EPA-600/2-77-120
July 1977

Environmental Protection Technology Series

PROCEDURES FOR ESTIMATING DRY WEATHER POLLUTANT DEPOSITION IN SEWERAGE SYSTEMS

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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by

William C. Pisano
Celso S. Queiroz

Energy & Environmental Analysis, Inc.
Boston, Massachusetts 02116

Grant No. R804579

Project Officer

Richard Field
Storm and Combined Sewer Section
Wastewater Research Division
Municipal Environmental Research Laboratory (Cincinnati)
Edison, New Jersey 08817

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

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The deleterious effects of storm sewer discharges and combined sewer overflows upon the nation's waterways have become of increasing concern in recent times. Efforts to alleviate the problem depend in part upon the development of improved flow attenuation and treatment devices.

This report presents a series of generalized predictive approaches for estimating the amount of sewage solids and other pollutants that deposit in sewerage systems during dry weather conditions. These procedures are intended to provide estimates of overall pollutant deposition for entire sewer collection systems.

Francis T. Mayo
Director
Municipal Environmental Research Laboratory

ABSTRACT

A set of generalized procedures for estimating pollutant loadings associated with dry weather sewage solids deposition in combined sewer systems has been prepared to provide planners, engineers and municipal managers with technical information so that they can make intelligent informed decisions on potential sewer flushing programs in combination with other combined sewer management controls.

The predictive equations relate the total daily mass of pollutant deposition accumulations within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter and other more complicated parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models are presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include suspended solids, volative suspended solids, biochemical oxygen demand, chemical oxygen demand, total organic nitrogen and total phosphorous. Sewer system age and degree of maintenance was also considered. Factors are presented for estimating the increase in collection system deposition resulting from improper maintenance. A user's guide has been presented to establish the necessary data input to utilize the predictive procedures.

This report was submitted in partial fulfillment of Grant No. R804579 by Northeastern University and Energy & Environmental Analysis, Inc., under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of August 1, 1976 to December 30, 1976. Work was completed as of April, 1975.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CDF - cumulative distribution function
ft - foot
gpcd - gallons per capit per day
kg - kilogram
lb/day- pounds/day
log - logarithm
mi - mile
WRNDB - sewerage system within the area covering portions of West Roxbury, Dedham, Newton and Brookline in metropolitan Boston.

SYMBOLS

A - Area of collection system (acres)
AV - Indicates a variable in the regression analysis which is available to enter the regression equation
BOD - Biochemical Oxygen Demand (5 day)
COD - Chemical Oxygen Demand
$\bar{D}$ - Mean pipe diameter of a collection system, (in)
D_i - Pipe diameter of sewer segment i, (in)
DP - Indicates the dependent variable in the regression analysis
e - Base of the natural logarithms;
FI - Indicates a variable in the regression analysis to be forced in the regression equation
FO - Indicates a variable in the regression analysis to be kept out of the regression equation.
F_S - Indicates the cumulative probability of a value s of the pipe slopes
G_S - Indicates complementary cumulative probability distribution
L - Total length of the collection system (ft)
l_i - Length of sewer segment i
LPD - Length of pipe over which 80% of the total loads deposit in the collection system
LPM - Estimated length of pipe over which the percentage PM of the total loads deposit in the collection system
n - The total number of pipe segments in a collection system
NH_3 - Ammonia
p - Particle size (mm)
P - Total Phosphorous
P(a) - Indicates the probability of a

PL - Percentage of pipe length corresponding to a percentage of PM of the loads depositing in the collection system

PL_D - Percentage of pipe length corresponding to 80% of the loads depositing in the collection system

$PL_D/4$ - One fourth of PL_D

PM - Any given percentage of the solids deposited in a collection system

PP - population in service area

q - Discharge per capita, including infiltration, (gpcd)

QAV - Average daily dry weather flow, (cfs)

QMAX - Peak daily dry weather flow (cfs)

r - hydraulic radius (ft)

R - Multiple regression coefficient in the regression analysis

R^2 - Portion of the total variation about the mean (predicted by the regression equation) which is explained by the re-regression

$\bar{S}$ - Mean pipe slope of the collection system

s - A particular value of pipe slope

ss - Energy slope

S_i - Slope of sewer segment i

S_G - Mean ground slope

S_{PD} - Slope corresponding to P_{LD} in the CDF of the pipe slopes

$\bar{S}_{PD}$ - Average of pipe slopes below S_{PD} in the CDF

$S_{PD}/4$ - One fourth of S_{PD}

S_{PL} - Slope corresponding to PL in the CDF of the pipe slopes

TKN - Total Kjeldhal Nitrogen

TS - Indicates the total mass of solids that deposit in the system (lb/day)

TS_{a-b} - Indicates the total mass of solids that deposit in the collection system, assuming pipe bottom sediment varying from a to b (inches)

TS - Total Suspended Solids

VSS - Volatile Suspended Solids

X - Major dimension of non-circular pipe

Y - Minor dimensions of non-circular pipe

Z_i - Percentage daily solids deposition rate in pipe segment i

ZS_i - Amount of daily dry weather sewage solids input along pipe segment i

ρ - specific weight of water

τ - Fluid shear stress

τ_c - Critical shear stress

ACKNOWLEDGEMENTS

The successful completion of this report was dependent on the cooperation and assistance of a number of individuals and organizations. We are indebted particularly to Richard Field, Chief of the Storm and Combined Sewer Section, Muncipal Environmental Research Laboratory--Cincinnati, EPA, Edison, New Jersey and Richard Traver, staff engineer of the Storm and Combined Sewer Section, for their guidance and review of the work.

The analytical results of the field flushing program was performed by Northeastern University, Boston, Massachusetts. Dr. Fredric C. Blanc and Dr. James O'Shaughnessy are the project officers for Northeastern University.

This work was conducted under the supervision and direction of Dr. William C. Pisano, Project Director and Celso S. Queiroz, Environmental Systems Analyst, Energy & Environmental Analysis, Inc. Gerald L. Aronson and Paul G. Soper of EEA were responsible for the field engineering phase of the sewer flushing experiments.

SECTION 1

INTRODUCTION

Control of combined and storm sewer runoff is a problem of increasing importance in the field of water quality management. The control of combined sewer overflows employing structural measures such as sewer separation, storage and treatment have been used for a number of major cities in the United States. Nationwide application of these techniques for the control of combined sewer overflows would require expenditures critically taxing present and forseeable future resource allocations. New strategies are needed to reduce these costs to tolerable limits. Non-structural controls such as sewer system upgrading and active maintenance, improved catchbasin operation, street sweeping and sewer flushing are upstream collection system management practices that collectively can reduce total combined sewer pollutant loadings and accordingly the costs of downstream structural controls.

The concept of depositing solids control in sewer lines, although widely used around the turn of the century as a maintenance practice, is still in its infancy in regard to being viewed as a viable pollution control alternative for combined sewer systems. Much theoretical but little applied research has been performed to develop and quantify uniform criteria for estimating deposition loadings and for flushing sewers.

The deposition of sewage solids during dry weather in combined sewer systems has long been recognized as a major contributor to "first-flush" phenomena occurring during wet weather runoff periods. The magnitude of these loadings during runoff periods has been estimated to range up to 30 percent of the total daily dry weather sewage loadings. Estimation of these loadings for a given sewer system is an extremely difficult task. Measurement for extended periods is possible but extremely expensive. Some literature information is available from experiments on build-up of sanitary sewage solids in a pilot sewer study conducted by the FMC Corporation (1). No predictive procedures are available for estimating deposition build-up as a function of collection system characteristics. These predictive procedures are necessary as a first step in the development of sewer flushing programs as a non-structural management practice.

1.1 Purpose of Study

The purpose of this study is to provide municipal managers and planners with technical information on the amount and location of pollutant deposition within sewerage collection systems so that they can make intelligent, informed decisions on the potential for sewer flushing systems in their community.

1.2 Report Format

The detailed findings derived from this study are presented in the two sections that follow which deal with development of the theoretical predictive model (Section 4); and the user's guidance procedures (Section 5). Section 4 is subdivided into five subsections: section 4.1 - the general methodology; section 4.2 - the conceptual model; section 4.3 - the design of the experiment; section 4.4 - the data preparation; and section 4.5 - the regression results.

1.3 Data and Information Sources

The data and information for this study were derived principally from four data sources: (1) the preliminary first phase field flushing results from Research Grant no. R804579 conducted by Northeastern University and Energy & Environmental Analysis, Inc., sponsored by U.S. EPA Storm and Combined Sewer Section; (2) sewer atlas physical data for portions of West Roxbury, Dedham, Newton and Brookline, Massachusetts for an infiltration/inflow study conducted by Energy & Environmental Analysis, Inc., for the Metropolitan District Commission; (3) sewer atlas physical data for portions of the City of Fitchburg, Massachusetts for a section of 208 combined sewer management study conducted by Energy & Environmental Analysis, Inc. for the Montachusetts Regional Planning Commission; and (4) sewer atlas physical data for portions of Dorchester and South Boston for a combined sewer management study sponsored by the Metropolitan District Commission.

SECTION 2

CONCLUSIONS

Conclusions derived from this investigation are as follows:

1. This present study develops a methodology for providing first-cut assessemnts of: a) the total amounts of solids and other pollution indicators, (lb/day), that deposit in a sewerage collection system; and b) the extent of the collection system over which the deposition takes place. A complex distributed-parameter dry weather sewage depostion model was first applied to 75 separate and combined sewer collection systems in eastern Massachusetts to generate estimates of solids deposited in the systems (lb/day). These estimated loads were then regressed with selected variables representing the physical characteristics of the collection system resulting in four predictive single term power functions with at most four independent variables. The regression analysis revealed a remarkable degree of fit of the nonlinear functions to the data set, with the R^2 values ranging from 0.85 to 0.95.

2. A comparative error analysis of predicted daily dry weather solids deposition for a test case collection system using the procedures generated in this study and the complex distributed-parameter model indicated a relative error ranging from 8 to 18 percent. The analysis also showed that the simplest of these procedures requiring comparatively little input data may be more cost effective than the more complex of these procedures for providing reliable "first-cut" estimates.

3. The complex distributed parameter model was tentatively calibrated using actual field flush information lending credulence to the adoption of the simplified procedures generated in this study.

4. The field analytical results of a sewer flushing project currently in progress were used to regress other pollutants such as BOD, COD, TKN, Total Phosphorous, NH_3 and VSS with suspended solids, all with high values of R^2, extending therefore the use of the predictive equations for total solids deposited to the estimation of other pollutants.

5. The effects of sewer system age and maintenance on solids deposition was simulated by considering prior sediment deposits to develop multiplicative coefficients to the four predictive equations for total solids deposited.

6. Extensive statistical analyses of sewerage system pipe slopes revealed that collection system pipe slopes can be represented by an exponential probability model. Analysis of the distribution of loads deposited versus cumulative pipe length lead to the development of generalized curves as a function of collection system mean slope for estimating the total fraction of collection system pipe footage over which a given percentage of the total loads deposit. These findings can be combined to locate segments associated with the required fractions.

SECTION 3

RECOMMENDATIONS

1. The major improvements to the methodology developed in this study involve extending the range of the regression model's applicability by expanding the observed ranges of the independent predictive variables used in the analysis. The reliability of the model's estimates will be improved. These improvements can be accomplished by augmenting the existing data base with new data from other sewer collection systems having different physical characteristics, in terms of average slopes, system configurations and extent, pipe sizes and shapes, etc., from those used in this study. Inclusion of systems with flatter and steeper average pipe slopes would broaden substantially the range of application of the regression equations derived in this study.

2. Another area meriting further study is the analysis of the cumulative distribution function of pipe slopes, especially for applications where only a limited amount of information on the collection system is available.

SECTION 4

DEVELOPMENT OF GENERALIZED PREDICTIVE MODELS

4.1 Overview

4.1.1 Objectives

The severity of combined sewer overflows is often associated with problems of dry weather solids deposition. Deposition build-up reduces conveyance capactiy and contributes to the pollutants that discharge into receiving waters. The analysis of remedial solutions to mitigate these problems involves estimating the amounts of solids deposited and their distribution throughout the system, so that control costs can be assessed.

The techniques presently available to estimate dry weather deposition in sewerage systems involve the use of computerized mathematical models, that are both complex and expensive and requiring more effort than appropriate for preliminary "first-cut", assessments. The objectives of this study is to develop predictive tools capable of defining on a preliminary basis:

a) the total amounts of solids and other pollutants that deposit in the sewerage system; and

b) the extent of the collection system over which the deposition takes place.

It is therefore possible with these two estimates to crudely evaluate the costs associated with sewer flushing and other means of reducing and/or eliminating these pollutants.

4.1.2 Executive Overview of Methodology

An empirical model relating pollutant deposition loadings to collection system characteristics is the goal of this study. The approach is to use least squares to fit parameters of a postulated model. The data base used in the fitting process consists, in part, of a number of collection system parameters developed from an extensive data analysis of the physical details of several major sewerage collection systems in eastern Massachusetts. These

characteristics are some of the independent variables used in the analysis. The data for the dependent variables are the total daily sewage solids deposited in these collection systems for a wide variety of different operating conditions. These quantities are estimated using an existing exogenous model that uses extremely detailed information to compute deposition loadings throughout an entire collection system network. An analysis of the detailed outputs of this model together with some of the physical data of the collection systems provided the remaining independent variables in the data base. Simply stated, the dependent variable data was generated from an exogenous predictive analysis while the independent variable data was obtained from primary collection system data and from a secondary analysis of the exogenous simulation outputs with selected collection system data.

The results of the first phase field flushing program are described in Appendix A along with a brief overview of the entire project. The methodological details of the existing exogenous deposition model that predicts solids deposition in all segments of an entire sewerage collection system are presented in Appendix B. Preliminary calibration efforts using the data in Appendix A and the model in Appendix B are presented in Appendix C. These results are given to justify the application of that model to produce simulated data for the purposes of this study.

4.2 General Methodology-Detailed Overview

The general methodology used in the study is outlined in Figure 1. The first step is to define the general characteristics and parameters of the conceptual model. This discussion is presented in Section 4.2.1. Next, a series of experiments is designed to generate deposition loadings using the model described in Appendix B for a wide range of conditions likely to be encountered in practice. The regression equations would be valid for use over these ranges of conditions. The design of the experiments, described in Section 4.3, consists of defining the study areas to be used in the experiments and the hydraulic conditions under which the numerical experiments would be performed. The suspended solids per capita waste rate is discussed in the design of the experiments.

The next step involved the collection of all pertinent physical data associated with the selected collection systems, such as system configuration, pipe lengths, shapes and sizes, invert elevations, so that the deposition model referred to in Appendix B could be used. This physical data, together with the deposition model and the total loads deposited simulated for each of the collection systems. This work is described in Section 4.4.1

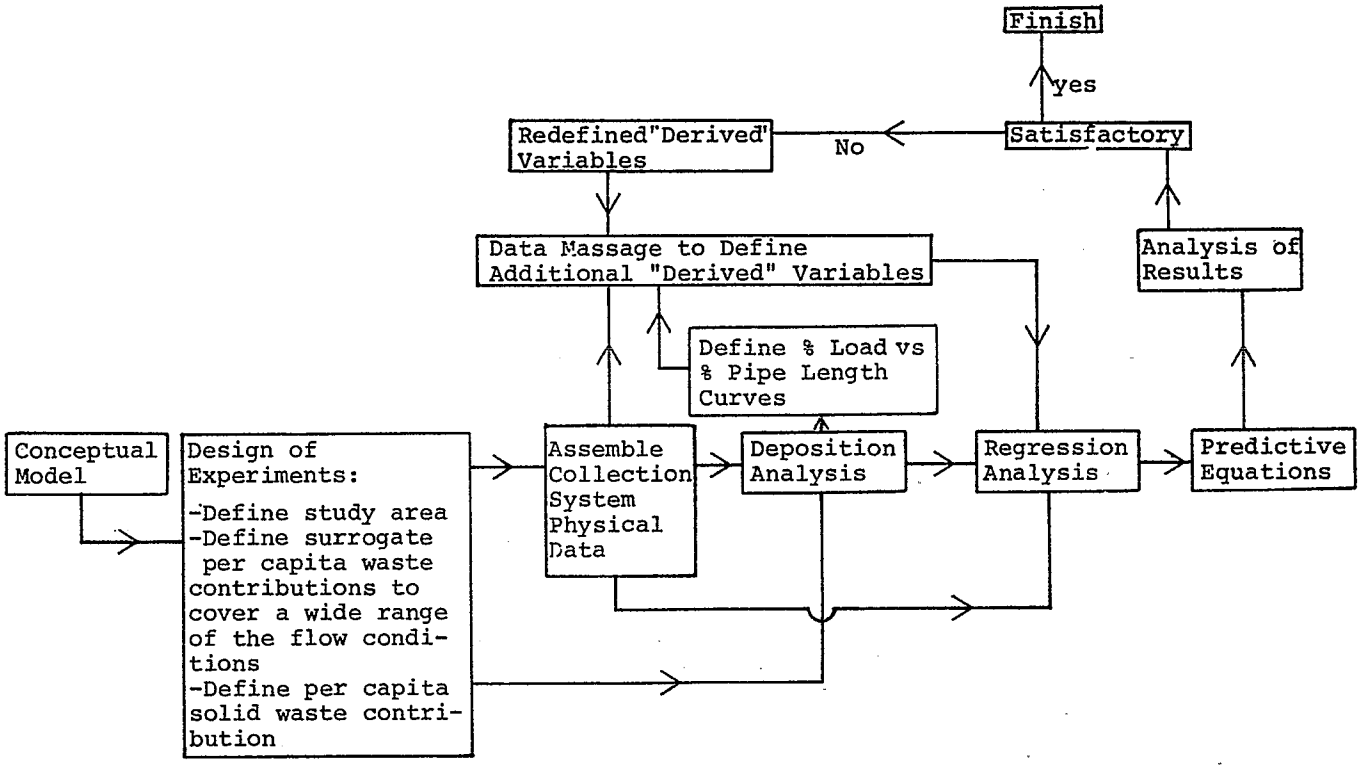

FIGURE 1. GENERAL METHODOLOGY OF THE STUDY

The analysis of the collection system service areas and total pipe lengths, distributions of pipe slopes and average collection system pipe diameters are presented in Section 4.4.2 and 4.4.4.

The deposition model results included the total lb/day deposited in each pipe segment of each basin and the total loads accumulated throughout each system. The information on loads by pipe segment is then used to generate curves for each basin, showing the accumulated percentages of the loads deposited against the accumulated percentage of pipe lengths where deposition took place. This part of the work is described in Section 4.4.5.

The physical data of the system together with the distribution of loads by pipe length are then used to define the derived variables L_{PD}, S_{PD} and $S_{PD/4}$ described in Section 4.4.6 to 4.4.8

The total loads by basin generated by the deposition model together with primary variables (pipe length, area, average slope, average diameter) and the derived variables (L_{PD}, S_{PD}, $S_{PD/4}$) are then used as input for the regression analysis described in Section 4.5.

Finally, the results of the regression analysis were examined and considered satisfactory and the process was complete.

4.2.1 Discussion of Model Variables

A discussion of the independent variables considered in the model and a few descriptive details of the preliminary analyses preceding the selection of the complete list of variables is given in this section.

The obvious and simplest of variables that can be used to characterize a collection system are the total service area, total pipe length, average slope and the average pipe diameter. It was believed from the onset of this study that these variables alone would not be adequate to explain the variability of the estimated loads from the deposition model. Clearly, a better characterization of the collection systems was necessary.

An exploratory analysis applying the deposition model on a number of sample collection systems revealed an interesting insight. Plots of the cumulative percentages of total loads deposited in each basin versus cumulative pipe lengths were prepared. A number of these curves can be inspected from Figures 12 and 13 on pages 36 and 37. The curves spread around the range of 70% to 90% of the total mass deposited suggested the use of the pipe length corresponding to 80% of the total mass deposited as a potential variable to include in the regression analysis.

Another set of plots of the cumulative distribution of pipe slopes for a few basins also suggested that the mean pipe slope alone would not be adequate to explain the effects of the pipe slopes on the variations of the deposition loads. A better characterization of the collection system pipe slopes could be obtained by defining various parameters at the flatter pipe slope range. Three other pipe slope parameters besides the mean pipe slope were initially selected for inclusion into the regression model. These parameters are as follows:

a) the pipe slope corresponding* to the percentage of the pipe length where 80% of the total load of the collection system deposits (S_{PD});

b) the average of the slopes in the basin below S_{PD} ($\bar{S}_{PD}$);

c) the slope corresponding to some fraction of S_{PD}, arbitraily taken as the slope corresponding to 1/4 the percentage of pipe lengths below which 80% of the total mass deposits ($S_{PD/4}$).

These slope parameters can be seen in Figure 2.

Further analyses revealed that $\bar{S}_{PD}$ and S_{PD} were very strongly correlated, so that retaining both in the regression analysis was not necessary. This finding was fortunate since the variable $\bar{S}_{PD}$ is much more difficult to determine than S_{PD}. The variable $\bar{S}_{PD}$ was excluded from the analysis.

