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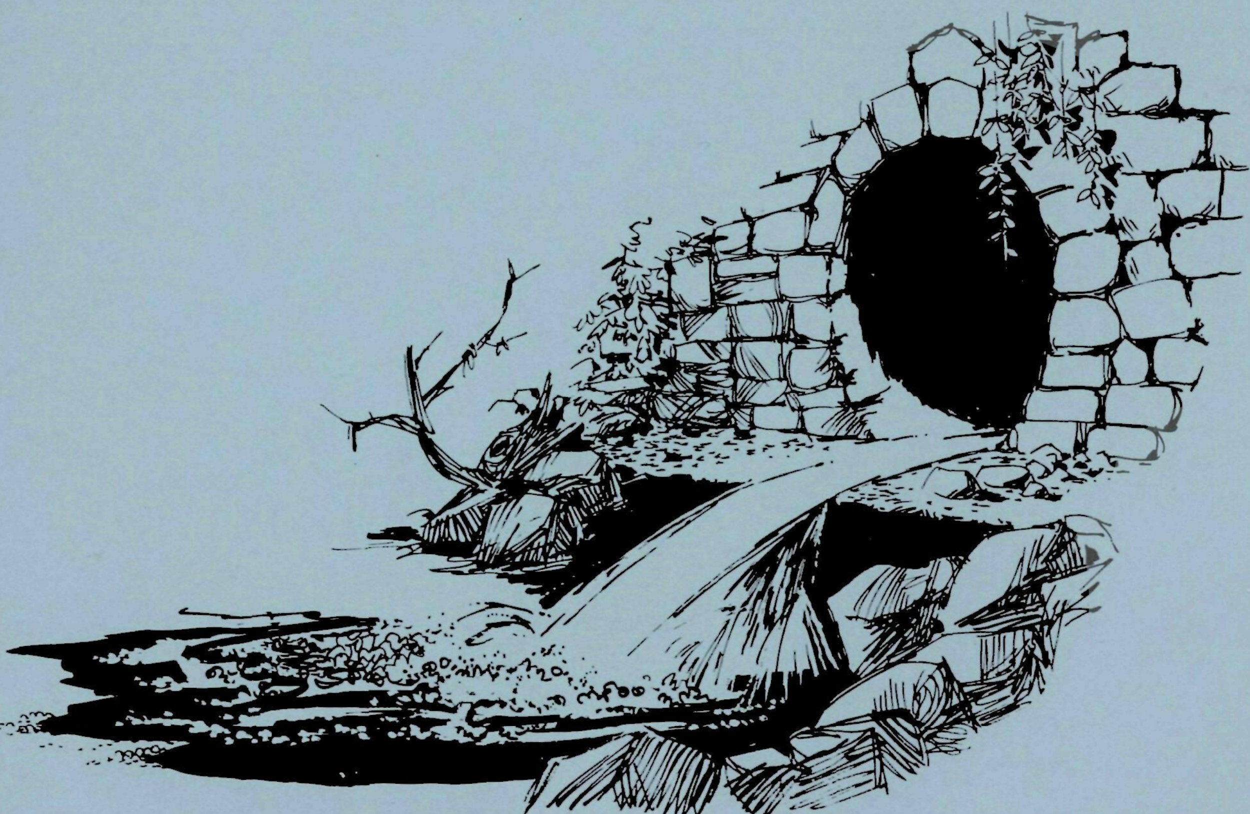
A FLUSHING SYSTEM FOR COMBINED SEWER CLEANSING



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A FLUSHING SYSTEM FOR COMBINED SEWER CLEANSING

by

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for

OFFICE OF RESEARCH AND MONITORING
ENVIRONMENTAL PROTECTION AGENCY

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ABSTRACT

Because solids deposits in lateral sewers are considered to contribute a significant quantity of pollutional material to storm water overflows from combined sewers, the use of a periodic flushing operation was evaluated as a means of maintaining lower levels of these deposited materials during low-flow, dry weather periods.

Full scale tests were conducted on two variable-slope test sewers (12- and 18-inch diameters). During the tests, solids were first allowed to build up in both test sewers by passing domestic sewage through the sewers for durations of 12 to 40 hours and then were removed by hydraulic flushing. The results from the tests showed that flush waves generated using flush volumes ranging from 300 to 900 gallons at average release rates ranging from 200 to 3,000 gpm were found to remove from 20 to 90 percent of the solids deposited in the 800-foot long test sewers.

The cost of installing a periodic flushing system in a typical system of lateral sewers was estimated to be $620 to $1,275 per acre.

This report was submitted in fulfillment of Project Number 11020 DNO, Contract Number 14-12-466 under the sponsorship of Water Quality Research, Environmental Protection Agency.

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SECTION I

CONCLUSIONS

1. Satisfactory predictions can be made of several cleansing efficiencies and wave depths for the flush waves and sewer sizes studied using the formulas developed in this project.

a. The percentage removal (cleansing efficiency) of deposited material by periodic flush waves is dependent on the following variables: flush volume, flush discharge rate, sewer slope, sewer length, sewage flow rate, and sewer diameter.

b. Cleansing efficiency is dependent on flush discharge rate and volume but is not otherwise significantly affected by details of the flush device inlet to the sewer.

c. Slight irregularities in sewer slope and pipe alinement do not significantly affect the percent cleansing efficiency.

d. Use of settled sewage as the flushing liquid causes only a minor and predictable reduction in cleansing efficiency.

2. The mathematical design model developed in this project provides an efficient means of selecting the most economical flushing system to achieve a desired cleansing efficiency within the constraints set by the engineer and limitations of the design equations.

3. Where sewers are over 8 ft deep, tanks inserted in existing manholes will usually provide adequate flush volumes for periodic sewer flushing.

a. The prototype flush station developed in this project can be inserted in a manhole and provides the functions necessary to pick up sewage from the sewer, store it in a coated fabric tank and release the stored sewage as a flush wave upon receipt of an external signal.

4. An estimate of the costs of periodically flushing combined sewer laterals indicated a range of costs from $630 per acre to $1,275 per acre for average removal efficiencies of 61 percent and 72 percent, respectively.

SECTION II

RECOMMENDATIONS

This project has succeeded in developing an engineering basis for periodic sewer flushing of combined sewer laterals within a limited size range. It is recommended that further studies be made for flushing of larger sizes of pipe, of wave sequencing, and of solids buildup over longer time periods. Although some of the additional work can be done in the existing test facility, a demonstration in an operating combined sewer system will be required to verify the relationships developed to date and to extend the range of the correlations.

Some of the more important areas which need further investigation are listed below:

1. Investigate the downstream redeposition of the solids removed by flush waves in the upstream section of the sewer.

2. Experimentally develop the flow hydrograph (wave depth as a function of pipe length and time) associated with the various flush waves investigated during this study and establish a correlation between these hydrographs and the cleansing efficiency relationships.

3. Investigate the effect of multiple flush wave release on the flush wave hydrographs.

4. Study the diurnal deposition and resuspension patterns of various dry weather sewage flows.

SECTION III

INTRODUCTION

BACKGROUND AND PURPOSE

Other studies have shown the need to minimize pollutional effects of stormwater overflows from combined sewer systems. Even though stormwater provides dilution of sanitary waste, Biological Oxygen Demand and suspended solids of the sewage are often very high during storms when flow is typically diverted to natural water courses.

This project attempts to improve the quality of the combined sewage flow as an alternative to retention of storm flow or treatment of the overflow at the outfall. It appears that in many cases the high pollutional load of the combined sewage flow is caused by the flushing out of solids which had settled in the sewer during the low flow of dry weather. The purpose of periodic sewer flushing as applied to combined sewers is to remove settled material during dry weather and hydraulically convey it to the treatment plant. To the degree that this purpose is accomplished the pollutional load of the combined sewage will be reduced. Only that sanitary sewage produced during the storm would have to be bypassed rather than also bypassing a major portion of the sewage solids produced prior to the storm.

PROJECT APPROACH

The program for study of the feasibility of a periodic flushing system for combined sewer cleansing has been divided into the following major phases.

PHASE I - Feasibility Study, Planning, and Preliminary Facility Design. This phase was funded under FWPCA Contract No. 14-12-19 completed in 1967. On the basis of literature review, field surveys, and limited experimental work, there was a strong indication of the feasibility of this technique.

PHASE II - Flushing Evaluation. This phase was funded under FWQA Contract No. 14-12-466 and is the subject of this report. This phase includes preparation of a test facility, hydraulic experiments, and prototype equipment.

PHASE III - Demonstration in a Combined Sewer System. This phase will be required to show the application of periodic flushing techniques and their effect on the discharge from a portion of a combined sewer system.

OBJECTIVES OF PHASE II

The objectives of this phase are:

- To experimentally determine the hydraulic requirements for effective cleansing of combined sewer laterals and to formulate design rules and criteria for application of periodic flushing equipment to existing combined sewer systems;

- To develop a prototype of a unit-flushing-station which would be applicable for demonstration of periodic flushing in a combined sewer system; and

- To expedite and promote arrangements for a demonstration as Phase III of this program of periodic flushing of laterals in a combined sewer system.

SCOPE OF PHASE II

This step of the project provided for preparation of a test facility, conduct of flushing experiments, evaluation of experimental results, and development of a mathematical design model for application of flushing equipment to combined sewer systems.

Test Facility

The scope of the experimental study was limited to combined sewer laterals of low slope with low sanitary sewage flow. Accordingly, the test facility required only two sizes of pipe with a moderate length and limited slope capability. The flush tank sizes were limited to a volume thought to be practical in an actual system. Means were provided for supply of sanitary sewage to the test pipes for solids deposition purposes.

Flushing Experiments

The basic philosophy of the flushing experiments was to provide the information for an engineering application of flushing. Therefore, the scope of the experiments was limited to a measurement of what flowed into the sewer prior to flushing, the flushing conditions, what was removed by flushing and what remained that could be removed by a simulated storm flow.

Such subjects as a complete description of deposition from sanitary sewage flow, of the flush wave hydraulic patterns, and of the interaction of the flush wave and the sediment layer, and of the effects on main and trunk sewers are not included in the scope of the flushing experiments.

Evaluation of Experimental Results

The relationships between the experimental variables were to be estimated using appropriate statistical techniques.

Formulate Mathematical Model

The mathematical model was to be developed for design purposes. It was not to be a general mathematical description of the sewer system nor extend beyond the laterals. The model was to predict performance of flush tanks applied to sewer laterals based on the experimental results.

Development of Prototype Flush Station

This step includes study of conceptual designs of flushing equipment and design construction and testing of one type of flush station which is expected to be needed for a flushing demonstration.

Arrangement for a Flushing Demonstration

This step provided for furnishing information needed to plan a periodic flushing demonstration for Hammond, Indiana, and for promoting that demonstration. It also provided for canvassing up to four other potential demonstration locations in the event that Hammond decided not to apply for a demonstration grant.

SECTION IV

DESIGN AND CONSTRUCTION OF THE TEST FACILITY

DESIGN OBJECTIVES AND APPROACH

The overall objective of this phase of the project was to design and construct a test facility that could be effectively used to determine the requirements and limitations associated with the hydraulic cleaning of combined sewers. The primary objective of the project was to study the cleansing of lateral sewers with mild slopes. As a result, the design of the facility was limited to relatively small diameter pipes and slopes between 0.001 and 0.01.

The fact that pipe diameter and pipe slope were considered to be of primary importance in the experimental work of this project greatly influenced the overall design of the facility. A minimum of two diameters of pipe had to be included to allow an effective comparison of pipe diameter effects. The 12 in. and 18 in. diameters were selected because they were representative of the range of small diameter sewers (8 to 24 in.). Establishment of the relative influence of pipe slope on the cleaning process required that the design allow for independent slope adjustment of the two sewers, with a minimum of effort.

Since the primary concern of the proposed experimental work was with solids deposited by sewage flowing through the sewers, the design had to include a complete sewage supply and control system. Also reliable sampling systems were needed so that the quality of the influent to test sewers as well as the discharge from each pipe could be accurately evaluated.

Hydraulically cleaning the sewers required that flush equipment capable of supplying known quantities of flush liquid at various rates to different points along the length of each sewer be included in the facility. Also the design had to include a system capable of separately cleaning individual sections of each test sewer to a consistent degree, in order to provide a constant reference for comparing the effectiveness of the various flush combinations and to establish the influence of pipe length on the cleansing process.

The objectives and requirements discussed above were combined with the economic and test site limitations of the project to produce a facility designed to meet the experimental needs of the project. A detailed description of the facility is given later in this next section.

PROBLEMS ENCOUNTERED

There were several problems encountered during the design and construction phases of this project which would be helpful to know about if another facility of this type is ever constructed. Most of the problems encountered during the mechanical design phase were satisfactorily solved and can be avoided by using the general arrangement described later in this section. Although the problems encountered during the construction phase were not too serious, several of them caused unexpected delays.

The problem that caused the most concern was the result of the high length tolerances of the vitrified clay sewer pipe. Despite careful grading of the pipe purchased, the effective length of the 18 in. section varied from near nominal to as much as 3 in. over nominal and the 12 in. section varied from slightly longer than nominal to as much as 2 in. less that nominal. As a result of these high tolerances, several special sections of pipe had to be cut to compensate for the buildup of tolerances.

Another problem that developed during the construction of the facility resulted from the fact that the outside diameter of the clay sewer pipe varied somewhat and many of the pieces were not round. This caused unexpected problems with the joints where the clay pipe was to be coupled to simulated manholes which were made of steel.

The fact that the clay sewer pipe is quite brittle also caused some problems. Two sections of pipe were cracked slightly when they were installed and the cracks were not apparent until after the installation was completed and water was run through the pipe. These cracked sections, which were near the center of the pipe span, had to be replaced, which was found to be a very difficult operation. The probability of this problem occurring undetected can be reduced by running water through the pipe periodically when it is being installed.

TEST FACILITY DESCRIPTION

The test facility combines two variable-slope test sewers with accurate and flexible influent quantity and quality control and complete effluent sampling and handling capabilities. The facility also includes a flush system that allows controlled induction of water or sewage at numerous points along the length of the test sewers. Figures 1 and 2 show the relative size and general arrangement of the overall test facility. A complete description of the mechanical design of the facility is given in the as-built drawings that are listed by number in Appendix E.

Variable-Slope Test Sewers

The pipeline assembly (see Figures 1 and 2) consists of two pipes that run parallel to each other. Each pipe is supported along its entire length by an I-beam. Attached to the top of each beam is a series of pipe saddles in which the pipe rests. The two I-beams are suspended between the legs of fabricated steel frames by means of long screws. Each beam spans the distance between two consecutive frames and is connected to the next beam by means of a single pin, making the connection flexible in the vertical direction. The screws which support the beams are attached to the top of the steel frames in such a manner as to allow the screws to be used to adjust the vertical heights of the beams. The two pipe lines are separately supported and their slopes can be independently adjusted.

Between the two pipelines, a wooden catwalk runs the entire length of the pipeline assembly. The walk is supported by the I-beam which supports the larger of the two test pipes. Since the position of the catwalk and the test pipes remains relatively constant, it provides easy access to the test pipes at all heights.

The test sewers are constructed of 12 in. and 18 in. clay sewer pipe. Each line is approximately 800 ft. long and consists of about 620 ft. on a straight-run and 180 ft. on a curve. (Approximately 300 ft. of straight run is upstream of the curve and the remainder downstream.) At the beginning and at the third point along each pipeline, there are fabricated steel sections that simulate manholes. In every 18 ft. section of pipe, with the exception of the curved section, there is one tee with a 12 in. side outlet this is positioned vertically to allow visual observation of flow in the pipeline. Also, a section of clear plastic pipe (6 ft. long in the 18 in. sewer and 5 ft. long in the 12 in. sewer) was used to replace a section of clay pipe in both test sewers to allow more extensive visual observation of the flow in the pipes (See Figure 3). These plastic sections have the same inside diameter as the clay pipe and are presently located approximately 140 ft. downstream of the influent end of the sewers.

The test pipes can readily be adjusted to virtually any slope desired between the limits of 0 and 0.01. Slope changes are accomplished by adjusting the screws which support the pipe at each support frame. The adjustment of the screws is easily accomplished through use of an air driven wrench. This system allows complete slope changes to be made in a matter of only a few hours.

