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 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).

$$v = \frac{1.486}{n} R^{2/3} S^{1/2} \qquad (1)$$

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

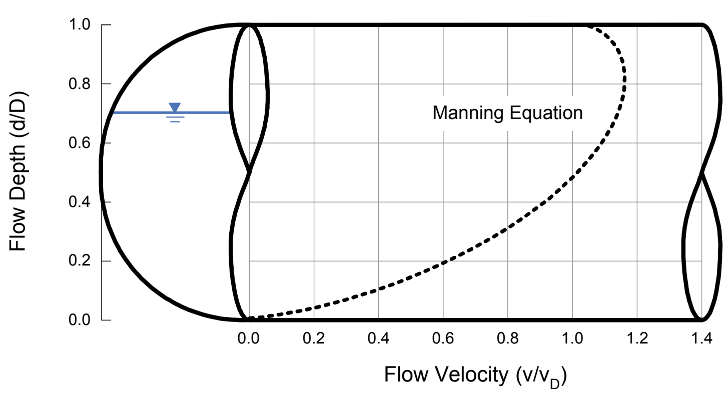
Several assumptions are generally made with respect to the Manning Equation: the roughness coefficient is constant, and the slope of the energy gradient equals the slope of the pipe.[2] Based on these assumptions, the Manning Equation can be algebraically rearranged such that these parameters are consolidated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

$$v = 1.486 C R^{2/3} \qquad (2)$$

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

The relationship between flow depth and velocity described by the Manning Equation 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

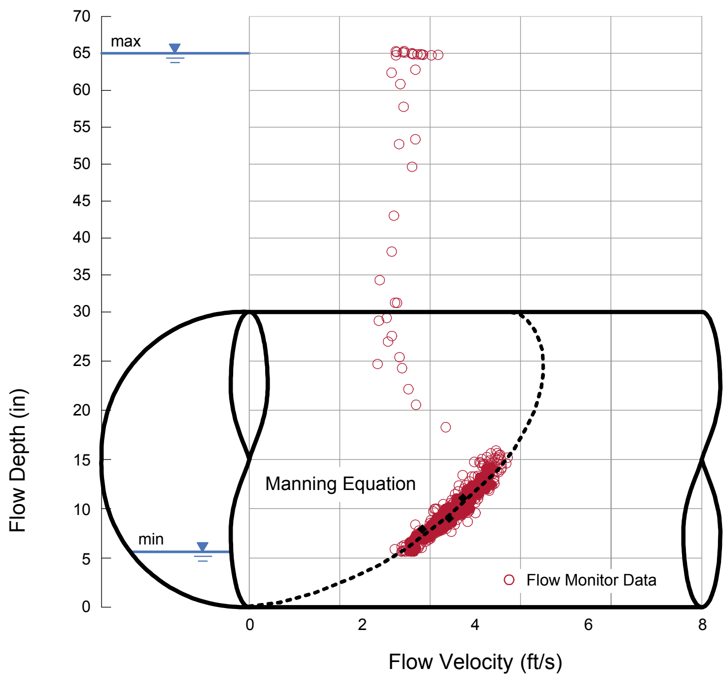


Manning Methods

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 up to a flow depth of about 15 inches. 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

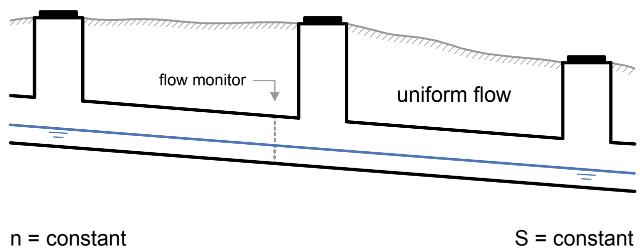


The Manning Equation is an important component of the scattergraph and can be applied using three different methods, defined as the Design Method, the Lanfear-Coll Method, and the Stevens-Schutzbach Method. The Design Method uses the Manning Equation to describe a relationship between flow depth and 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. 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).

$$v_{DM} = 1.486 C_{DM} R_{DM}^{2/3} \tag{3}$$

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

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

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).

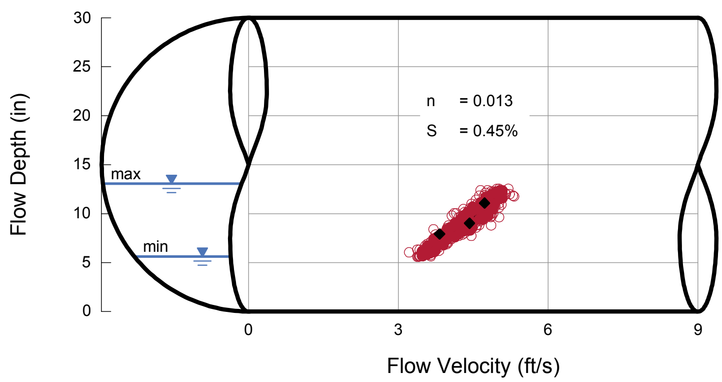
$$C_{DM} = \frac{1}{n} S^{1/2} \tag{5}$$

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 $0 \le d \le D$. The application of the Design Method is demonstrated in the following example.

