	2.50	1.27	0.56
28	250	2.50	2.50	1.89	0.66
29	150	2.50	2.50	1.27	0.56
30	150	2.50	2.50	1.27	0.56
31	150	2.50	2.50	1.27	0.56
32	150	2.50	2.53	1.28	0.56
33	500	2.78	3.13	3.37	0.82
34	300	2.86	3.69	2.56	0.67
35	500	2.73	3.10	3.27	0.66
36	150	2.50	2.73	1.33	0.54
37	200	2.50	2.50	1.65	0.70
38	150	2.50	2.50	1.27	0.56
39	200	2.50	2.50	1.52	0.53
40	250	2.50	2.50	1.80	0.57
41	250	2.50	2.78	2.06	0.72
42	150	2.50	2.86	1.36	0.53
43	300	2.61	3.10	2.35	0.63
44	500	2.55	2.73	3.12	0.65
45	150	2.50	2.50	1.27	0.56
46	150	2.50	2.50	1.27	0.56
47	150	2.50	2.50	1.27	0.56
48	150	2.50	2.50	1.27	0.56
49	150	2.50	2.50	1.27	0.56
50	500	2.58	2.78	3.21	0.72
51	300	2.52	2.86	2.29	0.64

		Cover Depth (m)			
Pipe	D(mm)	Upstream	Downstream	V (m/s)	y/d
98	200	2.5	2.5	1.65	0.70
99	150	2.5	2.5	1.27	0.56
100	300	2.5	2.5	2.20	0.78
101	250	2.5	2.5	1.92	0.71
102	250	2.5	2.5	1.80	0.57
103	150	2.5	2.5	1.27	0.56
104	150	2.5	2.5	1.27	0.56
105	200	2.5	2.5	1.65	0.70
106	150	2.5	2.5	1.27	0.56
107	150	2.5	2.5	1.27	0.56
108	250	2.5	2.5	1.92	0.71
109	150	2.5	2.5	1.27	0.56
110	150	2.5	2.5	1.27	0.56
111	200	2.5	2.5	1.60	0.62
112	200	2.5	2.5	1.68	0.80
113	250	2.5	2.5	1.94	0.76
114	150	2.5	2.5	1.27	0.56
115	200	2.5	2.5	1.52	0.53
116	200	2.5	2.5	1.68	0.80
117	200	2.5	2.5	1.68	0.80
118	200	2.5	2.5	1.68	0.80
119	200	2.5	2.5	1.60	0.62
120	150	2.5	2.5	1.27	0.56
121	150	2.5	2.5	1.27	0.56
122	200	2.5	2.5	1.68	0.80
123	150	2.5	2.5	1.27	0.56

		Cover Depth (m)			
Pipe	D(mm)	Upstream	Downstream	V (m/s)	y/d
52	150	2.50	2.61	1.30	0.55
53	250	2.50	2.55	1.91	0.65
54	200	2.50	2.50	1.65	0.70
55	150	2.50	2.50	1.27	0.56
56	200	2.50	2.50	1.52	0.53
57	250	2.50	2.50	1.80	0.57
58	250	2.50	2.58	1.98	0.75
59	150	2.50	2.52	1.28	0.56
60	300	2.50	2.61	2.11	0.58
61	450	2.50	2.55	2.88	0.70
62	150	2.50	2.50	1.27	0.56
63	150	2.50	2.50	1.27	0.56
64	150	2.50	2.50	1.27	0.56
65	150	2.50	2.50	1.27	0.56
66	150	2.50	2.50	1.27	0.56
67	450	2.50	2.58	2.94	0.79
68	300	2.50	2.52	2.08	0.59
69	150	2.50	2.50	1.27	0.56
70	250	2.50	2.50	1.89	0.66
71	200	2.50	2.50	1.65	0.70
72	150	2.50	2.50	1.27	0.56

		Cover Depth (m)			
Pipe	D(mm)	Upstream	Downstream	V (m/s)	y/d
124	150	2.5	2.5	1.27	0.56
125	150	2.5	2.5	1.27	0.56
126	150	2.5	2.5	1.27	0.56
127	150	2.5	2.5	1.27	0.56
128	150	2.5	2.5	1.27	0.56
129	150	2.5	2.5	1.38	0.74
130	150	2.5	2.5	1.38	0.74
131	150	2.5	2.5	1.38	0.74
132	150	2.5	2.5	1.27	0.56
133	150	2.5	2.5	1.38	0.74
134	150	2.5	2.5	1.38	0.74
135	150	2.5	2.5	1.38	0.74
136	150	2.5	2.5	1.27	0.56
137	100	2.5	2.5	1.05	0.73
138	100	2.5	2.5	1.05	0.73
139	100	2.5	2.5	1.05	0.73
140	100	2.5	2.5	1.05	0.73
141	100	2.5	2.5	1.05	0.73
142	100	2.5	2.5	1.05	0.73
143	100	2.5	2.5	1.05	0.73
144	100	2.5	2.5	1.05	0.73

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