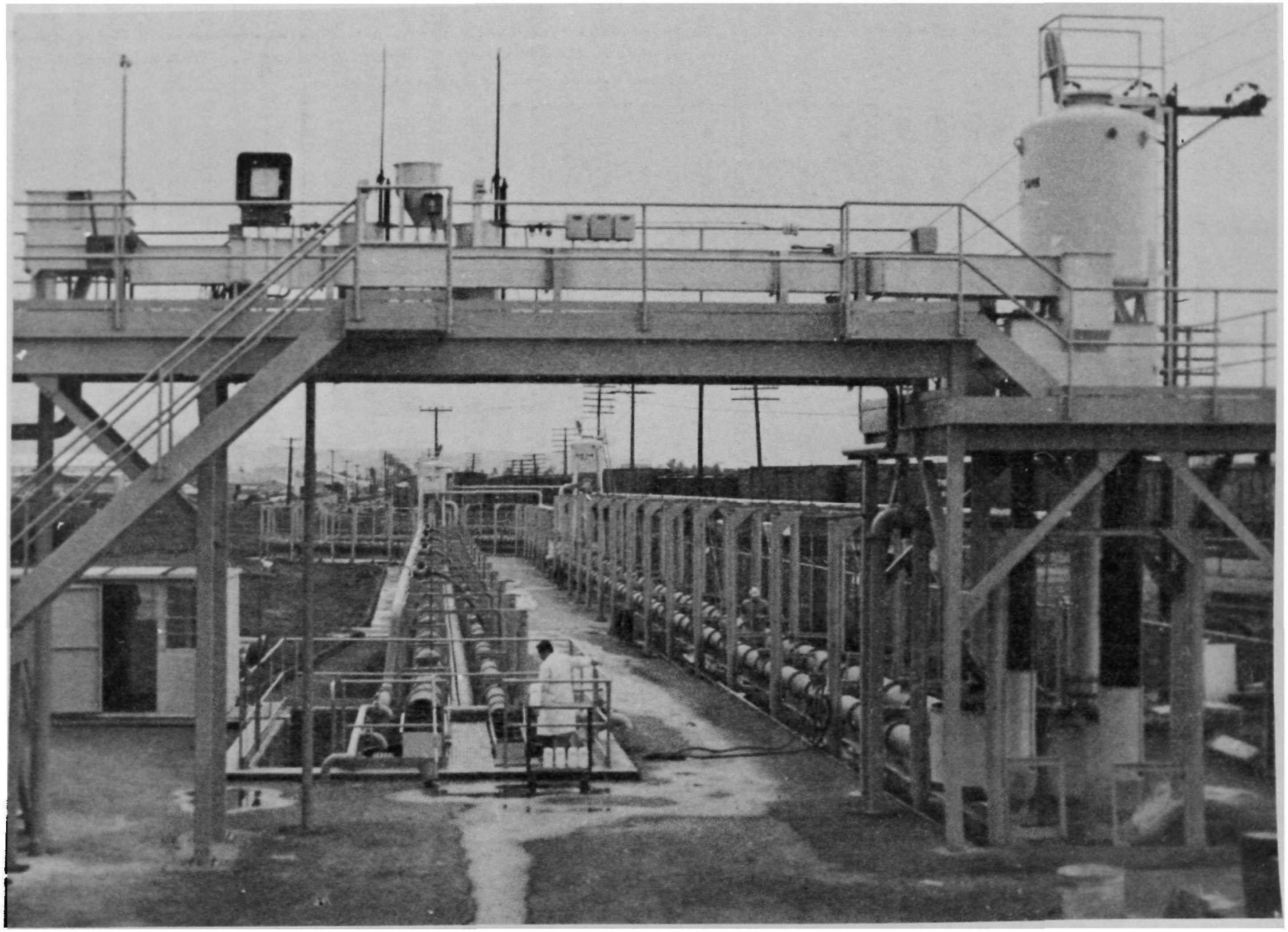


Figure 1 PERIODIC SEWER FLUSHING TEST FACILITY

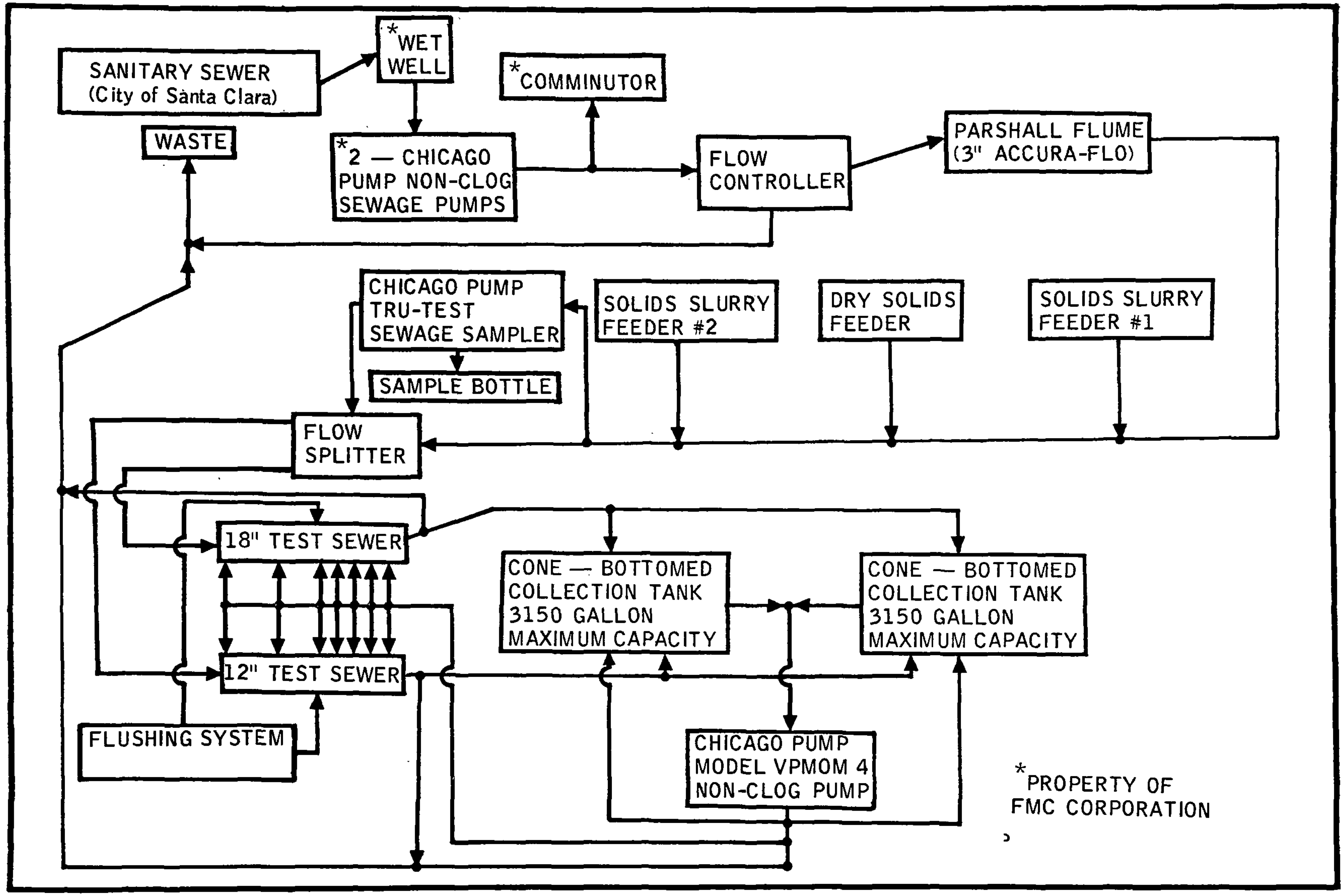


Figure 2 FLUSHING EVALUATION FLOW DIAGRAM

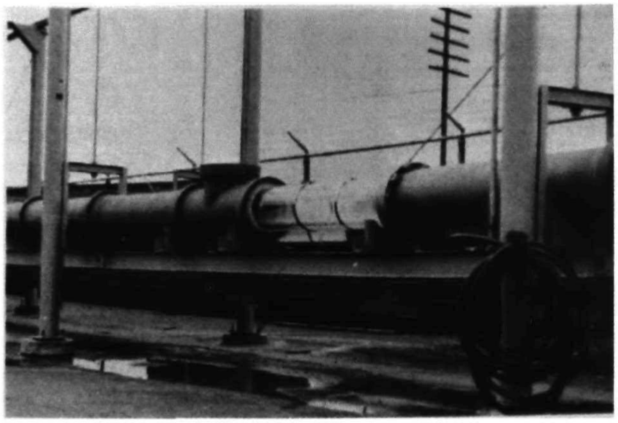


Figure 3 CLEAR PLASTIC PIPE SECTION IN 12 IN. SEWER

Influent Supply and Control

The sewage supplied to the Flushing Evaluation Facility is taken from an 18 in. sewer line that belongs to the City of Santa Clara, California. The sewage is transported by gravity through a 12 in. clay sewer line into a wet well at the bottom of a concrete pump pit. The sewage is then pumped from the wet well through a 6 in. C.I. line by means of one or both of two nonclog pumps, to a point where the flow is divided and part of the flow is diverted to other FMC experimental projects. The flow not diverted to the other projects passes through a 6 in. pressure line to the beginning of the Flushing Evaluation Facility.

The influent supply and control system of the test facility is shown in Figure 4. The influent enters first a flow control box where the portion of flow desired for testing is diverted into a 10 in. wide fabricated steel flume. The portion of flow not needed for testing is wasted back to the city sewer. The influent passes from the 10 in. flume through a 3 in. Parshall flume where the rate of flow is recorded and controlled by a float-activated flow meter and pneumatic controller. The flow through the Parshall flume is recorded on a single pen, 24 hr. circular chart. The pneumatic controller can be manually set for a desired flow rate, which can be adjusted by the operator at any given time.

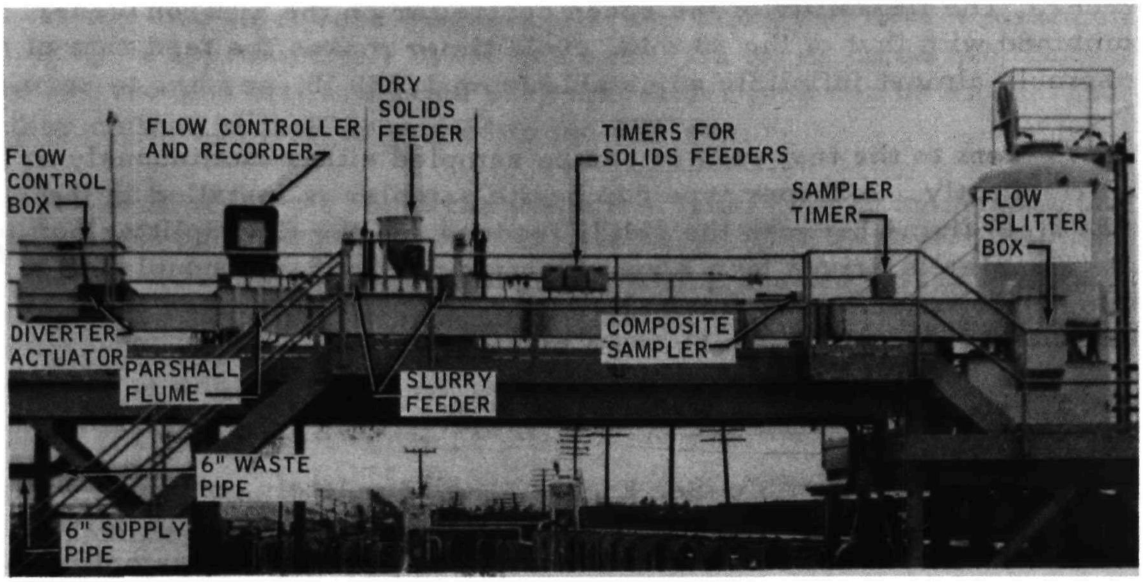


Figure 4 INFLUENT SUPPLY AND CONTROL SYSTEM

The controller continuously compares the actual flow as measured by the flow meter with the value set by the operator and corrects for any difference by sending the proper pneumatic signal to the pneumatic lever motor, which actuates and corrects the position of the flow diverter.

The effluent from the Parshall flume passes through approximately 19 ft. of fabricated steel flume 7 in. wide and approximately 6 ft. of flume 18 in. wide, all on a slope of 0.67 percent, to a fabricated steel splitter box where the total test flow is divided between the two test pipes. The splitter is manually operated and is capable of dividing the total flow into any two proportions desired.

The quality of the influent to the test facility can be altered by the addition of foreign materials such as sludge, paper, etc. Solids in the form of slurries can be added to the influent by use of one or both of the two available solids feeders (See Figure 2). These feeders each consist of a 40 gal. steel fabricated circular storage tank and a vertically acting dipper, actuated by a single solenoid air cylinder. The maximum feed rate of each of these feeders is more than 6.0 lb. per min. The 30-min. timer gives the feeder almost infinite feed rate control.

Dry solids such as sand and gravel, can be added to the influent by means of the dry solids feeder assembly. This assembly consists of a 20 gal. cone-bottomed hopper that discharges into a Syntron vibratory feeder. The flexibility of the speed controller on the Syntron feeder combined with that of the 30 min. cycle timer makes the feed rate of the assembly almost infinitely adjustable from 1,250 lb. per hr. to zero.

The influent to the test sewers can be sampled either continuously or intermittently. A dipper type composite sampler is installed in the 7 in. wide steel flume between the solids feeders and the flow splitter box. The sampler is driven by a 2 rpm electric motor that is coupled to a 30 min. cycle timer. The timer allows the sampling frequency to be adjusted from a low of 1 per hr. to a maximum of 120 per hr.

Effluent Handling Equipment

The catch basin assembly (See Figure 5) is completely contained within a concrete pit 14 ft. wide, 24 ft. long, and 12 ft. deep. This portion of the test facility was specifically designed for handling and sampling the effluent from the test pipes.

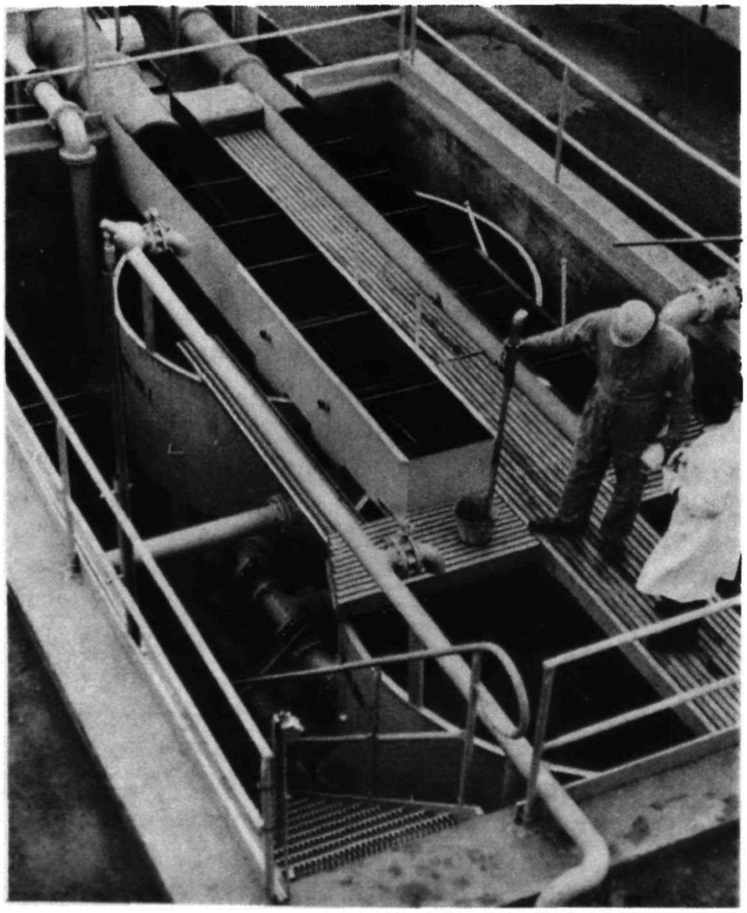


Figure 5 EFFLUENT COLLECTION AND RECIRCULATION SYSTEM

There are two steel cone-bottom collection tanks that have a maximum capacity of approximately 3,150 gal. each. On top of these two tanks are two troughs that are gated such that either pipe can be discharged to either collection tank or wasted to the city sewer.

On the floor of the pit below the collection tanks is a 20 hp nonclog pump designed to pump 800 gpm at a total discharge head of 67 ft. The pump is incorporated into a 6 in. piping and valving system that is designed to perform the following three separate tasks:

1. The pump can be used to pump the contents of either or both collection tank(s) to the city sewer by way of an 8 in. waste sewer.

2. It can also be used to hydraulically mix the contents of either tank by rapid recirculation. The contents of the tank can be circulated by pumping from the top and into the bottom or vice versa.

3. The contents of either or both tanks can also be pumped to any one of seven possible locations along the test sewers and discharged into either test pipe at each location. This arrangement makes possible continuous recirculation of effluent from either test pipe.

Flushing System

Experimental flushing operations can utilize any one or all of three available elevated flush tanks (Figure 6). The flush tanks are constructed of steel and are designed such that they can be pressurized up to 20 psig. The primary flush tank is the largest, 5 ft in diameter and 6 ft high with a capacity of 900 gal., and is located at the influent end of the test pipes. The other two tanks are also 5 ft in diameter, but only 5 ft in height. One of the smaller tanks is located approximately 1/3 of the total distance downstream from the primary tank and the other 2/3 of the way. All three of the tanks are elevated above the test pipes allowing gravity flushing.

