Scattergraph Principles and Practice

A Comparison of Various Applications of the Manning Equation

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ABSTRACT The Manning Equation is an empirical formula commonly used to design sewer systems. This equation is also used to describe the performance of existing sewers by evaluating flow monitor data on a scattergraph using a variety of methods, including the Design Method, the Lanfear-Coll Method, and the Stevens-Schutzbach Method. The proper selection and application of these methods have a significant impact on the calculation of sewer capacity and the evaluation of sewer performance based on flow monitor data.

Examples of each method are provided from flow monitor locations throughout the United States. Laboratory research by the authors is also provided to further explore the performance of these methods and provide guidelines for their proper application.

KEY WORDS Flow Monitoring, Manning Equation, Scattergraph, Sewer Capacity

Introduction

The scattergraph is a graphical tool that provides insight into sewer performance through a simple and intuitive display of flow monitor data. The resulting patterns form characteristic signatures that reveal important information about conditions within a sewer and the impact that these conditions have on sewer capacity.[1] The Manning Equation is an important component of the scattergraph and can be applied using a variety of methods. Proper selection and application of these methods have a significant impact on the calculation of sewer capacity and the evaluation of sewer performance based on flow monitor data. Therefore, the purpose of this paper is to provide an overview and comparison of three methods that use the Manning Equation to estimate sewer capacity and assess sewer performance from flow monitor data and provide guidelines for their proper application.

Manning Equation

The Manning Equation is an empirical formula used to design sewer systems. The most common expression of this formula is provided in Equation (1).

$$v = \frac{1}{n} R^{2/3} S^{1/2} \tag{1}$$

where: v = flow velocity, m/s
n = roughness coefficient
R = hydraulic radius, m
S = slope of the energy gradient

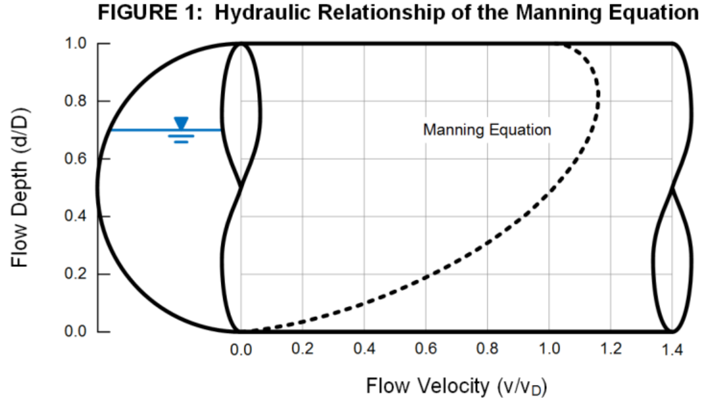
Several assumptions are generally made with respect to the Manning Equation: the roughness coefficient is constant, and the slope of the energy gradient equals the slope of the pipe.[2] Based on these assumptions, the Manning Equation can be algebraically rearranged such that these parameters are consolidated into a single coefficient, defined as the *hydraulic coefficient*, and restated as shown in Equation (2). This expression is useful in subsequent discussions.

$$v = CR^{2/3} \tag{2}$$

where: v = flow velocity, m/s
C = hydraulic coefficient
R = hydraulic radius, m

The relationship between flow depth and velocity described by the Manning Equation for a circular sewer is depicted in Figure 1 as a *pipe curve* (···) and provides a convenient reference to evaluate flow monitor data.

FIGURE 1: Hydraulic Relationship of the Manning Equation

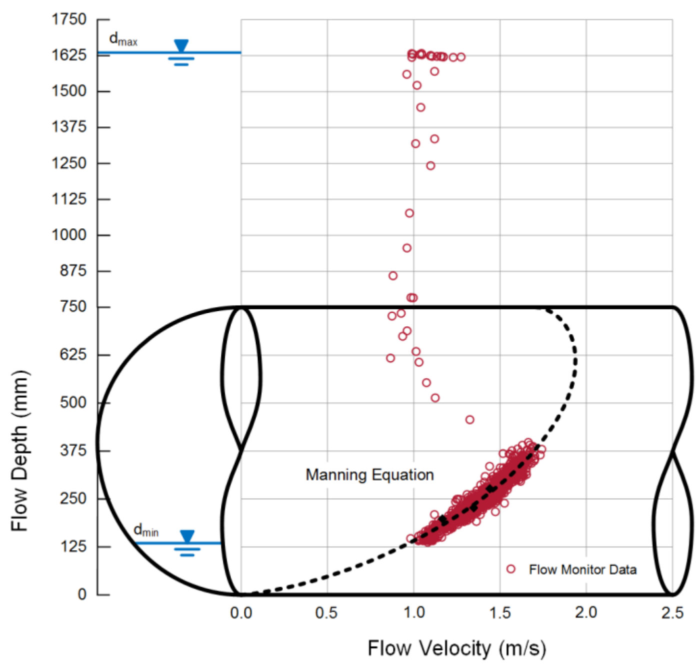


Manning Methods

The Manning Equation is also used to describe the performance of existing sewers by evaluating flow monitor data on a scattergraph, as shown in Figure 2. The Manning Equation is used to generate a pipe curve which is then compared to actual flow monitor data (○). This data may agree or disagree with the Manning Equation, depending on actual conditions at the monitoring location. In either case, important information can be learned about the performance of a sewer and its effect on sewer capacity.[3]

For example, the flow monitor data shown in Figure 2 indicate that this sewer operates as expected under uniform flow conditions up to a flow depth of about 375 mm. However, as backwater conditions develop, flow conditions become deeper and slower and are revealed on the scattergraph as a departure from the pipe curve, resulting in surcharge and overflow conditions at a much lower capacity than expected.[4] Three manual confirmations (◆) are also shown and provide a means to evaluate the accuracy of the flow monitor.

