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# Project Summary

# The Value of Flow Calibration for Decision Making in Infiltration/ Inflow Studies

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**A study was conducted to determine the value of flow calibration for decision making in sewer system studies. The results may be applied to any sewer system flow measurement program. Data indicated that the conventional use of Manning's equation for relating discharge from stage records collected by manual and automated recorders without primary flow calibration could grossly misestimate discharge conditions over all flow regimes. This problem translates into erroneous cost conclusions regarding treatment, transport, and rehabilitation recommendations.**

**Primary data used in this investigation were obtained from an earlier study conducted for the Metropolitan District Commission (MDC) in Boston, Massachusetts, covering portions of West Roxbury-Newton-Brookline-Dedham in the Boston metropolitan area (Environmental Design & Planning, Inc., "Infiltration/Inflow Study for West Roxbury-Brookline-Newton-Dedham Area," Metropolitan District Commission). This previous study included a number of primary discharge measurements at key manholes during both dry and wet weather flow conditions.**

**The present study developed a variety of scenarios for key manholes as to the amount of information available to develop stage/discharge calibration curves. Alternative stage/discharge curves were used to estimate costs for the resulting rehabilitation and treatment programs. The problem of increased gaging costs was weighed against possible reductions in erroneous recommendations. Results indicate that the additional care and cost involved in primary flow calibration of stage/discharge curves for sewer system evaluations are well worth the effort. The best method for developing stage/discharge curves was to curve-fit Manning's equation with a variable roughness coefficient to calibration data using least squares methods.**

***This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, Ohio, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Introduction

Accurate determination of sewer system flow characteristics in dry and wet weather is vital to establishing infiltration and/or inflow rehabilitation requirements. Inaccurate gaging (particularly for borderline situations) may lead to erroneous recommendations for further actions and result in the inefficient allocation of local or Federal resources.

Flow determinations are often performed in infiltration/inflow studies using a dipstick (instantaneous spot) procedure to obtain stage levels. These results are then converted into discharge using any one of a variety of different procedures such as Manning's, Chezy's, and/or Kutter's equation together with measurements of various hydraulic input parameters (size, shape, length, and slope) taken from plan and profile as-built drawings. Roughness coefficients are usually estimated by inspecting the conditions of the test segment and its age since construction. In other situations, automatic stage recording devices are installed to obtain a long-time series of stage records. Most often these records are then converted to discharge quantities using similar procedures for relating stage to discharge.

Accurate measurement of either dry or wet weather flow discharge in a sewerage system is a difficult process beset by constantly changing problems. For example, sediment accumulations erratically increase the values of roughness coefficients nominally determined for clean-pipe conditions, and also change the cross-sectional area of flow. Grit and debris tend to impair velocity determinations and bias discharge computations. Backwater problems elevate depths of flow and change velocity profiles.

Two different measurement procedures can be used: direct methods that meausre both depth of flow and velocity, and indirect methods that record only depth of flow and then convert to discharge using some predictive relationship. Direct measurement approaches can provide accurate determinations of flow for given instants of time, but they are not routinely used in gaging studies. Secondary or indirect methods provide a less accurate flow estimate, but they are commonly used in infiltration/inflow studies because of their simplicity and low cost. In many studies, no direct measurements are made to corroborate or calibrate indirect methods.

One approach used in some studies is to obtain primary measurements at several flow depths (most often at dry weather flow conditions) and then to use Manning's equation (or an equivalent) in dimensionless form to estimate full-pipe discharge conditions so that the upper end of the stage/discharge curve can be established. This method is very reasonable, provided that the calibration points are made without measurement error (which is often difficult). The presence of sediment beds complicates the numerical simplicity of this direct approach. This approach may be acceptable when measurements are made accurately. But when measurement errors exist, and when all the requisite assumptions underlying Manning's equation are not met, a least squares curve-fitting procedure can be used with Manning's equation (in dimensionless form) to fit observed data. This report presents an alternative and numerically equivalent method consisting of simple, statistical, least squares, curve-fitting techniques that compensate for both the measurement error problem and the inherent limitation of using a simple model (Manning's equation) to represent complicated phenomena.

## Study Design

In the earlier study, sewage flow depths at key manholes throughout a 3000-acre sewerage system were measured under both dry and wet weather conditions, including instantaneous and continuous measurements (see Figure 1). Discharge estimates at a number of locations using measured flow areas and velocities were also obtained. A single stage/discharge method was examined at a representative number of key manholes.