The release of water from each flush tank is controlled by a 12 in. and an 18 in. butterfly valve. The 12 in. valve is installed in a 12 in. steel pipe which runs down from the flush tank and discharges into the larger test pipe. The 8 in. valve is installed in an 8 in. line which runs down from the flush tank and discharges into the smaller test pipe.

The flush control valves are actuated by double-acting air cylinders equipped with pneumatic positioners. The flush control valves can be actuated either manually or automatically. The controls used for manual and automatic control of the valves are located on the instrument panel in the control building located near the catch basin (see Figure 7).

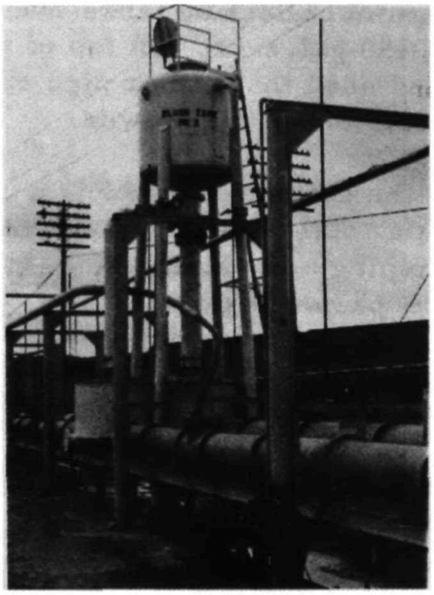


Figure 6 FLUSH TANK WITH PNEUMATICALLY CONTROLLED DISCHARGE VALVES

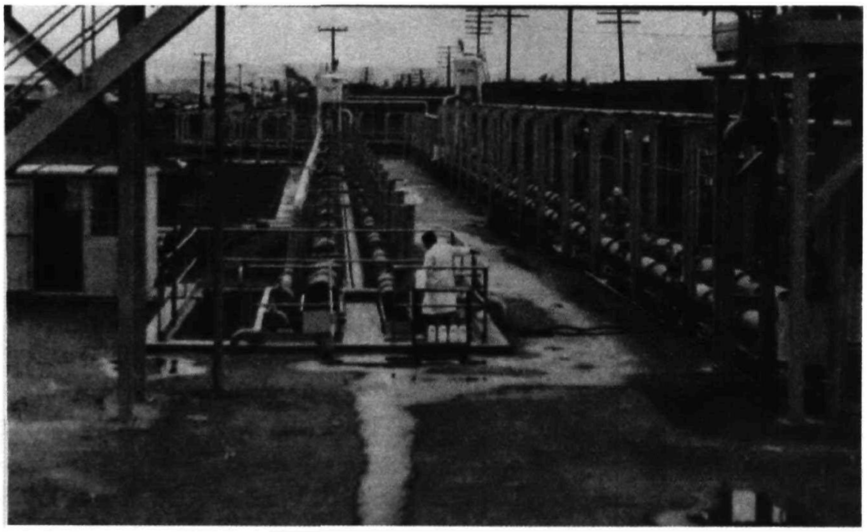


Figure 7 FLUSH CONTROL BUILDING

The valves are operated manually by opening the control line to the desired flush valve and transmitting a pneumatic signal to it by means of a pressure regulator. The control valve is completely closed when the pneumatic signal is 3 psig, and completely open when the signal is 15 psig. The percentage change in the signal is directly proportional to the percentage change in valve opening. The control valves at each tank can be manually operated independently of those at the other tanks. The 8 in. and 12 in. valves at each tank can be operated independently only if they are operated at different times. If both valves are to be operated simultaneously, they must be operated using the same pneumatic signal.

All of the flush control valves can be automatically controlled by means of a circular cam programmer. This programmer is electrically driven at one revolution per 8 min. and produces a pneumatic signal which is used as the set point for a pneumatic controller, which continuously adjusts the valve being used to obtain the liquid level desired. The water level in each tank is continuously monitored by a differential pressure transmitter with a fixed operating range of 0 to 100 in. of water. The transmitter receives the difference in pressures between the bottom and top of the flush tank (water level) and converts this pressure to a pneumatic signal (3 to 15 psig) which is transmitted to the pneumatic recorder and controller.

The 8 in. and 12 in. control valves at the flush tanks can be automatically operated independently or simultaneously. However, only those valves that are to be operated under the same control sequence can be operated simultaneously. If the control sequence is different for different valves, each of these valves must be operated separately.

The recorder that receives the signal from the transmitter is a three-pen (one for each tank), strip-chart-type pneumatic recorder. The recorder continuously monitors the liquid level in all three flush tanks. The signal received by the controller is the actual liquid level in the flush tank and is compared by the controller with the desired liquid level as indicated by the cam programmer. If a difference in the actual and desired liquid levels is present, the controller pneumatically adjusts the valve to compensate for the difference.

SECTION V

EXPERIMENTAL OPERATION

SHAKEDOWN AND PRELIMINARY TESTING

The 2-week period immediately following completion of the construction of the experimental equipment was used to ready the facility for full-scale testing. During this period, the experimental equipment was operated and adjusted for proper function and the tentative test procedures were checked experimentally to establish their reliability.

Equipment Check

The sewage supply equipment was checked for proper operation and accuracy. This was accomplished by collecting the total discharge from the test sewers in the calibrated collection tanks and recording the actual flow rate and fluctuation in flow rate as indicated by the time-rate-of-change of the volume of effluent collected. The flow rate recorded by the influent flow recorder was found to correlate satisfactorily (within 3 percent) over the expected operating flow range of 10 gpm to 100 gpm. The flow controller, after minor adjustments were made, was found to be capable of maintaining constant rates of flow, in the above range, with only minor fluctuations of extremely short duration. The flow splitter was checked and found to be capable of dividing the flow between the two test sewers within $\pm$ 1 percent of the desired proportions.

The flush control system was adjusted to obtain constant discharge rates and the tank level recorder was calibrated. These adjustments were accomplished by making numerous flush releases using total flush volumes ranging from 200 to 900 gal. The accuracy of the tank level recorder was checked by direct measurement of the tank volume and level and found to be satisfactory ($\pm$ 0.5 percent over the given range). The discharge rate was verified using the calibrated tank level recorder.

The solids feeders were adjusted and feed rate of each established. The dry solids feeder was operated using uniformly-graded clean sand and the maximum feed rate was found to be approximately 1,250 lb. per hr. for continuous operation. The slurry feeders were operated using a water-paper mixture and their maximum feed rates were found to be approximately 6.7 lb. per min. Note should be taken that although these solids feeders were installed and calibrated, the suspended solids content of the influent sewage remained consistently high throughout the testing and therefore they were not required during any of the actual experimental work.

Friction Coefficient Evaluation

The two test sewers were adjusted to the slope values (0.001 for the 18 in. sewer and 0.002 for the 12 in. sewer) selected as the minimums to be used in the proposed testing program, and a series of basic hydraulic tests was run using clean water. This test series had two objectives. The first was to check the actual discharge of the 20 hp recirculation pump at various discharge heads and the second was to experimentally check the flow characteristics of the clean sewers. The recirculation pump was used to pump clean water at various constant rates to the up-stream end of the test sewers and the depth of the flow and corresponding average discharge rate were recorded for each sewer. The measurements of the depth of the flow were made using a graduated depth gate at several different points along each sewer. The average discharge rate was determined by collecting 2,850 gal. of the discharge from each test sewer in the effluent collection tanks and recording the total elapsed time.

The results from the above tests (see Table 3, Appendix A) indicated that the performance of the recirculation pump closely followed the published performance curve, and that the Manning's-n values for the clean sewers ranged from 0.008 to 0.0135. The Manning's-n values were generated by solving Manning's Equation (Equation 1) for n using the experimentally determined flow rate and flow-depth data.

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

Where:

- Q is the average discharge in cubic ft. per sec.
- n is the empirically determined friction coefficient,
- S is the slope of the pipe in ft. per ft.,
- R is the hydraulic radius in ft.
- A is the cross-sectional area in sq. ft.

Although the tests were not precise enough to be all conclusive, the values obtained show good correlation with those usually used for clean vitrified clay pipe.

Effluent Mixing Evaluation

Several tests were conducted to establish the overall efficiency and reliability of the proposed effluent mixing and sampling procedures. The reliability of these procedures depend almost exclusively on the ability of the hydraulic mixing process to produce a mixture which very closely approximates a homogeneous mixture, without significant modifications in the characteristics of the particulate matter present.

The circulation patterns developed by the mixing process were visually evaluated by mixing various volumes of clean water (1,200 to 2,850 gal.) and introducing small amounts of Methylene Blue at several different points in the collection tank. In all cases, the circulation patterns appeared to be uniform throughout the tank and appeared to produce complete dispersion of the dye within one complete volume displacement.

The homogeneity of the mixture produced by the mixing process was checked by mixing given volumes of water containing known quantities of the fine sand, taking depth integrated grab samples after various mixing times, and analyzing these samples for suspended solids concentration. The results of these tests (Table 5, Appendix A) show that the suspended solids concentrations of the grab samples taken after one and two volume displacements were consistently within 2 percent of the expected values.

These results indicate that the mixing required for representative sampling is accomplished by the recirculation operation when mixing times that are equivalent to one or more volume displacements are used.

The character of the particulate matter presented in sewage was found not to be significantly altered by the mixing process. Several quantities of sewage of known suspended solids concentrations were placed in the collection tanks and mixed continuously for one and two complete volume displacements. In each case, the suspended solids concentrations of the samples taken after mixing were consistently within 5 percent of the suspended solids concentration of the composite sample taken before the sewage was mixed (see Table 4, Appendix A).

Sand Transport Test

The distribution of solids deposits along the length of the two test sewers was visually evaluated. This was accomplished by using the dry solids feeder to add approximately 200 ppm of uniformly graded fine sand to clean water passing through the 18 in. and 12 in. test sewers at 50 gal. per min. and 30 gal. per min., respectively, and observing the resulting deposits of sand at various points along the sewer.

More than 50 percent of the sand appeared to settle out in the first 100 to 150 ft, of the pipe. Significant quantities of sand could be resuspended and transported only by flush waves generated by flush releases of 300 gal. or more at flush rates of 500 gpm and greater. The amount of sand resuspended appeared to be more dependent upon the rate of flush release than on the volume of release, whereas the distance the sand was carried after resuspension appeared to depend more on the volume of the flush release.

Preliminary Flushing Evaluation Tests

Several preliminary flush tests were run to establish a realistic and workable plan of attack. During the first few of these tests, no sewage was used. Instead, clean water was used and the general characteristics of flush waves generated by various combinations of volume and rate of release were observed. Also, the time required for completion of the various testing operations was established to allow better time planning for future testing.

The second portion of these preliminary tests was run using sewage and in accordance with the preconceived test operational methods. Although data was gathered during these tests, it was not used in the final evaluation due to procedural errors and changes made during this learning phase. These tests served to increase the efficiency and reliability of the final test procedures, which will be described in the following section.

TEST PROCEDURES

The experimental work performed during the course of this project was designed and organized to empirically define the physical limitations and requirements associated with hydraulic cleansing of small sewers. The major portion of the work was directed at defining the relative influence of the various experimental parameters (flush rate, flush volume, pipe diameter, pipe slope, pipe length, and sewage base flow) on the efficiency of the cleansing process, with physical conditions such as pipe alinement and slope uniformity optimized. The remainder of the experimentation attempted to evaluate the changes in the cleansing efficiency when the various physical conditions were somewhat less than optimum.

The overall testing plan consisted of eight general groups of tests. Although each of the test groups had different objectives, all of them were operated in the same basic manner. The following discussion will first describe the general operational procedures common to most of the tests, and then discuss in more detail the specific operation of each of the groups of tests.

Basic Operation

Solids Buildup. The first step in nearly all of the tests run during this project was to build up solids in the test sewers. This was accomplished by adjusting the influent flow controller to maintain a constant flow rate, usually between 40 and 60 gpm, and setting the flow splitter to attain the desired apportionment of the total flow between the two test sewers. The selected sewage base flow was then allowed to continue flowing through the sewers for a specific length of time and was continuously sampled by the composite sewage sampler before entering the sewers. No solids were externally added to the sewage since the solids content in the sewage remained high enough for adequate solids buildup. This also avoided difficulty associated with correlating the quantity and quality of solids added to actual field conditions. The solids buildup periods usually extended from early afternoon until early the following morning, giving average durations of between 12 and 20 hrs. However, approximately one-fifth of these buildup periods extended over weekends and therefore had correspondingly longer duration times. Not in all cases was the sewage base flow held constant throughout the buildup period. This inconsistency resulted from the fact that during the early morning hours, the supply of domestic sewage was often not sufficient to maintain the flows desired and the flow would cease. When this stoppage of flow occurred, the duration time was taken as the time during which the sewage was actually flowing, based on the records from the flow recorder.

Pretest Preparation. Before the flush waves were released, several pretest operations were performed. First the sewage flow recorder chart was checked for any indication of abnormal flow conditions. Thus, if the solids buildup flow discontinuities were not excessive, the depth of the sewage base flow was measured and the general appearance and quantity of the solids deposited was recorded at several points along the length of each of the test sewers.

The maximum depth of the flush waves generated by the various combinations of the test variables was measured at several positions along each sewer. This was accomplished by inserting quarter-inch diameter steel rods, coated with a paste-type water level indicator, into the upturned tees at approximately 60 ft. intervals before release of the flush wave. Then after the flush waves had passed all of the stations, the rods were individually removed and maximum wave depth recorded by measuring the maximum depth shown by the water-level indicator. The accuracy of these measurements is estimated to be within $\pm$ 1/4 in.; with the majority of the reading being slightly higher than the actual depth.

Flush Release. The flush release, when included in the test, was made immediately after the end of the solids buildup period. A given quantity of flush liquid, usually 300 to 900 gals. was placed in the primary flush tank located at the upstream end of the test sewers. Then the sewage base flow to the 12 in. test sewer was shut off and at the same instant the flush release was made to the 12 in. sewer. Then the flush tank was refilled and the above process repeated for the 18 in. sewer. When the first appearance of the flush wave, indicated by an increase in depth of flow, was observed at the effluent end of the sewers, the discharge was diverted from waste to one of the cone-bottomed collection tanks (one for each sewer).

After collecting the complete flush discharges, the contents of tanks were individually mixed, using the hydraulic mixing process previously discussed, and samples of each taken for laboratory analysis. Also the total volume of each flush discharge was recorded by reading the corresponding tank-level indicator. When the flush volumes being investigated were small, clean water was added to the collection tanks before they were mixed, in order to allow use of the recirculation mixing process.

Storm Simulation. The storm simulation step was the final cleansing which the test sewers received in all of the tests. The flow rate used was in all cases approximately 1,000 gpm, the maximum allowed by the pumping system, and was designed to clean the sewer to the highest degree possible.

The first section of the 12 in. sewer was cleaned by pumping clean water from one of the cone-bottomed collection tanks to a point approximately 160 ft from the downstream end and collecting the total discharge from the sewer in the remaining collection tank, where it was mixed and sampled. The tank containing the discharge from the sewer was emptied and cleaned, and the other tank was again filled with clean water. Then the process was repeated for the downstream 160 ft of 18 in. sewer.

After cleaning the first 160 ft downstream section of each test sewer, in the manner described above, the flow induction point was moved upstream another 108 ft and the next 108 ft section of each sewer was likewise cleaned. Then the flow induction point was moved upstream another 260 ft along the 18 in. sewer and 247 ft along the 12 in. sewer and the next corresponding sections of each sewer cleaned. Finally the flow induction point was moved to the upstream end of each of the sewers and the last or upstream 267 ft section of each pipe cleaned.

Solids Distribution Tests

The purpose of this group of tests was to establish the relative distribution of the solids along the length of the test sewers as deposited by the various sewage base flows. These tests were generally conducted as described in basic operation section above, except that no flush release was made. Instead, the test sewers were cleaned using only the storm simulation process.

At the minimum slope values of 0.001 for the 18 in. sewer and 0.002 for the 12 in. sewer, a total of six tests were run on each sewer. Two tests were run for each of the sewage base flows of 10, 30, and 50 gpm for the 18 in. sewer and 10, 20, and 30 gpm for the 12 in. sewer.

At the slopes of 0.002 and 0.004 for the 18 and 12 in. sewers, respectively, a total of four tests were run on each pipe. Two tests were run for each of base sewage flows of 10 and 30 gpm for the 12 in. sewer and 10 and 50 gpm for the 18 in. sewer.

A total of six tests were run on each pipe when the two test sewers were at slopes of 0.004 (18 in.) and 0.006 (12 in.). Three tests were run for each of the sewage base flows of 10 and 30 gpm for the 12 in. sewer and 10 and 50 gpm for the 18 in. sewer.

Two tests were run on the 12 in. sewer at a slope of 0.008. The base sewage flows used were 10 and 30 gpm.

Clean-Water Flush Tests

The clean-water flush tests were run to determine the relative influence of pipe diameter, pipe slope, sewage base flow, pipe length, flush volume, and flush rate on the ability to clean sewers hydraulically. These tests were all operated as described in the basic operation previously, using clean water as the flush liquid.