EXAMPLE

Flow monitor data are obtained from a 30-in sewer, as shown in the scattergraph below. The roughness coefficient (n) and the 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

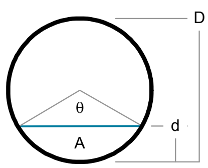
Solution: Calculate the hydraulic coefficient, construct pipe curve, and estimate sewer capacity

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

$C_{DM} = 5.16$

(b) Calculate v_{DM} for $0 \le d \le D$

For a circular sewer,[5]



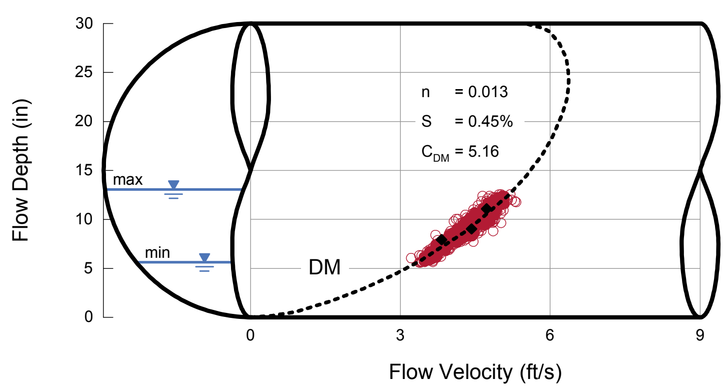
$\theta = 2\cos^{-1}(1 - 2d/D)$

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

$P = D\theta/2$

d	θ	A	P	R_{DM}	$R_{DM}^{2/3}$	v_{DM}
in	°	ft^2	ft	ft	$ft^{2/3}$	ft/s
0	0	0.00	0.00	—	—	—
5	96	0.54	2.10	0.26	0.40	3.09
10	141	1.43	3.08	0.47	0.60	4.61
15	180	2.45	3.93	0.63	0.73	5.61
20	219	3.48	4.78	0.73	0.81	6.20
25	264	4.37	5.75	0.76	0.83	6.39
30	360	4.91	7.85	0.63	0.73	5.61

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.

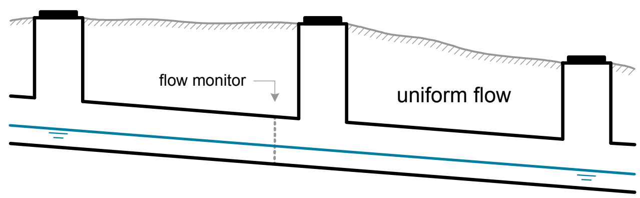
(c) Calculate Q_{DM} for d = D

The full-pipe capacity is calculated using the Continuity Equation, $Q_{DM} = Av_{DM}$. Therefore, $Q_{DM} = 4.91\ ft^2 \times 5.61\ ft/s = 27.5\ ft^3/s$ or 17.8 MGD.

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).

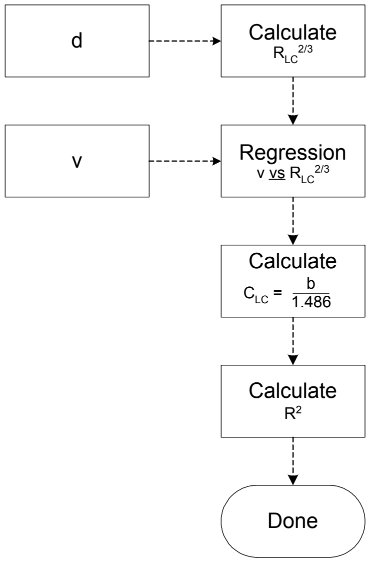
$$v_{LC} = 1.486 C_{LC} R_{LC}^{2/3} \qquad (6)$$

$$R_{LC} = \frac{A}{P} \qquad (7)$$

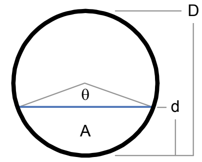
where: v_{LC} = flow velocity, ft/s
C_{LC} = hydraulic coefficient
R_{LC} = hydraulic radius, ft
A = wetted area, ft^2
P = wetted perimeter, ft