Finally, it is clear that the deposition process is also strongly affected by the sewage flows in the system. Variations in population density and the degree of infiltration affects the dry weather flow rates. These effects were incorporated into the per capita waste rates used in the deposition model simulations and in the regression analysis. The summary list of variables considered in the regression analysis is the following:

1. Total collection system pipe length (L) - ft;

2. Service area of collection system (A) - acres;

3. Average collection system pipe slope ($\bar{S}$) - ft/ft;

4. Average collection system pipe diameter ($\bar{D}$) - inches;

5. Length of pipe corresponding to 80% of the solids deposited in the system (L_{PD}) - ft;

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* Note that the correspondence indicated in Figure 2 does not necessarily imply that the pipe length over which 80% of the load deposits has slope smaller than or equal to S_{PD} at all segments. See section 5.3.2

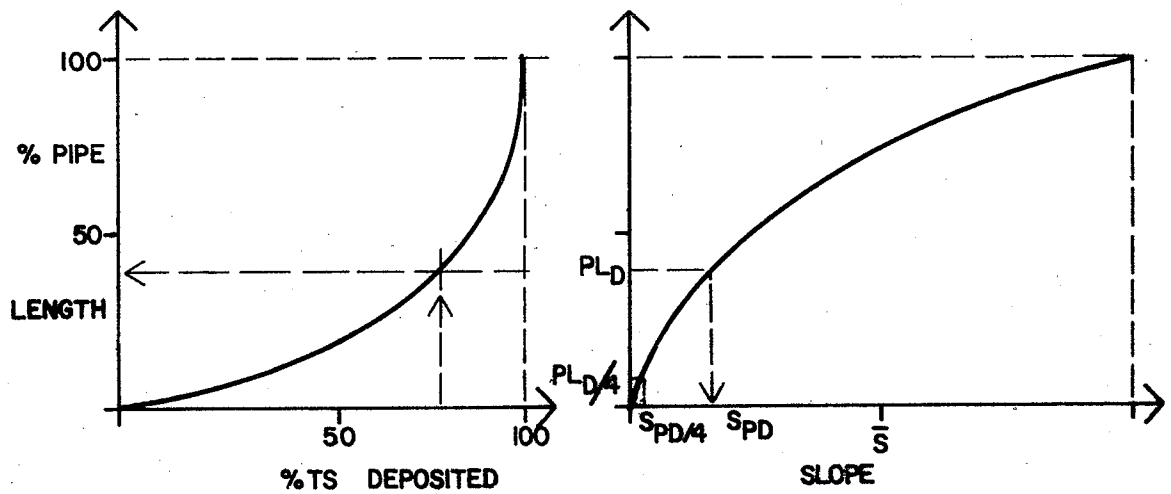

FIGURE 2. COLLECTION SYSTEM PIPE SLOPE VARIABLES

6. Slope corresponding to L_{PD} (S_{PD}) - ft/ft;

7. Slope corresponding to 1/4 of the percentage of pipe length (PL_D) below which 80% of the solids deposit ($S_{PD}/4$) - ft/ft; and

8. Flow rate per capita, including allowance for infiltration (q) - gpcd.

With respect to the mathematical forms of the regression model both linear and alternative non-linear models were initially postulated. Non-linear fitting techniques were not needed in the analysis since the linear models, that is, the strictly additive form and the logarithmic multiplicative form converted in the log domain, resulted in excellent fitting results with the R^2 approaching 95%.

4.3 Design of Experiment

In this section an overview will be presented of how collection system data from three major sewerage sytems was used to design the data base for the multivariate regression experiment. A description of the three sewer systems whose data were assumed to represent an adequate sample from the universe of all collection system is presented in section 4.3.1. A discussion of the per capita waste rates used in the experiment is presented in section 4.3.2. These surrogate waste rates reflect wide variations in population density and infiltration conditions encountered in practice. This parameter can be considered as a decision variable from a planning standpoint. Various sewer system age and maintenance considerations are discussed in section 4.3.3.

4.3.1 Description of Three Sewer Systems

The physical characteristics of the three major collection systems used in this analysis derive from three prior studies. The first area, covering portions of West Roxbury in Boston, Dedham, Newton and Brookline is strictly separated. The second area covering major portions of Dorchester and South Boston, two neighborhoods of the Boston metropolitan area is a mixed combined and separate area while the third basin covering a portion of the City of Fitchburg is served by a combined sewer system. The total pipe length, service area and pipe density for each basin are given in Table 1. The total pipe footage for all three areas entails 196 miles of separate and combined sewer systems encompassing a total area of 8.9 square miles.

TABLE 1. SEWER DENSITY (mi/acre)

Overall System	Pipe Length (mi)	Area (acres)	Pipe Density (mi/acre)*
WRNDB** 35 basins	64.87	2464.	0.026
Dorchester (37 basins)	119.85	2753.	0.044
Fitchburg (3 basins)	11.17	485.	0.023

* Weighted averages: by pipe length: 0.036, by area: 0.034.
** Sewerage system with area covering portions of West Roxbury, Dedham, Newton and Brookline in Boston metropolitan area.

The land use in the first area in West Roxbury and neighboring communities is mostly moderate to high density single and two family dwellings with a population density ranging from 10 to 15 people/acre. The topography is mild with several hilly portions in the area. This area was investigated in a recent infiltration/ inflow study and was subdivided into 35 distinct sewer collection subsystems.

The land use in Dorchester and South Boston is mostly high density multi-family dwellings with population density ranging from 30 to 60 people/acre. The topography in Dorchester is moderate with a number of hilly sections while portions of South Boston are fairly flat. There are a total of 37 distinct sewer collection systems in this study area.

The land use in the third area in Fitchburg is mixed commercial and high density multi-family dwellings with a small portion of single family homes. The population density is similar to Dorchester. The study area is subdivided into three collection systems.

A total of 75 different sewer collection systems form the data basis for the analysis. It is assumed that these basins collectively represent a wide variety of different pipe slope conditions, pipe sizes and shapes and network system configurations. Some basins serve narrow strips of land while others are broad fanned-shape with a high hierarchial network order. A central assumption is that the collection system characteristics represented by the sample of 75 sewer sheds is an adequate representation of the total universe of collection systems. This assumption is not completely valid since, for example, extremely flat collection systems were not part of the sample set. Future work should broaden this data base. This sample however is deemed reasonably complete for the purposes of this analysis.

A complete sewer atlas of manhole to manhole descriptive physical data including pipe length, slope, shape, size and network ordering designations was available for each of these systems. Much of this data had been previously processed for computer application although a considerable portion of the data had to be placed in EDP format for purpose of this study. Roughly 6000 manhole to manhole segments incorporating all of the aforementioned parameters were necessary to represent the hydraulic characterization of the 75 sewer collection systems.

4.3.2 Range of Flows

The degree of deposition in a sewer pipe is strongly dependent on the discharge. As flow increases through a pipe the depth, velocity, hydraulic radius all change resulting in higher shear stress with less deposition. Discharge therefore is an extremely

imporant parameter in the analysis. The dry weather discharge in a sewer system is dependent upon the local population density, the domestic per capita contribution, the degree of infiltration and any industrial waste contributions.

It was envisioned that a single per capital surrogate waste rate would be generated incorporating a wide range of population density and infiltration conditions encountered in practice.* This variable would embed all these variations and be used in both the deposition model to predict daily dry weather solids deposition and in the regression model as an independent variable.

Population densities ranging from 15 people/acre up to 90 people/acre were considered. Using a factor of 0.035 miles of sewer per acre the corresponding number of people per 100 feet of sewer pipe was computed. These factors are shown in Table 2 and are used in the deposition model which requires as input the number of people per 100 feet of sewer.

The dry weather per capita contribution of 85 gpcd was considered fixed in this analysis. Four different infiltration estimates of 500, 1000, 2000 and 4000 gallons per acre per day were used to cover the range of normally encountered infiltration conditions. The adjusted per capita waste rates incorporating the various rates of infiltration for the range of population densites considered in the analysis are shown in Table 3. These per capita values are again adjusted to the mid-range of population density of 45 people/acre and are given in Table 4. This last conversion permits considering one single range of surrogate per capita flow rates using 45 people/acre as the norm. Four different flow rates are considered in the analysis and cover the full range of per capita waste rates for different population densities and infiltration conditions. The per capita waste rate used in the analysis are: 40 gpcd, 110 gpcd, 190 gpcd and 260 gpcd.

The per capita solids waste rate of 0.5 lb/capita/day was used in all computations. This parameter was established from field measurements in the sewer flushing project described in Appendix C. All regression results presented in Section 4.5 can be linearly scaled for any other desired per capita solids waste rate.

4.3.3 Age and Maintenance Conditions

The presence of long-term accumulations of organic matter, sand, gravel, grit and debris in the form of sediment beds,

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* Industrial waste contributions were not explicitly considered. The user can readjust the per capita waste rates used in this analysis to reflect industrial contributions.

TABLE 2. POPULATION DENSITY (PERSONS/100 FT OF PIPE)

Density (person/acre)	Persons/100 ft of pipe*
15	8.15
30	16.30
45	24.46
60	32.61
90	48.91

* Assumes 0.035 mi/acre or 184.8 ft of pipe/acre

TABLE 3. PER CAPITA WASTE RATES FOR VARIOUS POPULATION DENSITIES AND INFILTRATION RATES*

Density (person/acre)	Infiltration Rate (gpad)**			
	500	1000	2000	4000
15	118.3	151.7	218.3	351.6
30	101.7	118.3	151.7	218.3
45	96.1	107.2	129.4	173.9
60	93.3	101.7	118.3	151.7
90	90.6	96.1	107.2	129.4

* Assumes a dry weather contribution of 85 gpcd

** gallons per acre per day

TABLE 4. PER CAPITA VALUES RELATIVE TO THE DENSITY OF 45 PERSONS/ACRE

Density (person/acre)	Infiltration Rate (gpad)			
	500	1000	2000	4000
15	39.09*	50.14	72.14	116.20
30	67.28	78.20	100.27	144.29
45	96.10	107.20	129.40	173.90
60	124.39	135.59	157.72	202.25
90	179.69	190.60	212.62	256.25**

* minimum value

** maximum value

shoals, or bars can significantly alter the hydraulic characteristics and accordingly the degree of deposition, particularly for lateral pipes with little dry weather discharge. These accumulations can easily result in new well-constructed sewer systems with sound joints and few hydraulic obstructions such as protruding house connections, etc. Similar deposits can occur in systems that are rodded and frequently cleaned but either are old and/or have poor joints and many hydraulic obstructions. Perforated manhole lids provide the perfect opportunity for children to jam sticks into manholes that can result in massive blockages of accumulated rags and toilet paper. The above conditions are but a few of the possible age and maintenance problems encountered in practice.

Three different categories of sewer system age and maintenance were considered in this analysis. The first category of clean pipe conditions represents good maintenance practices and well-constructed sewer systems. No sediment beds were considered in this case.

Two cases simulating different degrees of maintenance other than perfect clean pipe conditions were also considered. In the first case or the intermediate maintenance category, sediment beds ranging from 1 to 3 inches in depth were assumed for all pipes with slopes less than 0.0075. Figure 3 shows the assumed ranges of beds between pipe slopes of 0.0005 and 0.0075. In the third category, the zero maintenance care, the sediment beds range from 3 to 6 inches for the same range of pipe slopes. This range was established using judgment and also based on visual inspection of numerous combined sewer pipes in eastern Massachusetts combined sewer systems.

These three conditions were used in the deposition model analysis to compute daily collection system deposition loadings.

4.4. Data Preparation for the Regression Model

4.4.1 Deposition Model Results

4.4.1.1 Brief Description of the Deposition Model

The deposition model used in this study to generate estimates of solids deposition in the sewerage systems selected in Section 4.3 is described in detail in Appendix B. The model considers peak daily dry weather flow and uses a shear stress critera to determine the limiting diameter of the solid particles that deposit at each segment. Then, with this limiting particle size and assuming a given distribution for the particle sizes present in the dry weather sanitary flow, the model determines the percentage of the suspended solids that deposit at each pipe segment. The model also has mechanisms to account for the fact that particles of diameters up to a given size that deposit in a given pipe segment are not available for deposition in downstream segments.

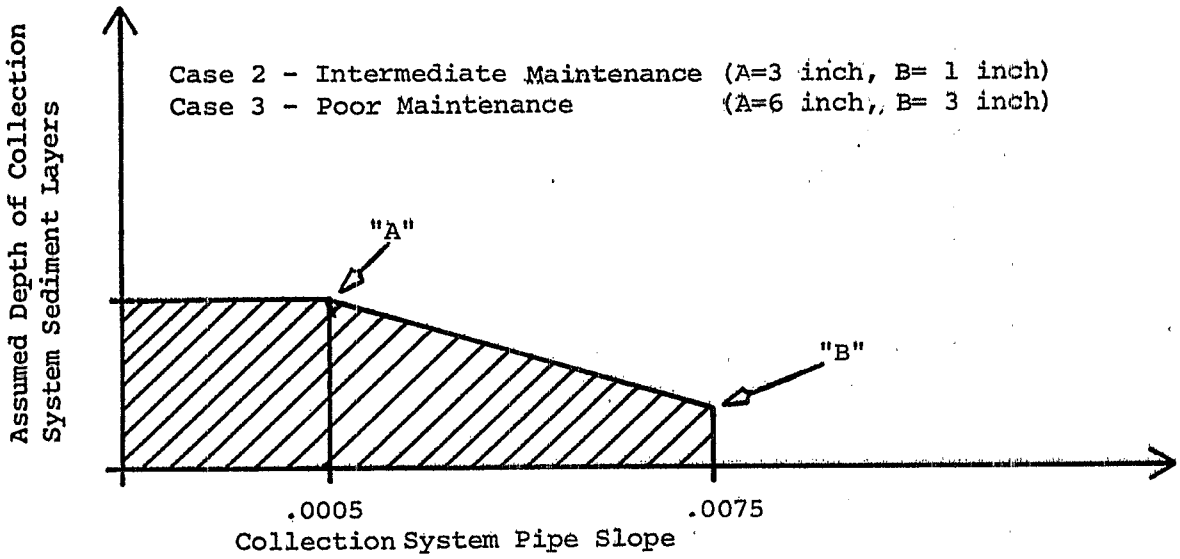

FIGURE 3. REPRESENTATION OF SEDIMENT BEDS AND PIPE SLOPE FOR TWO AGE AND MAINTENANCE CONDITIONS

Some of the results given by the model are: (1) the flow conditions at each pipe segment, including discharge, average velocity, water depth and shear stress; (2) the loads (lb/day) deposited at each pipe segment and (3) the accumulated value of the loads deposited in all upstream segments. A verification of the results given by the deposition model is presented in Appendix C.

4.4.1.2 Input Data Required by the Deposition Model

The input data required by the deposition model consists of:

- Segment identification (by a segment number);
- Segment upstream and downstream pipe inverts;
- Segment length;
- Pipe shape (10 shapes possible);
- Pipe sizes (diameter or height and width);
- Segment type (zero, one or two tributary segments);
- Network location designation (defined by the segment type in conjunction with the next downstream segment number);
- Sediment depth in the segment;
- Population per 100 feet of pipe;
- Average daily waste flow contribution in gpcd;
- Peak daily to average flow peaking coefficients (see page B-3);
- Manning's resistance coefficient, n, and its variability with flow depth; and
- Total solids contribution in lb/capita/day.

4.4.1.3 Deposition Input Data Preparation

In Section 4.3, the description of the three different sewerage systems considered in this study was presented. A total of 75 subsystems were used in this analysis including 35 separate collection systems from the WRNDB sewer system, 37 collection systems from the Dorchester and South Boston combined sewer systems; and 3 collection systems from the Fitchburg combined sewer system.

All the necessary physical data in the form of computer cards were available for the Dorchester and Fitchburg system from previous studies. For the WRNDB system all the pipe elevations, lengths, shapes and sizes were also available from a previous study, but all the segment numbering and the additional information required to establish the system configuration had to be generated in this study.

Other information on waste flow rates and solid matter contribution to the systems, necessary to run the model, were given in Section 4.3.

4.4.1.4 Deposition Model Runs and Results

Three sets of runs were performed for all 75 basins. The first set of runs were performed assuming no previous sediment deposits present in the pipes, that is clean pipe conditions. The second set of runs were performed in which sediment depths ranging from 1 to 3 inches were assumed to represent moderate maintenance conditions. The third set of runs were performed assuming sediment depths from 3 to 6 inches intended to simulate poor maintenance.

Selected information from these runs were punched out on cards for use in future phases of the study. The values of the loads (lb/day) deposited by pipe segment were used to define for each basin the accumulated percentages of the total load versus the accumulated percentages of total pipe lengths where deposition occurs. An overall curve for all 75 basins was also prepared. These curves were useful in deriving several variables used in the regression analysis. The total loads per basin were used as the observed values ofthe dependent variable in the regression analysis.

4.4.2 Areas and Total Pipe Lengths

The total service area and total pipe lengths were known from prior studies for all 75 basins. These values were necessary for the regression analysis described in Section 4.5, and are presented in Table 5. The first 35 basins cover portions of the WRNDB sewerage system. Basins 36 through 72 cover the Dorchester and South Boston sewerage system while the last three basins cover portions of the City of Fitchburg sewerage system. The data on Table 5 was also used for a simple regression of total pipe length on total area and is described in Section 5.2.2. This regression may be useful in extreme cases where the total pipe length is not known or cannot be immediately determined.

4.4.3 Distribution of Pipe Slopes

The regression model proposed in Section 4.2.1 included several collection system pipe slope parameters, S_{PD} and $S_{PD}/4$, that required computation of the cumulative pipe slope distributions. A computer program was prepared to compute these distributions from data on the pipe segments upstream and downstream invert elevations and segment lengths. The program computed the slope distribution weighing the segment slopes by their lengths. The mean, standard deviation, coefficient of variation, coefficient of skewness and coefficient of kurtosis of pipe slopes per collection system were also computed. The program computed the distribution and the aforementioned statistics for each system (WRNDB, Dorchester and Fitchburg) and finally an

TABLE 5. - TOTAL PIPE LENGTHS AND AREAS OF THE BASINS

BASIN NO	PIPE LENGTH (FT)	AREA (ACRE)
1	47180.	230.
2	5945.	38.
3	610.	5.
4	669.	7.
5	3309.	19.
6	360.	5.
7	1900.	9.
8	2251.	13.
9	650.	3.
10	1160.	8.
11	2158.	6.
12	1410.	13.
13	15610.	84.
14	1551.	70.
15	990.	70.
16	1305.	6.
17	71621.	641.
18	3279.	58.
19	14415.	100.
20	263.	6.
21	489.	8.
22	1146.	4.
23	4180.	6.
24	27385.	173.
25	12653.	90.
26	3331.	19.
27	14016.	82.
28	738.	6.
29	14997.	120.
30	14540.	140.
31	1374.	6.
32	16988.	96.
33	17131.	100.
34	7728.	45.
35	26981.	178.
36	6245.	42.
37	7735.	33.
38	1750.	29.
39	4265.	19.
40	3485.	17.
41	3400.	26.
42	3170.	16.
43	4000.	25.
44	5060.	25.
45	11325.	52.
46	13133.	44.
47	7757.	24.
48	7764.	42.
49	112638.	245.
50	875.	5.
51	5200.	36.
52	4501.	27.
53	11890.	51.
54	5830.	28.
55	2235.	15.
56	7145.	34.
57	5276.	91.
58	3115.	9.
59	10585.	120.
60	8741.	65.
61	35501.	228.
62	13051.	78.
63	5635.	26.
64	11325.	54.
65	33005.	177.
66	9899.	47.
67	5644.	30.
68	14220.	57.
69	4492.	24.
70	35033.	233.
71	134528.	315.
72	69274.	360.
73	31748.	264.
74	12092.	78.
75	14754.	143.

overall distribution and the first four moments of all data lumped into one data set.

Plots of the slope distributions for a few basins are shown in Figures 4 and 5. The concave shapes of those cumulative distributions (CDF) without a point of inflexion, suggest an exponential distribution for the pipe slopes. Several of the cumulative distributions were plotted on normal, log normal and Gumbel's probability paper. All plotted curves resulted in very non-linear shapes, indicating that the pipe slopes do not follow any of those distributions. Plots of the complementary CDF of the pipe slopes on semi-logarithmic paper, nontheless, resulted in remarkably linear shapes shown in the illustrative cases in Figures 6 through 10. Although no formal numerical test of goodness-of-fit was performed, this fact indicates that, at least for the sample data used in this study, the distribution of the pipe slopes is exponential.

The solid lines drawn on Figures 6 through 10 were plotted using the expression of the exponential cumulative distribution function given by:

$$F_S = 1 - e^{-s/\bar{S}} \qquad (1)$$

where $F_S = P(s \leq \bar{S})$ (cumulative pipe slope distribution);

s = any given slope;

$\bar{S}$ = the mean slope computed for the basin, as indicated above; and

e = the base of the natural logarithms.

Figure 11 presents the histograms for the WRNDB, Dorchester and Fitchburg sewerage systems and the overall histograms considering all data. The slope values corresponding to the intervals in Figure 11 are given in Table 6.

Two observations can be noted from these histograms:

a) the shapes of the histograms for all 13 systems are similar with minor differences between them (the same is true for the global histogram compared to any of the other three); and

b) they all indicate an exponentially decaying shape, characteristics of the exponential distribution with the CDF given by equation (1).