FIGURE 2: Scattergraph of Flow Depth and Velocity Data

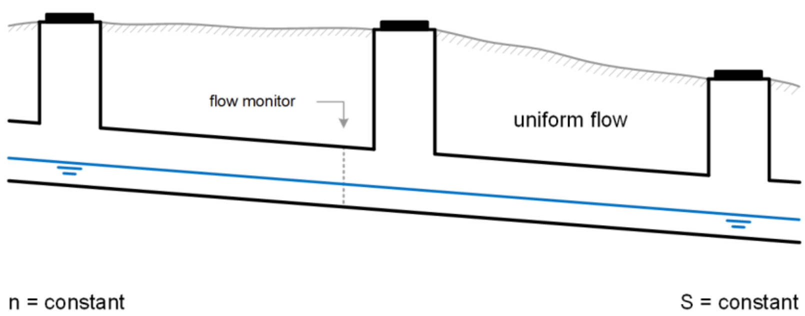


The Manning Equation is an important component of the scattergraph and can be applied using three different methods, defined as the *Design Method*, the *Lanfear-Coll Method*, and the *Stevens-Schutzbach Method*. The Design Method uses the Manning Equation to describe a relationship between flow depth and velocity using a specified roughness coefficient and pipe slope. This relationship is then compared with actual flow monitor data. The Lanfear-Coll Method and the Stevens-Schutzbach Method use curve fitting techniques to correlate the Manning Equation directly to such data, and each method may rely on assumptions different from design or as-built conditions. An overview and comparison of these methods are provided in the following sections.

Design Method

The Design Method uses the Manning Equation with a specified roughness coefficient and pipe slope. The Manning Equation is applied using this method under the general assumptions shown in Figure 3.

FIGURE 3: General Assumptions of the Design Method



The Design Method incorporates the Manning Equation as expressed in Equation (3) and the hydraulic radius as defined in Equation (4).

$$v_{DM} = C_{DM} R_{DM}^{2/3} \tag{3}$$

$$R_{DM} = \frac{A}{P} \tag{4}$$

where:
- v_{DM} = flow velocity, m/s
- C_{DM} = hydraulic coefficient
- R_{DM} = hydraulic radius, m
- A = wetted area, m^2
- P = wetted perimeter, m

The roughness coefficient and the pipe slope are specified based on design assumptions, as-built documentation, or field observations and are used to calculate the hydraulic coefficient as shown in Equation (5).

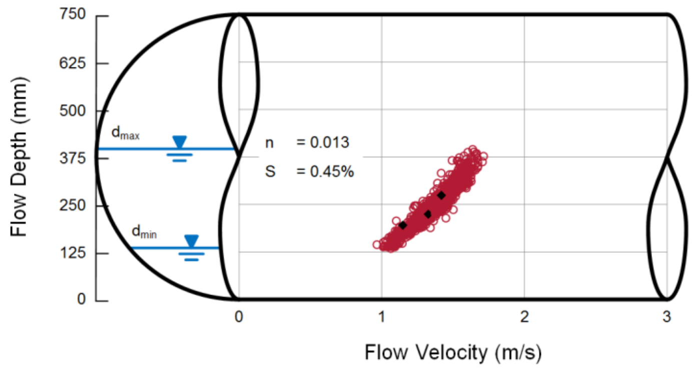
$$C_{DM} = \frac{1}{n} S^{1/2} \tag{5}$$

where:
- C_{DM} = hydraulic coefficient
- n = roughness coefficient
- S = pipe slope

The Design Method is then used to generate a pipe curve which is compared to actual flow monitor data on a scattergraph. If the data agree with the pipe curve, then this method can be used to estimate the full-pipe capacity of the sewer, assuming the assumptions of this method remain valid at the monitoring location from 0 < d ≤ D. The application of the Design Method is demonstrated in the following example.

EXAMPLE

Flow monitor data are obtained from a 750-mm sewer, as shown in the scattergraph below. The roughness coefficient (n) and the pipe slope (S) are also provided, based on design documentation.



Use the Design Method to construct a pipe curve on the scattergraph and estimate the full-pipe capacity of this sewer.

EXAMPLE

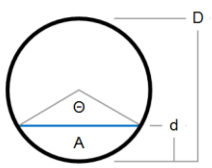
Solution: Calculate the hydraulic coefficient, construct pipe curve, and estimate sewer capacity

(a) Calculate C_{DM} assuming n = 0.013 and S = 0.45%.

$C_{DM} = 5.16$

(b) Calculate v_{DM} for $0 < d \leq D$.

For a circular sewer,[5]



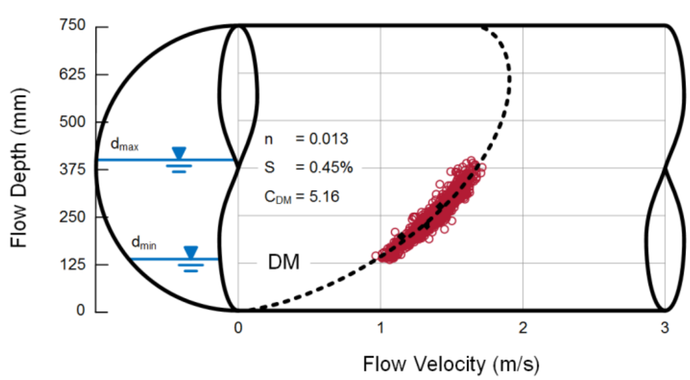
$\Theta = 2\cos^{-1}(1 - 2d/D)$

$A = (D^2/8)(\Theta - \sin\Theta)$

$P = D\Theta/2$

d	Θ	A	P	R_{DM}	$R_{DM}^{2/3}$	v_{DM}
mm	°	m^2	m	m	$m^{2/3}$	m/s
0	0	0.000	0.000	—	—	—
125	96	0.048	0.631	0.077	0.181	0.93
250	141	0.129	0.923	0.140	0.269	1.39
375	180	0.221	1.178	0.188	0.328	1.69
500	219	0.313	1.433	0.218	0.363	1.87
625	264	0.393	1.725	0.228	0.373	1.93
750	360	0.442	2.356	0.188	0.328	1.69

These results provide the necessary information to construct a pipe curve on a scattergraph, as shown below.



The conditions observed within this sewer are effectively described by the Manning Equation using the Design Method.

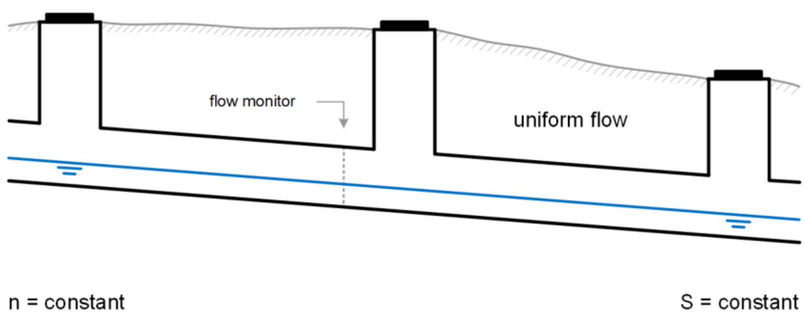
(c) Calculate Q_{DM} for d = D.