Step A of this study derives alternative stage/discharge relationships for all key manholes using different assumptions. Step B computes alternative estimates of flow conditions throughout the sewerage system for both dry and wet weather conditions using the alternative stage/discharge relationships derived in Step A, the raw flow depth information, and the discharge calibration points (computed from velocity and flow area measurements from the earlier study. Step C proposes various sewer system rehabilitation programs that attain a similar degree of extraneous flow reduction. Complete analyses of the required sewer system upgrading are prepared along with cost estimates for each set of assumed flow volumes. Finally, Step D assesses the economic benefits of measurements versus the implied costs of the alternative rehabilitation programs.

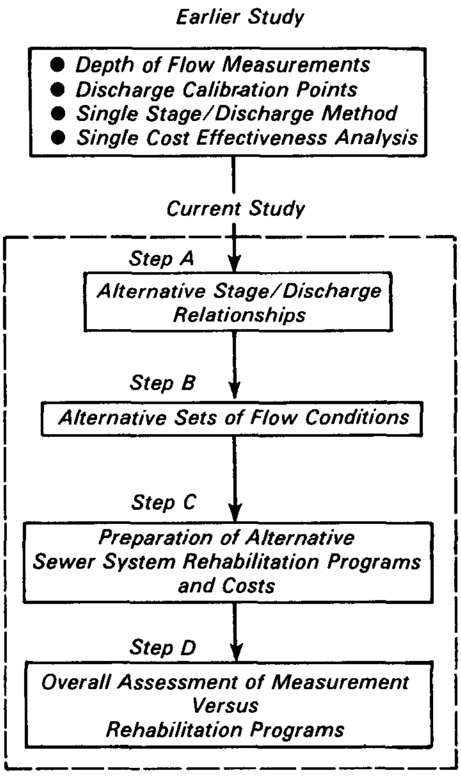

***Figure 1.*** *Schematic of project research and development.*

The full report presents several statistical methods for developing stage/discharge relationships in which Manning's equation with a variable roughness coefficient is curve-fitted by least squares methods of calibration data obtained by direct field measurements. A surrogate value of energy slope is determined that minimizes the sum of squares of field discharge information about a curve defined by Manning's equation. The procedure makes the best use of limited depth-of-flow/discharge measurements in developing the overall rating curve. Alternative fitting procedures are developed using ordinary least squares and weighted least squares approaches. The stage/discharge curve-fitting methodology is described in the following section.

In the case study examined in this report, depth-of-flow data collected at 45 key manholes were translated into discharge levels using three alternative methods for developing stage/discharge curves. The methods included: a) application of weighted least squares procedures to Manning's equation using a variable roughness coefficient, b) application of Manning's equation using plan and profile slope and a variable roughness coefficient formulation, and c) application of Manning's equation using plan and profile slope with a fixed roughness coefficient. These methods are compared to show the differences between the least squares procedures and methods commonly used in actual practice. The alternative stage/discharge methods prepared for one of the key manholes are described in the last section of this summary.

The three different sets of peak dry-weather flow, infiltration, and inflow for the 45 key manholes were then used as raw information to determine technically equivalent, least-cost infiltration/inflow control programs. The controls consisted of (1) infiltration rehabilitation and inflow remedial programs in areas tributary to an interceptor undergoing backwater and surcharge conditions, and (2) construction of replacement (increased conveyance) segments along the existing interceptor. The aim of the effort was to investigate how the mix of final recommended controls and their associated costs would change using flows computed by the different flow estimation schemes.

***Table 1.*** *Overview of Control Plans Developed Using Different Method of Flow Estimation*

| *Flow Estimation Method* | *Control Plan* | *Overall Program Cost* |
|---|---|---|
| *Method 1*<br>*(Least squares estimation of slope in Manning's Equation with variable roughness factor coefficient)* | ● *Infiltration control, 60%*<br>● *Inflow control, 71%*<br>● *New replacement segments in portions of upper westerly interceptor* | *$3,160,000* |
| *Method 2*<br>*(Manning's Equation with plan & profile slope and variable roughness coefficient)* | ● *Infiltration control, 85%*<br>● *Inflow control, 85%*<br>● *New replacement segments in portions of upper westerly interceptor system (about the same as plan 1)* | *$3,580,000* |
| *Method 3*<br>*(Manning's Equation with plan & profile slope and fixed roughness coefficient)* | ● *Infiltration control, 85%*<br>● *Inflow control, 85%*<br>● *New replacement segments throughout the entire system* | *$6,130,000* |