A total of 72 tests were run on each sewer. At the minimum slope values of 0.001 for the 18 in. sewer and 0.002 for the 12 in. sewer, a total of 45 tests were run. During these tests, the cleansing of the 12 in. sewer was related to flush volumes of 300, 600, and 900 gal., each of which were combined with three different flush rates ranging from 300 to 2,000 gpm. The effective cleansing of each of these combinations of flush rate and flush volume was evaluated at base sewage flows of 10, 20, and 30 gpm. The 18 in. sewer was tested in the same manner, except that the flush rates ranged from 200 to 3,000 gpm and the sewage base flows tested were 10, 30, and 50 gpm.

The remaining 27 tests were run at slopes greater than the minimum. Twenty-three tests were run on both pipes, 12 at slopes of 0.002 for the 18 in. sewer and 0.004 for the 12 in. sewer and 11 at slopes of 0.004 for the 18 in. sewer and 0.006 for the 12-in. sewer. Four tests were run at a slope of 0.008 on the 12 in. sewer only, as a steep-slope check of the empirical relationships developed from the results of the tests run at the lower slopes. In all of these tests, the relative cleansing of flush waves generated by flush volumes of 300 and 900 gal. each released at a high and a low flush rate (200 to 3,000 gpm) were evaluated with sewage base flow of 10 and 30 gpm in the 12 in. sewer and 10 and 50 gpm in the 18 in. sewer.

Sewage-Flush Correlation Tests

The purpose of this group of tests was to determine if using sewage in place of clean water affected significantly the cleansing ability of various flush waves and if so, to empirically define the effect. In general, the operation of these tests was the same as that used in the clean water tests previously described, with the only difference being that strained sewage, with known solids content was used as the flush liquid instead of clean water. All of these tests were run at slopes of 0.002 and 0.004 for the 18 in. and 12 in. sewers, respectively.

The sewage used as the flush liquid was strained because the sewage used in actual practice will need to be strained to allow reliable handling by passing raw sewage through a 1/4 in. mesh screen. The strained sewage was collected in one of the cone-bottomed collection tanks, where it was mixed and sampled for laboratory analysis. The mixed sewage was then pumped to the primary or upstream flush tank and was used in the tests in the same manner as the clean water previously used.

A total of eleven tests were run during this phase of the experimentation. This number is higher than was originally anticipated. The increase resulted from the fact that the results from the first few tests indicated a decrease in the efficiency of the cleansing processes when sewage was used for flushing as opposed to when clean water was used. Therefore, extra tests were run to establish the relative magnitude of the difference.

Flush Wave Sequencing Tests

The purpose of this group of tests was to determine the effect that the time-sequencing of multiple flush waves has on the efficiency of the flushing operation. The general operation of these tests followed the basic operation procedures outlined previously with one exception.

Instead of making one flush release at the upstream end of the sewers, as done in previous testing, up to three separate releases were made from three different locations along the test sewers and the sequential ordering and timing of these releases were varied.

A total of 10 tests were run on each sewer. All of these tests were run at slopes of 0.002 and 0.004 and sewage base flows of 50 gpm and 10 gpm for the 18 in. and 12 in. sewers, respectively. The first six tests were run by placing 300 gal. of clean water in each of the three flush tanks (one at the upstream end and the other two at approximately 260 ft intervals downstream) and varying the rate and the relative sequence of release. Two tests, one using a low rate of release (less than 1,000 gpm) and one using a higher rate of release (greater than 1,000 gpm) were run at each of the following three timing sequences:

1. The flush volumes were released independently beginning with the flush tank nearest the downstream end of the sewer (Tank Number 3) and were timed so that each of the three flush waves generated passed through the sewers independently.

2. The flush release at the upstream end of the sewer (Flush Tank Number 1) was made first. The flush release at the next downstream flush tank (Tank Number 2) was then released when the maximum depth of the flush wave generated by the first release was observed at this location. Then the third release was made from the flush tank located nearest the downstream end of the sewer (Tank Number 3) when the flush wave generated by the two previous releases was observed to be at its maximum depth at this location.

3. The release from the upstream tank (Tank Number 1) was made first and the wave allowed to pass completely through the sewers. Then the other two releases were made in the same manner beginning with the next downstream tank (Tank Number 2).

The four remaining tests were all run using the same timing sequence. Each release was made when the flush wave generated upstream reached its maximum depth at the respective induction point. In one of the tests, an average release rate of 1,450 gpm was used to release 900 gal. of flush liquid from the upstream flush tank (Tank Number 1) and 300 gal. from each of the other two tanks. Three tests were run using only two of the flush tanks. Release rates ranging from 200 gpm to 1,600 gpm were used to release 600 gal. of flush liquid from the upstream flush tank (Tank Number 1) and 300 gal. from the downstream flush tank (Tank Number 3).

Flow Obstruction Tests

This group of tests was designed to study the overall effect of various flow obstructions on the efficiency of the flushing operation. The flow obstructions studied included manhole channel covers, service connections, pipe misalinements, and slope discontinuities.

The effects of manhole-channel covers and service connections were not evaluated by means of tests specifically designed for this purpose. Instead, the effects of these discontinuities were qualitatively estimated based on the observed flow characteristics of the various flush waves that were generated and tested during the entire testing program.

Pipe misalinements were simulated by inserting steel rings into the pipe joints at various points along the length of each pipe. The effect of these discontinuities on the overall efficiency of the flushing operation was studied by duplicating several tests that were previously run with pipe misalinements minimized. A total of five tests were run on each sewer, all of which were run at slopes of 0.002 and 0.004 and sewage base flows of 50 gpm and 10 gpm for the 18 in. and 12 in. sewers, respectively. In all of the tests, three simulated misalinements were placed at approximately 260 ft intervals in the 18 in. sewer and six at approximately 130 ft intervals were placed in the 12 in. sewer, with the first being located near the upstream end of each sewer. Four of the tests were run with the steel rings extending 1/2 in. above the invert of the pipes and the remaining test was run with the steel rings extending 1 in. above the inverts. Flush volumes of 300 and 900 gal. were each combined with flush rates ranging from 200 gpm to 3,000 gpm and were tested in each sewer.

A total of three tests were run to study the effect of grade misalinements on the flushing operating efficiency. All of these tests were run at slopes of 0.002 and 0.004 and sewage base flows of 50 gpm and 10 gpm for the 18 in. sewer and 12 in. sewer, respectively. Forty-three grade discontinuities were created at approximately 18 ft intervals in each sewer, by placing wedges under a given pipe joint to raise the inverts a specified distance above true grade. One test was run on each sewer with the misalinements one-half in. above grade and two tests were run with the misalinements one in. above grade. Flush waves were generated by combining flush volumes of 300 gal. and 900 gal. with flush rates that were previously used in the testing done with grade discontinuities minimized.

Inlet Configuration Effects

The purpose of this portion of the investigation was to study the effect of changes in the configuration (size and shape) of the flush induction inlet on the flushing operation. There were no tests run specifically to evaluate this influence. The evaluation was made based on the observed flow patterns of the flush waves generated in the rest of the experimental testing.

Solids Buildup Tests

The purpose of this group of tests was to establish the growth of the solids deposits expected to occur in small sewers as a function of time. This was accomplished by allowing domestic sewage to run through the two test sewers for various lengths of time and determining the corresponding quantity of solids deposited.

Three separate tests were run during this investigation. All three tests were run at slopes of 0.002 and 0.004 for the 18 in. and 12 in. sewers, respectively. The sewage flows used were continuously varied by the influent controller which was programmed by a cam to vary the set point and simulate the daily flow patterns normally found to occur in lateral sewers during dry weather tests (1), (3), (4), (5). The average 24 hr. flow rates selected for these tests were 6 gpm for the 12 in. sewer and 12 gpm for the 18 in. sewer. These flows were derived based on the following assumptions:

1. The 800 ft of 12 in. sewer was assumed to be an upstream lateral section directly serving 25 single-family dwellings.

2. The 800 ft of 18 in. sewer was assumed to be an intermediate lateral section directly serving 25 single-family dwellings and carrying the flow from an upstream section serving 25 single-family dwellings.

3. The single-family dwellings were assumed to contribute an average flow of approximately 350 gal. per day, based on an average occupancy of 3.5 persons per dwelling and an average per capita discharge of 100 gal. per capita per day.

4. The flows in the sewers were assumed to be dry weather flows and therefore totally the result of the domestic wastes generated.

Figure 8 shows the typical 24 hr. hydrograph of the flow through the two sewers as used during all of the tests (1), (3), (4), (5). During the first test, the sewage was allowed to flow through each sewer for a duration

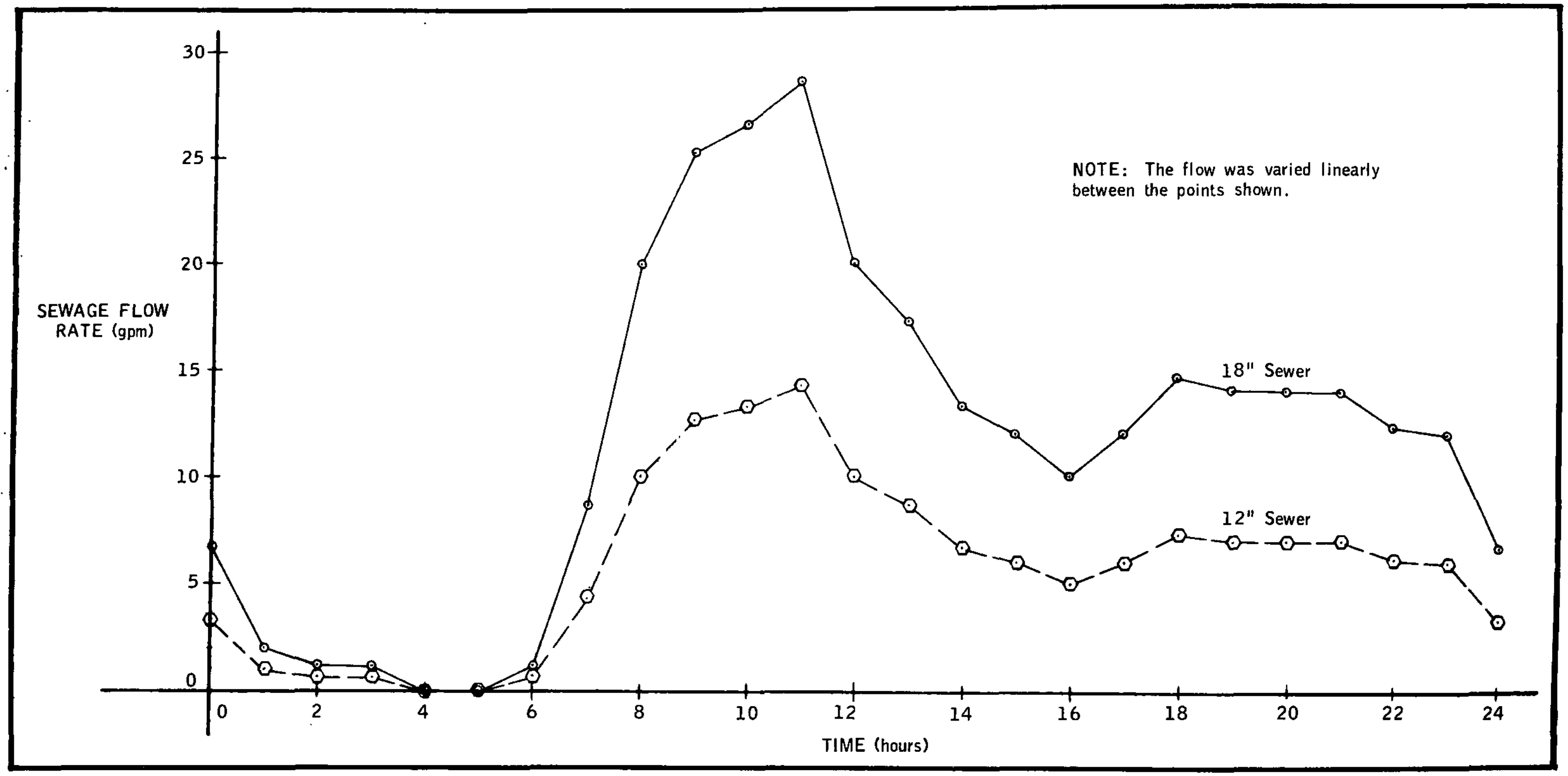


Figure 8 SEWAGE FLOW RATE HYDROGRAPHS USED IN SOLIDS BUILDUP TESTS

of approximately 42 hours, after which it was shut off. The quantity of deposited solids was then determined by completely cleaning each sewer, using the storm simulation operation in the manner previously described. Then the sewage flow was again started and the operation repeated for durations of approximately 94 hours and 188 hours.

Inflatable Dam Evaluation

The purpose of this group of tests was to study the operational feasibility of an in-line inflatable dam as a means of storing and releasing sewage to flush downstream sections. The dam used was made of neoprene-coated fabric and was patterned after the Firestone Fabridam. The dam was attached to the invert of an 18 in. O.D. stainless steel tube, as shown in Figure 9. The steel tube was then inserted into the 18-in. sewer, approximately 260 ft from the upstream end.

The testing done using the dam was quite brief. The tests consisted primarily of collecting various volumes of sewage in the sewer behind the dam and then observing the characteristics of flush wave produced. Also the solids deposits at several points above and below the dam were visually examined before and after the dam was deflated.

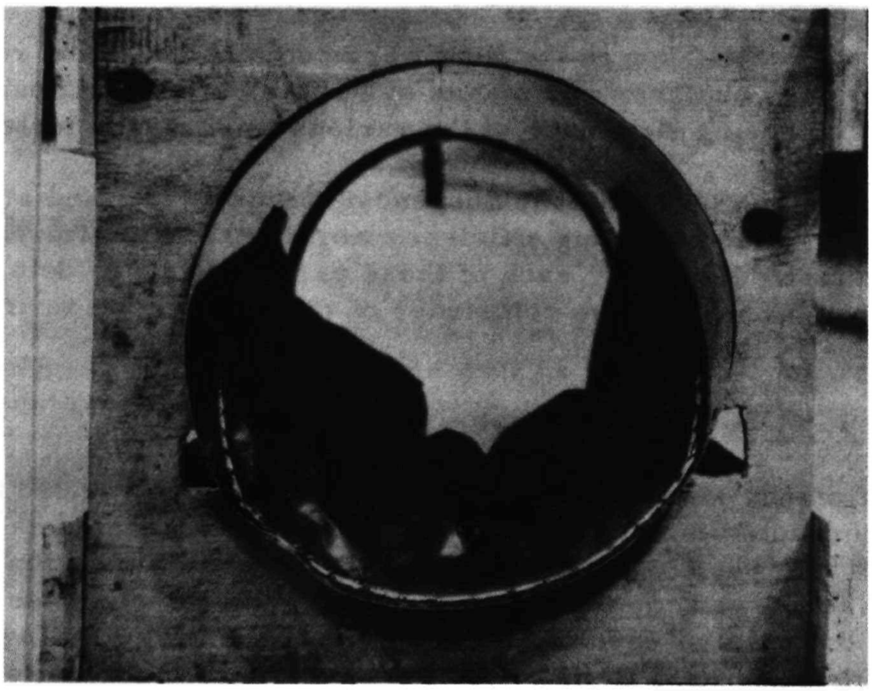


Figure 9 INFLATABLE DAM

FIELD AND LABORATORY PROCEDURES

The field data taken in all of the tests were recorded on the field data sheets shown in Appendix B. The first form is the form used to record the flow and volume data pertaining to each of the samples taken during the tests. The second form is the form on which the observed characteristics of the solids deposits present at various points along the length of each sewer were recorded before and after the flush release. This form was also used to record the measured depth of the sewage base flow and flush wave at various positions along the sewers.

All of the samples taken during the course of the project were analyzed in the laboratory for Total Suspended Solids, Volatile Suspended Solids, and Total Organic Carbon. All of these analyses were conducted in accordance with commonly accepted laboratory procedures and techniques. The laboratory procedures used are outlined in Appendix B. Also, Appendix B includes a summary of the results obtained in a study performed by FMC's Central Engineering Laboratories, which correlates the Total Organic Carbon concentration of the sewage used in the tests, to the 5-day BOD concentration.

DATA ANALYSIS

The experimental data taken in the field were combined with the results from the laboratory analyses, by means of a series of calculations, to determine the cleansing efficiency of the various flush waves tested.

A Suspended Solids (SS), a Volatile Suspended Solids (VSS), and a Total Organic Carbon (TOC) cleansing efficiency were determined for each sewer in each test. However, each of these parameters was determined in the same manner and for the remainder of this section the term "solids" will represent all three.

Solids Distribution Test

Before the efficiency of the various flush wave could be evaluated, the relative distribution of solids deposits had to be known. The data from the Solids Distribution Tests were used to predict the distribution of solids along each sewer, as deposited by each of the various base sewage flows used in the tests at each of the slopes tested. The following computational steps were used to make the predictions for each test sewer.