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,



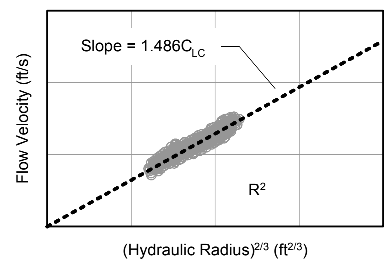
$$\theta = 2\cos^{-1}(1 - 2d/D)$$
$$A = (D^2/8)(\theta - \sin\theta)$$
$$P = D\theta/2$$

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

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

$$x = R_{LC}^{2/3}$$
$$y = v_{LC}$$
$$a = 0$$
$$b = 1.486C_{LC}$$

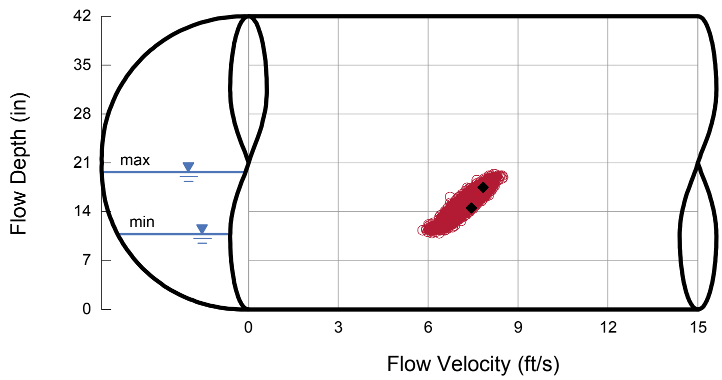
Perform least squares regression.



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 $0 \le d \le D$. The application of the Lanfear-Coll Method is demonstrated in the following example.

EXAMPLE

Flow monitor data are obtained from a 42-in 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	in	ft/s	o	ft^2	ft	ft	$ft^{2/3}$
11/01	00:00	13.99	7.18	141	2.80	4.31	0.65	0.75
11/01	00:15	14.03	7.40	141	2.82	4.31	0.65	0.75
11/01	00:30	13.71	7.11	139	2.73	4.26	0.64	0.74
11/01	00:45	13.59	7.15	139	2.70	4.24	0.64	0.74
11/01	01:00	13.22	6.89	137	2.59	4.17	0.62	0.73
11/01	01:15	13.16	7.00	136	2.58	4.16	0.62	0.73
11/01	01:30	13.14	6.82	136	2.57	4.16	0.62	0.73
11/01	01:45	13.01	6.71	135	2.54	4.13	0.61	0.72
11/01	02:00	12.81	6.71	134	2.48	4.10	0.61	0.72
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
11/30	23:45	15.64	7.22	150	3.26	4.59	0.71	0.80

v_{avg} ← 7.17

(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	$ft^{2/3}$	ft/s	$ft^{5/3}/s$	$ft^{4/3}$	ft/s	$(ft/s)^2$	$(ft/s)^2$
11/01	00:00	0.75	7.18	5.39	0.56	6.98	0.038	0.000
11/01	00:15	0.75	7.40	5.57	0.57	6.99	0.164	0.048
11/01	00:30	0.74	7.11	5.28	0.55	6.91	0.040	0.005
11/01	00:45	0.74	7.15	5.29	0.55	6.88	0.075	0.001
11/01	01:00	0.73	6.89	5.02	0.53	6.78	0.013	0.084
11/01	01:15	0.73	7.00	5.09	0.53	6.76	0.058	0.032
11/01	01:30	0.73	6.82	4.95	0.53	6.75	0.004	0.130
11/01	01:45	0.72	6.71	4.85	0.52	6.72	0.000	0.221
11/01	02:00	0.72	6.71	4.81	0.51	6.66	0.002	0.221
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
11/30	23:45	0.80	7.22	5.75	0.63	7.40	0.033	0.002
				$\sum xy$	$\sum x^2$		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.

$$C_{LC} = \frac{\sum xy \,/\, \sum x^2}{1.486} \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on the regression results, $C_{LC} = 6.26$ and $R^2 = 0.84$.