Identical criteria were used to determine the level and need for each type of control for the three different methods. Present value costs were computed for each plan, and they included infiltration rehabilitation, remedial inflow corrections, construction of replacement segments along the existing interceptor, and treatment costs of extraneous wet weather discharges. An overview of the rehabilitation analysis and the associated costs for the three methods appear in Table 1. Cost of the overall control program (present value) for the three methods of flow estimation were $3.16 million, $3.58 million, and $6.13 million, respectively. The mix of recommended controls was substantially different for each of the three plans. The engineering costs involved in performing the field calibration discharge measurements together with performing the least squares calculations were about $13,500 (as determined in the earlier study). Field calibration accounted for about 90 percent of the additional field effort. The least squares computations can be quickly performed using typical engineering-office desk calculators.

Significant benefit can be derived from carefully preparing stage/discharge rating curves in infiltration/inflow studies by performing primary measurements and making the best use of this information with curve-fitting procedures. This conclusion holds true for any sewerage system management study.

## Least Squares Stage/Discharge Methodology

A number of the hydraulic parameters in Manning's equation can be expressed as a function of the ratio of observed flow depths, $h_i$, to pipe diameter, D, for measured values of discharge, $Q_i$. Manning's equation is as follows:

$$Q_i = \frac{1.49\, r_i^{2/3}\, S^{1/2}\, a_i}{n_i} \qquad (1)$$

where:

$Q_i = f_1(h_i/D)$, measured flow rate (cfs)
$r_i = f_2(h_i/D)$, hydraulic radius (ft)
$S$ = constant, energy slope (ft/ft)
$a_i = f_3(h_i/D)$, wetted area (ft$^2$)
$n_i = f_4(h_i/D)$, Manning's roughness coefficient

The value of n at full pipe, $n_f$, and its variations with depth was assumed to be known, and the slope, S, was taken as a surrogate for all the uncertainties with respect to S itself and the roughness coefficient, n. We preferred to assume that n (or its variation with depth) is known and to let a surrogate slope, S, constant for all water depths, be the free parameter to be determined from the least squares procedure.

A number of least squares approaches are possible, depending on how we pose the minimization problem of fitting the observed values of ($h_i$, $Q_i$) about Manning's equation. Three approaches are possible.

The first approach is the standard, ordinary least squares formulation in which the standard deviation of the residuals (observed-predicted) is independent of the magnitude of discharge. The resulting expression for the sum of the squares of the residuals, O(S), can be written as:

$$\min_{S} O(S) = \sum_{i=1}^{m} [Q_i - S^{1/2} K_i(h_i/D)]^2 \qquad (2)$$

where: $Q_i$ = observed values of flow from the calibration

$$K_i(h_i/D) = \frac{1.49\, a_i\, r_i^{2/3}}{n_i} \qquad (3)$$

m = number of observed $Q_i$
all other variables = as defined before

To minimize O(S), its derivative is taken with respect to S and set equal to zero. The resulting expression for the best-fit $\hat{S}$ is:

$$\hat{S}^{1/2} = \frac{\sum_{i=1}^{m} K_i Q_i}{\sum_{i=1}^{m} K_i^2} \qquad (4)$$

In the second approach, the variance of the measured value, $Q_i$, from its computed *value is assumed to be proportional to the* magnitude of Q. The objective function to be minimized under this assumption is as follows:

$$\min_{S} O(S) = \frac{1}{S} \sum_{i=1}^{m} \frac{1}{K_i} [Q_i - K_i S^{1/2}]^2 \qquad (5)$$

*The resulting estimate of slope,* $\hat{S}$, *is* given by:

$$\hat{S}^{1/2} = \frac{\sum_{i=1}^{m} Q_i}{\sum_{i=1}^{m} K_i} \qquad (6)$$

Another feasible model would be to assume that the standard deviation of $Q_i$ is proportional to $Q_i$. This assumption is the same as a constant coefficient of variation. The resulting objective function, *O(S), is given by:*

$$\min_{S} O(S) =$$

$$1/S^2 \sum_{i=1}^{m} 1/K_i^2 (Q_i - K_i S^{1/2})^2 \qquad (7)$$

The resulting estimate of slope, $\hat{S}$, is given by:

$$\hat{S}^{1/2} = \frac{1}{m} \sum_{i=1}^{m} Q_i/K_i \qquad (8)$$

The choice of a particular model to use in any given application is somewhat arbitrary. The ordinary least squares approach given by Equation 4 weights large observations of $(Q_i, K_i)$ too heavily, whereas the estimate of S, resulting from the third approach given by Equation 8, weights large observations too little. The second approach, which assumes that the variance of the observed Q about its true value is proportional to its magnitude, seems to provide a reasonable compromise.