1. The quantity of solids deposited in each of the four sections of sewer (S_{Di}) was computed as follows:

$$S_{Di} = 8.34 \times 10^{-6} \text{ Ci Vi}, \quad (2)$$

where:

8.34×10^{-6} is the product of the conversion of Vi from gal. to lb and the conversion of Ci from ppm to lb per lb

S_{Di} is the total quantity of solids deposited in section i(lb)

Ci is the concentration of solids in the sample taken of the discharge from the sewer when section i was being cleaned (mg/l), and

Vi is the total volume of discharge collected when section i was being cleaned (gal)

2. The fractional contribution of each section (Pi) to the total solids deposited in the total length of sewer was determined as follows:

$$Pi = \frac{S_{Di}}{\sum_{i=1}^{i=4} S_{Di}} \tag{3}$$

where P_i is dimensionless.

Clean-Water Flush Tests

The data taken during the Clean-Water Flush Tests were combined with the results from the Solids Distribution Test and the average cleansing efficiency of each section of sewer as well as that for the entire pipe length was determined using the following computational steps:

1. The solids removed from the entire pipe length by the flush wave (S_{F_T}) was determined using the following equation:

$$S_{F_T} = 8.34 \times 10^{-6} C_F V_F , \tag{4}$$

where:

S_{F_T} is in lbs,

C_F is the concentration of solids in the sample taken of the discharge from the sewer following the flush (mg/l), and

V_F is the total volume of discharge collected in the collection tank (gal.)

2. The total quantity of solids remaining in each of the sections of pipe (S_{Ri}) was determined in the same manner that S_{Di} was calculated previously.

3. The total pounds of solids deposited in the sewer during the solids buildup period (S_{D_T}) was determined by taking the summation of the solids remaining in each section of pipe $\left(\sum_{i=1}^{i=4} S_{Ri}\right)$ and adding it to the solids removed from the sewer by the flushing wave (S_{F_T}).

4. The total pounds of solids deposited by the sewage base flow in each of the sections of pipe was estimated using the following relationship:

$$S_{Di} = Pi\, S_{D_T} \qquad (5)$$

5. The average cleansing efficiency of the flush wave in each section of pipe ($\overline{C}_{Ei}$) was determined as follows:

$$\overline{C}_{Ei} = \frac{S_{Di} - S_{Ri}}{S_{Di}} \times 100\% \qquad (6)$$

6. The average cleansing efficiency of the flush wave ($\overline{C}_E$) was determined for the combined pipe sections in the following manner:

$$\overline{C}_E = \sum_{L=1}^{L=n} \frac{(S_{Di} - S_{Ri})}{\sum_{L=1}^{L=n} S_{Di}} \times 100\% \qquad (7)$$

Where $\overline{C}_E$.

is the average cleansing efficiency over the length of pipe, $L = \Delta L_1 + \cdot\cdot \Delta L_n$, in percent ($\Delta L_1$ is the length of the first upstream section of pipe in feet and n is the number of pipe sections included).

Sewage-Flush Correlation Tests

The data from the Sewage-Flush Correlation Tests were handled in the same manner as that from the Clean-Water Flush Tests, except that the calculation used to determine the total quantity of solids removed by the flush wave (S_{F_T}) had to be corrected to account for the solids added to the system by the sewage used for the flush. To accomplish this correction, the following relationship was used:

$$S_{F_T} = 8.34 \times 10^{-6} \left(C_F V_F - C_{F_o} V_{F_o} \right) \qquad (8)$$

Where

C_{F_o} is the concentration of solids in the sewage used for the flush (mg/l) and

V_{F_o} is the volume of sewage used for the flush (gal.).

Miscellaneous Other Tests

The data taken during the Solids Buildup Tests were handled in the same manner as the data taken during the Solids Distribution Tests. The data taken in all of the other tests were analyzed in the same fashion as that described for the Clean-Water Flush Tests.

SECTION VI

DISCUSSION

TEST RESULTS

The experimental data from all of the tests run during the course of this project were analyzed using the computational procedures previously outlined in Section V. The results from these various computations are summarized in Appendix C of this report.

Solids Distribution Tests

The results of the Solids Distribution Tests were used in the analysis of the data from all of the Flushing Evaluation Tests to predict the relative distribution of solids deposits along the sewers. The figures given in Table 7 (Appendix C) were obtained by averaging the P_i values, obtained from Equation 3, that were observed in two separate test runs on each sewer at each of the given combinations of pipe slope and sewage flow rate. In all cases, the P_i values that were averaged to obtain $\overline{P}_i$ were within 5 percent of each other.

Examination of the values of P_i given in Table 7 (Appendix C) shows that in nearly every case the heaviest deposition of suspended solids occurred in the first 526 ft of pipe. However, as the pipe slopes (S_o) and sewage flows (Q_B) were increased, this phenomenon became progressively less significant and the solids were deposited more uniformly along the length of the sewers.

The effect of slope and flow rate on the relative distribution of the suspended solids deposits along the length of both the 12 in. and 18 in. sewer is demonstrated by the plot in Figure 10. The solid line represents the mean suspended solids distribution along the length of the sewers. This mean distribution was determined by taking the average of the distributions that were observed for each of the pipe sections at all of the various combinations of pipe slope and flow rate (Table 7, Appendix C). The broken line shown above the mean line represents the relative suspended solids distribution found to exist when a slope of 0.001 was combined with a sewage flow of 10 gpm. The broken line shown below the mean line represents the experimentally determined suspended solids distribution that resulted when a 30 gpm sewage flow was combined with a slope of 0.008. A visual comparison of the three curves shown in Figure 10 shows that the slope of the lower dashed line is much more uniform than that of either of the other two lines, which indicates that a more uniform distribution of solids along the length of the sewers

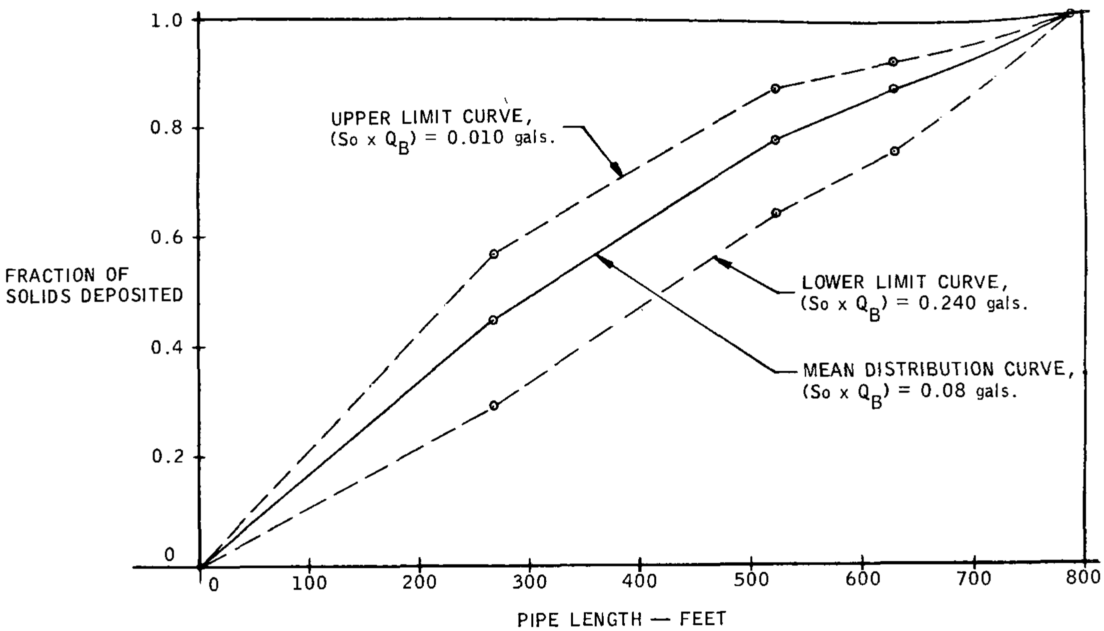


Figure 10 RELATIVE EFFECT OF SLOPE AND FLOW RATE ON THE DISTRIBUTION OF SOLIDS IN THE TEST SEWERS

resulted at the higher values of slope and sewage flow rate. Also, the relative shapes of the curves indicate that the uniformity of the distribution of solids along the sewer is a function of the product of the slope and sewage flow rate values. The results given in Table 7 show that in the tests where the product of slope and sewage flow rate was less than approximately 0.080 gpm (which is the arithmetic average of S_oQ_B for all the tests), the resulting distribution curves typically fall above the mean curve. In those tests where the product of slope and sewage flow rate was greater than the average value of 0.008 gpm, the resulting distribution curves typically fall below the mean curve.

The relative distribution of Volatile Suspended Solids and Total Organic Carbon along the length of each sewer changes with variations in slope and sewage flow in much the same manner as described above. However, the VSS and TOC results given in Table 7 (Appendix C) show that the distribution of these materials is consistently more uniform than the total solids distribution. This indicates that the equalization of the total solids distribution as a function of S_o and Q_B can be primarily attributed to the fact that the increased velocities, resulting from steeper slopes and higher sewage flows, cause the lighter organic materials to be carried further along the sewer before they are deposited.

Clean-Water Flush Tests

The results from the Clean-Water Flush Tests are given in Tables 8, 9, and 10 (Appendix C). Each of the Suspended Solids, Volatile Suspended Solids, and Total Organic Carbon cleansing efficiencies given in Table 8 (Columns 2, 3, and 4, respectively) are the average cleansing efficiencies over the corresponding pipe lengths shown adjacent (Column 5) and were determined using Equation 7 ($\overline{C}_E$). The wave depths given in Tables 9 and 10 are the results of the measurements made during each test. Each value represents the maximum depth that the flush wave reached at the given distances (Column 3) from the upstream end of each sewer.

Correlation of Suspended Solids Cleansing Efficiency. The correlation of the observed values of suspended solids cleansing efficiency ($\overline{C}_{ESS}$) to the six independent variables, pipe length (L), flush volume (V_F), flush rate (Q_F), pipe slope (S_o), pipe diameter (D), and sewage base (Q_B) was accomplished in two general steps. In the first step, several groups of results were randomly selected and systematically plotted, in the manner shown in Figure 11, to establish the general relationship between each of the independent variables (V_F, Q_F, L, S_o, Q_B, and D) and the dependent variable ($\overline{C}_{ESS}$).

The curves in Figure 11 are typical of those found for all of the combinations of results plotted. Examination of these curves shows that in general the value of $\overline{C}_{ESS}$ increases when the values of Q_F, V_F, S_o, and D are increased and decreases when the values of L and Q_B are increased.

In the second step of the analysis the correlation between $\overline{C}_{ESS}$ and the independent variables was evaluated mathematically by means of a series of regression analysis. The complete set of results were first subjected to a stepwise regression analysis using a general multiple correlation equation. The standard error of the estimate was minimized by separately varying the exponents of each of the independent variables. The relationship which resulted from the analysis is given in Equation 9. The cumulative reduction in the sum of squares was 0.621 (or 228,904) and the standard error of the estimate was 12.82.

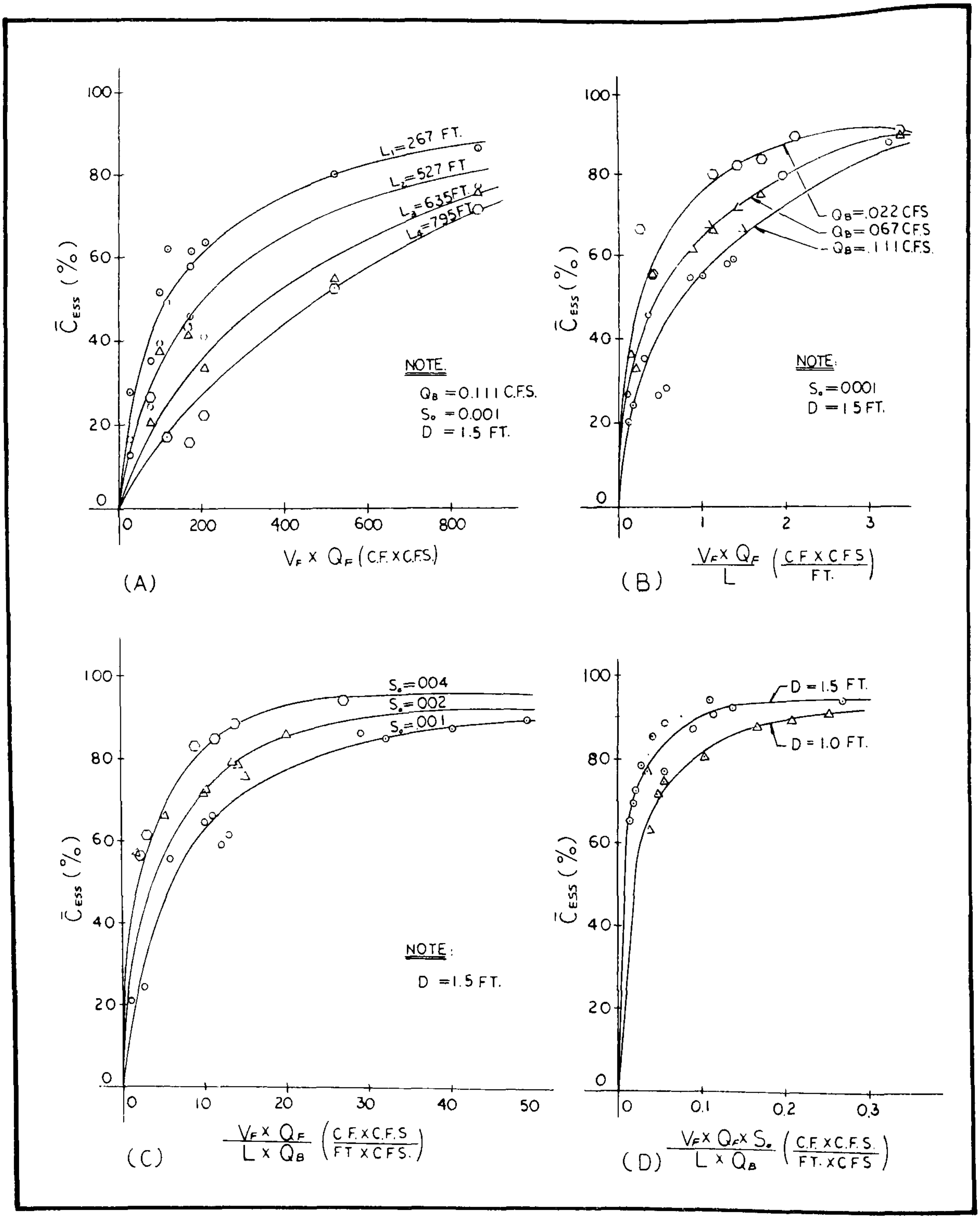


Figure 11 TYPICAL CORRELATION OF THE INDEPENDENT VARIABLES TO $\overline{C}_{ESS}$

$$C_{ESS} = -739.8 + 66.7\,(V_F \times Q_F)^{0.1} + 5.07\,Q_B^{-0.5} + 312.6\,L^{-0.1} + 57.7\,S_o^{0.5} + 111.1\,D^{0.1}, \qquad (9)$$

where

V_F = Flush Volume, cubic feet

Q_F = Flush Rate, cubic feet per second

Q_B = Sewage Base Flow Rate, cubic feet per second

L = Pipe length, feet

S_o = Pipe Slope, percent

D = Pipe diameter, feet

The multiple correlation coefficient and computed $F(D.F. = 5, 538)$ for the regression were 0.788 and 173.05, respectively, indicating that a correlation between $\bar{C}_{ESS}$ and the set of independent variables does exist. The relative order in which the independent variables influence the correlation between Equation 9 and the observed results is indicated by the order of their appearance in Equation 9, with the product of V_F and Q_F demonstrating the greatest influence. The information given in Table 18 of Appendix D gives a more complete statistical characterization of Equation 9 and indicates that the relationship is representative of a majority of the observed results. Also, the figures given in Table 18 for the reduction of the variance in each step of the regression, show that all of the independent variables significantly decrease the variance and therefore need to be included in the analysis to obtain maximum correlation.

Because of the shape of the curves shown in Figure 11 and the exponents of the independent variables in Equation 9, a logarithmic correlation of the results was attempted. The relative correlation of all of the dependent variables was found to be increased when each was replaced by its base 10 logarithm and the above multiple correlation regression repeated. After trying various arrangements of the variables, the relationship given by Equation 10 was found to give the maximum correlation. The values of the standard error and the multiple correlation coefficient were found to be 12.13 and 0.806 respectively, indicating that the correlation of Equation 10 was significantly better than obtained by Equation 9. An attempt was made to increase the correlation of Equation 10

$$\overline{C}_{ESS} = -13.70 + 24.68 \log_{10} \frac{V_F^{1.3}\, Q_F^{0.9}\, S_o^{1.4}\, D^{1.8}}{L^{1.6}\, Q_B^{1.2}} \times 10^4 \qquad (10)$$

by eliminating from the analysis some of the results, which were obviously not consistent with the bulk of the observed values. The results from three tests (12 observations) were eliminated and as a result the standard error and multiple correlation coefficient values were decreased to 11.34 and 0.828, respectively. However, the value of the intercept and the regression coefficient did not change significantly, indicating that the basic equation had not changed. Further elimination of questionable observed values from the analysis reduced the standard error and multiple correlation coefficient but did not significantly change the basic equation.