The full-pipe capacity is calculated using the Continuity Equation, $Q_{DM} = Av_{DM}$. Therefore, $Q_{DM} = 0.442\ m^2 \times 1.69\ m/s = 0.747\ m^3/s$ or 747 L/s.

Lanfear-Coll Method

The Lanfear-Coll Method uses a curve fitting technique to fit the Manning Equation to flow monitor data.[6] The Manning Equation is applied using this method under the general assumptions shown in Figure 4.

FIGURE 4: General Assumptions of the Lanfear-Coll Method



This method is applicable to flow monitor data obtained under uniform flow conditions and incorporates the Manning Equation as expressed in Equation (6) and the hydraulic radius as defined in Equation (7).

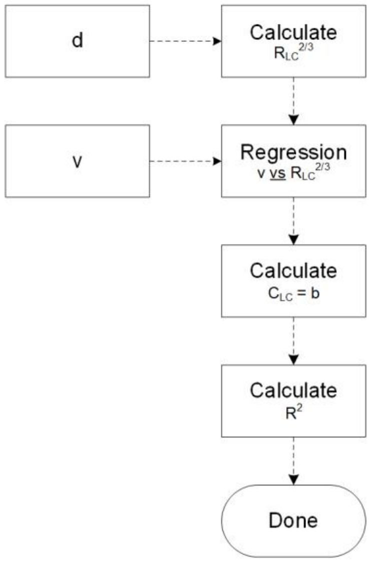
$$v_{LC} = C_{LC} R_{LC}^{2/3} \tag{6}$$

$$R_{LC} = \frac{A}{P} \tag{7}$$

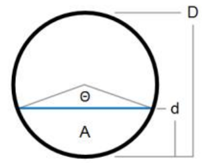
where:
- v_{LC} = flow velocity, m/s
- C_{LC} = hydraulic coefficient
- R_{LC} = hydraulic radius, m
- A = wetted area, m^2
- P = wetted perimeter, m

This method provides an implicit solution to the Manning Equation and requires no direct knowledge of the roughness coefficient or the slope of the energy gradient. Flow depth and velocity data are used to calculate the hydraulic coefficient based on a least squares regression of Equation (6), as described in Figure 5. Regression results are characterized using the coefficient of determination.[7]

FIGURE 5: Regression Using the Lanfear-Coll Method



For a circular sewer,



$$\Theta = 2\cos^{-1}(1 - 2d/D)$$

$$A = (D^2/8)(\Theta - \sin\Theta)$$

$$P = D\Theta/2$$

$$R_{LC} = \frac{A}{P}$$

Restate Equation (6) as y = a + bx using direct substitution, where:

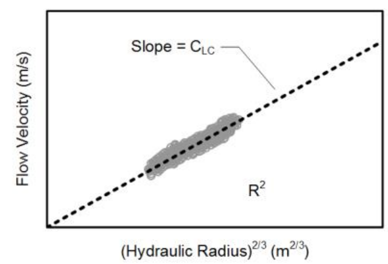
$$x = R_{LC}^{2/3}$$

$$y = v_{LC}$$

$$a = 0$$

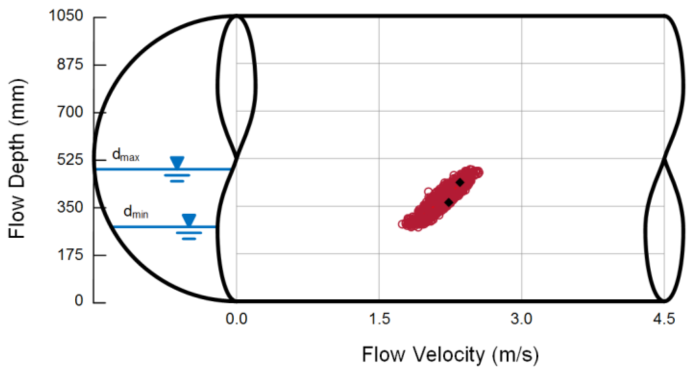
$$b = C_{LC}$$

Perform least squares regression.



The Lanfear-Coll Method is then used to generate a pipe curve which is compared to actual flow monitor data on a scattergraph. If the data agree with the pipe curve, then this method can be used to estimate the full-pipe capacity of the sewer, assuming the assumptions of this method remain valid at the monitoring location from $0 < d \leq D$. The application of the Lanfear-Coll Method is demonstrated in the following example.

EXAMPLE Flow monitor data are obtained from a 1050-mm sewer, as shown in the scattergraph below. Tabular data are provided on the following page.



Use the Lanfear-Coll Method to construct a pipe curve on the scattergraph and estimate the full-pipe capacity of this sewer.

EXAMPLE

Solution: Calculate the hydraulic coefficient

(a) Calculate $R_{LC}^{2/3}$.

date	time	d	v	Θ	A	P	R_{LC}	$R_{LC}^{2/3}$
mm/dd	hh:mm	mm	m/s	°	m^2	m	m	$m^{2/3}$
11/01	00:00	355	2.19	142	0.258	1.304	0.198	0.340
11/01	00:15	356	2.26	143	0.259	1.306	0.198	0.340
11/01	00:30	348	2.17	141	0.251	1.289	0.195	0.336
11/01	00:45	345	2.18	140	0.248	1.282	0.193	0.334
11/01	01:00	336	2.10	138	0.239	1.262	0.189	0.329
11/01	01:15	334	2.13	137	0.237	1.259	0.188	0.329
11/01	01:30	334	2.08	137	0.237	1.258	0.188	0.328
11/01	01:45	330	2.05	136	0.233	1.251	0.187	0.327
11/01	02:00	325	2.05	135	0.229	1.240	0.184	0.324
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
11/30	23:45	397	2.20	152	0.300	1.391	0.216	0.360
			v_{avg} ← 2.19					

(b) Calculate C_{LC} and R^2 based on a least squares regression.