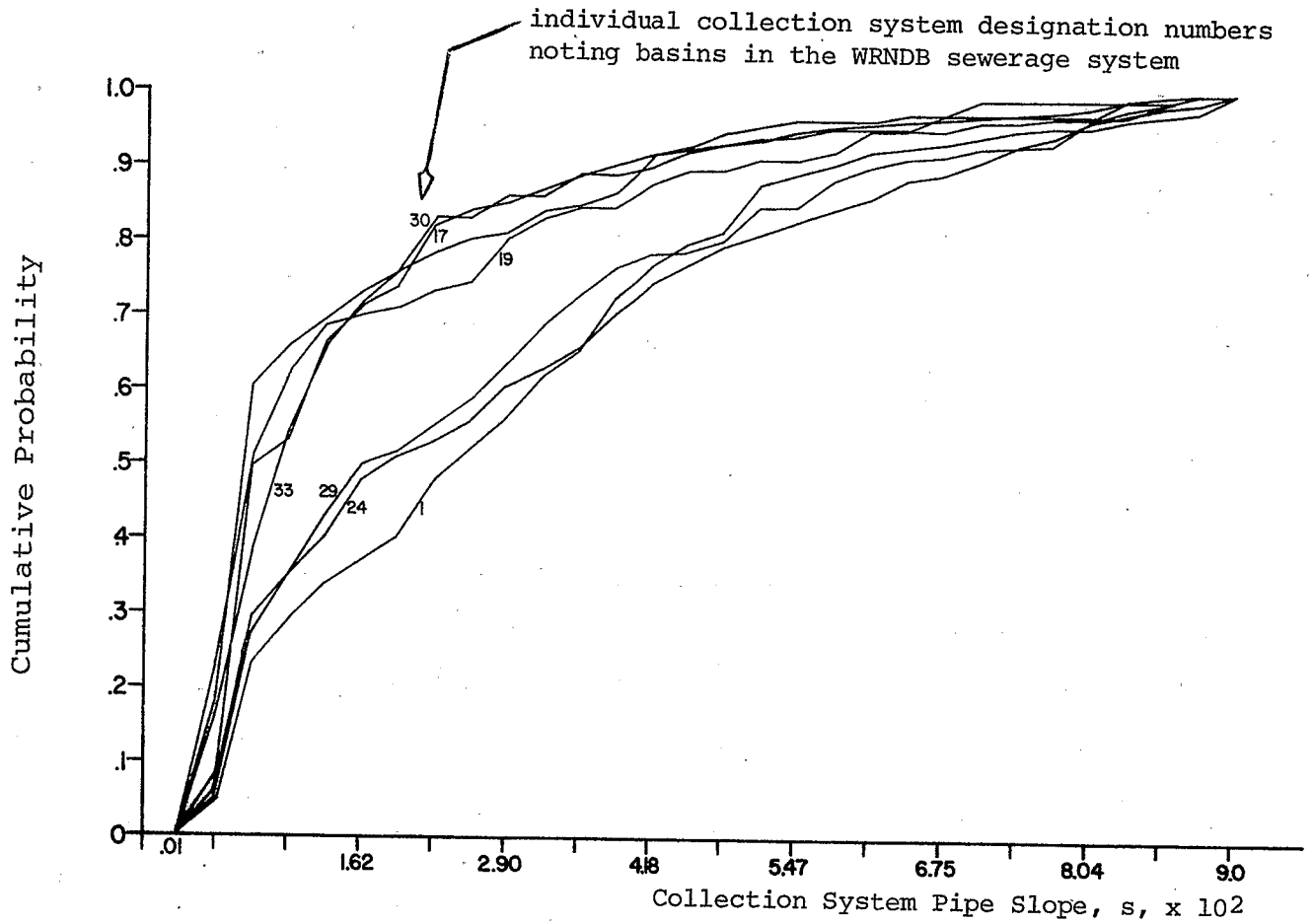

FIGURE 4. CUMULATIVE DISTRIBUTION OF PIPE SLOPES PER COLLECTION SYSTEM

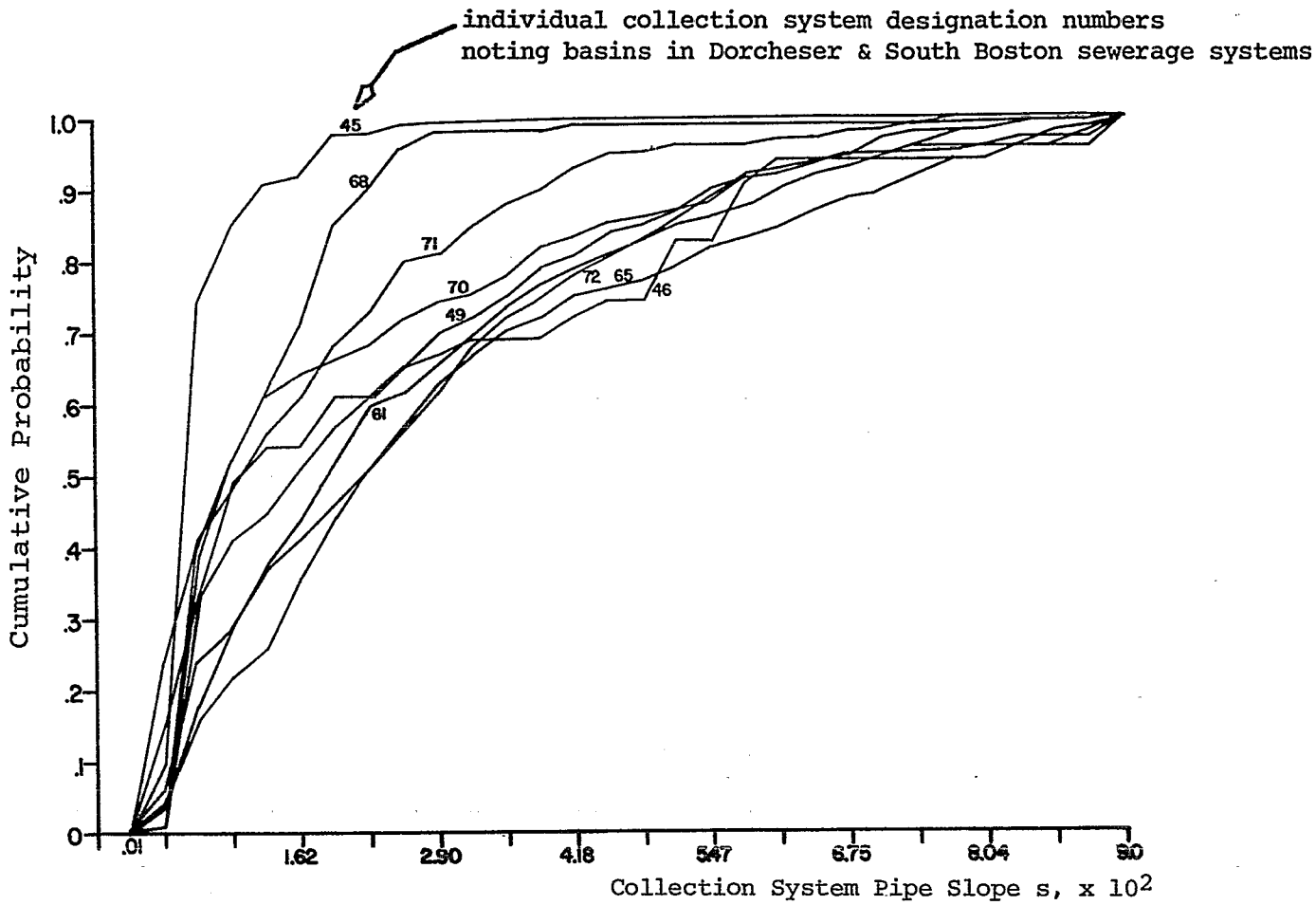

FIGURE 5. CUMULATIVE DISTRIBUTION OF PIPE SLOPES PER COLLECTION SYSTEM

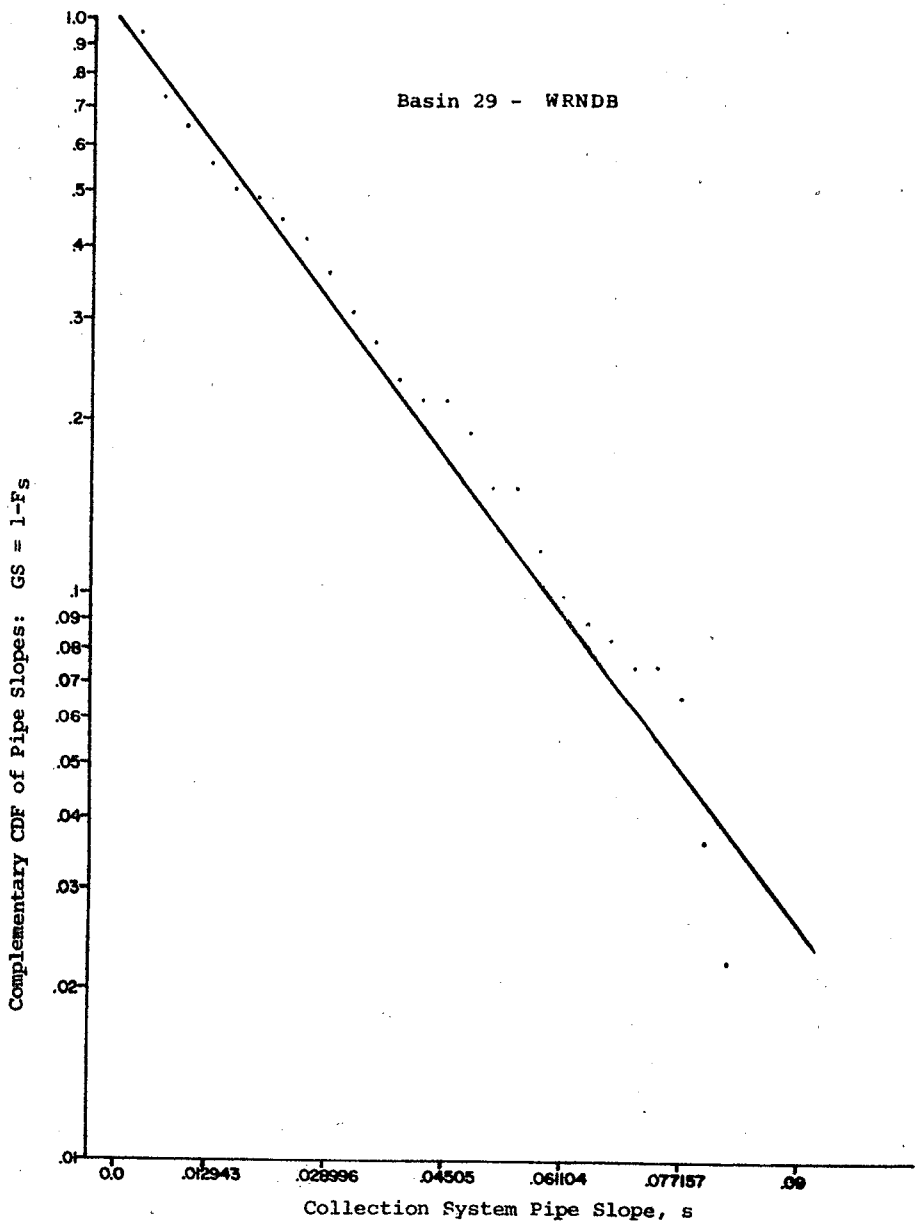

FIGURE 6. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_S = 1-F_S$

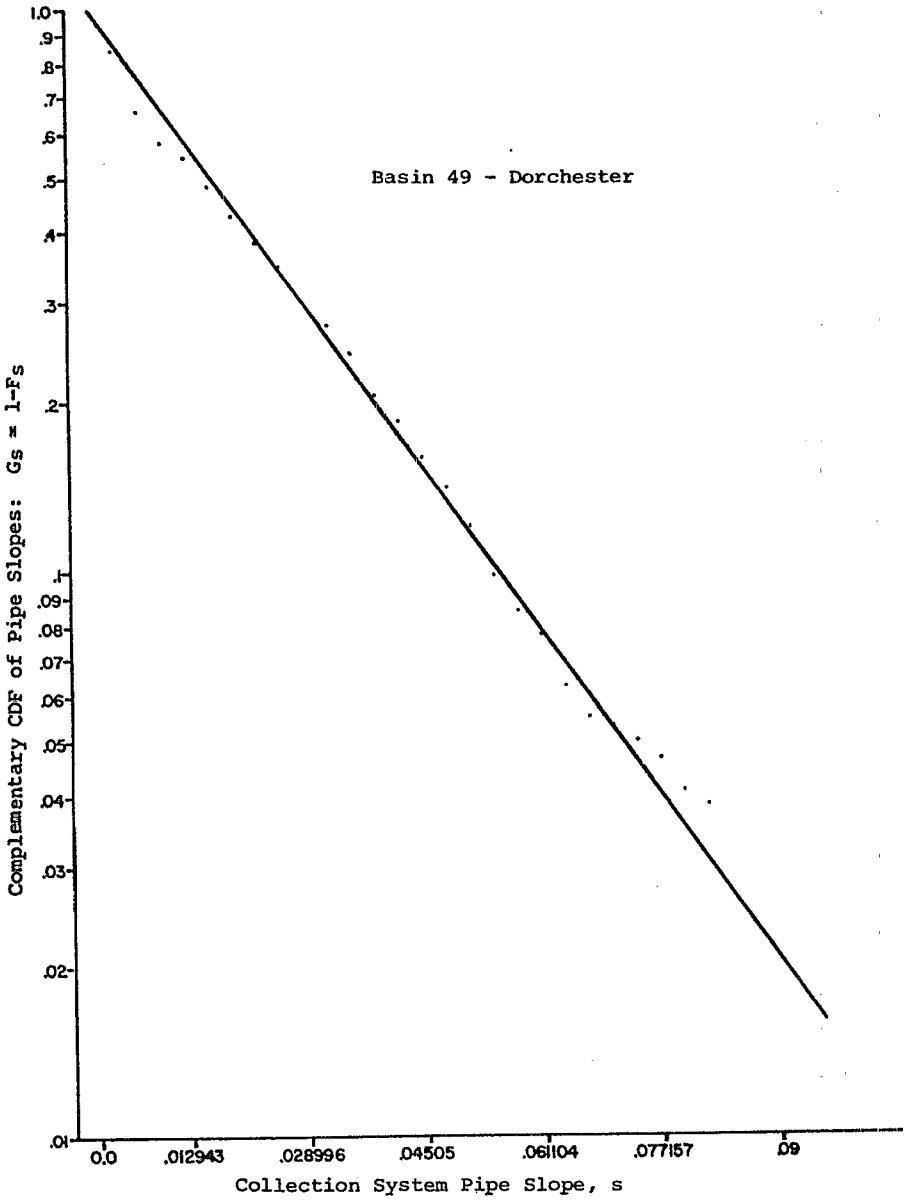

FIGURE 7. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_S = 1-F_S$

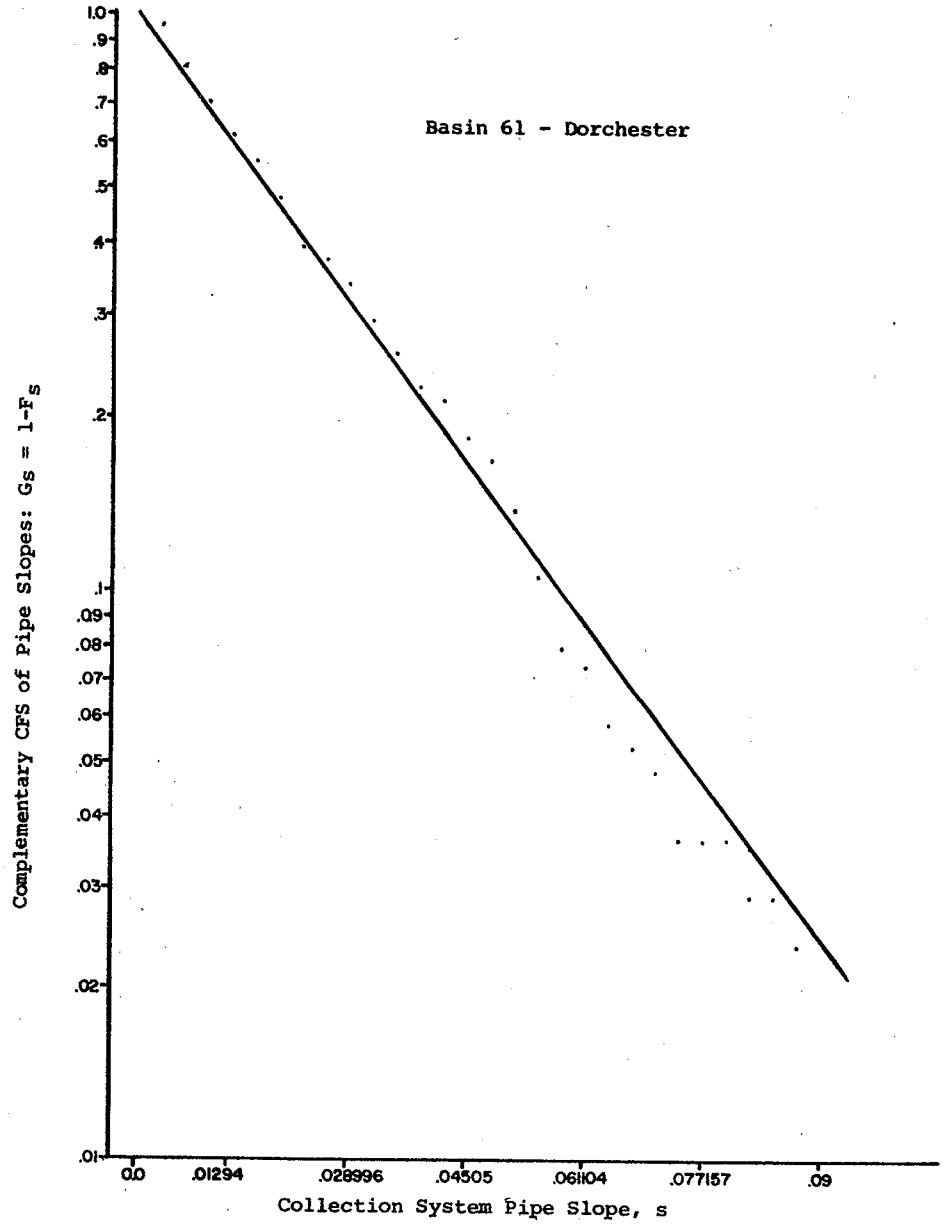

FIGURE 8 . COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_S = 1-F_S$

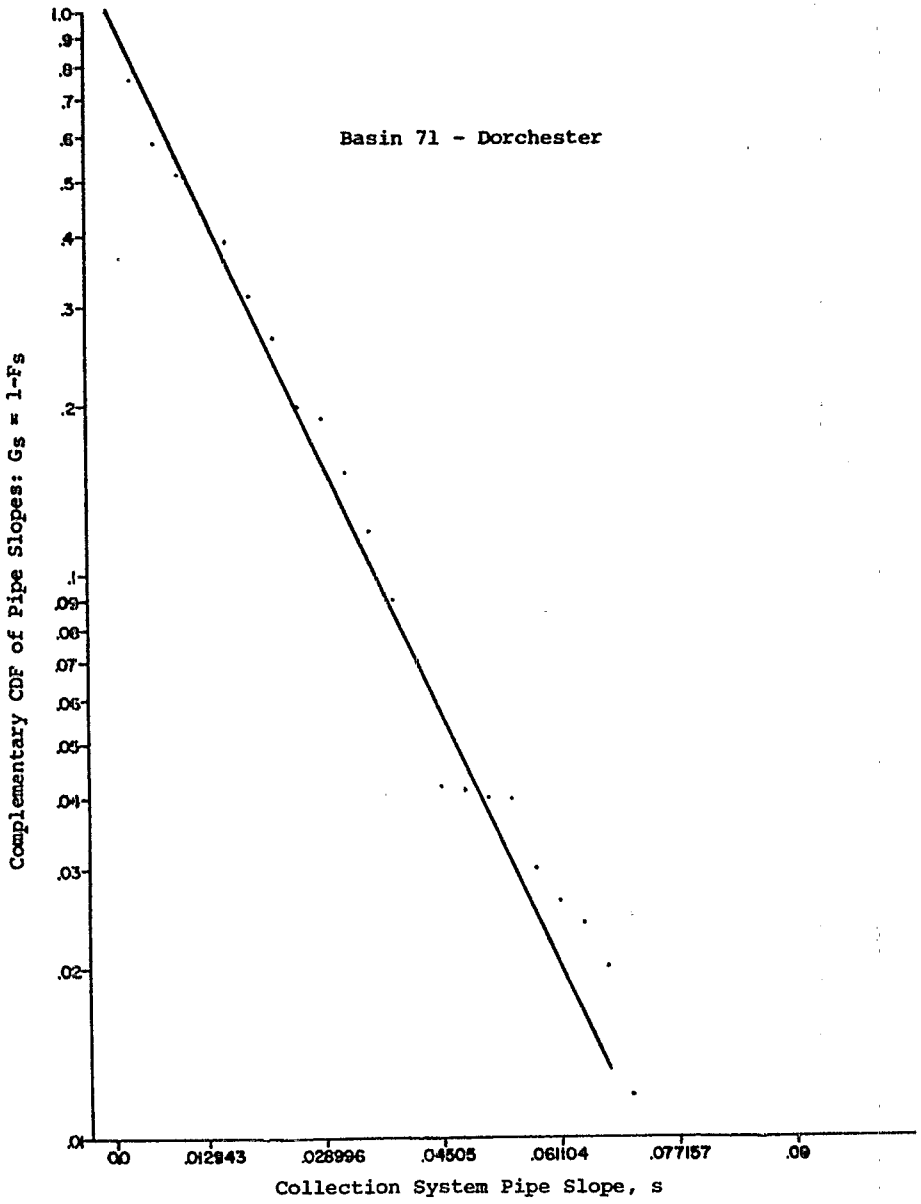

FIGURE 9. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: GS = $1-F_S$

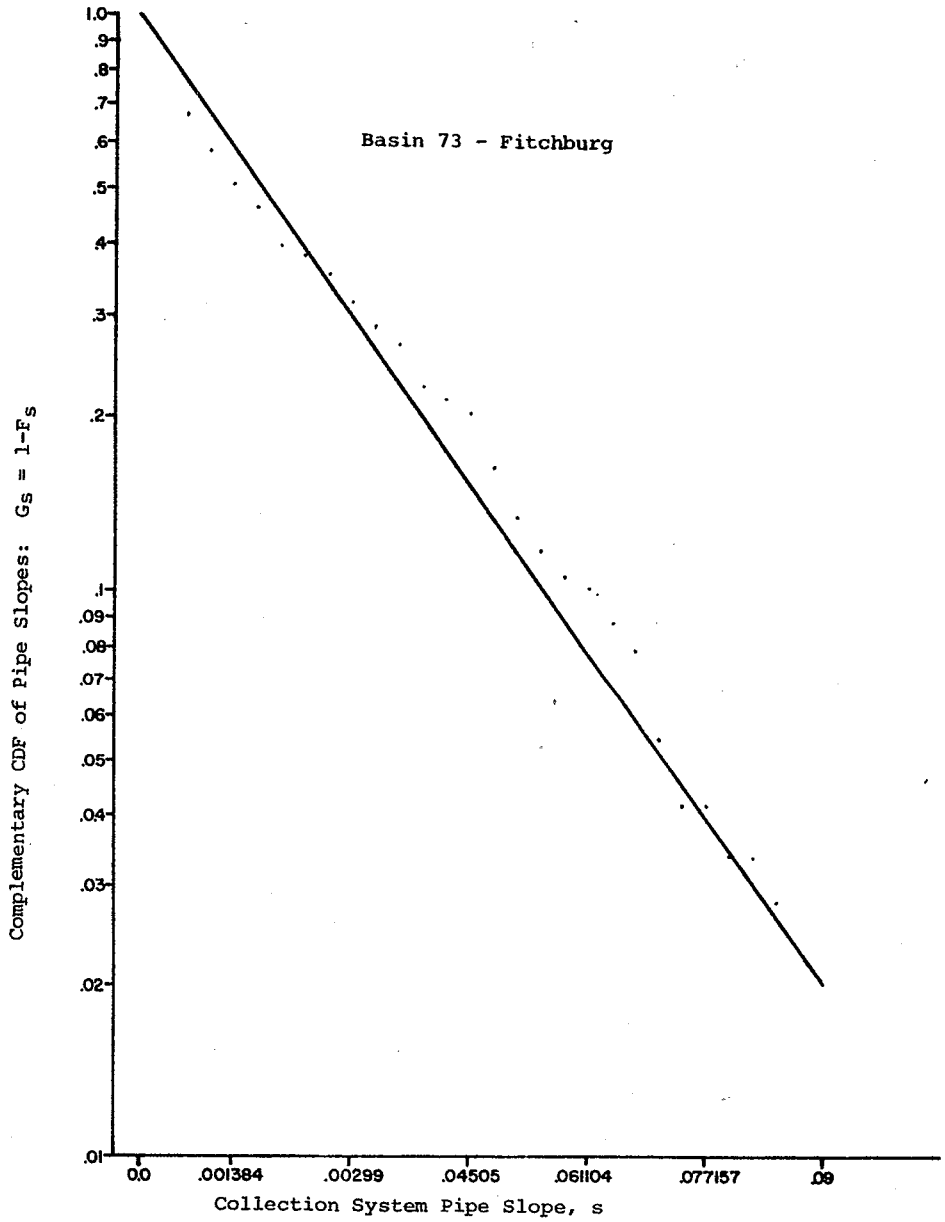

FIGURE 10. COMPLEMENTARY DISTRIBUTION OF PIPE SLOPES: $G_S = 1-F_S$

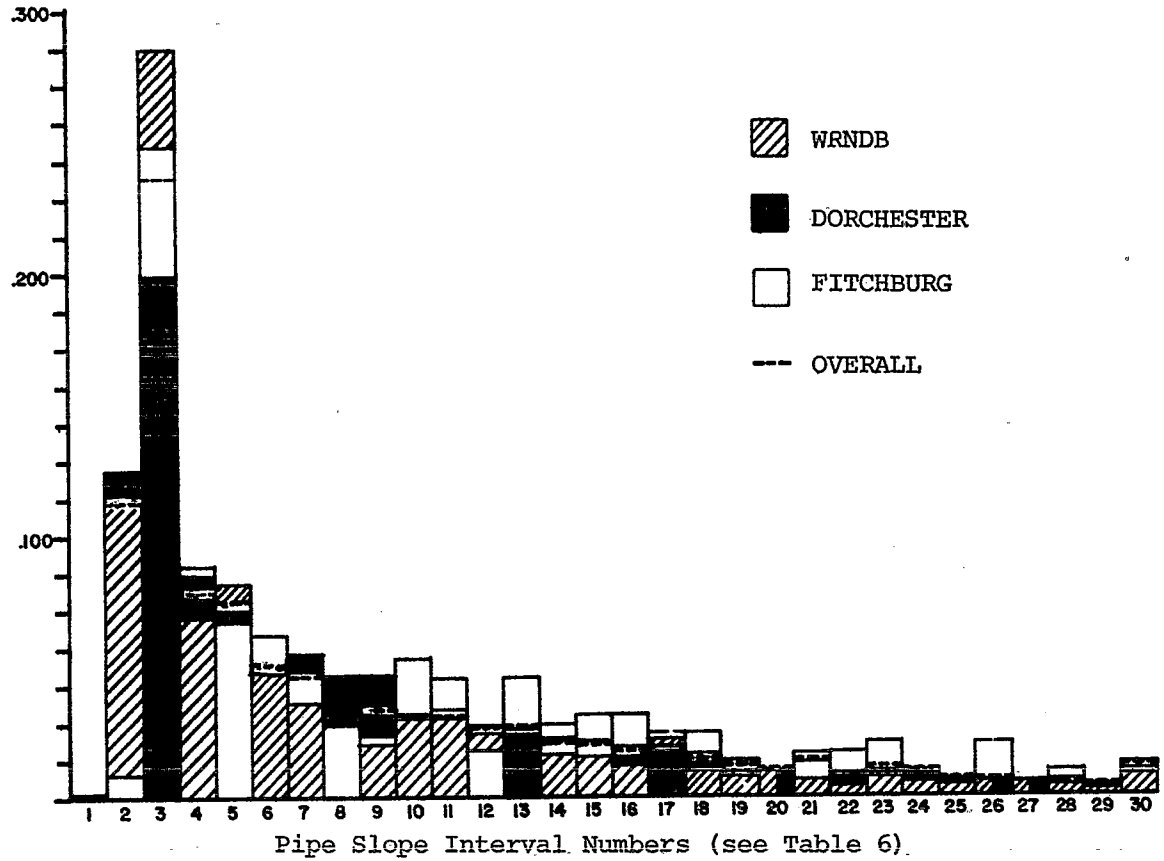

FIGURE 11. HISTOGRAMS OF COLLECTION SYSTEM PIPE SLOPES

TABLE 6. SLOPES CORRESPONDING TO THE INTERVALS SHOWN ON FIGURE 11

Interval	Slope Limit of Range
1	0.000100
2	0.003311
3	0.006521
4	0.009732
5	0.012943
6	0.016154
7	0.019364
8	0.022575
9	0.025786
10	0.028996
11	0.032207
12	0.035418
13	0.038629
14	0.041839
15	0.045050
16	0.048261
17	0.051471
18	0.054682
19	0.057893
20	0.061104
21	0.064314
22	0.067525
23	0.070736
24	0.073946
25	0.077157
26	0.080368
27	0.083578
28	0.086789
29	0.090000
30	> 0.090000

A final justification for the assumption that the pipe slopes are exponentially distributed is the following. The mean and standard deviation of the coefficients of variation of the slope for all 75 basins are 0.87 and 0.25, respectively. The mean value of 0.87 for the coefficients of variation very closely approximates the theoretical value of 1.0, characteristic of the exponential distribution.

This finding has significant importance in the practical application of the regression model developed in this study. This is especially true for cases where detailed statistical analysis of pipe slopes information is not available and only the mean value of the pipe slope is required to completely define with reasonable accuracy the pipe slope distribution.

The special slope parameters S_{PD} and $S_{PD/4}$ can then be estimated through this pipe approximation. Definition of the pipe slopes distribution using the exponential model is also important in delineating the extent and geographic location of the deposition loads in the system. This topic will be further discussed in Section 5.3.2*.

4.4.4 Average Pipe Diameter

The average pipe diameter of all segments within each collection system was computed by weighing circular diameters of each segments by its corresponding lenghts. An equivalent circular pipe diameter was first determined for non-circular sections before the weighted average was computed. The fraction of non-circular pipes was a small percentage of the total pipe length. All pipes are circular in the WRNDB system. The number of non-circular pipes represent about 5% of the total for the Dorchester system, whereas in Fitchburg they represent less than 1% of the total pipe lengths.

The formulas used for the equivalent circular diameter for the non-linear sections are presented in Table 7 and have been derived to yield roughly the same hydraulic radius at low depths of flow. For rectangular and U-shaped pipes a simple equivalence of total areas are indicated in Table 7. These forms are non-existent in the data for this study. The average pipe diameters determined for all 75 basins are presented in Table 8.

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* It should be stressed here that in the generation of the slope data for the regression analysis described in Section 4.5 the assumption that the pipe slopes are exponentially distributed was not used. The probability distributions of slopes for all basins were determined from their respective slope data.

TABLE 7. FORMULAS FOR EQUIVALENT CIRCULAR DIAMETERS USED IN COMPUTING THE BASIN AVERAGE DIAMETER

Pipe Shape	Dimensions	Equivalent Circular D
Circular	D	D
Rectangular	X,Y	$(1.273\ X\ Y)^{1/2}$
Ellipse	X,Y	$(X\ Y)^{1/2}$
Egg	X,Y	$5.51X^{5.38}/(X+Y)^{4.39}$
Horseshoe	X,Y	$(X+Y)/2.0$
Oval	X,Y	$0.67\ X$
Ovoid	X,Y	$5.51X^{5.38}/(X+Y)^{4.39}$
Modified Circle	X,Y	$(X\ Y)^{1/2}$
Arch	X,Y	Y
U	X,Y	$(1.273\ X\ Y)^{1/2}$

TABLE 8.— SUMMARY DATA ON DERIVED LENGTHS, SLOPES AND PIPE DIAMETERS

BASIN NO.	80% DEPOS. LENGTH(FT) PLD	AVERAGE DIAM(IN) $\bar{D}$	AVERAGE SLOPE $\bar{S}$	SLOPE SPD	SLOPE SPD/4
1	15050.	10.5	0.027901	0.009965	0.003870
2	2080.	10.0	0.036746	0.022575	0.007320
3	434.	10.0	0.046065	0.058940	0.024900
4	450.	10.0	0.009118	0.008010	0.004290
5	1502.	10.7	0.021963	0.017470	0.006230
6	180.	10.0	0.008611	0.009732	0.009030
7	741.	10.8	0.016157	0.005849	0.001900
8	1019.	10.0	0.015280	0.014440	0.005050
9	36.	10.0	0.006400	0.006118	0.002200
10	560.	10.0	0.017163	0.019364	0.004560
11	304.	10.0	0.012293	0.004222	0.003480
12	685.	10.0	0.013985	0.009732	0.004290
13	6056.	10.9	0.013979	0.005996	0.002040
14	634.	10.8	0.019666	0.007681	0.003660
15	405.	10.0	0.030103	0.021642	0.010600
16	715.	10.0	0.004528	0.005510	0.000089
17	34879.	12.1	0.014539	0.006521	0.001830
18	1983.	9.5	0.009127	0.005119	0.001230
19	5938.	8.6	0.017344	0.005765	0.003430
20	83.	8.0	0.017852	0.017050	0.006270
21	171.	8.0	0.026175	0.032207	0.010400
22	648.	8.0	0.019257	0.014923	0.004780
23	1839.	8.0	0.021631	0.012943	0.004460
24	9228.	8.6	0.027730	0.009732	0.003660
25	4517.	8.7	0.019560	0.004989	0.001850