Based on the above analyses, the relationship given by Equation 10 was found to provide the best estimate of the observed suspended solids cleansing efficiencies. The relative correlation of Equation 10 is given statistically in Table 19 (Appendix D) and is shown graphically in Figure 12.

Examination of the plot given in Figure 12 shows that the estimate of $\overline{C}_{ESS}$ that is provided by Equation 10 is quite acceptable for the range of V_F, Q_F, L, S_o, Q_B, and D values that were included in the experimentation. However, when this equation is to be used for the purpose of designing flush equipment for sewers with lengths, slopes, sewage flows, or diameters, which are not within the range of values that were tested during the experimental development of the equation, the reliability of the estimate may be reduced.

Correlation of Volatile Suspended Solids Cleansing Efficiency. The volatile suspended solids cleansing efficiencies ($\overline{C}_{EVSS}$) given in Table 8 (Appendix C) were correlated directly to the log function in Equation 10. This was done because time limitations did not allow for a complete analysis and because the observed values of $\overline{C}_{EVSS}$ showed consistently the same patterns of variation as those shown by the observed

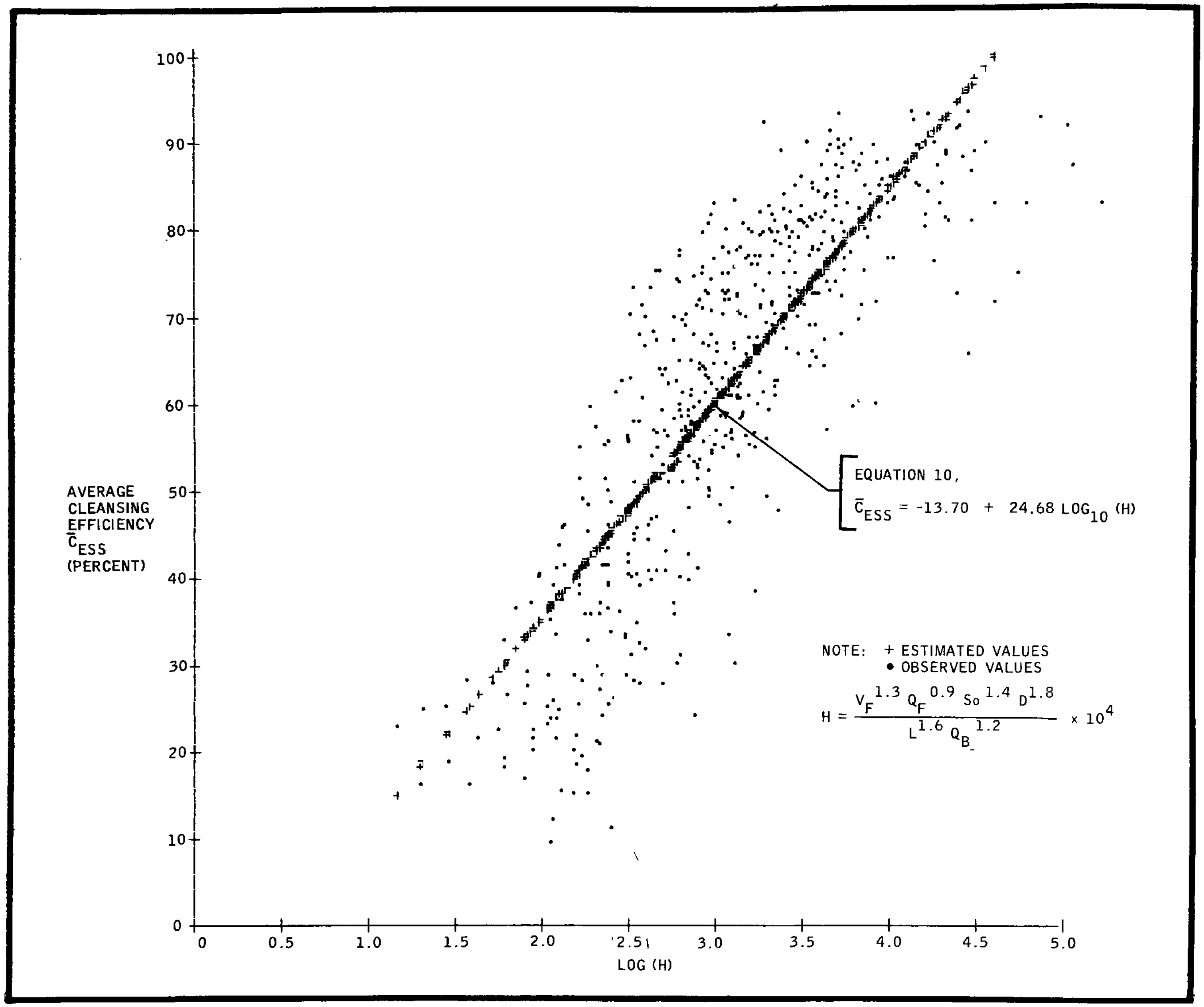


Figure 12 SUSPENDED SOLIDS CLEANSING EFFICIENCY CORRELATION

values of $\overline{C}_{ESS}$. The relationship that was developed is given in Equation 11. Figure 13 shows

$$\overline{C}_{EVSS} = -0.34 + 21.72 \log_{10} \frac{V_F^{1.3} Q_F^{0.9} S_o^{1.4} D^{1.8}}{L^{1.6} Q_B^{1.2}} \times 10^4 \qquad (11)$$

graphically the correlation of Equation 11 to the observed results, and the statistical characterization of the relationship is included in Table 20 (Appendix D). The plot in Figure 13 shows that Equation 11 correlates quite well with the majority of the observed values of $\overline{C}_{EVSS}$.

Correlation of Total Organic Carbon Cleansing Efficiency. The total organic carbon cleansing efficiency values given in Table 8 were correlated to the log function given in Equation 10 and the result is given by Equation 12. As can be seen by examining the plot given in Figure 14 and the statistics given in Table 21 (Appendix D) (only a 0.165 reduction in the sum of the squares), the estimate provided by Equation 12 is not reliable. There are two possible reasons for this poor correlation. First, time did not allow a complete correlation analysis to be made on the results and therefore the equation form used (Equation 10) may not be the most representative. Second, the TOC data gathered during the course of the project was not as consistent as the other data due to large variations in the quality of the discharges from several canneries which discharge into the sewer which was used as the source of sewage for the tests.

$$\overline{C}_{ETOC} = 22.36 + 10.30 \log_{10} \frac{V_F^{1.8} Q_F^{0.9} S_o^{1.4} D^{1.8}}{L^{1.6} Q_B^{1.2}} \times 10^4 \qquad (12)$$

Correlation of Flush Wave Depth. The results from the wave depth measurements, given in Tables 9 and 10 (Appendix C), were plotted against pipe length (L) for each test. The resulting curves indicated that the flush wave depths generally decreased with increased values of L and S_o and increased with values of V_F, Q_F, and D. Also, the wave depths appeared to decrease as a function of the square root of L.

Using the above general relationships for reference, an analysis was run on the complete set of results in Tables 9 and 10. The statistical results from this analysis indicated that there was good correlation with all of the independent variables, except pipe diameter (D). The

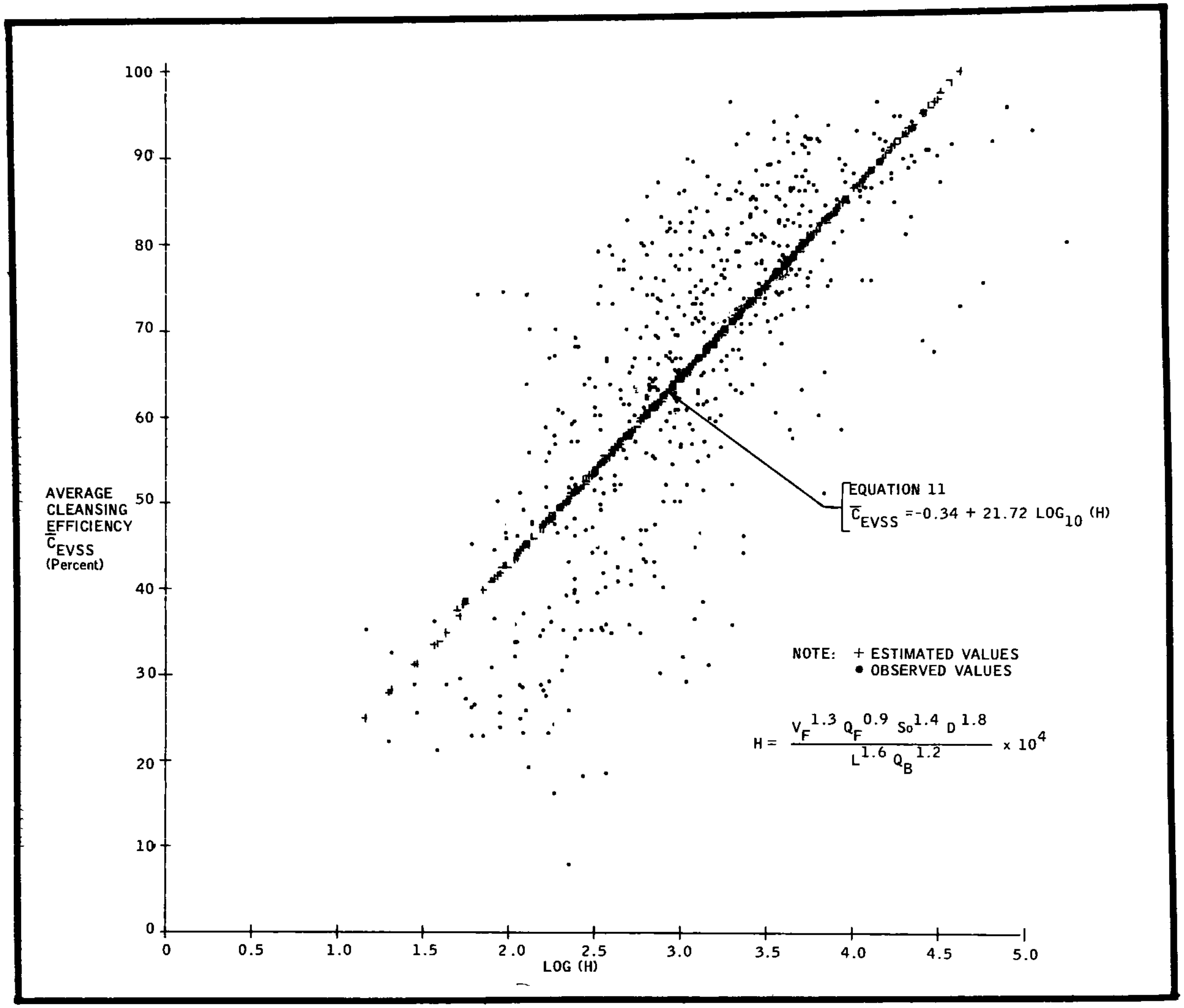


Figure 13 VOLATILE SUSPENDED SOLIDS CLEANSING EFFICIENCY CORRELATION

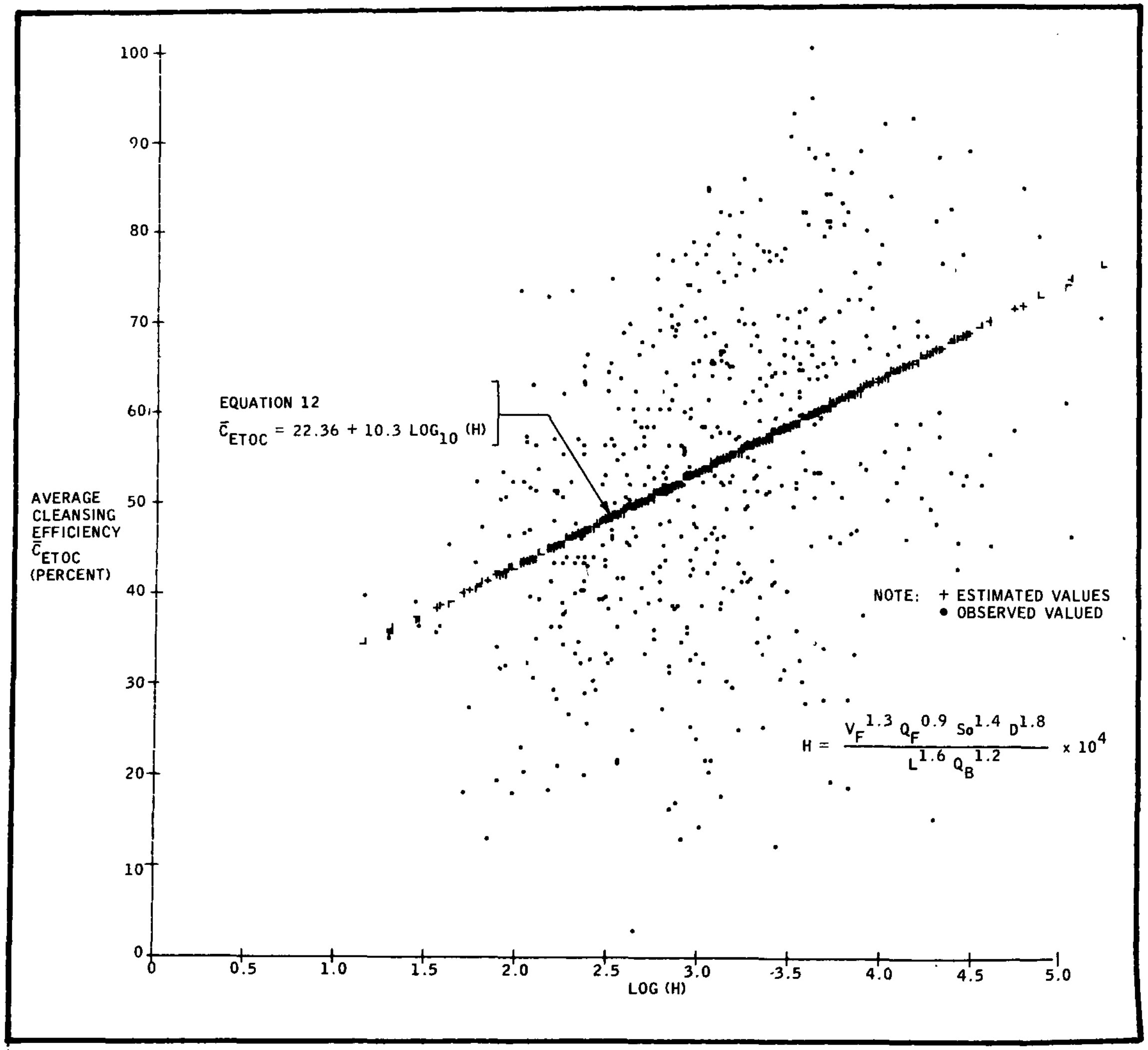


Figure 14 TOTAL ORGANIC CARBON CLEANSING EFFICIENCY CORRELATION

influence of pipe diameter was shown to be quite small. In order to verify this, the results in the two tables were analyzed separately and the relationships developed are given by Equations 13a and 13b. Equation 13a was generated using the results from the 12 in. sewer (Table 9) and Equation 13b was developed using the results from the 18 in. sewer (Table 10). The statistics associated with each of the relationships are given in Tables 22 and 23 (Appendix D). The relative correlation of Equations 13a and 13b is shown graphically in Figures 15 and 16, respectively. Examination of Figures 15 and 16 shows that the two equations generated are quite similar and that each shows good correlation with the majority of the observed values. Although the overall relationship appears to be curvilinear and the correlation might possibly be improved further by a more extensive analysis of the results, in the range of interest in this study it is represented quite well by the straight line relationship.

$$\overline{W}_D = 8.45 + 0.0230\ V_F + 0.534\ Q_F - 0.261\ L^{0.5} - 1.0\ S_o + 2.36\ Q_B \tag{13a}$$

$$\overline{W}_D = 8.84 + 0.0189\ V_F + 0.408\ Q_F - 0.322\ L^{0.5} - 0.215\ S_o + 7.29\ Q_B \tag{13b}$$

where $\overline{W}_D$ is the maximum wave depth in inches.