date	time	x	y	xy	x^2	v_{LC}	$(v_{LC} - v)^2$	$(v - v_{avg})^2$
mm/dd	hh:mm	$m^{2/3}$	m/s	$m^{5/3}/s$	$m^{4/3}$	m/s	$(m/s)^2$	$(m/s)^2$
11/01	00:00	0.340	2.19	0.743	0.115	2.13	0.004	0.000
11/01	00:15	0.340	2.26	0.767	0.116	2.13	0.015	0.004
11/01	00:30	0.336	2.17	0.728	0.113	2.11	0.004	0.000
11/01	00:45	0.334	2.18	0.729	0.112	2.10	0.007	0.000
11/01	01:00	0.329	2.10	0.692	0.109	2.07	0.001	0.008
11/01	01:15	0.329	2.13	0.701	0.108	2.06	0.005	0.003
11/01	01:30	0.328	2.08	0.683	0.108	2.06	0.000	0.012
11/01	01:45	0.327	2.05	0.668	0.107	2.05	0.000	0.021
11/01	02:00	0.324	2.05	0.662	0.105	2.03	0.000	0.021
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
11/30	23:45	0.360	2.20	0.792	0.129	2.26	0.003	0.000
				$\sum xy$	$\sum x^2$		SSE	SYY

For this example, a total of 2,880 data points were used. Complete calculations are available in a spreadsheet that accompanies this technical paper.

$$C_{LC} = \sum xy \Big/ \sum x^2 \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on the regression results, $C_{LC} = 6.27$ and $R^2 = 0.84$.

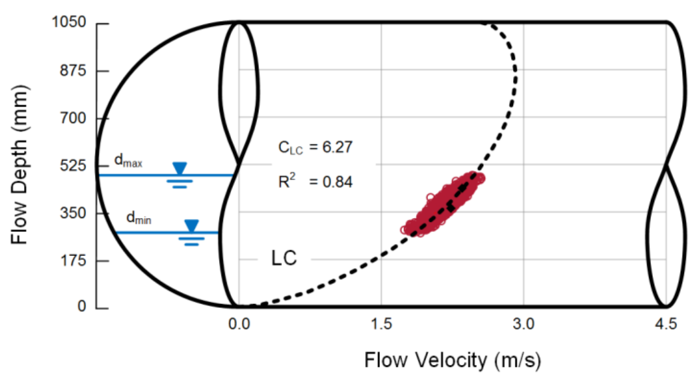
EXAMPLE

Solution: Construct pipe curve and estimate sewer capacity

(c) Calculate v_{LC} for $0 < d \leq D$.

d	Θ	A	P	R_{LC}	$R_{LC}^{2/3}$	v_{LC}
mm	°	m^2	m	m	$m^{2/3}$	m/s
0	0	0.000	0.000	—	—	—
175	96	0.095	0.883	0.107	0.226	1.42
350	141	0.253	1.293	0.195	0.337	2.11
525	180	0.433	1.649	0.263	0.410	2.57
700	219	0.613	2.006	0.306	0.454	2.85
875	264	0.771	2.416	0.319	0.467	2.93
1050	360	0.866	3.299	0.263	0.410	2.57

These results provide the necessary information to construct a pipe curve on a scattergraph, as shown below.



The conditions observed within this sewer are effectively described by the Manning Equation fitted to observed flow depth and velocity data using the Lanfear-Coll Method.

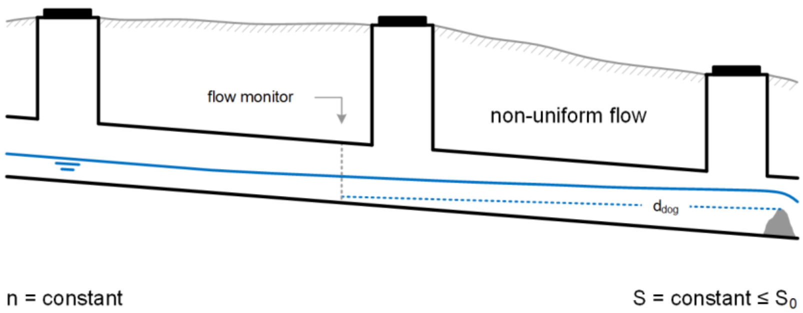
(d) Calculate Q_{LC} for d = D.

The full-pipe capacity is calculated using the Continuity Equation, $Q_{LC} = Av_{LC}$. Therefore, $Q_{LC} = 0.866\ m^2 \times 2.57\ m/s = 2.226\ m^3/s$ or 2226 L/s.

Stevens-Schutzbach Method

The Stevens-Schutzbach Method uses an iterative curve fitting technique to fit the Manning Equation to flow monitor data.[8] The Manning Equation is applied using this method under the general assumptions shown in Figure 6.

FIGURE 6: General Assumptions of the Stevens-Schutzbach Method



This method is applicable to flow monitor data obtained under uniform flow conditions or non-uniform flow conditions resulting from a variety of downstream obstructions, or *dead dogs*, where the slope of the energy gradient is less that the pipe slope. Examples include offset joints, debris, and other related conditions. The Stevens-Schutzbach Method incorporates the Manning Equation as expressed in Equation (8) and the hydraulic radius as defined in Equation (9).