26	1379.	11.1	0.016939	0.009732	0.003810
27	5914.	11.0	0.016298	0.009732	0.001840
28	480.	12.0	0.004485	0.005012	0.002130
29	929.	10.2	0.025510	0.003311	0.001060
30	6005.	12.7	0.013617	0.005064	0.001910
31	526.	10.8	0.016448	0.006521	0.003280
32	7967.	8.7	0.016991	0.006344	0.004070
33	6903.	10.0	0.015655	0.006870	0.002180
34	3956.	11.6	0.017855	0.008449	0.002240
35	10954.	12.6	0.018203	0.006143	0.003460
36	2591.	13.3	0.014155	0.002892	0.000798
37	1461.	10.3	0.034669	0.004463	0.001100
38	936.	11.7	0.005660	0.005396	0.003380
39	1100.	12.0	0.030361	0.011499	0.004090
40	1913.	12.3	0.005365	0.004528	0.001230
41	1445.	9.3	0.027941	0.025786	0.007380
42	786.	12.0	0.037994	0.013749	0.004240
43	2540.	12.7	0.002575	0.002542	0.007100
44	1695.	12.0	0.029394	0.019364	0.004800
45	4869.	12.0	0.006341	0.004945	0.003330
46	5279.	14.1	0.024465	0.007763	0.004180
47	2893.	19.9	0.011737	0.003065	0.000841
48	7647.	12.4	0.025934	0.016154	0.006410
49	5293.	12.2	0.022566	0.001077	0.000344
50	571.	11.7	0.038857	0.047799	0.002560
51	1040.	11.4	0.035336	0.007467	0.002350
52	2295.	11.8	0.012463	0.011354	0.007200
53	1545.	14.6	0.015249	0.002514	0.000704
54	2530.	13.9	0.011539	0.007625	0.004020
55	929.	10.6	0.005995	0.005086	0.002170
56	1972.	11.2	0.041951	0.012943	0.000788
57	1461.	14.1	0.015366	0.002852	0.001370
58	1373.	13.1	0.010369	0.004675	0.001780
59	4847.	14.3	0.017349	0.009732	0.003930
60	2613.	12.7	0.024400	0.006521	0.003930
61	4934.	12.2	0.025037	0.005449	0.002820
62	6016.	12.6	0.055506	0.002802	0.000776
63	642.	12.1	0.022864	0.002143	0.000611
64	3408.	12.5	0.027835	0.009732	0.003800
65	1815.	12.9	0.029568	0.003311	0.001180
66	3434.	13.1	0.034241	0.012943	0.004610
67	2726.	14.3	0.079921	0.008435	0.001790
68	6498.	12.7	0.011681	0.008106	0.003280
69	2106.	12.0	0.018102	0.011068	0.004420
70	13312.	15.6	0.019405	0.006521	0.003020
71	26905.	13.3	0.015667	0.002787	0.000772
72	18773.	12.4	0.026287	0.008287	0.000310
73	13588.	12.4	0.002375	0.009732	0.004270
74	1306.	10.7	0.033799	0.006521	0.004020
75	4751.	13.6	0.029285	0.016154	0.005560

4.4.5 Distribution of Solids Deposited by Pipe Length

The cumulative distribution of solids deposited in the collection system versus the cumulative length of sewer pipe where the deposition occurs is the only exogenous information that the user will have to accept in applying this methodology. In other words, this distribution is the only information that cannot be derived from local data and can only be modified in a minor way by input from local conditions. These modifications will be covered later.

Some simplifications had to be made in deriving these distributions especially considering the great number of pipe segments (around 6000) that were numerically considered. The procedure established for each basin, as a function of the maximum and minimum estimated loads, a series of 200 intervals where loads of approximately equal values were accumulated, together with their corresponding pipe lengths. Whenever the basin had less then 200 pipe segments the number of intervals would be made equal to the number of pipe segments of the basin. The cumulative values of loads versus lengths were then computed for each of these intervals.

Plots of several cumulative probability functions for a few basins are presented in Figures 12 and 13. An overall curve computed from all 75 basins is also presented in Figure 13. A total of 5000 intervals were used, in computing the overall curve, yielding a smooth curve as can be seen from Figure 13. Plots in semi-log paper of the complementary values of the load probabilities, (1.-Fload) (in the log axis) versus the cumulative probability of pipe lengths, resulted in nearly straight lines, indicating that this distribution is also exponential.

It was observed by associating the curves in Figures 12 and 13 with their respective mean slopes that the average basin slope increases moving from the lower to the upper curves. This explains comparatively higher percentages of loads depositing in lower percentages of pipe lengths. Based on this observation, Figure 14 was prepared. In its preparation a smooth curve was drawn at approximately the middle of the range of curves from Figures 12 and 13 with mean slopes corresponding approximately to the range limits in the legend of Figure 14. With the mean pipe slope known for a given basin, Figure 14 can be used to estimate the percentages of pipe lengths corresponding to given percentages of total solids deposited. Further discussion on the applications of Figure 14 will presented in Section 5.3.3.

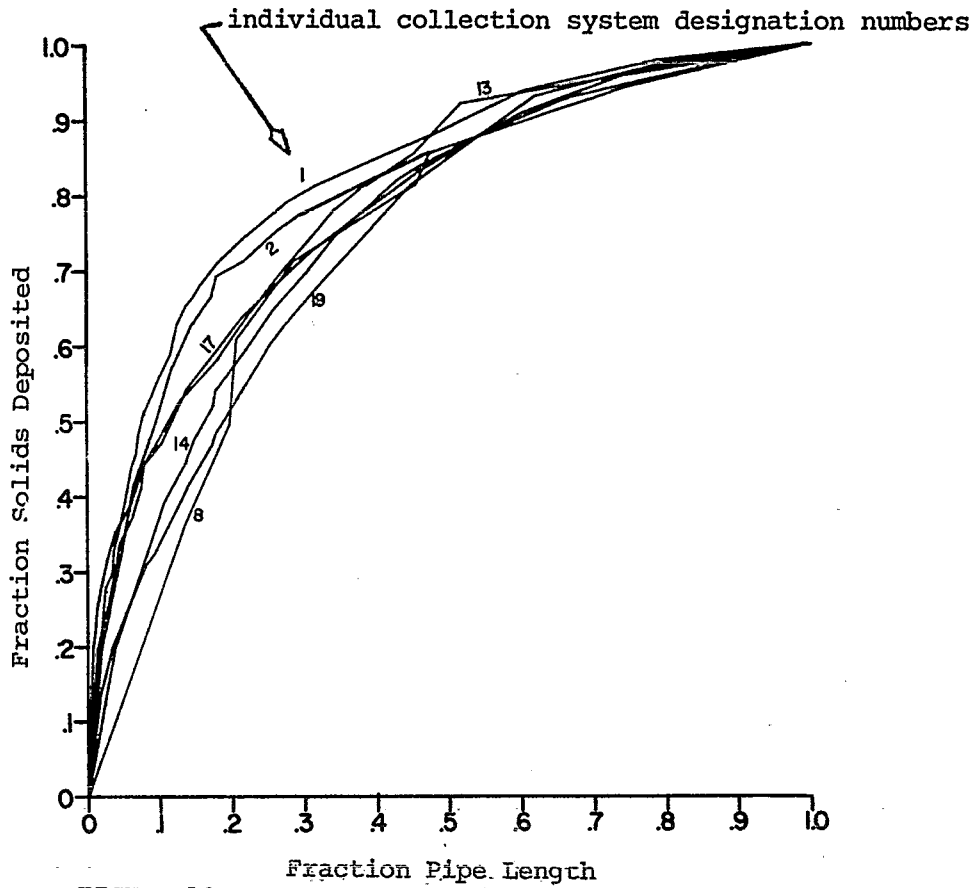

FIGURE 12. DISTRIBUTION OF SOLIDS DEPOSITED BY PIPE LENGTH-WRNDB SYSTEM

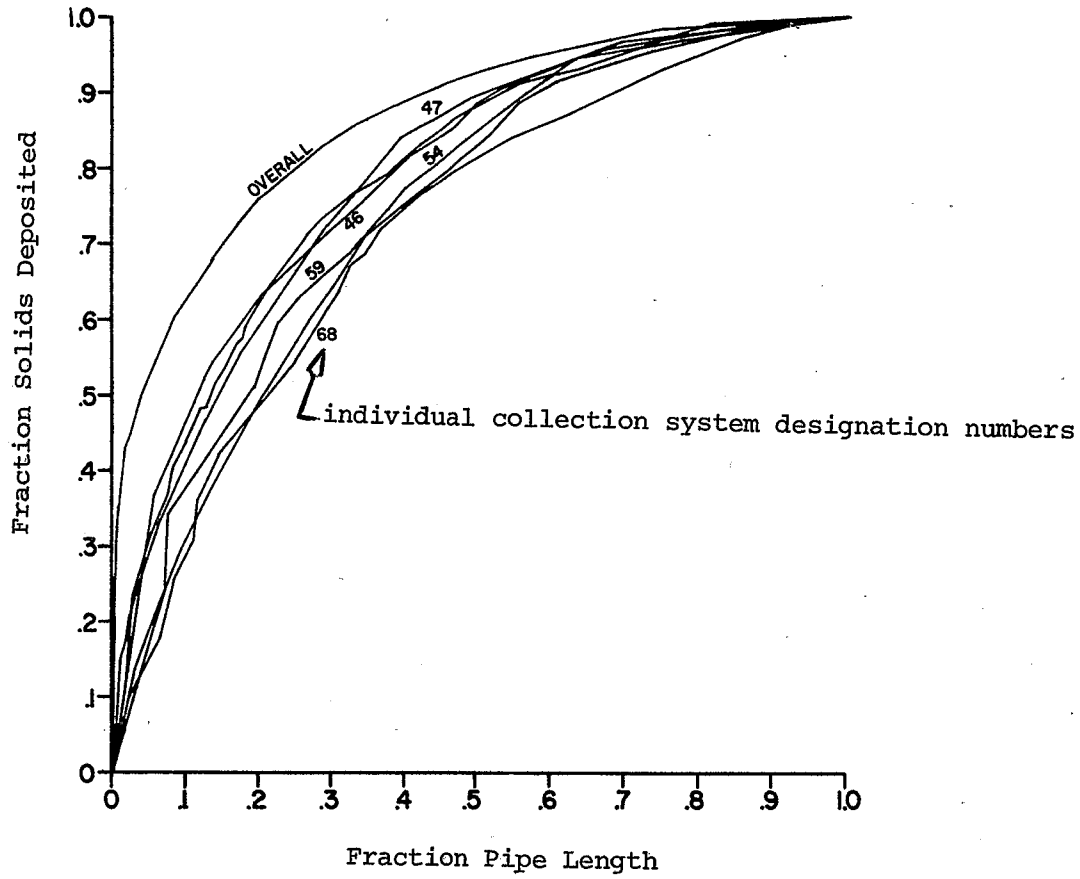

FIGURE 13. DISTRIBUTION OF SOLIDS DEPOSITED BY PIPE LENGTHS-DORCHESTER SYSTEM.

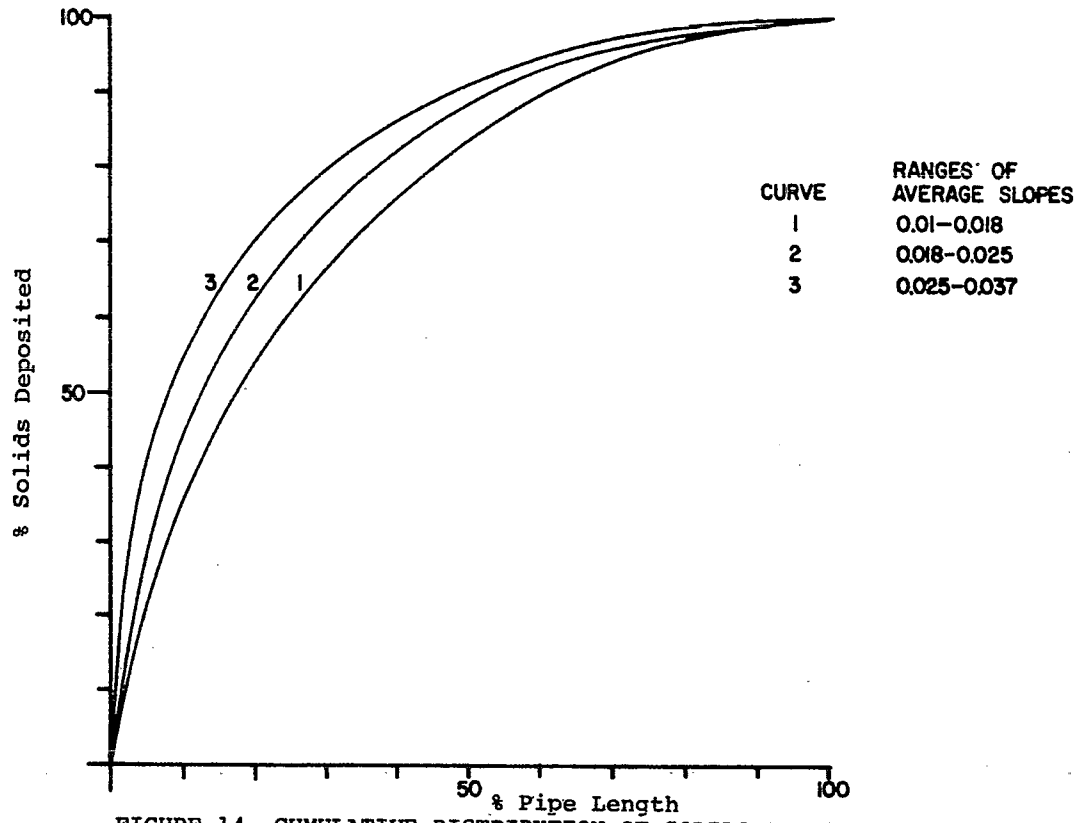

FIGURE 14. CUMULATIVE DISTRIBUTION OF SOLIDS DEPOSITED VS PIPE LENGTH

The choice of the pipe length corresponding to 80% of the loads deposited as an independent variable in the regression analysis discussed in section 4.2.1, resulted solely from the observation of higher separation of the curves around the value of 80%. Other percentages of mass deposited could have given the same results. It should be noted that the loads estimated by the regression equations presented in Section 4.5 correspond to 100% of the loads deposited. The length L_{PD} corresponding to 80% of the loads is only one regressor devised to explain the variation in the total loads.