Pertinent data illustrating the least squares fitting procedures are presented in Table 2. Depth of flow and velocity measurements in a 27-in., vitrified clay pipe (vcp) sanitary trunk sewer in the Boston area were determined on four separate occasions. Depth of flow and velocities were measured using a Marsh-McBirney* meter. The tabulation of variable Manning's roughness coefficient for $n_f = 0.015$ was used to prepare the estimates shown in Table 2.

The ordinary least squares estimate of the surrogate slope parameter $\hat{S}$, using Equation 4, is computed as follows:

$$\hat{S} = \left[\frac{562.557}{9902.724}\right]^2 = 0.00323$$

The weighted least squares estimate of the surrogate slope parameter using Equation 6 is computed as follows:

$$\hat{S} = \left[\frac{8.746}{161.925}\right]^2 = 0.00292$$

A sensitivity analysis was performed (Table 3) using two alternative least squares approaches on different sets of data derived by various representative assumptions of measurement error. Four different cases of measurement error for the field data in Table 2 are considered. The first case entails a positive velocity meter bias of 10 percent for all four observations. An erroneous positive depth-of-flow error of 1 in. for all observations in considered in the second case. An erroneous positive depth-of-flow error of 1 in. for only the high-flow measurements is depicted for the third case. And the last case considers both depth of flow error and positive velocity meter bias for the high-flow measurements. Many other combinations of measurement error are also possible. The square root of the ratio of the fitted ordinary least squares (ols) and the weighted least squares (wls) slopes for each case (Table 3) reflect the increase of hydraulic conveyance about the nominal estimate, assuming that the derived relationships are thereafter used without error (i.e., correct depths of flow are entered into the computations). The results show that for these data sets, either method will yield comparable rates of error. The greatest degree of error derives from the first case, involving velocity measurement bias.

Estimates provided by the wls approach are nevertheless preferred, particularly when very high (full pipe) flow conditions are gaged with the possibility of both velocity and depth-of-flow measurement errors. The wls approach tends to reduce the impact of large $(Q_i, K_i)$ values. A good compromise in practice would be to calculate the slopes by both methods and then compute the geometric average of the two estimates.

Two types of discharge estimates were compared for the 27-in. trunk sewer — those computed using plan and profile slopes of 0.003 with fixed roughness coefficients of 0.013 and 0.015, and those computed using both least squares approaches for various flow depths (Table 4). The calculations show that discharges computed using plan and profile slope with fixed roughness coefficients (cases A and B) greatly exceed those computed by either of the least squares procedures. Thus the differences in Table 4 between cases A and B and Cases C and D are considerably decreased if the variable roughness coefficient formulation is used for cases A and B.

## Comparison of Stage/Discharge Curves from the Earlier Study

Alternative stage/discharge curves for a key manhole in area 25 in the study area is presented in Figure 2. Field discharge measurements are also shown. The sewer segment is a 12-in. vcp with 1½ in. of sediment and was constructed at a slope of 0.00208. Four alternative curves are plotted for the following conditions: (1) minimum square fit (wls) for $\hat{S}$ assuming variable n ($n_f = 0.015$); (2) minimum square fit (wls) for $\hat{S}$ assuming a constant n = 0.015 and considering sediment, if present; (3) clean pipe, with slope from the plans and a constant n = 0.013; and (4) clean pipe with slope from the plans and a constant n = 0.015.

Common practice in flow measurement studies is to use the pipe slope from as-built drawings in Manning's equation and to disregard the presence of sediments in the estimation process. Implicit assumptions are that the pipe slope is known with certainty and that the hydraulic flow profile equals the pipe slope (i.e., the water slope is parallel to the pipe slope). These important assumptions underlie the computational process used to derive curves 3 and 4. The least squares fitting process used to establish curves 1 and 2 makes no such limiting assumptions; instead, it uses actual flow measurements affected by sediment beds and by pipe and water slope irregularities to develop realistic rating curves.

Comparisons of curves 1 and 2 in Figure 2 show that though both curves comply with the mathematical condition that the sum of squares of the deviations from the observed values is minimum, curve 1 seems to adhere better to the observed points. This fact can be interpreted as additional evidence that Manning's equation is more capable of reproducing the physical phenomena of flow in pipes if n is considered a function of flow depth.