Steep-Slope Equation Check. All of the relationships that were developed in the above analyses are somewhat questionable with respect to their ability to make accurate predictions about flushing sewers where the values of L, S_o, Q_B, and D are not in the range of the values that were tested during the experimental work in this project. For this reason, four flush tests were run on the 12 in. sewer at a slope of 0.008 to attempt to check the ability of these empirical relationships to make predictions about flushing sewers with slopes steeper than those previously tested. The cleansing efficiency results from these four tests are given in Table 11 (Appendix C). Also shown in Table 11 are the corresponding values of $\overline{C}_{ESS}$, $\overline{C}_{EVSS}$, and $\overline{C}_{ETOC}$, that were predicted using Equations 10, 11, and 12, respectively. Comparison of these observed and estimated cleansing efficiencies shows that Equations 10 (C_{ESS}) and 11 ($\overline{C}_{EVSS}$) were quite accurate in their predictions. However, Equation 12 ($\overline{C}_{ETOC}$) had a much poorer correlation with the observed results, as would be expected because of its unreliable representation of the original experimental results.

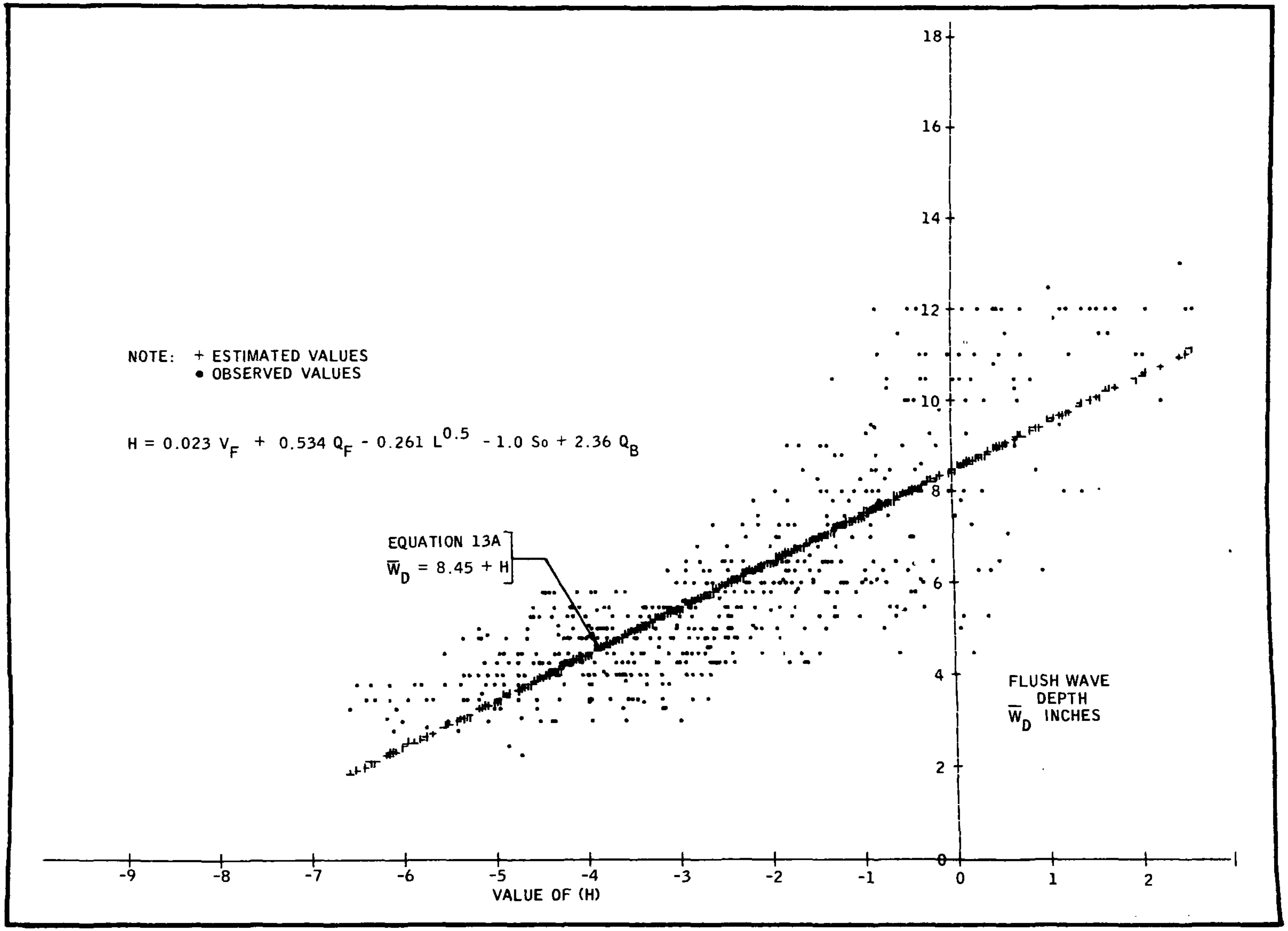


Figure 15 WAVE DEPTH CORRELATION FOR 12-INCH SEWER

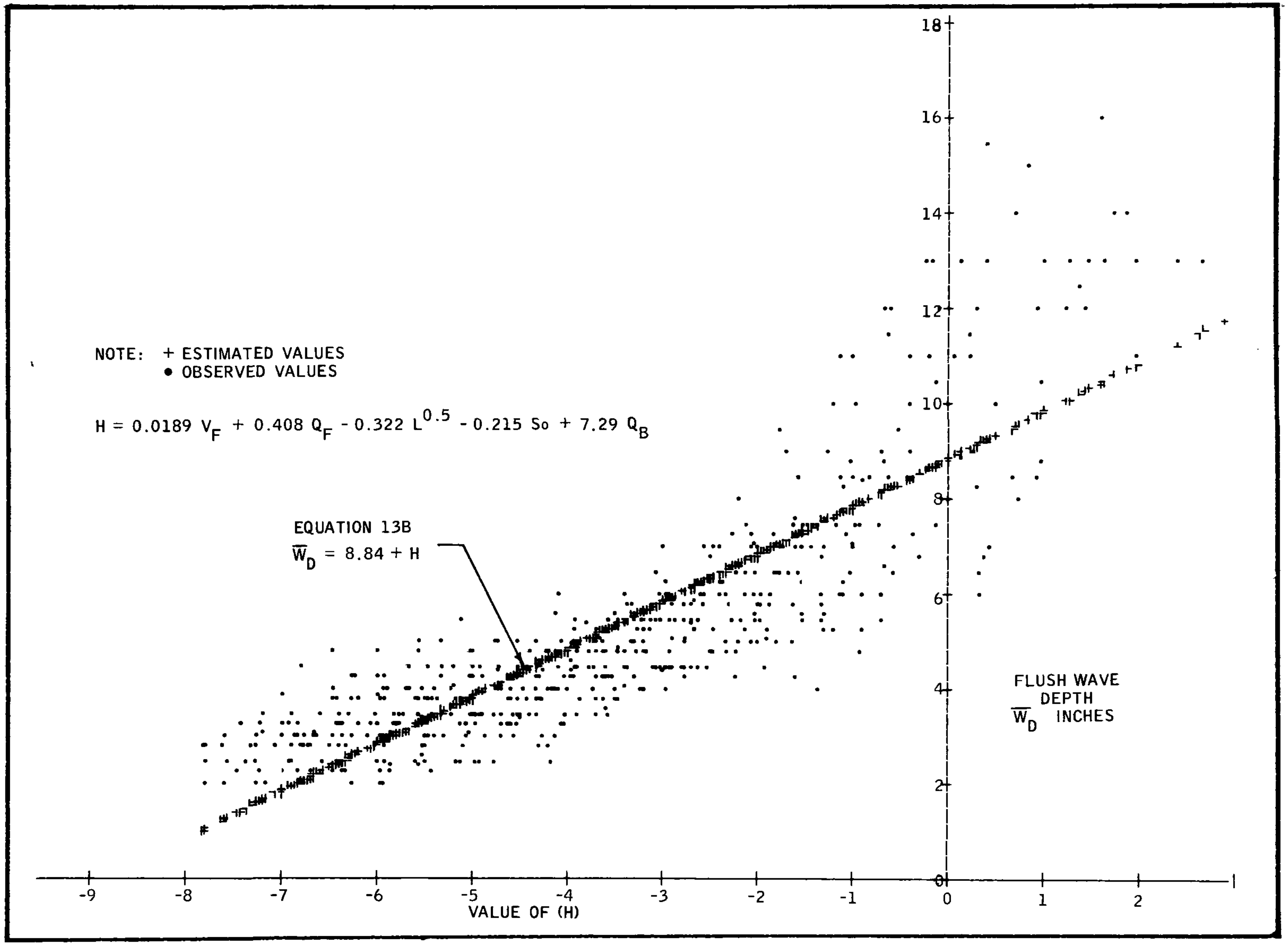


Figure 16 WAVE DEPTH CORRELATION FOR 18-INCH SEWER

The wave depth measurements made during these tests are compared to the values estimated by Equation 13a in Table 12 (Appendix C). The correlation between the estimated and observed results are very good and indicates that Equation 13a is capable of giving quite reliable estimates of the flush wave depths at this steeper slope value.

Sewage-Flush Correlation Tests

The results from these tests, where sewage was used as the flush liquid, are given in Table 13 (Appendix C). The cleansing efficiency values given in the table were determined using Equation 8 and were used to calculate the change in cleansing efficiency that resulted from using sewage. This was accomplished using the following equation:

$$\Delta\bar{C}_{ESS} = \bar{C}_{ESS} - \bar{C}_{ESS}', \qquad (14)$$

where $\bar{C}_{ESS}$ was determined from Equation 10 for the given values of V_F, Q_F, L, S_o, Q_B, and D and $\bar{C}_{ESS}'$ is the corresponding suspended solids cleansing efficiency observed during the Sewage-Flush Tests.

The resulting values of $\Delta\bar{C}_{ESS}$ are given in Table 13 and were subjected to a multiple correlation regression analysis. The relationship given by Equation 15 was found to give the best correlation. The statistical parameters associated with

$$\Delta\bar{C}_{ESS} = 14.3 - 0.14\,V_F - 0.242\,Q_F + 0.00711\,L \qquad (15)$$

Equation 15 are given in Table 24 (Appendix D). Figure 17 shows the relationship between the observed values of $\bar{C}_{ESS}'$ and the clean-water cleansing efficiency equation (Equation 10). Examination of the plot shows that in general the overall cleansing efficiency was reduced slightly by using sewage instead of clean water. Also shown in Figure 17 is the plot of Equation 16, which is representative of Equation 10 ($\bar{C}_{ESS}$) after being corrected by Equation 15 ($\Delta\bar{C}_{ESS}$ for flushing with sewage. The statistical parameters associated with Equation 16 are given in Table 25 (Appendix D). The standard error of the estimate (10.94) and the correlation coefficient (0.763) indicate that Equation 16 gives an adequate representation of the experimental values of $\bar{C}_{ESS}'$.

$$\bar{C}_{ESS}' = -13.70 + 23.7\log_{10}\frac{V_F^{1.4}\,Q_F^{0.9}\,S_o^{1.4}\,D^{1.8}}{L^{1.6}\,Q_B^{1.2}} \times 10^4 \qquad (16)$$

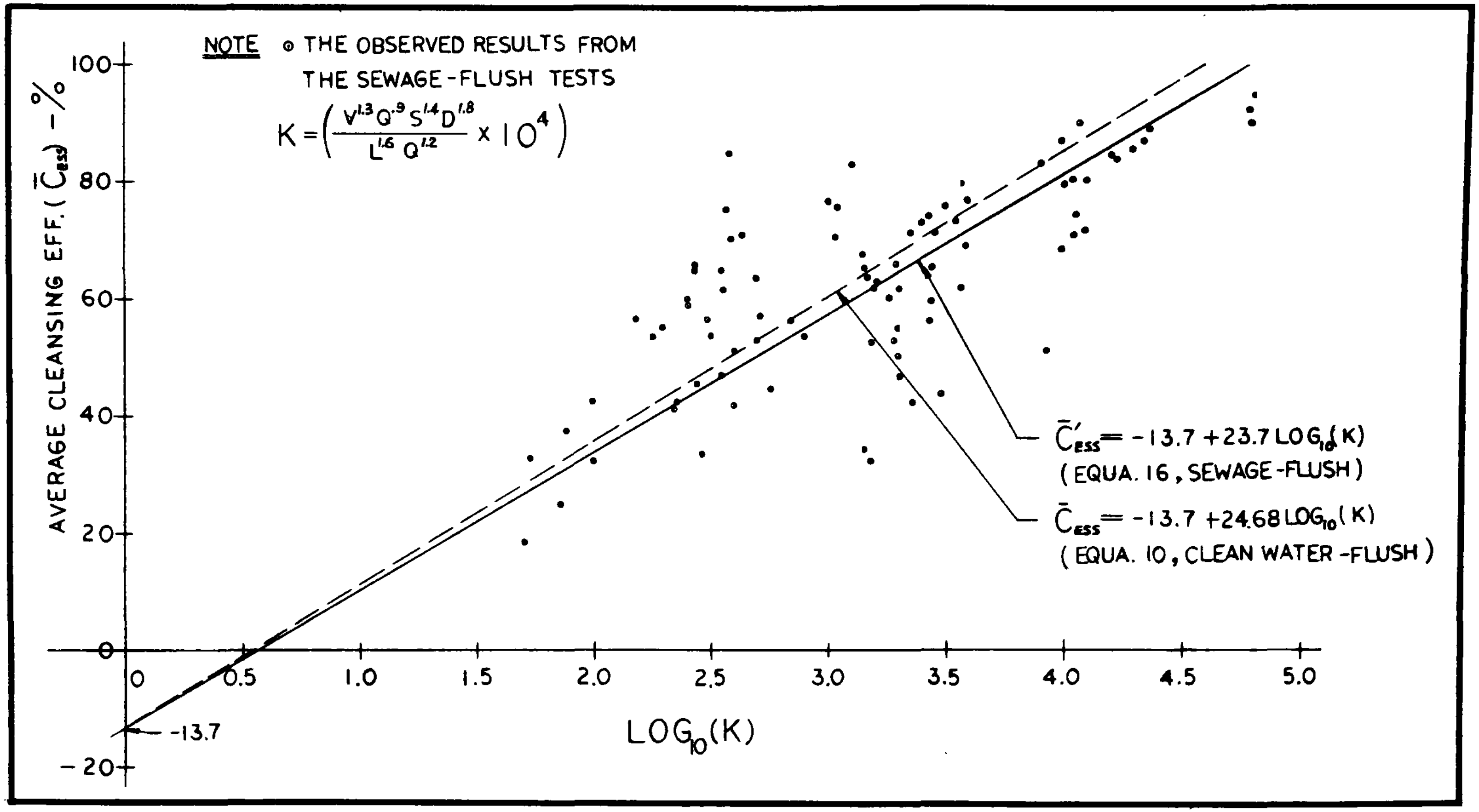


Figure 17 SEWAGE-FLUSH CORRELATION

Flush Wave Sequencing Tests. The results from these tests, where multiple flush waves were used to clean the test sewers, are summarized in Table 15 (Appendix C). The observed values of cleansing efficiency given in the table are the values of $\overline{C}_{ESS}$ that were determined for the total length of the sewers. The equivalent volume of flush (V_F') that is given for each of the multiple flush combinations is the weighted average volume for the total length of sewer and was determined as follows:

$$V_F' = \frac{\sum_{i=1}^{i=4} V_i L_i}{\sum_{i=1}^{i=4} L_i} , \qquad (17)$$

where V_i is the total volume of flush water that passed through section i in gallons and L_i is the length of section i in feet.

The values of $\overline{C}_{ESS}$ that were estimated for each of the equivalent single-flush volumes was determined by solving Equation 10, using the corresponding average flush rate and the equivalent single-flush volume. Comparison of the values of $\overline{C}_{ESS}$ that were observed during each of the three different flush release sequences, indicates that the sequence of release of multiple flush waves is not very critical to the overall cleansing operation, as long as the upstream releases are made first. When the flush waves were released separately beginning at the tank nearest the downstream ends of the sewers, the observed values of $\overline{C}_{ESS}$ were consistently lower than those obtained using the other two release sequences. The difference between releasing at maximum wave depth and releasing after the upstream wave has passed was found, as shown by the close correlation of the observed $\overline{C}_{ESS}$ values in each case, to be insignificant.

The estimated $\overline{C}_{ESS}$ values for the equivalent single-volume flushes show fairly good correlation to the $\overline{C}_{ESS}$ values determined for the various multiple flushes tested. This indicates that in general the efficiency of multiple flush release was not significantly different from the efficiency of the equivalent single-flush release, at least in the relative short lengths of pipes used in these tests (800 ft). In longer lengths of pipe, where pipe length becomes the primary influence on the cleansing efficiency, the use of multiple flush waves may very possibly become a very important consideration.

Flow Obstruction Tests

Three general types of flow obstructions were studied in this portion of the investigation. The data from the tests that were run were analyzed using Equation 7 and the results are given in Table 14 of Appendix C.

Pipe-Joint Misalinement Tests

The suspended solids cleansing efficiencies determined during these tests, where steel rings were used to simulate pipe joint misalinements, are given in Table 14. Figure 18 shows the relative correlation of the values of $\bar{C}_{ESS}$ observed during these tests to the values of $\bar{C}_{ESS}$ that were predicted, for the corresponding values of V_F, Q_F, L, S_o Q_B, and D, using Equation 10. As can be seen by examining Figure 18, the simulated misalinements had a negligible effect on the overall cleansing operation. Also, there was no consistent difference demonstrated between the results from the tests where 1/2 in. high rings were used and the tests where 1 in. high rings were used.