4.4.6 Pipe Lengths Corresponding to 80% of the Loads Deposited - L_{PD}

The cumulative distribution of loads deposited versus the cumulative lengths of pipe for all basins were prepared. The values of L_{PD} to be used in the regression analysis were determined in the following manner. The computer printouts of the distributions were scanned for the percentages of pipe length (PL_D) corresponding to 80% of the total loads deposited and either read directly or more often they were interpolated. Those percentages were then applied to the total pipe lengths in the basins resulting in the L_{PD} values for all basins presented in Table 8.

4.4.7 Slope Corresponding to PL_D (S_{PD})

The determination of S_{PD}, the slope corresponding to the percentage of pipe (PL_D) where 80% of the total loads deposits is illustrated in Figure 2. The value of PL_D in the cumulative distribution of pipe slopes for a given basin is established and the corresponding slope value S_{PD} is determined. This was performed for all basins by reading directly or interpolating values in the tables of the cumulative distributions of the pipe slopes of these basins. The values of S_{PD} for all the 75 basins considered are given in Table 8.

There is no theoretical justification for the choice of S_{PD} as a regressor. As a matter of fact the average of the slopes ($\bar{S}_{PD}$) below S_{PD} had originally been thought of as a better regressor than S_{PD} itself, and was the first to be included in the regression analysis. A high correlation between S_{PD} and $\bar{S}_{PD}$ was observed and S_{PD} was included in the regression since its reduction of the sum of squares was slightly better than $\bar{S}_{PD}$. The variable $\bar{S}_{PD}$ was dropped from further consideration since its determination required far more effort than that for S_{PD}.

4.4.8 Slope Corresponding to $PL_D/4$ - ($S_{PD}/4$)

The determination of $S_{PD}/4$ is illustrated in Figure 2. First of all, multiply by 1/4 the percentage , PL_D, corresponding

to 80% of the loads deposited. Next enter that value in the cumulative distribution of pipe slopes for a given basin and determine the corresponding value, $S_{PD}/4$. This step was done by reading directly or interpolating values in the tables of the cumulative distributions of the pipe slopes for the basins. The values of $S_{PD}/4$ for all 75 basins are presented in Table 8.

The choice of $S_{PD}/4$ as an independent variable in the analysis regression did not involve any theoretical consideration. It's choice resulted from an "a priori" belief that representing the lower ranges of the pipe slope distribution would be significant in the regression analysis. It is shown in Section 4.5 that this assertion is true.

4.4.9 Summary of Results

Descriptions of how the data for the regression analysis was generated was presented in Sections 4.4.1 through 4.4.8 and of how the values of the dependent variable, TS, were generated by the use of a deposition model. The independent variables of the regression were described in Sections 4.4.2 through 4.4.8. The only remaining independent variable not described in those sections is the waste flow rate contribution in gpcd. This variable, as described in Section 4.3 and mentioned again in Section 4.3.2, was fixed at the values of 40., 110., 190., and 260. gpcd, covering, therefore, a wide range of flows.

To summarize, the values obtained for the independent variables are given in Tables 6 and 8. The tabular values of L and A are given in Table 6 and the values of L_{PD}, $\bar{D}$, $\bar{S}$, and S_{PD} and $S_{PD}/4$ determined for all 75 basins are given in Table 8. The results from the deposition model are lengthy and are not presented in this report.

4.5 Regression Analysis

4.5.1 Regression Procedures

The linear regression program used to empirically establish the relationships of the total daily suspended solids (TS) deposition within a sewerage collection system with the independent variables described in previous sections, is one that operates in a step forward manner. At each step in the analysis the particular variable entered into the regression equation accounts for the greatest amount of variance between it and the dependent variable, i.e., the variable with the highest partial correlation with the dependent variable. The program is flexible to allow any independent variable to be: (1) left free to enter the regression equation by a criteria of the sum of squares reduction; (2) forced into the regression equation; or (3) be kept definitely out of the regression equation in one given selection. The procedure permits examination of several alternative considerations of the independent variables by optional selections of variables to be forced

in and out of the regression equation or to be simply left free to enter the equation using variance reduction criteria. The relative importance of each variable in the regression equation can be ascertained using this procedure.

4.5.2 Regression Results

In this analysis various predictive models are analyzed relating total suspended solids deposition within a collection system with the aforementioned independent variables under the assumption of clean pipe conditions. These relationships are therefore applicable for situations in which the sewer piping system is properly maintained. The effects of age and improper maintenance on collection deposition loadings were examined and the results are presented in section 4.5.4. The degree of increased daily deposition resulting from improperly maintained systems was crudely simulated using several assumed depths of bottom sediments.

In this analysis both linear additive and multiplicative models were investigated. The untransformed observed values of the dependent and independent variables were initially used, leading to a strictly linear regression equation. In the second case the observed values of both the dependent and independent variables were transformed by taking their natural logarithms, leading to a linear equation in the logarithmic domain which can then be put into a non-linear multiplicative form.

The results of the regression analysis are presented in Tables 9 through 12 noting only those selections considered more significant. Tables 9 and 10 refer to the linear model regression results and Tables 11 and 12 refer to the multiplicative model logarithmic regression results. The sequence of independent variable inclusions for several selections using the linear form are given in Table 9. The symbols in the table are explained as follows. The letters DP under the variable TS indicates that TS is the dependent variable. The other letters under the independent variables for any selection indicate:

AV - the variable is available to enter the regression equation subject to the threshold variance reduction limit fixed at 0.0001 for all selections and all runs, implying that a variable will enter the regresson if it can further reduce the total sum of squares be at least 0.01%.

FI - the variable is to be forced in the regression although it is also subject to the 0.0001 limit noted above. FI implies priority over the AV variables in entering the regression.

TABLE 9. LINEAR REGRESSION RESULTS: MULTIPLE CORRELATION COEFFICIENT AND STANDARD ERROR OF THE ESTIMATE

Selection No.	TS	L	A	$\bar{S}$	$\bar{D}$	L_{PD}	S_{PD}	$S_{PD/4}$	Q	R
1		(1)*	(3)	(5)	(6)	(2)			(4)	0.906
	DP	AV	AV	AV	AV	AV	AV	AV	AV	
		0.776**	0.901	0.906	0.906	0.892			0.905	
		252.4***	170.9	167.4	167.6	177.9			167.8	
2		(1)	(2)		(4)				(3)	0.814
	DP	AV	AV	AV	AV	FO	FO	FO	AV	
		0.766	0.810		0.813				0.814	
		252.4	230.9		229.7				229.0	
3		(1)	(3)		(6)	(2)	(5)		(4)	0.905
	DP	AV	AV	FO	AV	AV	AV	FO	AV	
		0.766	0.901		0.905	0.892	0.905		0.905	
		252.4	170.9		168.3	177.9	167.9		167.8	
4		(1)	(3)		(5)	(2)		(6)	(4)	0.905
	DP	AV	AV	FO	AV	AV	FO	AV	AV	
		0.766	0.901		0.905	0.892		0.905	0.905	
		252.4	170.9		168.0	177.9		168.5	167.8	
5		(2)	(4)	(1)	(6)	(3)			(5)	0.906
	DP	AV	AV	FI	AV	AV	AV	AV	AV	
		0.765	0.902	0.013	0.906	0.892			0.906	
		253.2	170.5	392.7	167.6	177.9			167.4	
6		(3)	(5)	(2)	(7)	(4)		(1)	(6)	0.906
	DP	AV	AV	FI	AV	AV	AV	FI	AV	
		0.765	0.902	0.228	0.906	0.892		0.228	0.906	
		253.9	171.0	383.0	168.2	178.4		382.3	167.9	

* Order of entrance of the variable in the regression equation
** Multiple correlation coefficient
*** Standard error of the estimate
DP Dependent variable
AV Available to enter the regression equation
FI Forced in the regression equation
FO Forced out of the regression equation
R Multiple correlation coefficient

TABLE 10. COEFFICIENTS OF THE LINEAR REGRESSION EQUATIONS

Selection No.	TS	a	b	c	d	e	f	g	h	i
1	DP	42.030	0.022	1.317	-1428.22	5.472	-0.067			-0.421
2	DP	42.235	0.019	1.690		2.199				-0.421
3	DP	44.838	0.022	1.269		3.733	-0.066	-1168.40		-0.421
4	DP	32.760	0.022	1.279		4.309	-0.066		-1863.57	-0.421
5	DP	42.030	0.022	1.317	-1428.22	5.472	-0.067			-0.421
6	DP	47.612	0.022	1.314	-1392.30	5.172	-0.067		- 695.85	-0.421

DP = dependent variable

General equation: $TS=a+bL+cA+d\bar{S}+e\bar{D}+fL_{PD}+gS_{PD}+hS_{PD/4}+iq$

Units:

- TS - lbs/day,
- L - ft,
- A - acres
- $\bar{S}$ - ft/ft,
- $\bar{D}$ - inches,
- L_{PD} - ft,
- S_{PD} - ft/ft,
- $S_{PD/4}$ - ft/ft, and
- q - gpcd.

TABLE 11. LOG REGRESSION RESULTS: MULTIPLE CORRELATION COEFFICIENT AND STANDARD ERROR OF ESTIMATE

Selection No.	TS†	L†	A†	$\bar{S}$†	$\bar{D}$†	L_{PD}†	S_{PD}†	$S_{PD/4}$†	Q†	R†
1		(1)	(5)	(7)		(6)	(2)	(4)	(3)	0.974
	DP	AV	AV	AV	AV	AV	AV	AV	AV	
		0.873**	0.973	0.974		0.974	0.946	0.974	0.973	
		0.777***	0.363	0.364		0.364	0.518	0.363	0.369	
2		(1)	(4)	(3)	(5)				(2)	0.923
	DP	AV	AV	AV	AV	FO	FO	FO	AV	
		0.873	0.921	0.919	0.923				0.902	
		0.777	0.622	0.629	0.617				0.689	
3		(1)	(6)	(3)	(5)	(4)			(2)	0.939
	DP	AV	AV	AV	AV	AV	FO	FO	AV	
		0.873	0.939	0.919	0.938	0.936			0.902	
		0.777	0.554	0.629	0.555	0.564			0.689	
4		(1)		(4)	(6)	(5)		(2)	(3)	0.954
	DP	AV	AV	AV	AV	AV	FO	AV	AV	
		0.873		0.947	0.954	0.954		0.910	0.938	
		0.777		0.512	0.479	0.481		0.660	0.552	
5		(1)	(4)			(5)	(2)		(3)	0.973
	DP	AV	AV	FO	AV	AV	AV	FO	AV	
		0.873	0.973			0.973	0.916		0.973	
		0.777	0.367			0.368	0.518		0.369	
6		(1)			(5)	(4)		(2)	(3)	0.942
	DP	AV	AV	FO	AV	AV	FO	AV	AV	
		0.873			0.942	0.941		0.910	0.938	
		0.777			0.537	0.541		0.660	0.552	
7		(1)	(4)	(6)		(5)	(2)		(3)	0.973
	DP	AV	AV	AV	AV	AV	AV	FO	AV	
		0.873	0.973	0.973		0.973	0.946		0.973	
		0.777	0.367	0.369		0.368	0.518		0.369	
8		(2)	(7)	(1)		(6)	(3)	(5)	(4)	0.974
	DP	AV	AV	FI	AV	AV	AV	AV	AV	
		0.890	0.974	0.023		0.974	0.946	0.974	0.973	
		0.725	0.364	0.591		0.364	0.520	0.364	0.370	

continued

TABLE 11. (continued)

Selection No.	TS†	L†	A†	$\bar{S}$†	$\bar{D}$†	L_{PD}†	S_{PD}†	$S_{PD/4}$†	Q†	R†
9		(2)	(5)	(7)		(6)	(3)	(1)	(4)	0.974
	DP	AV	AV	AV	AV	AV	AV	FI	AV	
		0.910	0.974	0.974		0.974	0.947	0.566	0.974	
		0.620	0.363	0.364		0.364	0.515	1.311	0.363	
10		(3)	(7)	(2)		(6)	(5)	(1)	(4)	0.974
	DP	AV	AV	FI	AV	AV	AV	FI	AV	
		0.919	0.974	0.566		0.974	0.974	0.566	0.947	
		0.628	0.364	1.314		0.364	0.364	1.311	0.512	

* Order of entrance of the variable in the regression equation
** Multiple correlation coefficient
*** Standard error of the estimate
† Regression carried out with the natural logs of the variables
DP Dependent variable
AV Available to enter the regression equation
FI Forced in the regression equation
FO Forced out of the regression equation
R Multiple correlation coefficient

TABLE 12. COEFFICIENTS OF THE NATURAL LOG REGRESSION EQUATIONS

Selection No.	TS	a	b	c	d	e	f	g	h	i
1	DP	0.0028	0.932	-0.055	-0.059		-0.064	-0.770	-0.104	-0.510
2	DP	0.0013	1.180	-0.178	-0.418	0.604				-0.510
3	DP	0.0011	1.560	-0.109	-0.499	0.687	-0.508			-0.510
4	DP	0.0011	1.252		-0.396	0.398	-0.355		-0.368	-0.510
5	DP	0.0036	0.927	-0.077			-0.043	-0.884		-0.510
6	DP	0.0044	1.096			0.499	-0.239		-0.443	-0.510
7	DP	0.0032	0.952	-0.077	-0.040		-0.062	-0.859		-0.510
8	DP	0.0028	0.932	-0.055	-0.059		-0.064	-0.770	-0.104	-0.510
9	DP	0.0028	0.932	-0.055	-0.059		-0.064	-0.770	-0.104	-0.510
10	DP	0.0028	0.932	-0.055	-0.059		-0.064	-0.770	-0.104	-0.510

DP = dependent variable

General equation: $TS = aL^{b}A^{e}\bar{S}^{d}\bar{D}^{e}L_{PD}^{f}S_{PD}^{g}S_{PD/4}^{\bar{h}}q^{i}$

Units:

- TS - lbs/day,
- L - ft,
- A - acres,
- $\bar{S}$ - ft/ft,
- $\bar{D}$ - inches,
- L_{PD} - ft,
- S_{PD} - ft/ft,
- $S_{PD/4}$ - ft/ft, and
- q - gpcd.

FO - means that the variable is to be kept out of the regression equation.

In selection number 1 shown in Table 9 all variables were free to enter the regression equation. The numbers above the selection symbols, AV, FO, and FI indicate the order in which the variables stepped into the equation. They reflect, therefore, the relative marginal importance of each variable present in the final equation of a given selection. Variables available to enter the regression shown without this ordering number are the ones that did not meet the 0.0001 variance reduction requirement.

The first number below the AV, FO and FI symbols is the multiple regression coefficient (adjusted for the degrees of freedom) achieved with the entrance in the regression of the present variable. The square of that number is the R^2 value at that step. For example, referring to selection 1 in Table 9, the first variable to enter the regression is the total pipe length in the basin L. At the first step the regression coefficient, R, is 0.776 implying $R^2 = 0.602$. When the second variable, L_{PD}, enters the regression the multiple regression coefficient improves to 0.892, explaining therefore 79.57% of the total sum of squares ($R^2 = 0.7957$). The successive reductions in the total sum of squares and the marginal contribution of each addition variable can be assessed by following through the order of the variables entering the regression. The second number below the AV, FI and FO symbols represent the standard error of the estimate, adjusted for the degrees of freedom. The square of that number is the variance of the estimate. The reduction in the uncertainty of the estimate can be noted by following that number throughout the sequence of variables introduced to the regression. An increase of the standard error at a given step indicates that the additional information realized by introducing the variable is off-set by the loss in degrees of freedom, implying that the regression equation is better off without that particular variable.

Other selections shown in Table 9 were designed to: (1) compare regression equations based on primary variables only, such as total length of pipe, L, total area, A, average pipe slope, $\bar{S}$, etc. and equations containing more refined variables, derived from primary data, such as L_{PD}, S_{PD}, $S_{PD}/4$; or (2) to assess the importance of a given variable or variables given that others were forced into the regression. Although several selections may have the same final equation, the order in which the variables entered the regression is useful to assess the importance of the individual variables. The last column in Table 9 indicates the maximum multiple correlation coefficient for a given selection. The linear regression is very good for all selections, with correlation coefficients ranging from 0.814 to 0.906 (R^2 from 0.663 to

0.821, respectively). The coefficients of the variables selected in Table 9 which entered the regression equation are given in Table 10. For each of the selections shown on Table 9 these coefficients define the corresponding regression equations using the general equation presented at the bottom of Table 10. A blank in Table 10 indicates that the corresponding variable does not belong to the regression equation of the given selection.

Similar results for the logarithmic regression are contained within Tables 11 and 12. The last column in Table 11 shows excellent results for the logarithmic regression in all selections, with a minimum multiple regression coefficient of 0.923 and a maximum of 0.974. This implies values of R^2 ranging from 0.852 to 0.949. The multiplicative model is superior to the linear forms explaining roughly 95 percent of the total variability of the dependent variable.

4.5.3 Alternative Model Selections

In this section several of the regression models described in Section 4.5.2 with all the relevant information presented in Tables 9 through 12 will be recommended for user application. Alternative forms reflecting the availability of data and/or user resources will be presented. The simplest forms require little data and have the least predictive reliability whereas the more complicated models, requiring greater user resources and data availability, provide estimates with extremely high reliability.

Comparison of the multiple correlation coefficients for the linear and the logarithmic regressions in Tables 9 and 11, respectively, indicates that the logarithmic multiplicative models are superior. Therefore, all the models selected below will derive from the logarithmic regression results.

4.5.3.1 The Elaborate Model

The highest multiple correlation coefficient, 0.974 (R^2 = 0.949) was obtained in selection 1 in Table 11. Inspection of that table indicates that this maximum correlation value had already been attained at the fourth regression step (under SPD/4). The addition of a fifth variable, A, in the regression does not improve the multiple correlation coefficient nor the standard error of the estimate. Beyond the fifth variable the standard error increases. Therefore, only the first four variables should be retained in the regression equation yielding:

$$TS = 0.0038\ L^{0.8142}\ S_{PD}^{-0.8187}\ S_{PD/4}^{-0.1078}\ q^{-0.5098}\ (R^2=0.949) \qquad (2)$$

where TS is deposited solids loading in lbs/day, L is total length of sewer system in feet, S_{PD} and $S_{PD/4}$ are slope parameters defined in Section 4.4 and q is the per capita waste rate in gpcd. The above coefficients are slightly different from those shown on Table 12, which are for the full equation, that is, for all seven variables entered into the equation.

Utilization of equation (2) requires knowledge of total pipe length, the per capita contribution and the two pipe slope parameters, S_{PD} and $S_{PD/4}$. These slope parameters in turn are a function of the percentage of pipe where 80% of the total mass (TS) deposits (PL_D) and the probability distribution of the pipe slopes. The value PL_D is assumed given for the regression analysis, derived from the extensive computer analyses performed during this study and reported in Section 4.4.5. The probability distribution of the pipe slopes can either be derived from histograms computed from local pipe slope data or it can be defined with reasonable approximation from the mean pipe slope ($\bar{S}$) only, as described in Section 5.2.5.2. If the pipe slopes are not available a regression of mean ground slope and mean pipe slope, as also described in Section 5.2.3.2, could be performed.

4.5.3.2 An Intermediate Model

A simpler model than that given by equation (2), including only the primary variables, can be derived from selection 2 in Table 11 and is given by:

$$TS = 0.001303\ L^{1.18}\ A^{-0.178}\ (\bar{S})^{-0.418}\ (\bar{D})^{0.604}\ \bar{q}^{0.51}\ (R^2=.852) \qquad (3)$$

where $\bar{S}$ is average pipe slope, and $\bar{D}$ is the average equivalent diameter in inches; and A is service area (acres).

In this case the coefficients above are the same as shown in Table 12, since all variables that entered the regression were retained. All five independent variables present in equation (3) can be defined with good precision in any practical application. Neither the distribution of deposited loads versus pipe length nor the probability distribution of the pipe slopes are required. The mean pipe slope $\bar{S}$, again, can be correlated to the mean ground slope as described in Section 5.2.3.2, if no information on pipe slopes is available. A fitted equation for L as a function of A was derived from the data used in this study and is presented in Section 5.2.2

If the mean pipe diameter, $\bar{D}$, is eliminated from this regression the loss in precision of the estimate is not significant, resulting in the expression:

$$TS = 0.00389\ L^{1.2195}\ A^{-0.1866}\ (\bar{S})^{-0.4343}\ q^{-0.51}\ (R^2=0.848) \qquad (3)$$

4.5.3.3 The Simplest Model

The highest R^2 value that can be obtained with the least number of independent variables is also derived from selection 2 in Table 11. That is given by the regression equation:

$$TS = 0.0076\ L^{1.063}\ (\bar{S})^{-0.4375}\ q^{-0.51}\ (R^2=0.845) \qquad (5)$$

4.5.3.4 Final Comments on the Selection of the Model

The selection of the regression equations was meant to summarize the 16 possibilities presented in Tables 9 through 12. Other choices can be made from other selections presented, that may be more compatible with particular applications, although at lower values of R^2. It should be noted that the coefficients presented in Tables 10 and 12 apply only to the complete regression equations, and if one variable is deleted from the equation those coefficients do not remain the same.