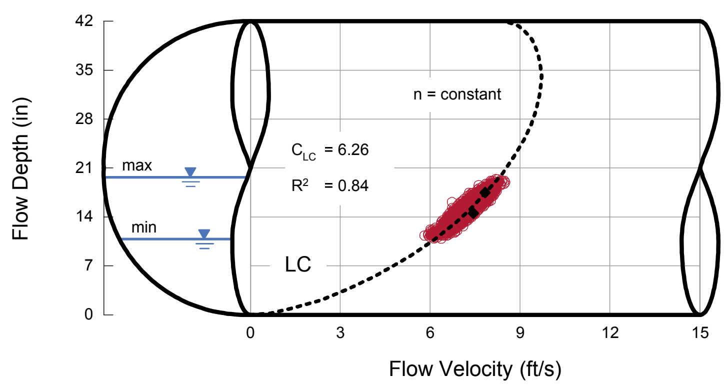
EXAMPLE

Solution: Construct pipe curve and estimate sewer capacity

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

d	θ	A	P	R_{LC}	$R_{LC}^{2/3}$	v_{LC}
in	°	ft^2	ft	ft	$ft^{2/3}$	ft/s
0	0	0.00	0.00	—	—	—
7	96	1.05	2.94	0.36	0.50	4.69
14	141	2.81	4.31	0.65	0.75	6.99
21	180	4.81	5.50	0.88	0.91	8.50
28	219	6.81	6.69	1.02	1.01	9.41
35	264	8.57	8.05	1.06	1.04	9.69
42	360	9.62	11.00	0.88	0.91	8.50

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.

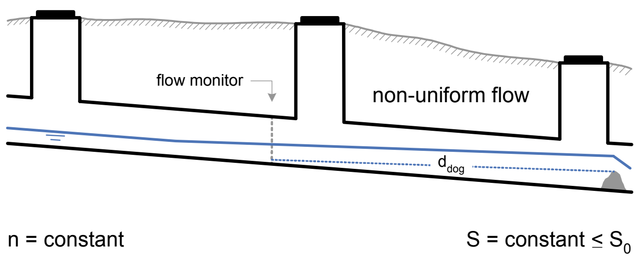
(d) Calculate Q_{LC} for d = D

The full-pipe capacity is calculated using the Continuity Equation, $Q_{LC} = Av_{LC.}$ Therefore, $Q_{LC} = 9.62\ ft^2 \times 8.50\ ft/s = 81.8\ ft^3/s$ or 52.9 MGD.

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*. 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).

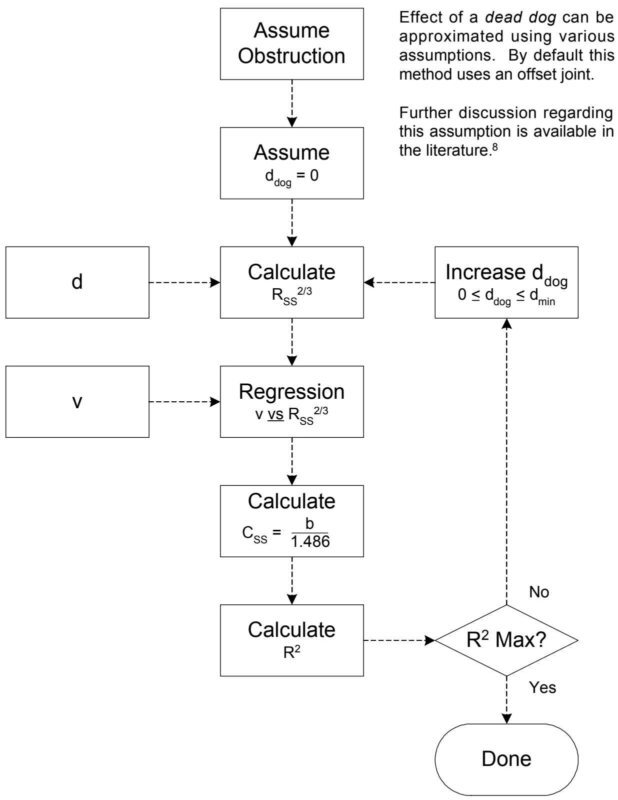
$$v_{SS} = 1.486 C_{SS} R_{SS}^{2/3} \tag{8}$$

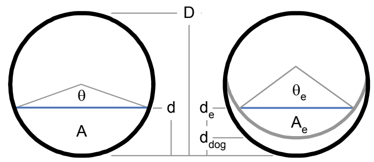
$$R_{SS} = \frac{A_e}{P} \tag{9}$$

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

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





For a circular sewer,

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

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

$P = D\theta/2$

$d_e = d - d_{dog}$

$\theta_e = 2\cos^{-1}(1 - 2d_e/D)$

$A_e = (D^2/8)(\theta_e - \sin\theta_e)$

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

Restate Equation (8) as y = a + bx using direct substitution, where:

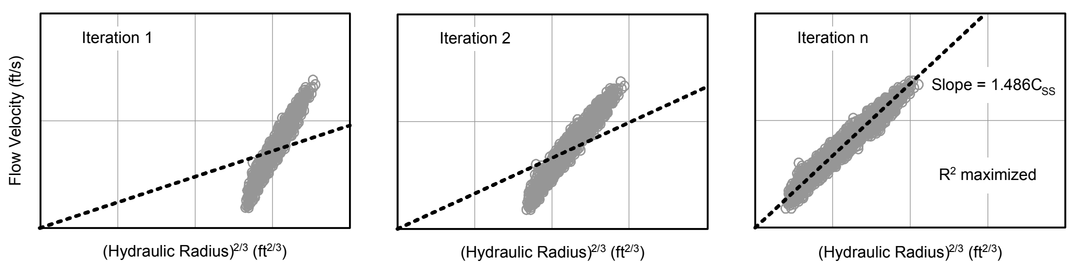
$x = R_{SS}^{2/3}$

$y = v_{SS}$

$a = 0$

$b = 1.486C_{SS}$

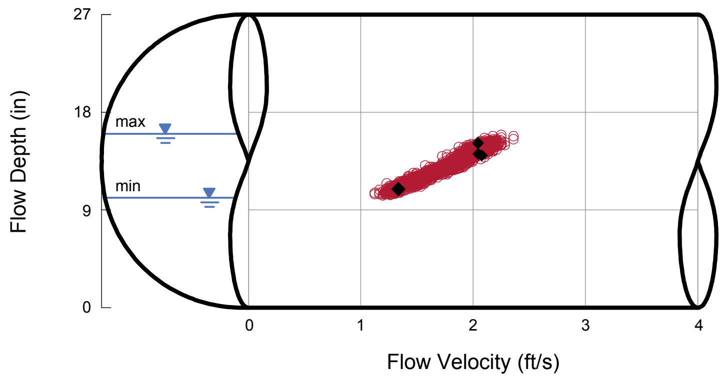
Perform iterative least squares regression.



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 $0 \le d \le D$. The application of the Stevens-Schutzbach Method is demonstrated in the following example.

EXAMPLE

Flow monitor data are obtained from a 27-in 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} = 0.00 in. 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	in	ft/s	in	°	ft^2	°	ft	ft	ft$^{2/3}$
08/01	00:00	14.34	2.11	14.34	187	2.15	187	3.67	0.58	0.70
08/01	00:15	14.08	2.03	14.08	185	2.10	185	3.63	0.58	0.69
08/01	00:30	13.91	1.99	13.91	183	2.06	183	3.60	0.57	0.69
08/01	00:45	13.81	1.96	13.81	183	2.05	183	3.59	0.57	0.69
08/01	01:00	13.48	1.99	13.48	180	1.98	180	3.53	0.56	0.68
08/01	01:15	13.14	1.92	13.14	177	1.92	177	3.47	0.55	0.67
08/01	01:30	12.93	1.84	12.93	175	1.88	175	3.44	0.55	0.67
08/01	01:45	13.04	1.88	13.04	176	1.90	176	3.46	0.55	0.67
08/01	02:00	12.88	1.80	12.88	175	1.87	175	3.43	0.55	0.67
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	14.19	2.07	14.19	186	2.12	186	3.65	0.58	0.70
	10.35 →	d_{min}	v_{avg}	← 1.86						

(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	ft$^{2/3}$	ft/s	ft$^{5/3}$/s	ft$^{4/3}$	ft/s	(ft/s)^2	(ft/s)^2
08/01	00:00	0.70	2.11	1.47	0.49	1.92	0.037	0.063
08/01	00:15	0.69	2.03	1.41	0.48	1.90	0.016	0.030
08/01	00:30	0.69	1.99	1.37	0.48	1.89	0.009	0.017
08/01	00:45	0.69	1.96	1.35	0.47	1.89	0.005	0.010
08/01	01:00	0.68	1.99	1.36	0.46	1.87	0.015	0.017
08/01	01:15	0.67	1.92	1.29	0.45	1.85	0.005	0.004
08/01	01:30	0.67	1.84	1.23	0.45	1.84	0.000	0.000
08/01	01:45	0.67	1.88	1.26	0.45	1.84	0.001	0.000
08/01	02:00	0.67	1.80	1.20	0.45	1.83	0.001	0.003
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.70	2.07	1.44	0.48	1.91	0.026	0.045
				$\sum xy$	$\sum x^2$		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.

$$C_{SS} = \frac{\sum xy \,/\, \sum x^2}{1.486} \qquad R^2 = 1 - \frac{SSE}{SYY}$$