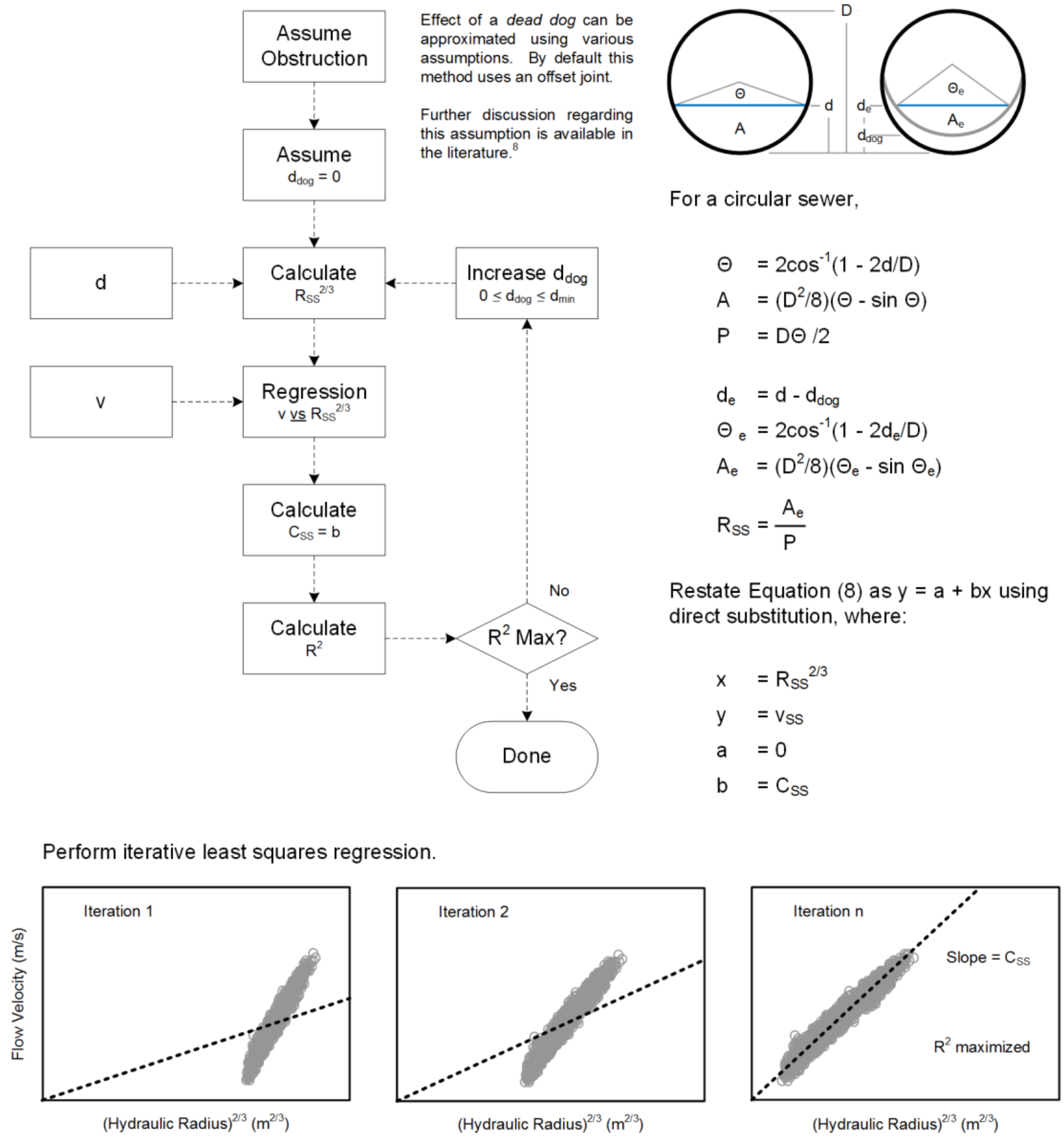
$$v_{SS} = C_{SS} R_{SS}^{2/3} \tag{8}$$

$$R_{SS} = \frac{A_e}{P} \tag{9}$$

where:
v_{SS} = flow velocity, m/s
C_{SS} = hydraulic coefficient
R_{SS} = hydraulic radius, m
A_e = effective wetted area, m^2
P = wetted perimeter, m

Note that the definition of the hydraulic radius is modified from the traditional definition and requires certain assumptions regarding the shape and magnitude of the *dead dog*. Based on these assumptions, flow depth and velocity data are used to calculate the hydraulic coefficient based on an iterative least squares regression method, as described in Figure 7. The magnitude of the *dead dog* (d_{dog}) is varied in successive iterations until the coefficient of determination is maximized.

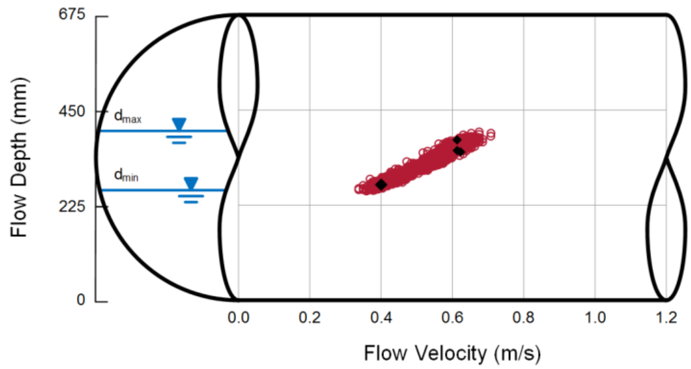
FIGURE 7: Regression Using the Stevens-Schutzbach Method



The Stevens-Schutzbach Method is then used to generate a pipe curve which is compared to actual flow monitor data on a scattergraph. If the data agree with the pipe curve, then this method can be used to estimate the full-pipe capacity of the sewer, assuming the assumptions of this method remain valid at the monitoring location from $0 < d \le D$. The application of the Stevens-Schutzbach Method is demonstrated in the following example.

EXAMPLE

Flow monitor data are obtained from a 675-mm sewer, as shown in the scattergraph below. Tabular data are provided on the following page.



Use the Stevens-Schutzbach Method to construct a pipe curve on the scattergraph and estimate the full-pipe capacity of this sewer.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration 1

(a) Assume d_{dog} = 0 mm. Calculate $R_{SS}^{2/3}$.

date	time	d	v	d_e	Θ_e	A_e	Θ	P	R_{SS}	$R_{SS}^{2/3}$
mm/dd	hh:mm	mm	m/s	mm	°	m^2	°	m	m	$m^{2/3}$
08/01	00:00	364	0.64	364	189	0.197	189	1.114	0.177	0.315
08/01	00:15	358	0.62	358	187	0.193	187	1.101	0.175	0.313
08/01	00:30	353	0.61	353	185	0.190	185	1.092	0.174	0.311
08/01	00:45	351	0.60	351	185	0.188	185	1.087	0.173	0.310
08/01	01:00	342	0.61	342	182	0.182	182	1.070	0.170	0.307
08/01	01:15	334	0.59	334	179	0.176	179	1.053	0.168	0.304
08/01	01:30	328	0.56	328	177	0.173	177	1.042	0.166	0.302
08/01	01:45	331	0.57	331	178	0.175	178	1.048	0.167	0.303
08/01	02:00	327	0.55	327	176	0.172	176	1.040	0.165	0.301
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	360	0.63	360	188	0.194	188	1.106	0.176	0.314

263 ↦ d_{min} v_{avg} ↤ 0.57

(b) Calculate C_{SS} and R^2 based on a least squares regression.

date	time	x	y	xy	x^2	v_{SS}	$(v_{SS} - v)^2$	$(v - v_{avg})^2$
mm/dd	hh:mm	$m^{2/3}$	m/s	$m^{5/3}/s$	$m^{4/3}$	m/s	$(m/s)^2$	$(m/s)^2$
08/01	00:00	0.315	0.64	0.203	0.099	0.58	0.003	0.006
08/01	00:15	0.313	0.62	0.194	0.098	0.58	0.001	0.003
08/01	00:30	0.311	0.61	0.189	0.097	0.58	0.001	0.002
08/01	00:45	0.310	0.60	0.185	0.096	0.58	0.000	0.001
08/01	01:00	0.307	0.61	0.186	0.094	0.57	0.001	0.002
08/01	01:15	0.304	0.59	0.178	0.092	0.56	0.000	0.000
08/01	01:30	0.302	0.56	0.169	0.091	0.56	0.000	0.000
08/01	01:45	0.303	0.57	0.174	0.092	0.56	0.000	0.000
08/01	02:00	0.301	0.55	0.165	0.091	0.56	0.000	0.000
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.314	0.63	0.198	0.098	0.58	0.002	0.004
				$\sum xy$	$\sum x^2$		SSE	SYY