The user should note that the parameters of the regression equation estimated by the least squares procedure are a function of the data used in their estimation. These parameters are not known with certainty and represent only estimates of the true parameters of the model. The estimation of the parameter is improved as the number of data points increase and as the spread or variance of the independent variables also increases.

It is known from regression theory that the procedure provides the best estimates (least variance) around the means of the independent variables used in computing the parameters of the regression equation. As the values of the independent variables depart from the mean the uncertainty of the estimation given by the equation increases and can become large outside the range of values used as data in the regression. In other words. the uncertainty of the estimate given by the regression equation may be large when the model is used for conditions requiring extrapolation beyond the range of data used to develop the model.

The values of the independent variables used in the regression analysis for all 75 basins were presented in Tables 6 and 8. The range, mean and standard deviations of the independent variables were computed from the data given in Tables 6 and 8 and are presented in Table 13. A total of 300 observations were used in the regression analysis since the deposition loadings for each of the 75 basins were computed for four per capita waste generation rates.

4.5.4 Effects of Age and Maintenance

The regression equations presented in Section 4.5.3 were derived from deposition data computed under the assumption of

TABLE 13. RANGES, MEANS AND STANDARD DEVIATIONS OF THE INDEPENDENT VARIABLES USED IN THE REGRESSION

Variable	Range	Mean	Standard Deviation
L (ft)	263.-134528.	13702.	22867.
A (acre)	3.-641.	76.	102.
$\bar{S}$ (ft/ft)	0.002375-0.079921	0.021	0.0126
$\bar{D}$ (in)	8.-20.	11.5	1.97
L_{PD} (ft)	36.-34879.	4026.	5811.
S_{PD} (ft/ft)	0.001077-0.058940	0.0101	0.0093
$S_{PD/4}$ (ft/ft)	0.000089-0.024900	0.0037	0.0033
q (gpcd)	40.-260.	*	*

* q is not a random variable

clean pipes, with no bottom sediments. In this section the impact of poorly maintained systems was crudely simulated by arbitrarily assuming various levels of prior sediment accumulation in the pipes. These sediment levels would change the bottom cross-sectional shape of the pipe channel and hence the depth of flow, the hydraulic radius and the shear stress characteristics.

Two cases simulating different degrees of maintenance other than perfect clean pipe conditions were considered. In the first case, or the intermediate maintenance category, sediment beds ranging from 1 to 3 inches in depth were assumed for all pipes with slopes less than 0.0075. A sediment bed of 3 inches was assumed for all pipes with slopes less than 0.0005. The bed depths then ranged linearly starting at 3 inches for a pipe slope of 0.0005 up to one inch for a pipe slope of 0.0075. This range was established using judgment and also based on visual inspection of numerous combined sewer laterals in eastern Massachusetts sewerage systems. In the second category of maintenance, the zero maintenance case, sediment beds ranging from 3 to 6 inches for the same range of slopes was considered.

Considering the two age and maintenance criteria mentioned here, the deposition model was used to estimate total deposition loadings for each of the 75 sewer systems for each of the four per capita waste generation rates of 40, 110, 190 and 260 gpcd. Before similar regression computations were performed on the deposition results obtained for pipes with bottom deposits, a comparison was made of the total deposited loads computed under the assumptions of clean and sedimented pipes.

For each basin the ratios of TS computed for sedimented pipes with sediment beds of 1-3 inches and 3-6 inches and the TS values for clean pipes were calculated for all four per capita waste rates considered, i.e., 40, 110, 190 and 260 gpcd. The resulting ratios were very stable for a given per capita waste rate for both cases of sediment deposits. The mean and coefficient of variation of these ratios are presented in Table 14 for both conditions of bottom deposits.

The results shown on Table 14 suggest that the prediction of TS in sedimented pipes could be accomplished by a simple functional multiplicative correction of the results given by any of the regression equations for clean pipes. An equation was fitted using the data of Table 14 for each of the bed deposit conditions.

These equations are:

- For a system with deposits ranging from 1 to 3 inches;

$$TS_{1-3\ inches} = 1.68\ q^{-0.076}\ TS(clean) \quad (R^2=0.988) \qquad (6)$$

TABLE 14. AVERAGE VALUES OF THE RATIOS OF COMPUTED LOADS IN DEPOSITED PIPES OVER CLEAN PIPES

Ratios	Average Values of Ratios for Per Capita Waste Rates			
	40	110	190	260
$TS_{1-3\,inches}/TS(clean)$	1.263	1.186	1.128	1.094
	(0.18)	(0.14)	(0.07)	(0.12)
$TS_{3-6\,inches}/TS(clean)$	1.312	1.211	1.151	1.121
	(0.14)	(0.11)	(0.09)	(0.09)

The numbers in parenthesis indicate the coefficient of variation of the ratios.

where q = flow per capita, and TS(clean) = load of total solids computed from any of the regression equations presented in Section 4.5.2

- For a system with deposits ranging from 3 to 6 inches:

$$TS_{3-6\ inches} = 1.79\ q^{-0.084}\ TS(clean)\quad (R^2=0.999) \qquad (7)$$

The R^2 values indicated above refer to the regression of the ratios of TS on the values of flow per capita. The small difference found between the two conditions of bottom deposits may well be the result of an inappropriate accounting of these factors by the deposition model. On the other hand it may simply have resulted from the particular combination of pipe diameters and sediment depths used as data, which may have led to actually small differences in flow depths above the sediment levels, and therefore small differences in shear stress between the cases.

4.5.5 Predictions of Other Parameters

In Appendix A some of the results from the first phase of the sewer flushing experiments are presented. In Table A-1 of the appendix the results of 83 flushing experiments performed at 4 different sites in the Boston area are presented indicating the mass removals per flush of various pollutants including BOD, COD, TKN, NH_3, P, TS and VSS. The values represent estimates of the various pollutant masses removed by flushing as well as the total mass of depositing pollutants. Those results can serve as a basis for the estimation of other parameters associated with the total solids that deposit in the system.

A regression was performed between TS and each one of the other 6 indicators presented in Table A-1. The resulting regression equations are presented in Table 15, with their associated correlation coefficients.

Estimates of the total daily BOD, COD, TKN, NH_3, P and VSS depositing loads within a given collection system can be made using the regression equations in Table 15 with the predicted TS loadings calculated from any of the regression equations presented for clean pipe conditions in Section 4.5.3 and the bias correction factors for pipes with sediment beds given in Section 4.5.4.

TABLE 15. REGRESSION OF DIFFERENT POLLUTANTS ON TS

Regression Equation*	Correlation Coefficient
$BOD = 0.344TS^{1.308}$	0.80
$COD = 0.875TS^{1.04}$	0.77
$TKN = 0.039TS^{1.135}$	0.67
$NH_3 = -0.0336 + .017TS$	0.44
$P = -0.006 + .00768TS$	0.67
$VSS = 0.689TS^{1.033}$	0.97

* Units are lb/day

SECTION 5

MODEL UTILIZATION

5.1 Introduction

This section summarizes the steps required by the user to achieve the objectives set forth in Section 4.1.1, which are to define on a preliminary basis: a) the total amounts of solids and other pollutants that deposit in the sewerage system; and b) the extent of the collection system over which the deposition takes place.

The nature of the available data and/or the degree of resources the user can commit will define different work programs which in turn will lead to different levels of confidence in the results. In order to avoid references to past sections, all necessary formulas will be summarized in Sections 5.2.1 to 5.2.6.

5.2 Summary of Formulas for the Estimation of TS

This section summarizes all necessary formulas for the estimation of TS, separating formulas already presented in Section 4 and introducing a few new formulas. Only variable symbols introduced here will be defined in the following sections.

5.2.1 Formulas for Estimation of Total Loads Deposited - TS*

5.2.1.1 The Elaborate Model

The elaborate model derived in Section 4.5.3.1 for clean pipe conditions is given by:

$$TS = 0.0038\ L^{0.8142}\ S_{PD}^{-0.8187}\ S_{PD/4}^{-0.1078}\ q^{-0.5098}\quad (R^2=0.949) \qquad (8)$$

---

* These equations are for predicting deposited solids for clean pipe conditions. The user is referred to Sections 4.5.3 and 4.5.4 for age and maintenance considerations and for the prediction of other pollutants.

5.2.1.2 Intermediate Model

The intermediate models in Sections 4.5.3.2 for clean pipe conditions are given by:

$$TS=0.001303\ L^{1.18}\ A^{-0.178}\ (\bar{S})^{-0.4343}\ q^{-0.51}\ (R^2=0.852) \quad (9)$$

$$TS=0.00389\ L^{1.2195}\ A^{-0.1866}\ (\bar{S})^{-0.4343}\ q^{-0.51}\ (R^2=0.848) \quad (10)$$

The difference between the two models is that the second neglects the average pipe diameter $\bar{D}$, with a small loss in precision.

5.2.1.3 The Simplest Model

The simplest model defined in Section 4.5.3.3 for clean pipe conditions is given by:

$$TS=0.0076\ L^{1.063}(\bar{S})^{-0.4375}\ q^{-0.51}\ (R^2=0.845) \quad (11)$$

5.2.2 Estimation of Total Pipe Length

The total pipe length of the system, L, and its corresponding collection area, A, are generally assumed to be known. In cases where this information is not known and where crude estimates will suffice, the total pipe length can be estimated from the total basin area using the expressions:

$L = 168.95\ A^{0.928}$ (R^2= 0.821)-low population density (10-20 people/acre)

$L = 239.41\ A^{0.928}$ (R^2= 0.821)-moderate-high population density (30-60 people/acre)

These expressions were derived from the data for the 75 basins used in this study, yielding a correlation coefficient of 0.906. Since detailed population density estimates for each collection system in the data set were not available, the following approach was used to account for the effect of population density on length of sewer. The data for the 75 basins were separated into two distinct data sets representing low population densities (the 35 basins from the West Roxbury-Newton-Dedham-Brookline sewerage system) and moderate to high population densities (the latter 40 basins from the Dorchester and Fitchburg sewerage systems). A dummy variable approach was used in the regression analysis to obtain the two expressions given in equation (12). A more explicit treatment of population density would be possible if detailed population density estimates per collection system were available.

5.2.3 Estimation of Mean Pipe Slope $\bar{S}$

5.2.3.1 Pipe Slope Data is Available

In this case:

$$\bar{S} = \frac{\sum_{i=1}^{n} S_i l_i}{\sum l_i} \qquad (13)$$

where: S = slope of segment i

l = length of segment i

n = total number of pipe segments

5.2.3.2 Pipe Slope Data Not Available

If data on pipe slope is not available the user will determine a mean value for the ground slope using any procedure, such as the techniques of uniform grid sampling or random sampling. With the mean ground slope value, determine the mean pipe slope by:

$$\bar{S} = 0.348\ (\bar{S}_G)^{0.818} (R^2=0.96) \qquad (14)$$

where: $\bar{S}_G$ = mean ground slope (ft/ft)

The expression above resulted from a regression of mean ground versus mean pipe slope for all 75 basins of this study. The resulting correlation coefficient was 0.98.

This relation was derived in the following manner. Topographic mylar overlays with ground contour at ten feet intervals were developed for the WRNDB and the Fitchburg sewer system service areas. Similar maps existed for the Dorchester and South Boston sewer systems. Using the topographic maps the collection system areas were subdivided into smaller fractions considered to have uniform slopes. The ground slopes were computed for each of the subareas. Those ground slopes were then associated with the percentages of the collection system area they covered. The basin average ground slope was then computed by weighing the individual slopes by their associate subarea percentages. Ground slopes in the smaller basins were determined by using one or two subareas whereas the ground slopes in the large basins were determined using 10 to 21 subareas.

5.2.4 Distribution of Total Solids Deposited by Pipe Segment - Determination of PL_D

The distribution of total solids deposited by pipe length is presented in Figure 14. The user can determine PL_D corresponding

to 80% of the solids deposited by entering the graph with "% of mean deposited" equal to 80% and, from the curve that best appropriate the average pipe slope $\bar{S}$, read in the horizontal axis, "% pipe length", the value of PL_D. This value will be required to determine S_{PD} and $S_{PD/4}$ in Section 5.2.5.2

5.2.5 Determination of Slopes S_{PD} and $S_{PD/4}$

5.2.5.1 Pipe Slope Data is Available

The collection system pipe slopes can be directly used to define the cumulative pipe slope distribution. In this study the pipe lengths (as integer values) associated with the observed slopes were taken as their frequencies. The user should adopt the same approach for compatability with the equations for TS derived in this study. Simplified methods may also be used, with less accurate results. If, for example, the slopes are not weighted by their lengths, this is equivalent to assuming that all pipe segments have the same length, which in some cases may be a reasonable assumption.

5.2.5.2 Pipe Slope Information Not Available

The average slope $\bar{S}$ can be computed using either equation (13) or equation (14) to define the pipe slope cumulative density function (CDF) as follows:

$$FS = 1-e^{-s/\bar{S}} \qquad (15)$$

If the probability F_S is known, with a fixed $\bar{S}$ the corresponding slopes can be computed, and vice-versa. For the basins used in this study, equation (15) was verified with excellent results.

To determine the slope S_{PD}, use the value of PL_D determined in Section 5.2.4, and make:

$$F_S=1-e^{-s/\bar{S}}=PL_D$$

and determine s. Then:

$$S_{PD}=s$$

To determine the slope $S_{PD/4}$, make:

$F_S=1=e^{-s/S}=1/4PL_D$ and determine s. Then:

$$S_{PD/4}=s.$$

5.2.6 Formula for the Average Pipe Diameter

If the system contains non-circular shapes, first compute their equivalent circular diameters using the equations for

equivalent pipe diameters presented in Table 7. Then, compute the average diameter by:

$$D = \frac{\sum_{i=1}^{n} D_i l_i}{\Sigma l_i} \qquad (16)$$

where: D_i = diameter of segment i

l_i = length of segment i

n = total number of pipe segments.

5.3 General Description of User's Steps

5.3.1 Determination of the Total Solids Deposited

The generalized procedure for obtaining total solids deposited estimates is presented in Figure 15 and should be referred to in the ensuing discussion.

The first question to be answered at the onset is whether pipe slope data are available. If the answer is positive the user should use equation (13) to determine the average pipe slope $\bar{S}$; otherwise, a mean ground slope should be determined as described in Section 5.2.3.2 and then equation (14) should be used to determine $\bar{S}$.

The next question that arises is whether the total pipe length of the collection system is known. In the negative case the total area of the collection system is assumed known and the total pipe length is estimated by equation (12). The per capita waste rate including infiltration is then established.

The selection of the equation for the estimation of the solids deposited, TS, follows. If the simplest model is desired the user has at this point all the elements required by equation (11) to compute TS. If the intermediate model is chosen and the pipe diameter information is available the mean pipe diameter is computed by equation (16). All information is computed to estimate TS from equation (9). If pipe diameters are not available then use equation (10). If the elaborate model is chosen, the value of PL_D must be determined using Figure 14 as described in Section 5.2.4. The next variables to be determined are S_{PD} and $S_{PD}/4$.

If no pipe slope information is available the user has no alternative but to use the exponential approximation for the pipe slope cumulative distribution. If the pipe data are available but the user considers the exponential approximation satisfactory he may use equation (15), associated with PL_D and $\bar{S}$

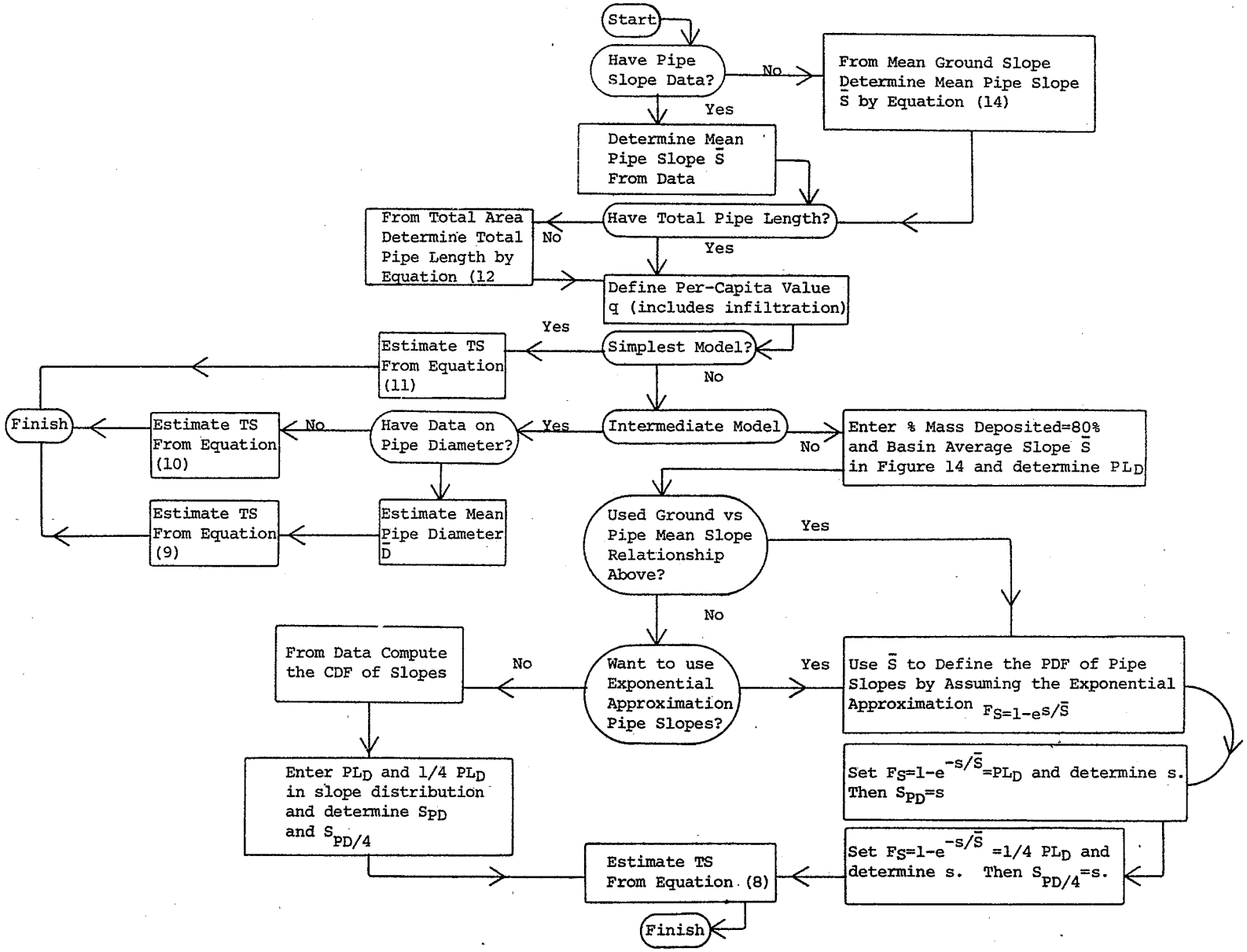

FIGURE 15. USER STEPS TO DETERMINE SOLIDS DEPOSITED-TS

to determine S_{PD} and $S_{PD}/4$ as described in Section 5.2.5.2. Finally, the user can define the pipe slope CDF from the pipe slope data and derive from it, the values of S_{PD} and $S_{PD}/4$ as described in Section 5.2.5.2. Finally, the user can define the pipe slope CDF from the pipe slope data and derive from it, the values of S_{PD} and $S_{PD}/4$ corresponding to the percentages PL_D and $1/4PL_D$, respectively. At this point all the elements are prepared to estimate TS from equation (8) which provides the most reliable estimate of TS.

The resulting estimate of TS is the total daily solids deposition in the collection system of interest. If the user wishes to modify this estimate for pipes with existing sediment beds the multiplicative equations in Section 4.5.4 should be used. If estimates of other pollutants are desired, the deposited solids results, TS, should then be used as predictors to compute other pollutant estimates using the equations given in Section 4.5.5.

5.3.2 Application of Procedures

In this section an example problem illustrating the methodologies developed in this report is presented. The test case is one of the collection systems in the Dorchester sewerage system. Estimates of total daily solids deposition in this collection system will be given for different assumptions of data availability using the simplified procedures. These estimates will also be compared with the results computed for this system using the much more detailed procedure described in Appendix B.

The test case used is basin number 70 of the Dorchester combined sewer system. There are 190 manhole segments in this collection system. The topography of this combined sewer collection system is fairly hilly. The land use in the area is exclusively high density multi-family dwellings with a population density of 30 people/acre. The areal extent and total collection system pipe footgate is about one standard deviation above the mean of all the systems used in the regression analysis. The values of all the independent variables for basin 70 are given in Tables 5 and 8.

5.3.2.1 Data Requirements

The total pipe length, L, for the basin is 35,033 feet and the total service area, A, is 233 acres. The total pipe length can also be computed using equation (12) for high population density yielding 37,740 feet, representing an overestimation error of 7.7 percent.

There are three possible ways to compute the values of the pipe slope variables required as input for the various regression equations. The first method involves computing these parameters from

the distribution derived from actual pipe slope data. The second procedure requires knowledge of only the mean collection system pipe slope, $\bar{S}$, and assuming that the pipe slopes can be represented by an exponential distribution. The third alternative approach assumes that only ground slope information is available and that the exponential distribution is applicable to represent collection system pipe slopes.

The collection system pipe slope histogram representing the distribution of 190 pipe segments in basin 70 of the Dorchester sewerage system is given in Table 16. This table was prepared using the invert elevations for each of the 190 segments. The pipe slope histogram is divided into 30 intervals with the upper pipe slope limit of each interval given. The elements under the column labeled "frequency" are the actual pipe footages associated with each pipe slope interval. The last two columns give the interval probability computed using the pipe footage per interval relative to total pipe footage and the cumulative probability. The mean and standard deviation are also given in Table 16. The average equivalent circular diameter, $\bar{D}$, is 15.6 inches and was computed using the formulas given in Table 7, page 33 and equation (16).