The presence of sediment beds can be considered in the least squares curve-fitting procedure by appropriate adjustment of the hydraulic parameters defined in Equation 1. The cross sectional area, $a_i$, and the hydraulic radius, $r_i$, are directly computed using the top of the sediment bed as the reference level. The variable roughness factor tabulation is based on a circular cross section. Estimates of the variable roughness factor can be generated for noncircular cross sections (circular or noncircular, with or without sediment) using equivalent circular estimates. First, an equivalent diameter is computed for the total cross section free from sediments. Next, an equivalent depth of flow (circular section) is computed using the wetted area of the noncircular section for each flow observation. Last, the appropriate estimate of variable n is determined using the equivalent circular depth of flow and the equivalent diameter estimates.

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*Mention of trade names or commercial products does not constitute endorsement or recommendation for use

**Table 2.** *Sample Calculations of Least Squares Procedures*

| *Measured Information* | | *Physical Data* | | | *Calculations* | | | |
|---|---|---|---|---|---|---|---|---|
| *Depth of Flow* (in.)* | *Measured Velocity (fps)* | $r_i$ (ft) | $a_i$ (ft$^2$) | $n_i^+$ | $Q_i$ (cfs)‡ | $K_i^\delta$ | $K_i^2$ | $K_iQ_i$ |
| 9.5 | 2.50 | .437 | 1.249 | .0192 | 3.123 | 55.868 | 3121.233 | 174.464 |
| 11.5 | 2.90 | .504 | 1.614 | .0190 | 4.680 | 80.282 | 6445.200 | 375.743 |
| 4.75 | 1.15 | .242 | .471 | .0190 | 0.542 | 14.322 | 205.120 | 7.756 |
| 4.25 | 1.10 | .219 | .401 | .0189 | 0.401 | 11.453 | 131.171 | 4.594 |
| Sum | | | | | 8.746 | 161.925 | 9902.724 | 562.557 |

**27-in. vcp trunk sewer with no sediment, plan and profile slope = 0.0036.*

*+Variable Manning's roughness coefficient with $n_f$ = 0.015.*

$^\delta K_i = \dfrac{1.49\, a_i\, r_i^{2/3}}{n_i}$.

‡Cubic meters/second = 0.0283 cfs.