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} = 1.00 in. 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	in	ft/s	in	°	ft^2	°	ft	ft	$ft^{2/3}$
08/01	00:00	14.34	2.11	13.34	179	1.96	187	3.67	0.53	0.66
08/01	00:15	14.08	2.03	13.08	176	1.91	185	3.63	0.53	0.65
08/01	00:30	13.91	1.99	12.91	175	1.88	183	3.60	0.52	0.65
08/01	00:45	13.81	1.96	12.81	174	1.86	183	3.59	0.52	0.65
08/01	01:00	13.48	1.99	12.48	171	1.80	180	3.53	0.51	0.64
08/01	01:15	13.14	1.92	12.14	168	1.73	177	3.47	0.50	0.63
08/01	01:30	12.93	1.84	11.93	167	1.69	175	3.44	0.49	0.62
08/01	01:45	13.04	1.88	12.04	168	1.71	176	3.46	0.50	0.63
08/01	02:00	12.88	1.80	11.88	166	1.69	175	3.43	0.49	0.62
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	14.19	2.07	13.19	177	1.93	186	3.65	0.53	0.65
	10.35 ↦	d_{min}	v_{avg}	↤ 1.86						

(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	$ft^{2/3}$	ft/s	$ft^{5/3}/s$	$ft^{4/3}$	ft/s	$(ft/s)^2$	$(ft/s)^2$
08/01	00:00	0.66	2.11	1.39	0.43	1.93	0.033	0.063
08/01	00:15	0.65	2.03	1.32	0.42	1.91	0.014	0.030
08/01	00:30	0.65	1.99	1.29	0.42	1.90	0.008	0.017
08/01	00:45	0.65	1.96	1.26	0.42	1.89	0.004	0.010
08/01	01:00	0.64	1.99	1.27	0.41	1.87	0.014	0.017
08/01	01:15	0.63	1.92	1.21	0.40	1.85	0.006	0.004
08/01	01:30	0.62	1.84	1.15	0.39	1.83	0.000	0.000
08/01	01:45	0.63	1.88	1.18	0.39	1.84	0.002	0.000
08/01	02:00	0.62	1.80	1.12	0.39	1.83	0.001	0.003
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.65	2.07	1.35	0.43	1.92	0.023	0.045
				$\sum xy$	$\sum x^2$		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.

$$C_{SS} = \frac{\sum xy \,/\, \sum x^2}{1.486} \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 1.97 and R^2 = 0.58. R^2 is not maximized.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration 3

(a) Assume d_{dog} = 2.00 in. 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	in	ft/s	in	o	ft^2	o	ft	ft	$ft^{2/3}$
08/01	00:00	14.34	2.11	12.34	170	1.77	187	3.67	0.48	0.61
08/01	00:15	14.08	2.03	12.08	168	1.72	185	3.63	0.47	0.61
08/01	00:30	13.91	1.99	11.91	166	1.69	183	3.60	0.47	0.60
08/01	00:45	13.81	1.96	11.81	166	1.67	183	3.59	0.47	0.60
08/01	01:00	13.48	1.99	11.48	163	1.61	180	3.53	0.46	0.59
08/01	01:15	13.14	1.92	11.14	160	1.55	177	3.47	0.45	0.58
08/01	01:30	12.93	1.84	10.93	158	1.51	175	3.44	0.44	0.58
08/01	01:45	13.04	1.88	11.04	159	1.53	176	3.46	0.44	0.58
08/01	02:00	12.88	1.80	10.88	158	1.50	175	3.43	0.44	0.58
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	14.19	2.07	12.19	169	1.74	186	3.65	0.48	0.61

10.35 ↦ d_{min} v_{avg} ↤ 1.86

(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	$ft^{2/3}$	ft/s	$ft^{5/3}/s$	$ft^{4/3}$	ft/s	$(ft/s)^2$	$(ft/s)^2$
08/01	00:00	0.61	2.11	1.30	0.38	1.94	0.029	0.063
08/01	00:15	0.61	2.03	1.23	0.37	1.92	0.012	0.030
08/01	00:30	0.60	1.99	1.20	0.36	1.91	0.007	0.017
08/01	00:45	0.60	1.96	1.18	0.36	1.90	0.004	0.010
08/01	01:00	0.59	1.99	1.18	0.35	1.87	0.014	0.017
08/01	01:15	0.58	1.92	1.12	0.34	1.84	0.006	0.004
08/01	01:30	0.58	1.84	1.06	0.33	1.82	0.000	0.000
08/01	01:45	0.58	1.88	1.09	0.34	1.83	0.002	0.000
08/01	02:00	0.58	1.80	1.04	0.33	1.82	0.000	0.003
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.61	2.07	1.26	0.37	1.93	0.020	0.045
				$\sum xy$	$\sum x^2$		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.

$$C_{SS} = \frac{\sum xy \,/\, \sum x^2}{1.486} \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 2.12 and R^2 = 0.66. R^2 is not maximized.