The average pipe slope, $\bar{S}$, is 0.0194. The slope parameter S_{PD} can be estimated in the following manner. Three curves are available in Figure 14, page 38, for relating the cumulative distribution of solids deposited to cumulative distribution of collection system pipe length. Curve 2 is applicable in this case since the average pipe slope is 0.0194. The percentage of pipe associated with 80 percent of the total daily load deposited is 38%.* The value of the variable, S_{PD}, can then be determined by entering 0.38 in the last columun of Table 16 and interpolating the corresponding value of slope in column two. The interpolated value of S_{PD} is 0.00629. The value of $S_{PD}/4$ is obtained by entering the same table with 0.38/4 = 0.095, yielding $S_{PD}/4$ = 0.00302.

In the second procedure the mean pipe slope can be used in the exponential cumulative distribution function given by equation (1), page 22, to compute the values of S_{PD} and $S_{PD}/4$. The value of S_{PD} is 0.00928 results from using FS = 0.38, s = S_{PD} and $\bar{S}$ = 0.0194 in equation (1). The value of $S_{PD}/4$ is 0.00194 results from setting FS = 0.38/4 = .095 in equation (1).

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* The distribution of loads by pipe length derived for basin 70 yields exactly 38% at 80% of the total load. The error involved in using Figure 14 is zero in this example.

TABLE 16. DISTRIBUTION OF PIPE SLOPES FOR BASIN 70

AVG. DIAMETER = 15.6

HISTOGRAM FOR FIXED RANGES (MAX. AND MIN. ABCISSA VALUES SPECIFIED)

INTERVAL	UPPER LIMIT OF RANGE	FREQUENCY	PROBABILITY	CUMMULATIVE PROBABILITY
1	0.000100	0	0.0	0.0
2	0.003311	3680	0.1045	0.1045
3	0.006521	10477	0.2974	0.4019
4	0.009732	3239	0.0920	0.4938
5	0.012943	4099	0.1164	0.6102
6	0.016154	1189	0.0338	0.6440
7	0.019364	680	0.0193	0.6633
8	0.022575	832	0.0236	0.6869
9	0.025786	1229	0.0349	0.7218
10	0.028996	752	0.0213	0.7431
11	0.032207	472	0.0134	0.7565
12	0.035418	909	0.0258	0.7823
13	0.038629	1485	0.0422	0.8245
14	0.041839	371	0.0105	0.8350
15	0.045050	752	0.0213	0.8564
16	0.048261	247	0.0070	0.8634
17	0.051471	315	0.0089	0.8723
18	0.054682	460	0.0131	0.8854
19	0.057893	1528	0.0434	0.9288
20	0.061104	0	0.0	0.9288
21	0.064314	560	0.0159	0.9447
22	0.067525	68	0.0019	0.9466
23	0.070736	1033	0.0293	0.9759
24	0.073946	334	0.0095	0.9854
25	0.077157	16	0.0005	0.9858
26	0.080368	0	0.0	0.9858
27	0.083578	340	0.0097	0.9955
28	0.086789	126	0.0036	0.9991
29	0.090000	0	0.0	0.9991
30	> 0.090000	32	0.0009	1.0000

Mean = .0194058 Standard Deviation = .020859

The only information required for the third procedure is the average ground slope, $\bar{S}_G$. The average ground slope for basin 70 was determined by graphical procedures to be 0.0359. An estimate of the mean pipe slope, $\bar{S}$, can be obtained using the mean ground slope in equation (14). The estimated value of mean pipe slope, $\bar{S}$, using the mean ground slope, $\bar{S}_G$, is 0.02287 differing from the actual mean pipe slope by 17%. Values of S_{PD} and $S_{PD/4}$ can now be estimated using the exponential relationship in equation (1), yielding S_{PD} = 0.00985 and $S_{PD/4}$ = 0.00228.

5.3.2.2 Estimation of Loads

The detailed manhole to manhole dry weather deposition model described in Appendix B was used to estimate total solids deposited for the entire collection system network in basin number 70. The estimated load is 169.11 lbs/day using an average per capita waste rate of 190 gpcd. This model requires detailed specification of the hydraulic parameters for each segment in the system and the use of a computer. Similar estimates will be computed from using the simplified power functions generated in this study for the three different estimates of the pipe slope variables.

The elaborate model given in equation (8) requires specification of L, S_{PD}, $S_{PD/4}$ and the per capita flow rate, q. This equation was solved for the three different estimates of S_{PD} and $S_{PD/4}$ with q = 190 gpcd. The deposited load, TS, is 155.73 lbs/day using the values of S_{PD} and $S_{PD/4}$ derived from the analysis of detailed collection system pipe slope information. The estimated load is 118.72 lbs/day using values of S_{PD} and $S_{PD/4}$ computed from the mean pipe slope and the exponential cumulative function. The estimated load is 111.11 lbs/day using values of S_{PD} and $S_{PD/4}$ for the third situation where the mean ground slope is used to compute mean pipe slope for input into the exponential function.

The intermediate model given by equation (10) requires that L, A, $\bar{S}$, and q be specified. Three variations are computed using this formulation. The first estimate is determined using the measured pipe length, L and pipe slope, $\bar{S}$, derived from data; the second case uses the measured pipe length and an estimate of mean pipe slope from ground slope estimate; and the third result is computed using the estimated pipe slope, $\bar{S}$, and an estimate of pipe length derived from equation (12). These three estimates are 186.89, 174.02 and 190.55 lbs/day, respectively.

The simplest model given by equation (11) requires specification of L, $\bar{S}$ and q. The estimated loads are 198.82 lbs/day using exact estimates of L and $\bar{S}$, 195.02 lbs/day using exact estimates of pipe length and an estimate of pipe slope ground ground slope, and, 200.26 lbs/day using estimated values of both pipe length and mean pipe slope.

A comparison of all computed loadings for the different predictive models under different assumptions of data availability is given in Table 17. The percentage error relative to the estimate provided by the procedure in Appendix B is also provided. These results show that the estimated values given by all three regression equations are reasonably close to the value derived from the detailed model described in Appendix B. The elaborate model consistently gave over estimates.

It is an invalid conclusion to infer from this comparison that the simpler approach might be superior to the more elaborate one. It should be noted that this comparative result is only for one basin and that on the average, the elaborate model will provide consistently superior results because the coefficient of determination R^2, is higher for the elaborate model. The under estimates given by the elaborate model using approximations for the pipe slopes are explained by the fact that, for this particular basin, the exponential approximation over estimated by about 50% the slope, SPD. Nevertheless, one of the simpler models would be more appropriate in cases where little data is available requiring many assumptions and approximations. Moreover, the utilization of the simpler models for planning "first-cut" purposes may be more cost effective from the standpoint of collecting, analyzing and preparing the required data inputs.

In sum the simplified procedures given by equations (8), (10) and (11) provide estimates of daily solids deposition using exact data for basin 70 with a relative error of 8 to 18 percent in comparison to the estimate given by the complicated procedure described in Appendix B. It is shown in Appendix C of this report that the complicated procedure given in Appendix B was tentatively calibrated using actual field flush information lending credulence to the adoption of the simplified procedures generated in this report.

TABLE 17. COMPARISON OF ESTIMATED DAILY SOLIDS DEPOSITED FOR BASIN 70 USING DIFFERENT PROCEDURES

Procedure	Solids Deposited (lbs/day)	Percentage Error Relative to Appendix B Results
Deposition Model (Appen. B)	169.11	
Elaborate Model (Eq. (8))		
Exact Data	155.73	-7.9%
Exponential Data	118.72	-30.0%
S_G and Exponential Approx.	111.11	-34.0%
Intermediate Model (Eq. (10))		
Exact Data	186.89	+10.5%
Estimated Slope $\bar{S}$	174.02	+3.0%
Estimated L and $\bar{S}$	190.55	+12.7%
Simplest Model (Eq. (11))		
Exact Data	178.82	+17.6%
Estimated $\bar{S}$	185.03	+9.4%
Estimated L and $\bar{S}$	200.26	+18.4%

5.3.3 Determination of Deposition Extent in Collection Systems

Estimates of total pipe footage for given percentages of the total solids deposition can be made using Figure 14. These estimates are computed irrespective of their actual location in the collection system. The appropriate curve in Figure 14 can be chosen. Using the average pipe slope $\bar{S}$ as a guide, several values of "% pipe length" can be read directly from the figure as a function of values of "% mass deposited". Multiplication of the total basin pipe length by those percentages yields estimates of pipe footage corresponding to the various percentages of total solids deposited. Those estimates can be used in preliminary assessments of costs associated with pipe cleaning by mechanical or flushing techniques to achieve different levels of total deposited mass removals.

It should be noted that the estimates of total pipe footage corresponding to given levels of deposition do not define where in the system those pipes lie. With one simple assumption, the locations in the system of the deposited pipes can be tentatively established. This assumption can be understood considering Figure 16. In part a of Figure 16, an estimate of the percentage of the total pipe length PL over which a percentage of the total mass of solids, PM, deposits is shown. The percentage of total pipe length in the basin with pipe slope smaller than or equal to S_{PL} is shown in part b of Figure 16. Combining the two parts in Figure 16, does not necessarily mean that the pipes over which PM deposits all have slopes flatter than or equal to S_{PL}. This may be a reasonable working assumption and, if it is made, locations of depositing segments can be determined. This step can be accomplished by noting on a sewerage system map all pipe segments with slopes equal to or smaller than S_{PL}. This procedure will quantify the sewer segments associated with the percentage PM of the total load. A check of the approach can be made be measuring those pipe lengths and comparing their sum with the estimate given by $L_{PM} = PL \times L$

where: L_{PM} = estimated length over which the percentage PM of the total mass deposits;

PL = the corresponding percentage of pipe length (from Figure 14); and

L = total length of pipe in the basin.

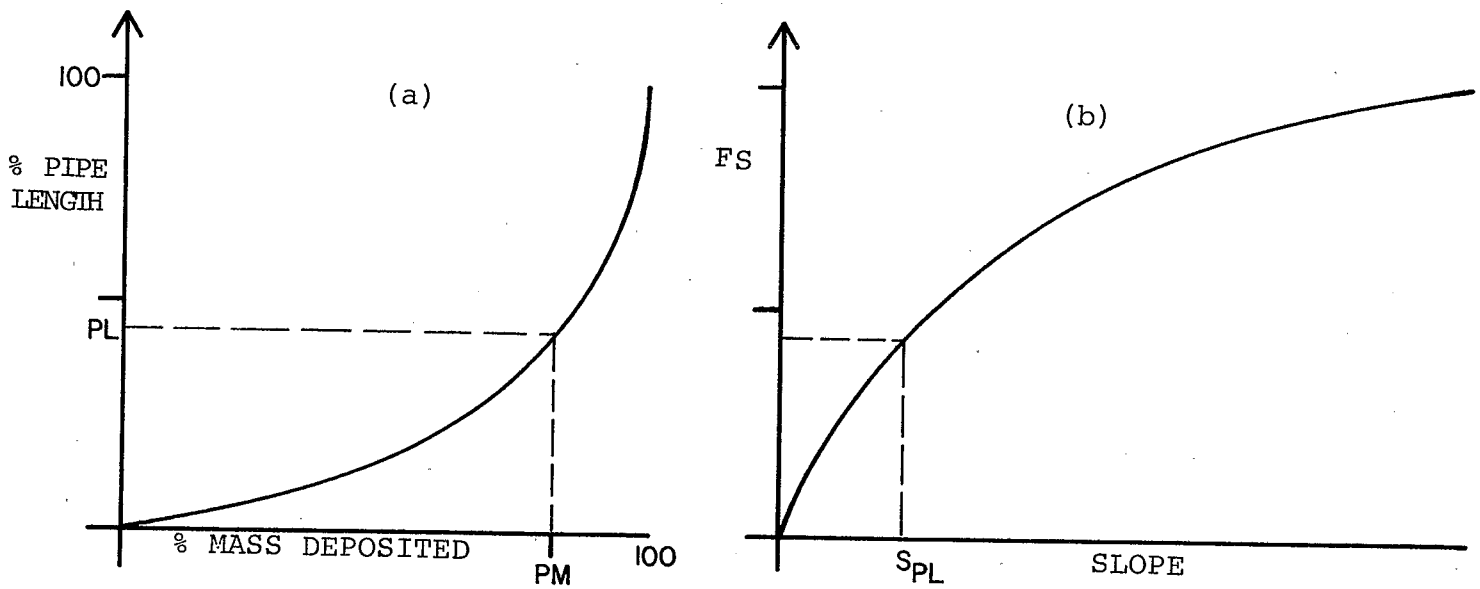

FIGURE 16: DETERMINATION OF THE CUT-OFF SLOPE FOR A PERCENTAGE OF MASS DEPOSITED

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APPENDIX A

BRIEF REVIEW OF R&D SEWER FLUSHING PROJECT

A brief review of the R&D sewer flushing program objectives and project scope will be presented in this appendix. Next a summary review of the pollutant removals resulting from manual flushing of four test segments during the first phase of the program will then be provided.

Conceptual Views of Program

The solids control demonstration/research program has been developed to address many of the issues relating to the feasibility, cost-effectiveness, and ease of application of upstream solids control program as an integral part of overall combined sewer management. Basically, there are five fundamental issues that must be answered before widespread acceptance of upstream solids control may be considered. The issues include: 1) what are the best flushing methods to use for a given situation; 2) what is the expected pollutant removal efficiency associated with the various methods; 3) what are the costs associated with such programs; 4) how do you screen large systems to identify problem pipes with respect to deposition and; 5) what are the effects of stormwater runoff on such a strategy as applied to combined sewer systems.

Program Objectives

1. Test the feasibility of applying various solids control techniques as a method of deposition control in combined and sanitary sewer lines on test segments in the Boston sewer system.

2. Carefully monitor deposition rates on a number of test segments.

3. Monitor pollutant removals including solids, organics and nutrients associated with the various solids control techniques.

4. Assess pollution oriented characteristics of both the flushed and remaining materials versus maintenance problems of grit, sand and gravel accumulations.

5. Recommend most favorable solids control techniques for operational testing by both automated and manual means.

6. Develop, test and evaluate automated control systems in a field operational testing program.

7. Develop, test and evaluate manual sewer flushing techniques utilizing specially equipped water tankers in a field operational testing program.

8. Assess the operational feasibility and performance of flushing both long and short upstream collection segments and/or networks.

9. Assess the effects of stormwater washoff on the characterization of combined sewer solids.

10. Refine existing deposition model and flushing criteria.

11. Compare solids control vs selected structural options as a combined sewer abatement technique.

12. Develop user guideline for solids control program as an integral part of sewer management schemes.

Figure A-1 is an overview schematic of the program. The program is broken into three distinct phases: 1) a field feasibility analysis of various solids control (flushing) techniques to test the feasibility of applying various techniques to actual sewer lines; 2) an operational testing program to assess the operational feasibility of applying optimum strategies to sewer systems; and 3) a detailed data analysis and costing phase to develop a reasonable deposition model and flushing criteria, and analyze the concept of upstream solids control as an integral part of combined sewer abatement schemes.

The feasibility analysis is aimed at answering the question of what are typical deposition rates in sewerage collection systems, what are the best flushing techniques to use, and what pollutant reductions can be reasonably expected as well as supplying a wealth of data for the refinement of the existing deposition model and flushing criteria. The operational testing program will take the optimum strategies developed in the feasibility analysis and put them into an actual 10 week program aimed at continuing data development as well as testing the operational feasibility of such a program by both manual and automated means.

From the large data base developed during the two field programs, a refined practical deposition model and flushing criteria will be generated. These refined formalisms will allow for scanning of large-scale sewer systems to identify problem pipes with respect to deposition. The refined tools will allow for

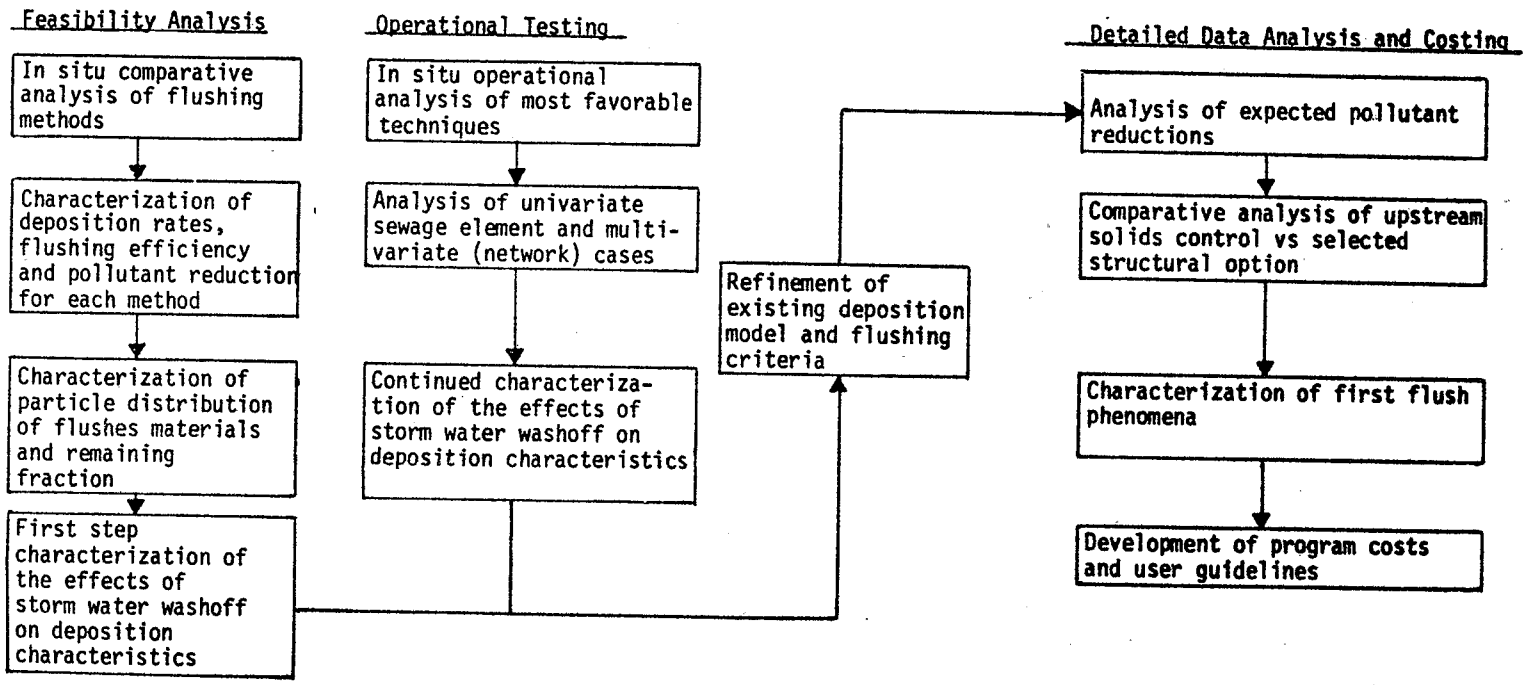

FIGURE A-1. SCHEMATIC OVERVIEW OF PROGRAM

comparative analysis of upstream solids control vs selected structural options to compare program efficiencies. The tools will also allow for rough assessment of first flush phenomena as related to combined sewer systems to better clarify the questions over the use of upstreams "first-flush" collection devices. Finally, the program will develop data to generate a set of engineering user guidelines to apply the deposition analysis to large-scale systems.

Results of First-Phase Feasibility Flushing Programs

After a careful review and inspection program, four streets were selected for the flushing experiments. These streets are all in Dorchester characterized by high density, 3-story multi-family dwellings. Two of the test segments located on Port Norfolk and Walnut Street are served by flat combined sewer laterals of 12" and 15" circular pipe, respectively. The total tributary population down to and including the test segments are 94 and 71 people, respectively. The other two test segments on Shepton and Templeton Streets, are serviced by separate sewer laterals of 12" and 15" circular pipe, respectively. There are downspouts on both streets connected to the sanitary sewer. The total tributary population for these two streets are 224 and 221, respectively. The pipe slopes of the test segments range from 0.003 to 0.004. The flushing program in this phase is concerned only with the effects of flushing a single manhole to manhole segment. Three different methods of manual flushing were performed. The first method consisted of backing up the upper end of the flushing manhole with an inflatible rubber stopper with quick release. The other two methods were gravity and pressurized dump discharge into the flush manhole with the upper end of the flush manhole blocked off. These flushes were performed using a specially designed water tanker with two 1000 gallon tanks mounted on a steel I-beam skid. The tanker was equipped with a pneumatic system to pressuirze the tanks to 30 psi. The operation under gravity conditions provided a controlled flush release of 35 to 50 cubic feet at a rate of 0.25 to 0.50 cfs. Under pressurized conditions the same volumetric range of flush was accomplished at a rate of 0.5 to 1.25 cfs. Sixteen to eighteen grab samples of flush wave were taken at 10 second intervals for the first 80 seconds after the flush wave reached the downstream manhole and then at 20 second intervals. Wave heights were taken at each interval of time which were later used to determine the instantaneous flow rate for computing mass pollutants removed by the flushing experiment.