For this example, a total of 2,016 data points were used. Complete calculations are available in a spreadsheet that accompanies this technical paper.

$$C_{SS} = \sum xy \Big/ \sum x^2 \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 1.85 and R^2 = 0.50. R^2 is not maximized.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration 2

(a) Assume d_{dog} = 25 mm. Calculate $R_{SS}^{2/3}$.

date	time	d	v	d_e	Θ_e	A_e	Θ	P	R_{SS}	$R_{SS}^{2/3}$
mm/dd	hh:mm	mm	m/s	mm	°	m^2	°	m	m	$m^{2/3}$
08/01	00:00	364	0.64	339	181	0.180	189	1.114	0.162	0.297
08/01	00:15	358	0.62	333	178	0.176	187	1.101	0.160	0.294
08/01	00:30	353	0.61	328	177	0.173	185	1.092	0.158	0.292
08/01	00:45	351	0.60	326	176	0.171	185	1.087	0.157	0.291
08/01	01:00	342	0.61	317	173	0.165	182	1.070	0.155	0.288
08/01	01:15	334	0.59	309	170	0.160	179	1.053	0.152	0.284
08/01	01:30	328	0.56	303	168	0.156	177	1.042	0.150	0.282
08/01	01:45	331	0.57	306	169	0.158	178	1.048	0.151	0.283
08/01	02:00	327	0.55	302	168	0.155	176	1.040	0.149	0.281
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	360	0.63	335	179	0.178	188	1.106	0.160	0.295
	263 ↦	d_{min}	v_{avg}	↤ 0.57						

(b) Calculate C_{SS} and R^2 based on a least squares regression.

date	time	x	y	xy	x^2	v_{SS}	$(v_{SS} - v)^2$	$(v - v_{avg})^2$
mm/dd	hh:mm	$m^{2/3}$	m/s	$m^{5/3}/s$	$m^{4/3}$	m/s	$(m/s)^2$	$(m/s)^2$
08/01	00:00	0.297	0.64	0.191	0.088	0.59	0.003	0.006
08/01	00:15	0.294	0.62	0.182	0.087	0.58	0.001	0.003
08/01	00:30	0.292	0.61	0.177	0.086	0.58	0.001	0.002
08/01	00:45	0.291	0.60	0.174	0.085	0.58	0.000	0.001
08/01	01:00	0.288	0.61	0.175	0.083	0.57	0.001	0.002
08/01	01:15	0.284	0.59	0.166	0.081	0.56	0.001	0.000
08/01	01:30	0.282	0.56	0.158	0.079	0.56	0.000	0.000
08/01	01:45	0.283	0.57	0.162	0.080	0.56	0.000	0.000
08/01	02:00	0.281	0.55	0.154	0.079	0.56	0.000	0.000
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.295	0.63	0.186	0.087	0.58	0.002	0.004
				$\sum xy$	$\sum x^2$		SSE	SYY

For this example, a total of 2,016 data points were used. Complete calculations are available in a spreadsheet that accompanies this technical paper.

$$C_{SS} = \sum xy \Big/ \sum x^2 \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 1.98 and R^2 = 0.57. R^2 is not maximized.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration 3

(a) Assume d_{dog} = 50 mm. Calculate $R_{SS}^{2/3}$.

date	time	d	v	d_e	Θ_e	A_e	Θ	P	R_{SS}	$R_{SS}^{2/3}$
mm/dd	hh:mm	mm	m/s	mm	°	m^2	°	m	m	$m^{2/3}$
08/01	00:00	364	0.64	314	172	0.163	189	1.114	0.147	0.278
08/01	00:15	358	0.62	308	170	0.159	187	1.101	0.144	0.275
08/01	00:30	353	0.61	303	168	0.156	185	1.092	0.143	0.273
08/01	00:45	351	0.60	301	168	0.154	185	1.087	0.142	0.272
08/01	01:00	342	0.61	292	165	0.149	182	1.070	0.139	0.268
08/01	01:15	334	0.59	284	162	0.143	179	1.053	0.136	0.264
08/01	01:30	328	0.56	278	160	0.139	177	1.042	0.134	0.261
08/01	01:45	331	0.57	281	161	0.141	178	1.048	0.135	0.263
08/01	02:00	327	0.55	277	159	0.138	176	1.040	0.133	0.261
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	360	0.63	310	171	0.161	188	1.106	0.145	0.276
	263 $\mapsto$	d_{min}	v_{avg}	$\leftarrow$ 0.57						

(b) Calculate C_{SS} and R^2 based on a least squares regression.

date	time	x	y	xy	x^2	v_{SS}	$(v_{SS} - v)^2$	$(v - v_{avg})^2$
mm/dd	hh:mm	$m^{2/3}$	m/s	$m^{5/3}/s$	$m^{4/3}$	m/s	$(m/s)^2$	$(m/s)^2$
08/01	00:00	0.278	0.64	0.179	0.077	0.59	0.003	0.006
08/01	00:15	0.275	0.62	0.170	0.076	0.59	0.001	0.003
08/01	00:30	0.273	0.61	0.166	0.075	0.58	0.001	0.002
08/01	00:45	0.272	0.60	0.162	0.074	0.58	0.000	0.001
08/01	01:00	0.268	0.61	0.163	0.072	0.57	0.001	0.002
08/01	01:15	0.264	0.59	0.154	0.070	0.56	0.001	0.000
08/01	01:30	0.261	0.56	0.147	0.068	0.56	0.000	0.000
08/01	01:45	0.263	0.57	0.151	0.069	0.56	0.000	0.000
08/01	02:00	0.261	0.55	0.143	0.068	0.55	0.000	0.000
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.276	0.63	0.174	0.076	0.59	0.002	0.004
				$\sum xy$	$\sum x^2$		SSE	SYY

For this example, a total of 2,016 data points were used. Complete calculations are available in a spreadsheet that accompanies this technical paper.

$$C_{SS} = \sum xy \Big/ \sum x^2 \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 2.13 and R^2 = 0.65. R^2 is not maximized.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration n