EXAMPLE

Solution: Calculate the hydraulic coefficient - Iteration n

(a) Assume d_{dog} = 6.45 in. 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	in	ft/s	in	°	ft^2	°	ft	ft	$ft^{2/3}$
08/01	00:00	14.34	2.11	7.89	131	0.97	187	3.67	0.26	0.41
08/01	00:15	14.08	2.03	7.63	129	0.92	185	3.63	0.25	0.40
08/01	00:30	13.91	1.99	7.46	128	0.90	183	3.60	0.25	0.40
08/01	00:45	13.81	1.96	7.36	126	0.88	183	3.59	0.25	0.39
08/01	01:00	13.48	1.99	7.03	123	0.82	180	3.53	0.23	0.38
08/01	01:15	13.14	1.92	6.69	119	0.77	177	3.47	0.22	0.37
08/01	01:30	12.93	1.84	6.48	117	0.73	175	3.44	0.21	0.36
08/01	01:45	13.04	1.88	6.59	118	0.75	176	3.46	0.22	0.36
08/01	02:00	12.88	1.80	6.43	117	0.73	175	3.43	0.21	0.36
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	14.19	2.07	7.74	130	0.94	186	3.65	0.26	0.41
	10.35 ↦	d_{min}	v_{avg}	↤ 1.86						

(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	$ft^{2/3}$	ft/s	$ft^{5/3}/s$	$ft^{4/3}$	ft/s	$(ft/s)^2$	$(ft/s)^2$
08/01	00:00	0.41	2.11	0.87	0.17	2.02	0.008	0.063
08/01	00:15	0.40	2.03	0.82	0.16	1.98	0.003	0.030
08/01	00:30	0.40	1.99	0.79	0.16	1.94	0.002	0.017
08/01	00:45	0.39	1.96	0.77	0.15	1.93	0.001	0.010
08/01	01:00	0.38	1.99	0.75	0.14	1.86	0.016	0.017
08/01	01:15	0.37	1.92	0.70	0.13	1.80	0.015	0.004
08/01	01:30	0.36	1.84	0.66	0.13	1.76	0.007	0.000
08/01	01:45	0.36	1.88	0.68	0.13	1.78	0.010	0.000
08/01	02:00	0.36	1.80	0.64	0.13	1.75	0.003	0.003
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
08/21	23:45	0.41	2.07	0.84	0.16	2.00	0.006	0.045
				$\sum xy$	$\sum x^2$		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.

$$C_{SS} = \frac{\sum xy \,/\, \sum x^2}{1.486} \qquad R^2 = 1 - \frac{SSE}{SYY}$$

Based on this iteration, C_{SS} = 3.31 and R^2 = 0.95. R^2 is maximized.

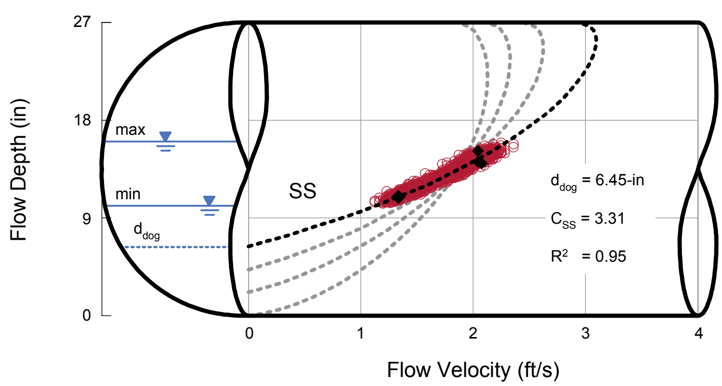
EXAMPLE

Solution: Construct pipe curve and estimate sewer capacity

(c) Calculate v_{SS} for $0 \le d \le D$

d	d_e	θ_e	A_e	θ	A	P	R_{SS}	$R_{SS}^{2/3}$	v_{SS}
in	in	°	ft²	°	ft²	ft	ft	ft	ft/s
0	0.00	0	0.00	0	0.00	0.00	—	—	—
3	0.00	0	0.00	78	0.24	1.53	0.00	0.00	0.00
6	0.00	0	0.00	113	0.66	2.21	0.00	0.00	0.00
9	2.55	72	0.19	141	1.16	2.77	0.07	0.17	0.83
12	5.55	108	0.59	167	1.71	3.28	0.18	0.32	1.57
15	8.55	137	1.08	193	2.27	3.78	0.29	0.43	2.13
18	11.55	163	1.62	219	2.82	4.30	0.38	0.52	2.57
21	14.55	189	2.19	247	3.32	4.86	0.45	0.59	2.89
24	17.55	215	2.74	282	3.73	5.54	0.49	0.62	3.07
27	20.55	243	3.25	360	3.98	7.07	0.46	0.60	2.93

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} = 3.98 ft² x 2.93 ft/s = 11.7 ft³/s or 7.5 MGD.