**Table 3.** *Sensitivity Analysis of Least Squares Procedures*

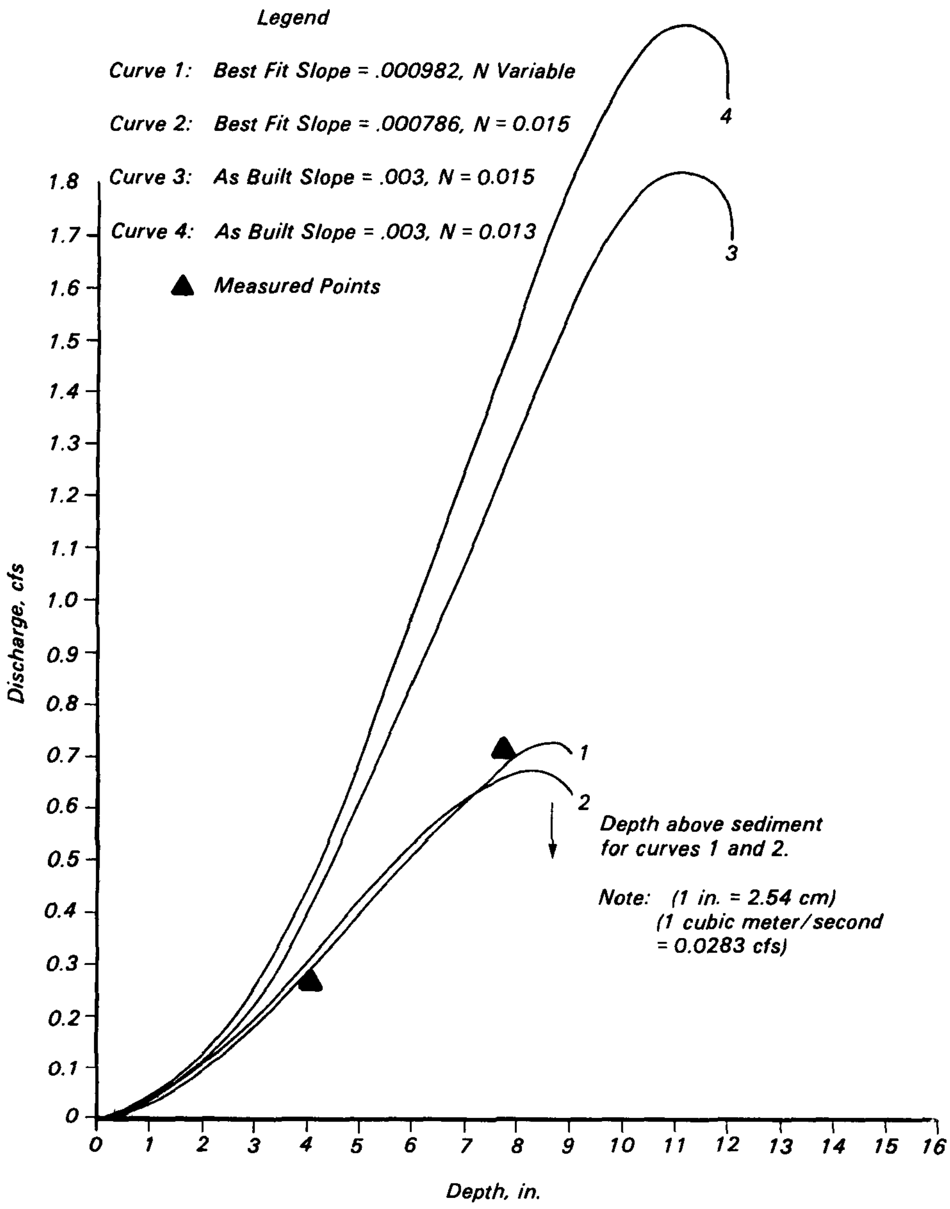
| *Case* | *Ordinary Least A.** | *Squares-Eq. 5 B.* | *Weighted C.* | *Least Squares-Eq. 7 D.* |
|---|---|---|---|---|
| Existing data (nominal estimate) | .00323 | 1.00 | .00292 | 1.00 |
| Velocity measurement increase (10%) for all observations | .00391 | 1.10 | .00353 | 1.10 |
| Depth of flow increase (1 in.) for all observations | .00286 | 0.94 | .00253 | 0.93 |
| Depth of flow increase (1 in.) for 1st and 2nd observations | .00294 | 0.95 | .00270 | 0.96 |
| Depth of flow increase (1 in.) and velocity increase (10%) for 1st and 2nd observations | .00354 | 1.05 | .00321 | 1.05 |

**A. Ordinary least squares estimate of slope.*
*B. Square root (estimate slope for stated data/estimated nominal slope). Slopes computed by ordinary least squares formulation — Equation 5.*
*C. Weighted least squares estimate of slope.*
*D. Square root (estimated slope for stated data/estimated nominal slope). Slopes computed by weighted least squares formulation — Equation 7.*

**Table 4.** *Comparison of Discharges Computed Using Various Stage/Discharge Formulations**

| *Assumed Depth of Flow (in.)+* | *Discharges (cfs)+* | | | | *Ratio of* | | |
|---|---|---|---|---|---|---|---|
| | *A‡* | *B* | *C* | *D* | *A/D* | *B/D* | *C/D* |
| 10 | 4.98 | 4.22 | 3.50 | 3.33 | 1.495 | 1.267 | 1.051 |
| 18 | 13.98 | 11.43 | 9.98 | 9.55 | 1.372 | 1.197 | 1.045 |
| 25 | 18.27 | 15.86 | 15.64 | 14.80 | 1.234 | 1.072 | 1.057 |

**27-in. trunk sewer.*
*+1 in. = 2.54 cm.*
*Cubic meters/second = 0.0283 cfs.*
*‡KEY:*
*A. Manning's equation, plan and profile slope = 0.003, fixed n = 0.013*
*B. Manning's equation, plan and profile slope = 0.003, fixed n = 0.015*
*C. Manning's equation, fitted slope (ols), variable n with $n_f$ = 0.015*
*D. Manning's equation, fitted slope (wls), variable n with $n_f$ = 0.015*



Depth above sediment for curves 1 and 2.

Note: (1 in. = 2.54 cm)
(1 cubic meter/second
= 0.0283 cfs)

**Figure 2.** Alternative stage/discharge curves for Area 25.

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*The complete report, entitled "The Value of Flow Calibration for Decision Making in Infiltration/Inflow Studies," (Order No. PB 83-259 739; Cost: $10.00, subject to change) will be available only from:*
*National Technical Information Service*
*5285 Port Royal Road*
*Springfield, VA 22161*
*Telephone: 703-487-4650*

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