(a) Assume d_{dog} = 164 mm. Calculate $R_{SS}^{2/3}$.

date	time	d	v	d_e	Θ_e	A_e	Θ	P	R_{SS}	$R_{SS}^{2/3}$
mm/dd	hh:mm	mm	m/s	mm	°	m^2	°	m	m	$m^{2/3}$
08/01	00:00	364	0.64	200	132	0.089	189	1.114	0.080	0.185
08/01	00:15	358	0.62	194	130	0.085	187	1.101	0.077	0.181
08/01	00:30	353	0.61	189	128	0.082	185	1.092	0.075	0.178
08/01	00:45	351	0.60	187	127	0.081	185	1.087	0.074	0.177
08/01	01:00	342	0.61	178	124	0.076	182	1.070	0.071	0.171
08/01	01:15	334	0.59	170	120	0.071	179	1.053	0.067	0.165
08/01	01:30	328	0.56	164	118	0.067	177	1.042	0.065	0.161
08/01	01:45	331	0.57	167	119	0.069	178	1.048	0.066	0.163
08/01	02:00	327	0.55	163	118	0.067	176	1.040	0.064	0.160
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	360	0.63	196	131	0.087	188	1.106	0.078	0.183
	263 $\mapsto$	d_{min}	v_{avg}	$\leftarrow$ 0.57						

(b) Calculate C_{SS} and R^2 based on a least squares regression.

date	time	x	y	xy	x^2	v_{SS}	$(v_{SS} - v)^2$	$(v - v_{avg})^2$
mm/dd	hh:mm	$m^{2/3}$	m/s	$m^{5/3}/s$	$m^{4/3}$	m/s	$(m/s)^2$	$(m/s)^2$
08/01	00:00	0.185	0.64	0.119	0.034	0.62	0.001	0.006
08/01	00:15	0.181	0.62	0.112	0.033	0.60	0.000	0.003
08/01	00:30	0.178	0.61	0.108	0.032	0.59	0.000	0.002
08/01	00:45	0.177	0.60	0.105	0.031	0.59	0.000	0.001
08/01	01:00	0.171	0.61	0.104	0.029	0.57	0.001	0.002
08/01	01:15	0.165	0.59	0.097	0.027	0.55	0.001	0.000
08/01	01:30	0.161	0.56	0.090	0.026	0.54	0.001	0.000
08/01	01:45	0.163	0.57	0.093	0.027	0.54	0.001	0.000
08/01	02:00	0.160	0.55	0.088	0.026	0.53	0.000	0.000
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.183	0.63	0.115	0.033	0.61	0.001	0.004
				$\sum xy$	$\sum x^2$		SSE	SYY

For this example, a total of 2,016 data points were used. Complete calculations are available in a spreadsheet that accompanies this technical paper.

$$C_{SS} = \sum xy \Big/ \sum x^2$$

$$R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 3.33 and R^2 = 0.95. R^2 is maximized.

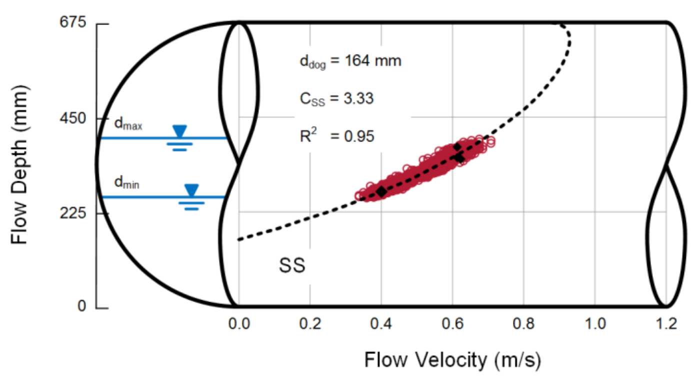
EXAMPLE

Solution: Construct pipe curve and estimate sewer capacity

(c) Calculate v_{SS} for $0 < d \leq D$.

d	d_e	Θ_e	A_e	Θ	A	P	R_{SS}	$R_{SS}^{2/3}$	v_{SS}
mm	mm	°	m^2	°	m^2	m	m	$m^{2/3}$	m/s
0	0	0	0.000	0	0.000	0.000	—	—	—
75	0	0	0.000	78	0.022	0.459	0.000	0.000	0.00
150	0	0	0.000	113	0.059	0.663	0.000	0.000	0.00
225	61	70	0.016	141	0.104	0.831	0.019	0.072	0.24
300	136	107	0.051	167	0.154	0.985	0.052	0.140	0.46
375	211	136	0.096	193	0.204	1.135	0.084	0.192	0.64
450	286	162	0.144	219	0.253	1.290	0.112	0.232	0.77
525	361	188	0.195	247	0.299	1.458	0.134	0.261	0.87
600	436	214	0.244	282	0.336	1.662	0.147	0.279	0.93
675	511	242	0.291	360	0.358	2.121	0.137	0.266	0.88

These results provide the necessary information to construct a pipe curve on a scattergraph, as shown below.



The conditions observed within this sewer are effectively described by the Manning Equation fitted to observed flow depth and velocity data using the Stevens-Schutzbach Method.

(d) Calculate Q_{SS} for $d = D$.

The full-pipe capacity is calculated using the Continuity Equation, $Q_{SS} = Av_{SS}$. Therefore, $Q_{SS} = 0.358\ m^2 \times 0.88\ m/s = 0.316\ m^3/s$ or 316 L/s.

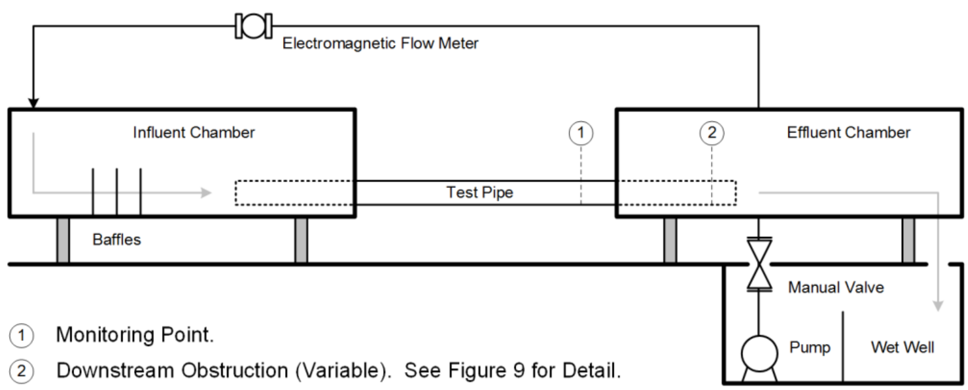
Laboratory Investigation

Laboratory investigations were designed to demonstrate the performance of these methods under controlled conditions and were performed using hydraulic testing facilities located at Accusonic Technologies in Falmouth, Massachusetts.