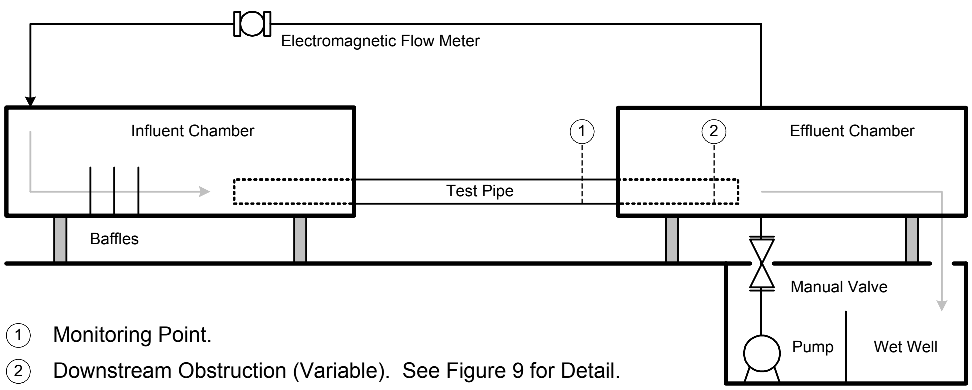
Laboratory Investigation

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

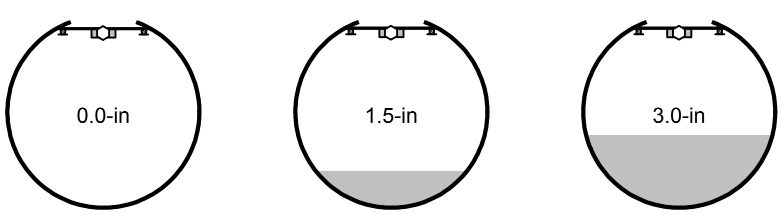
The laboratory equipment used during this investigation was designed and configured to simulate hydraulic conditions encountered in the urban sewer environment. The general arrangement of this equipment is provided in Figure 8.

FIGURE 8: Laboratory General Arrangement



A pump provides flow through a 6-in 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 an 8-in 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 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

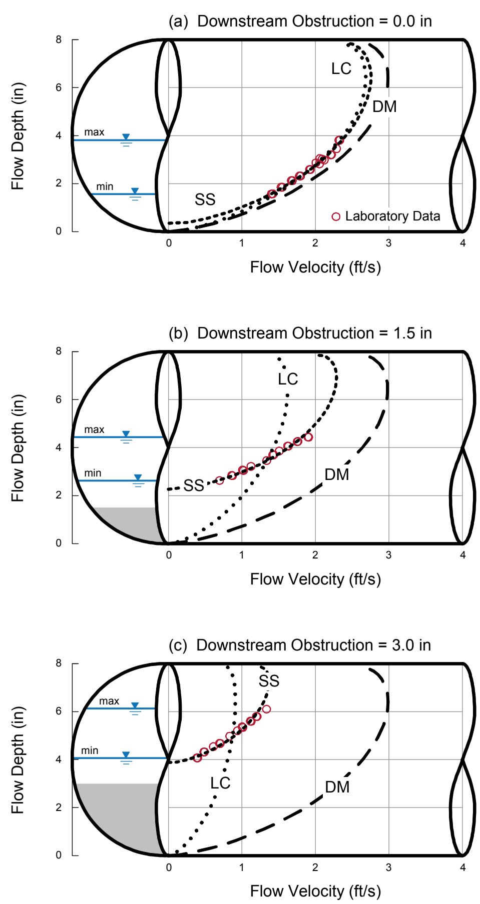


After placing an obstruction within the test pipe, the pump is activated, and flow is introduced into the system. Once the system has reached equilibrium, flow depth and quantity measurements are obtained at three consecutive one-minute intervals. Flow depth is measured in the test pipe with a stainless 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, in or ft
v = flow velocity, ft/s
Q = flow rate, ft^3/s or MGD
n = roughness coefficient
R = hydraulic radius, ft
S = slope of the energy gradient
C = hydraulic coefficient
D = diameter, in or ft
A = wetted area, ft^2
P = wetted perimeter, ft
R^2 = coefficient of determination

SUBSCRIPTS

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

Acknowledgement

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