The total pollutant mass removals in kilograms, for each of the four test segments are given in Table A-1. This data is preliminary and is subject to change pending further field refinment of stage/discharge rating procedures used to convert flush wave heights to discharge quantities. The mean and standard

deviation of the pollutant mass removals in kilograms for each of the four test segments is given in Table A-2. The mean and standard deviation of the pollutant mass removals normalized for the number of antecedent days between flushing experiments is provided in Table A-3. These statistics are computed for all experiments including those impacted by rainfall events occurring between the flushing experiments. Statistics for subsets of this data excluding the rainfall impacted experiments are presented in Appendix C. The data used in the regression analysis presented in Table 15 of Section 4.5.4 was prepared by normalizing the raw results given in Table A-1 and then converting the results into lbs/day.*

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* It is assumed in the regression analysis cited in Section 4.5.4 that the normalized pollutant loads removed by flushing equals the daily deposition rate. Preliminary results of the second phase of field flushing indicates flushing removal effectiveness ranging from 75 to 90 percent. These results will be used during a later phase in this project to reexamine the results given in Section 4.5.4

TABLE A-1. TOTAL MASS OF POLLUTANT REMOVED BY FLUSH

Location: Port Norfolk Street

	TOTAL MASS (kg)						
DATE	COD	BOD	TKN	NH3	P	TSS	VSS
8/30/76	1.54	0.81	0.04	0.01	0.02	3.94	1.24
9/2						12.37	7.58
9/7	5.49	2.92	0.25	0.05	0.05	16.04	11.02
9/16						2.90	1.96
9/21	4.60	0.78	0.22	0.04	0.06	6.50	3.14
9/24						5.74	3.67
10/1	9.37	3.40	0.33	0.04	0.04	11.36	9.35
10/4	7.49	2.90	0.28	0.06	0.06	7.10	5.42
10/8						2.97	1.92
10/12	4.51	1.61	0.16	0.02	0.04	5.81	4.27
10/15						2.73	2.16
10/18	5.68	2.00	0.16	0.03	0.001	4.90	4.03
10/25						1.52	1.11
10/22						2.36	1.79
10/29						3.04	2.49
11/1	3.71	1.17	0.12	0.03	0.02	2.94	2.30
11/5						2.23	2.04
11/8	3.36	1.42	0.10	0.03	0.03	3.32	2.57
11/12		3.30				4.79	4.47

continued

TABLE A-1 (continued)

Location: Templeton Street

	TOTAL MASS (kg)						
	COD	BOD	TKN	NH_3	P	TSS	VSS
8/30						10.84	4.01
9/2		2.96				7.68	4.93
9/7						1.19	1.01
9/10		3.66				8.51	6.52
9/13	2.54	0.45	0.07	0.01	0.01	2.26	1.70
9/16		0.08				0.23	0.16
9/21						1.88	1.10
9/24						0.32	0.27
10/1						5.13	3.60
10/4						2.70	2.19
10/8		1.50				6.89	5.95
10/12						13.06	10.49
10/15		0.96				4.97	3.45
10/18						13.95	11.09
10/22		3.92				5.06	3.32
10/25						4.40	3.58
10/29		4.41				10.04	7.44
11/1						4.70	3.23
11/5		5.25				12.74	10.52
11/8						5.38	3.96
11/12		3.80				-	-

continued

TABLE A-1 (continued)

Location: Shepton Street

	TOTAL MASS (kg)						
	COD	BOD	TKN	NH3	P	TSS	VSS
8/23	5.63	1.21	0.09	0.03	0.03	3.91	2.81
8/30						2.84	1.71
9/2		1.75				5.70	4.17
9/7						14.11	11.04
9/10		1.58				5.71	4.58
9/13						2.42	1.93
9/16		1.89				5.67	4.46
9/21						4.27	2.83
9/24		0.65				2.57	1.87
10/1						3.34	2.31
10/4						5.76	4.71
10/8		2.31				6.09	4.84
10/12						4.32	3.12
10/15		2.64				4.82	3.87
10/18						6.54	5.24
10/22		1.38				2.93	2.31
10/25	8.00	2.09	0.20	0.04	0.05	4.53	3.83
10/29		0.99				3.51	2.86
11/1						3.60	2.93
11/5		2.35				5.49	4.55
11/8						5.51	4.37
11/12						1.03	0.89

continued

TABLE A-1 (continued)

Location: Walnut Street

	TOTAL MASS (kg)						
	COD	BOD	TKN	NH_3	P	TSS	VSS
8/23	3.5	0.83	0.07	0.04	0.03	2.74	1.17
8/26		1.18				0.52	0.22
8/30	12.44	1.29	0.35	0.1	0.07	14.94	7.72
9/2						1.76	0.90
9/7	0.66	0.22	0.03	0.02	0.01	0.63	0.27
9/10						0.98	0.87
9/13	3.06	0.61	0.08	0.07	0.02	14.23	8.25
9/16						0.46	0.37
9/21	1.36	0.24	0.03	0.01	0.02	2.75	0.78
10/1	3.37	1.26	0.10	0.02	0.04	2.83	1.91
10/4	1.15	0.45	0.05	0.01	0.01	1.21	0.84
10/12	13.70	3.61	0.25	0.05	0.04	14.32	8.13
10/15						0.57	0.30
10/18	1.21	0.57	0.07	0.03	0.0005	1.08	0.82
10/22						4.24	4.17
10/25	2.12	0.52	0.07	0.03	0.02	1.53	0.87
10/29						1.34	1.00
11/1	1.67	0.70	0.06	0.02	0.01	1.01	0.74
11/5						3.33	2.39
11/8	4.25	1.67	0.11	0.06	0.02	3.34	2.18
11/12						0.48	0.48

TABLE A-2. STATISTICS OF POLLUTANT MASS REMOVALS (kg) RAW DATA

STREET	STATISTICS	COD	BOD	TKN	NH3	P	TSS	VSS
Port Norfolk	Mean	5.08	2.03	0.18	0.03	0.04	5.39	3.82
	St. Deviation	2.31	1.02	0.09	0.02	0.02	3.90	2.76
Shepton	Mean	6.82	1.71	0.145	0.035	0.04	4.76	3.69
	St. Deviation	1.68	0.62	0.078	0.007	0.01	2.53	2.03
Templeton	Mean	2.54	2.70	0.07	0.01	0.01	6.10	4.43
	St. Deviation	-	1.81	-	-	-	4.27	3.33
Walnut	Mean	4.04	1.01	0.11	0.04	0.024	3.54	2.11
	St. Deviation	4.37	0.90	0.10	0.03	0.019	4.71	2.64

- Too few data points to compute standard deviation.

TABLE A-3. STATISTICS OF POLLUTANT MASS REMOVALS (kg/ANTECEDENT DAY) DATA NORMALIZED FOR ANTECEDENT DAYS

STREET	STATISTICS	COD	BOD	TKN	NH_3	P	TSS	VSS
Port Norfolk	Mean	1.41	0.55	0.05	0.01	0.01	1.49	1.03
	St. Deviation	0.53	0.25	0.02	0.04	0.005	1.04	0.64
Shepton	Mean	1.89	0.50	0.05	0.01	0.02	1.36	1.06
	St. Deviation	1.09	0.21	0.04	*	0.01	0.63	0.52
Templeton	Mean	0.85	0.81	0.02	0.002	0.003	1.66	1.25
	St. Deviation	-	0.54	-	-	-	1.17	0.92
Walnut	Mean	0.95	0.25	0.027	0.010	0.006	0.90	0.54
	St. Deviation	0.83	0.15	0.021	0.008	0.004	1.19	0.67

- Too few data points to compute standard deviation
* Smaller than 0.0001

APPENDIX B

DISCUSSION OF SIMPLIFIED SEWER SYSTEM DEPOSITION MODEL

The details of a procedure for obtaining quick and inexpensive estimates of the amount of daily dry weather deposition loadings within each manhole to manhole segment of a sewer collection system are provided in this appendix. A number of crude approximations and simplifications are used in this procedure and therefore, the results are not purported to be a substitute for those provided by more rigorous approaches.

One distinct advantage of this model is that it is devised to consider each element of an entire collection system network. It is intended to provide estimates for only dry weather conditions and has no provisions for considering transient wet weather phenomena. No distinction is made between bedload, suspended load and washload deposition and resuspension characteristics. The major simplifying assumption of the model is that the amount of deposition remaining in any segment over the course of a day is computed as the residual loadings not washed or moved downstream during peak dry weather flow conditions. No detailed accounting is made of the temporal pattern of diurnal deposition, resuspension and transport phenomena. The basic structure of the model was developed during a prior combined sewer management study (2). In a latter phase of this R&D sewer flushing project the data obtained from the field flushing program will be used to further refine formalisms presented in this appendix.

General Concepts

A well designed sewerage system should not only convey flows but should also minimize the deposition of sewage solids during dry weather conditions. There are in use an ample number of suitable empirical and theoretical equations for flow design but no uniform criteria have been established to prevent solids depostion.

The approach commonly used to prevent deposition is the method of minimum permissible velocity (3). However, the use of average velocity consideration is not necessarily the most robust criterion to use for a wide range of typical operating conditions.

A more fundamental approach is the method of critical shear stress, τ, given by equation (1).

$$\tau = \rho r ss \qquad (1)$$

where ρ = specific weight of water

r = hydraulic radius, and

ss = energy slope

Yao (4) reviewed experimental results dealing with fluid shear stress measurements and concluded that the average boundary shear stress computed by equation (1) will approximate the actual local boundary shear stress within the possible region of deposition, provided that the flow depth is equal to or greater than one-third of the sewer diameter.*

Yao also included that a shear stress of .02 or .04 psf is adequate for self-cleaning sanitary sewers, while a shear stress of .06 to .08 psf is necessary to dislodge heavy sand and gravel, and is required for self-cleaning of combined systems. In addition, this work showed that the present practice of using a constant minimum velocity for all sewer sizes tends to under-design larger sewers and over design smaller sewers.

Deposition Mechanisms

Shield's classic results are commonly used to predict solids deposition in sewerage systems. Shield's results, however, relate to bedload movement and specifically to uniform particles moving on the surface of the bed. In simple terms, there are two primary mechanisms involved in the transport of sewage particles: bedload transport and suspension.

The first to used bedload transport considerations to predict deposition was Camp (5,6,) and others have since used this technique (7,8,9). Shield's relationship** for bedload transport is given by:

$$\tau_c = .020\ p \qquad (2)$$

where p = particle diameter, (mm) and

τ_c = critical wall shear (psf)

---

* The actual or local boundary shear stress varies considerably, with the maximum occurring around the center line of the channel and the minimum near the water surface.

** Shield's constant equals 0.06 in this formulation.

The second transport mechanism is suspension. Hughmark (10) correlated 14 sets of data on slurry transport and Raths (7) conducted experiments on sand sediment in sewers. In order to prevent deposition of sand particles (specific gravity = 2.7), a critical wall shear must be maintained or exceeded. The results of their experiments can be summarized by the following relationship:

$$\tau_c = .021\ p^{1/3} \qquad (3)$$

The smaller particles (less than .05 mm) of Hughmark's data closely agree with the above functional form. A reasonable first order approximation is to assume that both mechanisms transport heterogenous materials through sewer systems. The geometric average of equations (2) and (3) can be used to predict transport requirements. The equation relating the critical wall stress, τ_c, necessary to move (and conversely to settle)* a particle of given diameter, p, is the following:

$$\tau_c = .02\ p^{2/3} \qquad (4)$$

Single Segment Deposition Model

Equation (4) and sewage particle size distributions can be used to predict the quantity of suspended solids deposited from dry-weather flow over a single length of pipe. The results computed from equation (4) with two particle distributions (11, 8) and the experimental results from the FMC study (1) were fitted by a simple single term power function given by equations (5) and (6):

$$Z = 40\left(\frac{\tau}{.004}\right)^{-1.2} \quad \text{for } \tau > .004 \text{ psf} \qquad (5)$$

$$Z = 40 \quad \text{for } < .004 \text{ psf} \qquad (6)$$

where Z is the percentage of the suspended solids in the dry weather sanitary flow that is deposited if the wall shear is less than τ.

The shear stress, τ, would be computed for maximum daily dry weather flow conditions. Maximum daily flow, Q_{MAX}, can be computed from average dry weather flow, QAV, using equation (7).

$$\frac{Q_{MAX}}{Q_{AV}} = a\ P\bar{P}^{b} \qquad (7)$$

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* Recent findings have shown that this assumption is erroneous, that is, a greater shear stress is required to move a particle of a given diameter than to permit settling. In a later phase of this project this assumption will be examined.

where PP is the contributing population in 1000's and a and b are determined from analysis of flow measurements. Typical values of the constant "a" range from 1.25 to 1.5 and a value of 1.47 was used in the computations described in Section 4. A value of 0.08 was used for the exponent "b". Both values were established from analysis of flow measurements.

Multi-Segment Models

In considering a series of sewer pipes having low values of fluid tractive shear, that is, characterized by low slopes or low flows (or both), the condition can arise where solids from an upstream reach can successively deposit in downstream pipes. The relative amounts deposited in any section would depend on the shear stress during peak flow in that link and also on the amounts deposited upstream. A general procedure is desired to predict the total cumulative load in any section from all upstream sources.

The procedure used is the following:

1. Segment the collection system into a network of "m" links where each link may be a section of pipe between manholes or several sections combined into a single section (similar hydraulic characteristics);

2. Establish, for all links, a list of all downstream sections that convey waste from the given link;

3. Compute cumulative upstream length of pipe at each link;

4. Compute average daily dry weather flow for each link using the cumulative length from step 3 and an average per capita waste rate;

5. Compute maximum daily dry-weather flow for each link using equation (7);

6. Compute shear stress for each link associated with the maximum daily flow, using equation (1) for the appropriate pipe shape;

7. Compute the dry-weather suspended solids deposition rates, $Z_i (i = 1,...,m)$ from the shear stresses calculated in Step 6, using equations (5) and (6);

8. Compute the suspended solids load $ZL_i (i = 1,...m)$ developed along each link using length of link, population per unit length and daily solids generated per capita;

9. Starting at the uppermost link, i, compute the amount of input material that will deposit, that is $Z_i \cdot ZL_i$;

10. Search the list of downstream links for the deposition rate, Z_j, greater than the rate at the link where the load is initially generated, and compute the amount deposited as the jth link from the ith component input load using $(Z_j - Z_i) \cdot ZL_i$;

11. Continue searching the list of downstream links for a deposition rate Z_k greater than Z_j and compute the deposition at the kth link from the ith component using $(Z_k - Z_j) \cdot ZL_i$;

12. Set $Z_k = Z_j$ and repeat Steps 10 and 11 until the complete list of downstream links is completed;

13. Start with the next uppermost link in the system and repeat Steps 9 through 12 while maintaining a running sum of all the deposited loads in each link from previous iterations; and

14. Sequentially proceed downstream until all components are completed.

In other words, a fraction of the load generated in an upstream section may deposit in that section (if the shear stress is sufficiently low) and more of that load may deposit in downstream sections only if the shear stress falls below levels experienced upstream.

The present model is coded to assume any collection system geometry with the one rule that only three segments can be considered at a given manhole. The model is coded to compute shear stress for circular, egg, ovoid, rectangular, horseshoe shaped cross-sections with and/or without pre-set sediment beds.

An idealized example using the schematic in Figure B-1 illustrates this procedure. Assume that the shear stress developed during peak dry-weather flow in links 1, 4, 5, 8 and 11 results in deposition rates of 10, 5, 5, 15 and 20 percent, respectively. Assume that the shear in all other links, i.e., 2, 3, 6, 7, 9 and 10, is sufficiently high to preclude any localized deposition. The dry weather load developed along each of the 11 links is, say, 100 units of dwf solids.

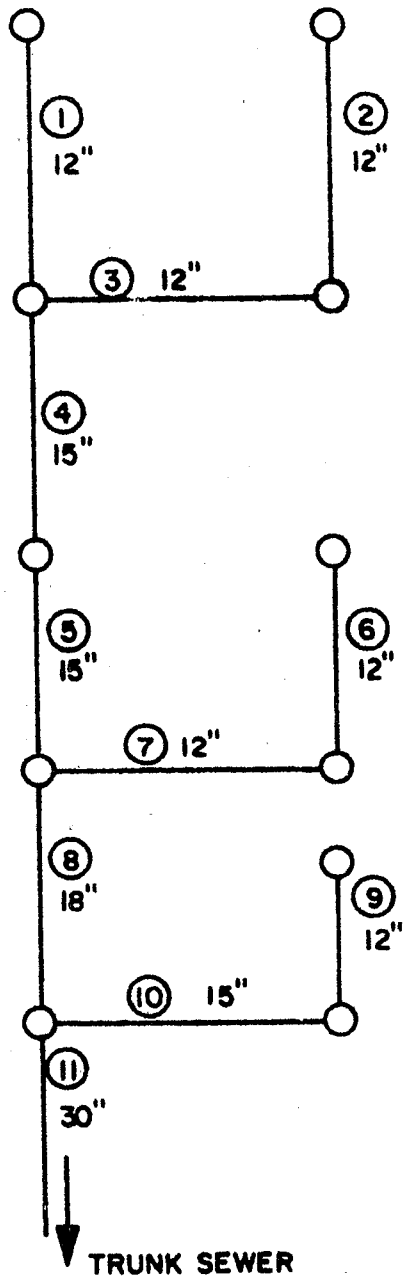

FIGURE B-1. SCHEMATIC OF COLLECTION SYSTEM

TABLE B-1. DEPOSITION ANALYSIS OF IDEALIZED SYSTEM

Link Numbers	Link Numbers											Total Amount Deposited in Each Link
	1	2	3	4	5	6	7	8	9	10	11	
1	10.											10
2	-	0.										0.
3	-	0.	0.									0.
4	0.	5.	5.	5.								15.
5	0.	0.	0.	0.	5.							5.
6	-	-	-	-	-	0.						0.
7	-	-	-	-	-	0.	0.					0.
8	5.	10.	10.	10.	10.	15.	15.	15.				90.
9	-	-	-	-	-	-	-	-	0.			0.
10	-	-	-	-	-	-	-	-	0.	0.		0.
11	5.	5.	5.	5.	5.	5.	5.	5.	20.	20.	20.	100.

The ijth in the table represents the amount deposited in link i that originated in link j. Thus element (8,1) = 5 represents the amount deposited in link 8 that originated in link 1.

Table B-1 shows contributions from all upstream links on each downstream link and the total deposition in section 4 consists of loads from sections 2, 3, 4 but not from section 1 because the deposition rate, Z_1 is greater than Z_4. At link 5, the only amount deposited is from the load developed along that link (Z_1 is greater than Z_5: no deposits, Z_2 and Z_3 less than Z_5 but Z_4 equals Z_5: no deposits; Z_4 less than Z_5: deposits). The overall deposition rate for entire system is 20 percent (220 units deposited/1100 units total load) with nearly equal loadings in links 8 and 11.

APPENDIX C

PRELIMINARY DEPOSITION MODEL CALIBRATION RESULTS

In this appendix a preliminary verification is presented of the deposition model described in Appendix B using field flushing results derived from the data presented in Appendix A. The results presented here reflect no change in the model's internal relationships. It is envisioned that modifications will be made in a later phase of the study.

A comparison of field flushing results for four test segments with predicted deposition rates is presented in Table C-1. The contents of this table are described as follows: column (1) - test segment location; column (2) - average mass of suspended solids removed per flush normalized by the number of antecedent days between each of the flushes for all experimental data; column (3) - average mass of suspended solids removed per flush normalized by antecedent days for selected subset of the experimental results including only good experimental points free of rainfall events occurring between the flush periods; column (4) - predicted daily deposition rates over test segment for two per capita waste rates of 125 and 250 gallons per capita per day; column (5) - pipe size of test segment; column (6) - length of test segment; column (7) - plan slope of pipe segment; and column (8) - depth of sand and gravel sediment bed. A suspended solids waste rate of 0.5 lb/capita/day was used in the analysis. This rate was determined from an analysis of background samples taken during the flushing program. Additional sewage background sampling is presently being conducted in the study and these results will later be used to sharpen the preliminary results presented here. The background sewage flow per capita determined from field measurements conducted during the flushing program ranged from 125 gpcd up to 275 gpcd. The peaking factors relating maximum daily flow to average flow were determined from field data.

Inspection of the measured results shown in column (3) with the predicted values given in column (4) indicates the deposition model estimates compare reasonably well with field results. In general, the model under-estimates deposition loadings and will be modified to reflect this bias in future phases of work.

TABLE C-1. PRELIMINARY OVERALL COMPARISON OF MEASURED AND PREDICTED RESULTS OF SOLIDS DEPOSITION IN TEST SEGMENTS

(1)	(2)*	(3)**	(4)***		(5)	(6)	(7)	(8)
Test Segment Location	Measured		Predicted					
	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Port Norfolk	1.33	1.47	1.37	1.1	12	247	0.00486	2
Shepton	1.41	1.24	1.1	.85	12	226	0.00345	2
Templeton	1.74	1.66	1.15	.92	15	187	0.0032	3
Walnut	1.03	0.65	.74	.40	15	136	0.0048	4

* All results including good and questionable experiments.
** Selected data: only good experiments free of wet weather impacts.
*** A waste generation rate of 0.5 lb/capita/day of suspended solids used (derived) from average of measured background sewage characteristics)
(A) Mean TSS Removal/Flush/Antecedent Day (kg/day)
(B) Mean TSS Removal/Flush/Antecedent Day (kg/day)
(C) Predicted Daily TSS Deposition Rates (kg/day - Per Capita Waste Rate = 125 gpcd
(D) Predicted Daily TSS Deposition Rates (kg/day) - 250 gpcd
(E) Pipe Size - Circular (in)
(F) Test Segment Length (ft)
(G) Pipe Slope Plan/Profile Maps
(H) Sediment (in)

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-77-120	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE PROCEDURES FOR ESTIMATING DRY WEATHER POLLUTANT DEPOSITION IN SEWERAGE SYSTEMS		5. REPORT DATE July 1977 (Issuing Date)
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) William C. Pisano and Celso Queiroz		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Energy & Environmental Analysis, Inc. 264 Beacon Street Boston, Massachusetts 02116		10. PROGRAM ELEMENT NO. 1BC611
		11. ~~CONTRACT~~/GRANT NO. R- 804579
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environment Research Laboratory-- Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268 Cin., OH		13. TYPE OF REPORT AND PERIOD COVERED Interim Final Planning Doc.
		14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES
Project Officer - Richard Field
201/321-6674(8-340-6674)

16. ABSTRACT

A set of generalized procedures for estimating pollutant loadings associated with dry weather sewage solids deposition in combined sewer systems has been prepared to provide planners, engineers and municipal managers with technical information so that they can make intelligent informed decisions on potential sewer flushing programs in combination with other combined sewer management controls.

The predictive equations relate the total daily mass of pollutant deposition accumulations within a collection system to physical characteristics of collection systems such as per capita waste rate, service area, total pipe length, average pipe slope, average diameter and other more complicated parameters that derive from analysis of pipe slope characteristics. Several alternative predictive models are presented reflecting anticipated differences in the availability of data and user resources. Pollutant parameters include suspended solids, volative suspended solids, biochemical oxygen demand, chemical oxygen demand, total organic nitrogen and total phosphorous. Sewer system age and degree of maintenance was also considered. Factors are presented for estimating the increase in collection system deposition resulting from improper maintenance. A user's guide has been presented to establish the necessary data input to utilize the predictive procedures.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Combined Sewers, *Flushing, *Water Pollution, *Water Quality, Economics, Mathematical Models, Methodology, *Maintenance	Field Measurements, Pollution Abatement, Regression Analysis, Sewer Flushing	13B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 104
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

☆ U. S. GOVERNMENT PRINTING OFFICE: 1977-757-056/5642 Region No. 5-11