Equipment and Methodology

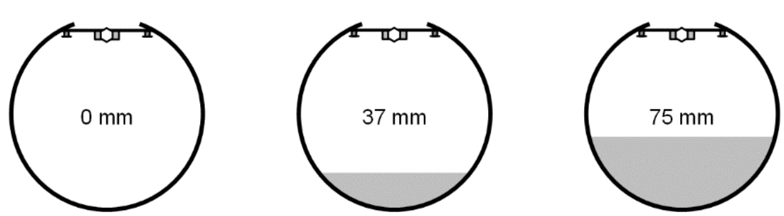
The laboratory equipment used during this investigation was designed and configured to simulate hydraulic conditions encountered in the urban sewer environment. The general arrangement of this equipment is provided in Figure 8.

FIGURE 8: Laboratory General Arrangement



A pump provides flow through a 150-mm PVC force main to an influent chamber. A manual valve regulates the pump, and an electromagnetic flow meter measures the pump discharge. Flow passes through three consecutive baffles within the influent chamber, minimizing surface disturbances before entering a 200-mm PVC test pipe. Uniform and non-uniform flow conditions are observed and measured at a monitoring point located within the test pipe. Flow conditions are controlled using one of three obstructions, or *dead dogs*, of known depth, as depicted in Figure 9, positioned a fixed distance downstream from the monitoring point. Following discharge from the test pipe to an effluent chamber, the flow is returned to a wet well for re-circulation by the pump.

FIGURE 9: Downstream Obstructions for Laboratory Investigation

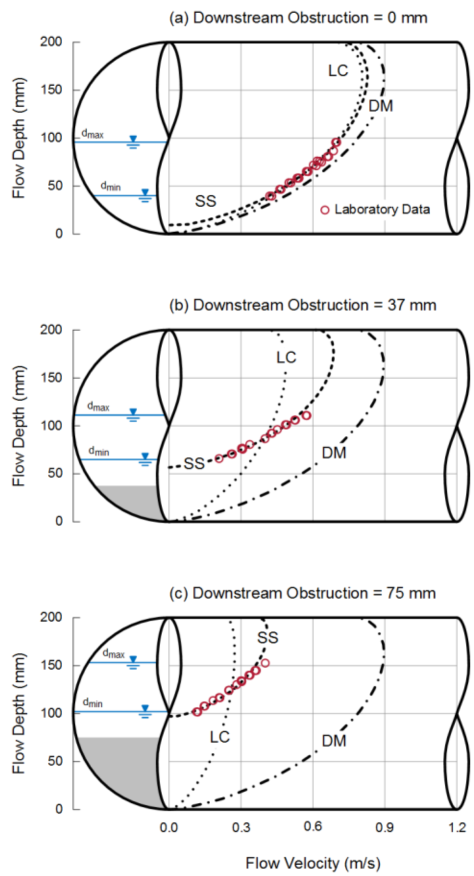


After placing an obstruction within the test pipe, the pump is activated, and flow is introduced into the system. Once the system has reached equilibrium, flow depth and quantity measurements are obtained at three consecutive one-minute intervals. Flow depth is measured in the test pipe with a stainless steel ruler, and flow quantity is measured in the force main with the electromagnetic flow meter. These measurements are then used to calculate flow velocity in the test pipe using the Continuity Equation. A total of 30 flow depth and quantity measurements were obtained at a variety of pump settings for each obstruction.

Results and Discussion

Flow depth and velocity data obtained during the laboratory investigations are plotted on scattergraphs and evaluated with respect to the Manning Equation using the Design Method, the Lanfear-Coll Method, and the Stevens-Schutzbach Method, as shown in Figure 10. The Design Method is applied using a roughness coefficient of 0.009 and a pipe slope of 0.72%. These values were selected based on the recommendation of the Uni-Bell PVC Pipe Association and laboratory measurements, respectively.[9]

FIGURE 10: Laboratory Results



The laboratory observations demonstrate that these methods provide similar results under uniform flow conditions, as shown in Figure 10a. However, the Stevens-Schutzbach Method best describes the relationship between flow depth and velocity under non-uniform flow conditions resulting from various *dead dogs*, as shown in Figure 10b and Figure 10c.

Conclusion

The scattergraph is a graphical tool that provides insight into sewer performance through a simple and intuitive display of flow monitor data. The resulting patterns form characteristic signatures that reveal important information about conditions within a sewer and the impact that these conditions have on sewer capacity. The Manning Equation is an important component of the scattergraph and can be applied using a variety of methods, including the Design Method, the Lanfear-Coll Method, and the Stevens-Schutzbach Method. Each method applies a specific set of assumptions to the Manning Equation, and an understanding of these assumptions is essential to effective application of these methods. Proper selection and application of these methods have a significant impact on the calculation of sewer capacity and the evaluation of sewer performance based on flow monitor data. Laboratory results indicate that these methods provide similar results under uniform flow conditions. However, the Stevens-Schutzbach Method best describes the relationship between flow depth and velocity under non-uniform flow conditions resulting from various *dead dogs*.

Symbols and Notation

The following symbols and notation are used in this paper:

VARIABLES

d = flow depth, mm or m
v = flow velocity, m/s
Q = flow rate, m^3/s or L/s
n = roughness coefficient
R = hydraulic radius, m
S = slope of the energy gradient
C = hydraulic coefficient
D = diameter, mm or m
A = wetted area, m^2
P = wetted perimeter, m
R^2 = coefficient of determination

SUBSCRIPTS

$_{DM}$ = Design Method
$_{LC}$ = Lanfear-Coll Method
$_{SS}$ = Stevens-Schutzbach Method
$_{dog}$ = *dead dog*
$_{0}$ = specified
$_{e}$ = effective
$_{avg}$ = average
$_{min}$ = minimum

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Enfinger, K.L. and Kimbrough, H.R. (2004). “Scattergraph Principles and Practice – A Comparison of Various Applications of the Manning Equation,” *Proceedings of the Pipeline Division Specialty Conference*; San Diego, CA; American Society of Civil Engineers: Reston, VA.