Grade Misalinement Effects. The suspended solids efficiencies determined during these tests, where grade misalinements were simulated by raising several sections of pipe above true grade, are given in Table 14. Figure 19 shows that the values of $\bar{C}_{ESS}$ observed during these tests correlate quite well with the $\bar{C}_{ESS}$ values predicted using Equation 10, indicating that the grade misalinements had little effect on the overall cleansing operation. The only flush waves that were noticeably affected by the discontinuities in the grade of the sewer were those that were generated by very low flush volumes and flush rates.

Manhole-Channel Covers and Service Connection Effects. The effect of covering the channels in manholes was determined to be insignificant, based on the observed wave patterns and the results from the other flow obstruction tests. Interference in the flow pattern of the flush wave can only occur, as a result of these covers, when the depth of the wave is greater than one-half the diameter of the pipe. Consequently, the only flush waves that would be hydraulically affected by the installation of these covers are those generated by large flush volumes and rapid rates of release, and these are the flush waves that were shown in the flow obstruction tests previously described to be the least affected by physical discontinuities.

The effect of service connections on the overall efficiency of the cleansing operation was also found to be insignificant based on the same reasons that were given above for the insignificant effects of covering the channels in manholes.

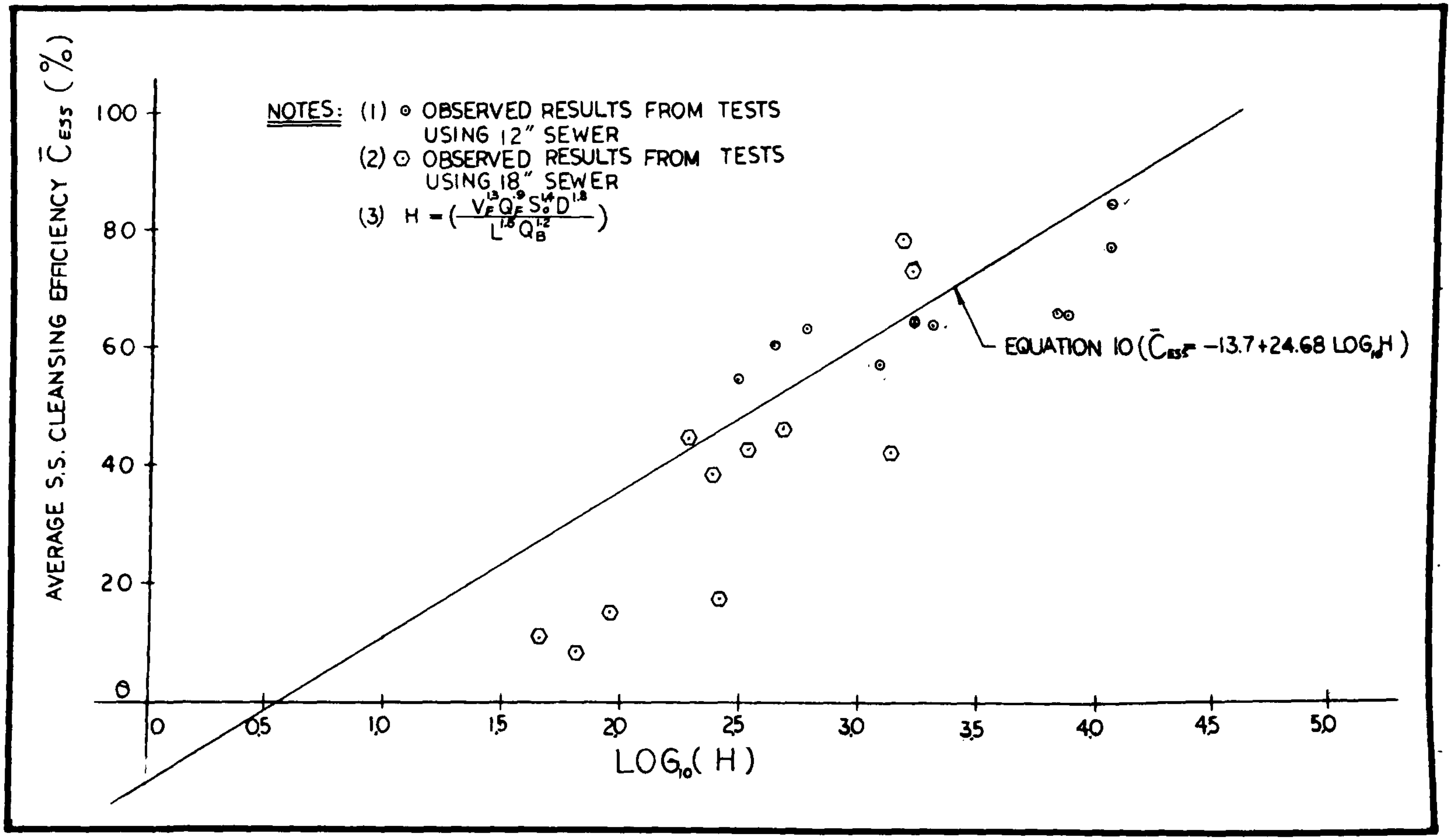


Figure 18 PIPE JOINTS MISALINEMENT EFFECTS

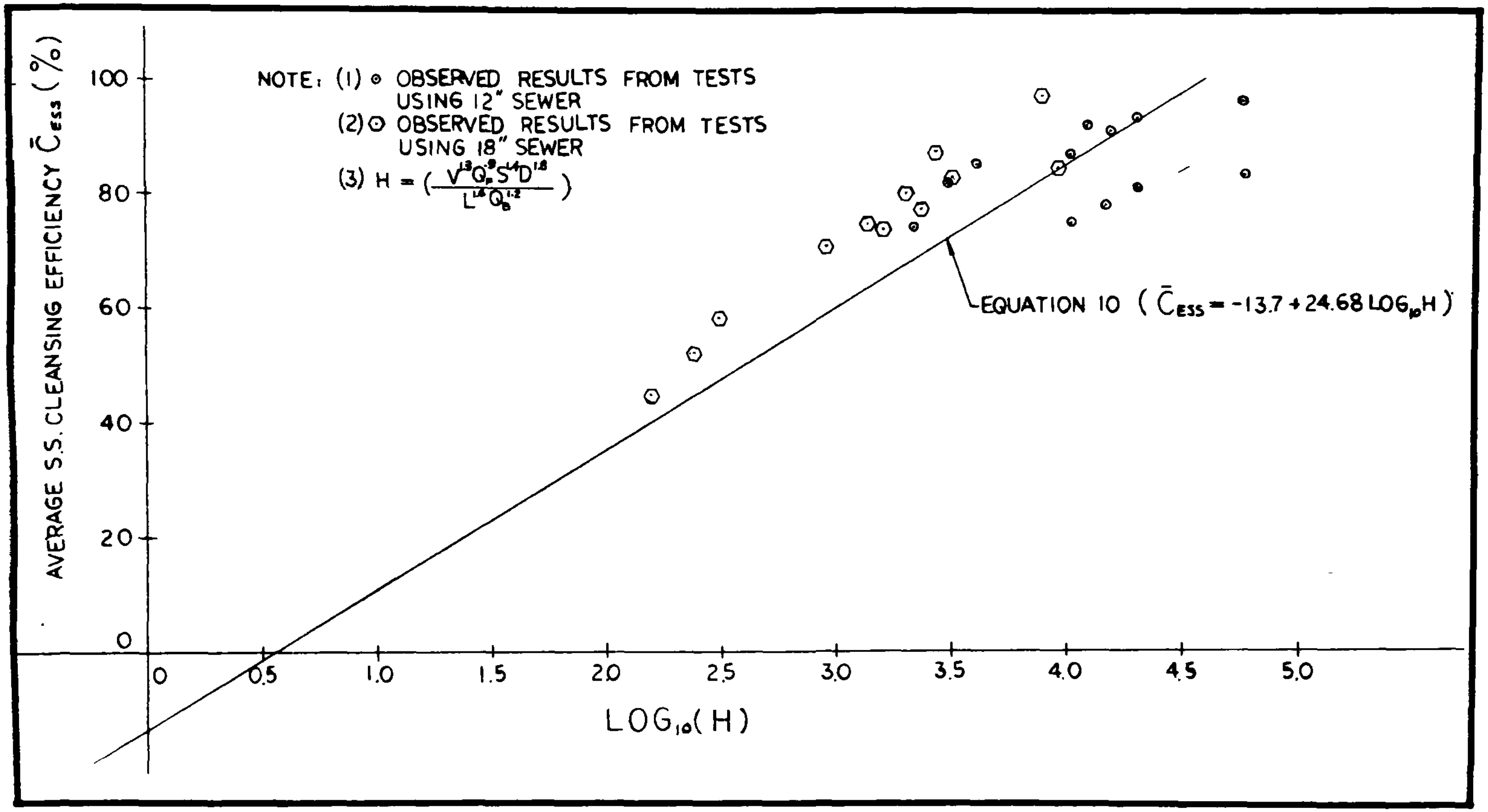


Figure 19 GRADE MISALINEMENT EFFECTS

Inlet Configuration Effects

During the early stages of the investigation, the inlet configuration used to induce the flush liquid into the sewer was considered to be one of the primary factors affecting the relative efficiency of the flushing operation. However, the flow patterns that were observed for the various flush waves tested during this project show that these inlet effects are quite insignificant, except in limiting the rate of flush release. The volume of flush liquid and the rate at which this volume is added to the sewer are the important factors affecting the cleansing operation. Directing the flow downstream in the sewer, by means of an elbow or other device, would only affect the cleansing operation in the first few feet of pipe. Moreover, the effect in the first few feet of pipe would be significant only for a very short time after the beginning of the release, because the flush volumes and rates necessary for realistic cleansing are high enough that the sewer becomes surcharged shortly after the release is made.

Solids Buildup Tests

The complete set of results from the three Solids Buildup Tests that were conducted are given in Table 16 (Appendix C). These results were derived from the experimental data in the manner described in Section V.

Analysis of the results given in Table 16 shows that a relatively high percentage of the solids deposited in the sewers consisted of organic or volatile material. An average of 60.7 percent (Standard Deviation = ± 5.90) of the deposited materials were volatile solids and 19.4 percent (Standard Deviation = ± 3.0) was organic carbon. These percentages are quite representative of those found in all the tests and can be used to estimate the proportions of volatile solids and organic solids based on the total solids distributions and buildups that will be discussed in the remainder of this section.

The distribution of the solids deposits over the length of the sewers is shown graphically in Figure 20, for each of the sewage flow duration times tested. Examination of the distribution curves in Figure 20 shows that in all cases 77 to 90 percent of the solids deposited were deposited in the first 520 ft of pipe. In general, the longer the buildup period the higher the percentage of solids in the first portion of the sewers. This heavy deposition of solids found to occur in the upstream portion of the sewers indicates that in lateral sewers where the sewage is added more or less uniformly along the length of the pipe, instead of to the upstream end as was done in these tests, the major portion of solids will probably

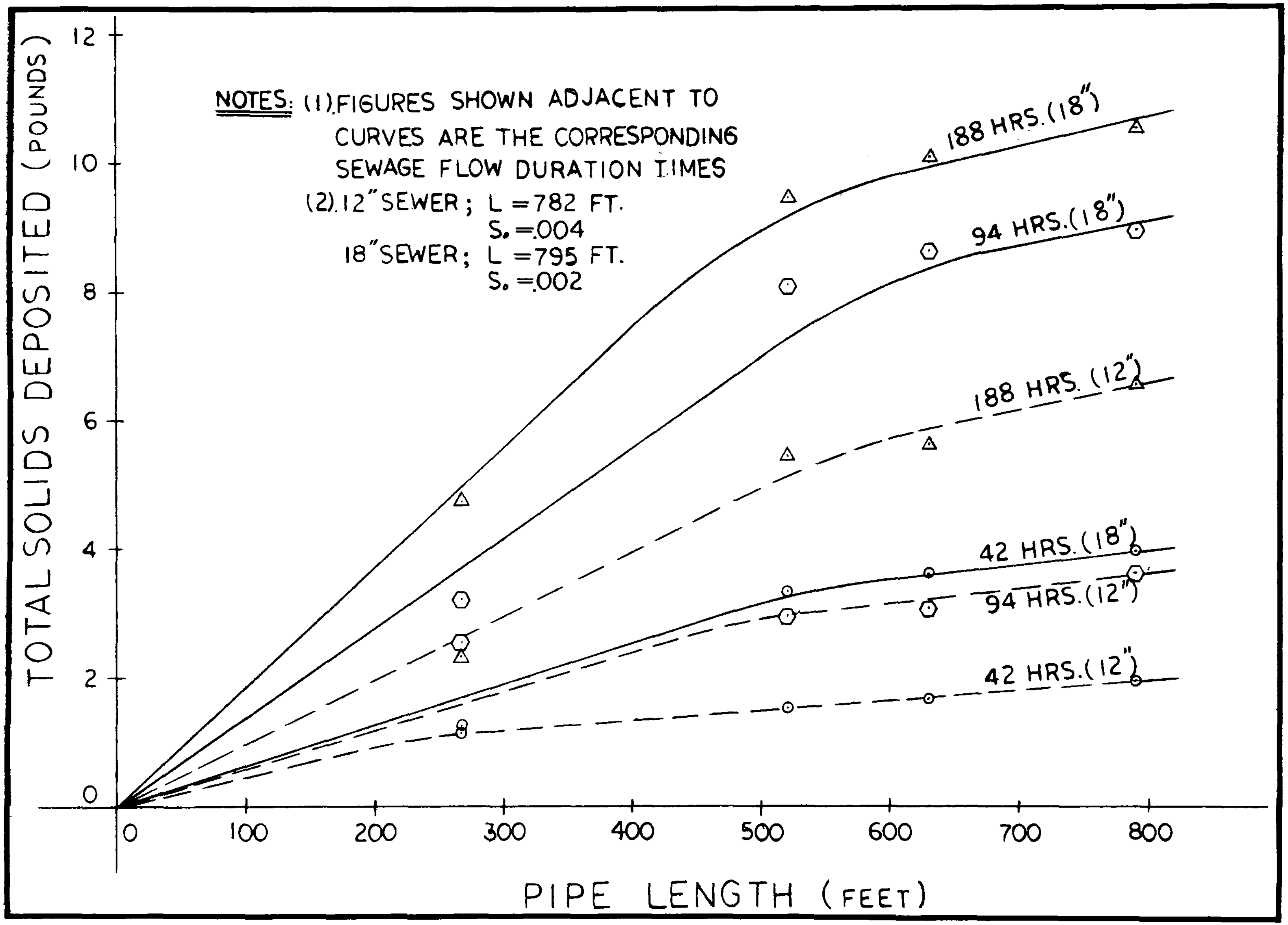


Figure 20 RELATIVE DISTRIBUTION OF SOLIDS DEPOSITS

be deposited within a relatively short distance downstream of where they are introduced to the sewer.

The build up of solids deposits in the test sewers, as a function of time, is shown by the curves in Figure 21. The curves show that the total quantity of solids deposited in the 12 in. sewer was approximately one-half that deposited in the 18 in. sewer after 188 hours. However, the deposition of solids in the 18 in. sewer reached a peak after approximately 120 hours, whereas the deposition of solids in the 12 in. sewer had not reached a maximum even after 188 hours. These two facts, combined with the fact that the sewage flow rate in the smaller sewer was approximately one-half that in the larger sewer, indicate that the difference in total quantity of material deposited in the two sewers may well be the result of the difference in the total quantities of solids that passed through the two sewers, rather than purely a hydraulic phenomenon.

The quality of the sewage that was supplied to the sewers during these tests should be considered when evaluating the total quantities of solids deposited in the sewers. The suspended solids concentration (SS) of the influent sewage varied from a high of approximately 150 mg/l to a low of 120 mg/l, with approximately 90 percent of the composite samples taken having concentrations within ± 10 mg/l of an average of 133 mg/l. The volatile suspended solids concentrations (VSS) varied from approximately 94 mg/l to 114 mg/l with the majority of the composite samples taken having concentrations within ± 5 mg/l of the average of 102 mg/l. The total organic carbon concentration (TOC) varied over a wider range of approximately 94 mg/l to 148 mg/l, with only about 50 percent of the composite samples taken having concentrations within ± 20 mg/l of the average of 112 mg/l.

The figures given above for the solids content of the influent sewage are not as high as those that are sometimes found for domestic sewage, and therefore should be considered when evaluating the magnitude of the solids deposits. However, the quality of the sewage does not seriously alter the relative effect of time. Although much more extensive testing would be required before absolute relationships could be developed, the test results given in Figure 21 show that more than three times as many solids were deposited in the sewers after 5 days as were deposited after 1 day. This is definitely a significant increase in pollutional material and deserves serious consideration.

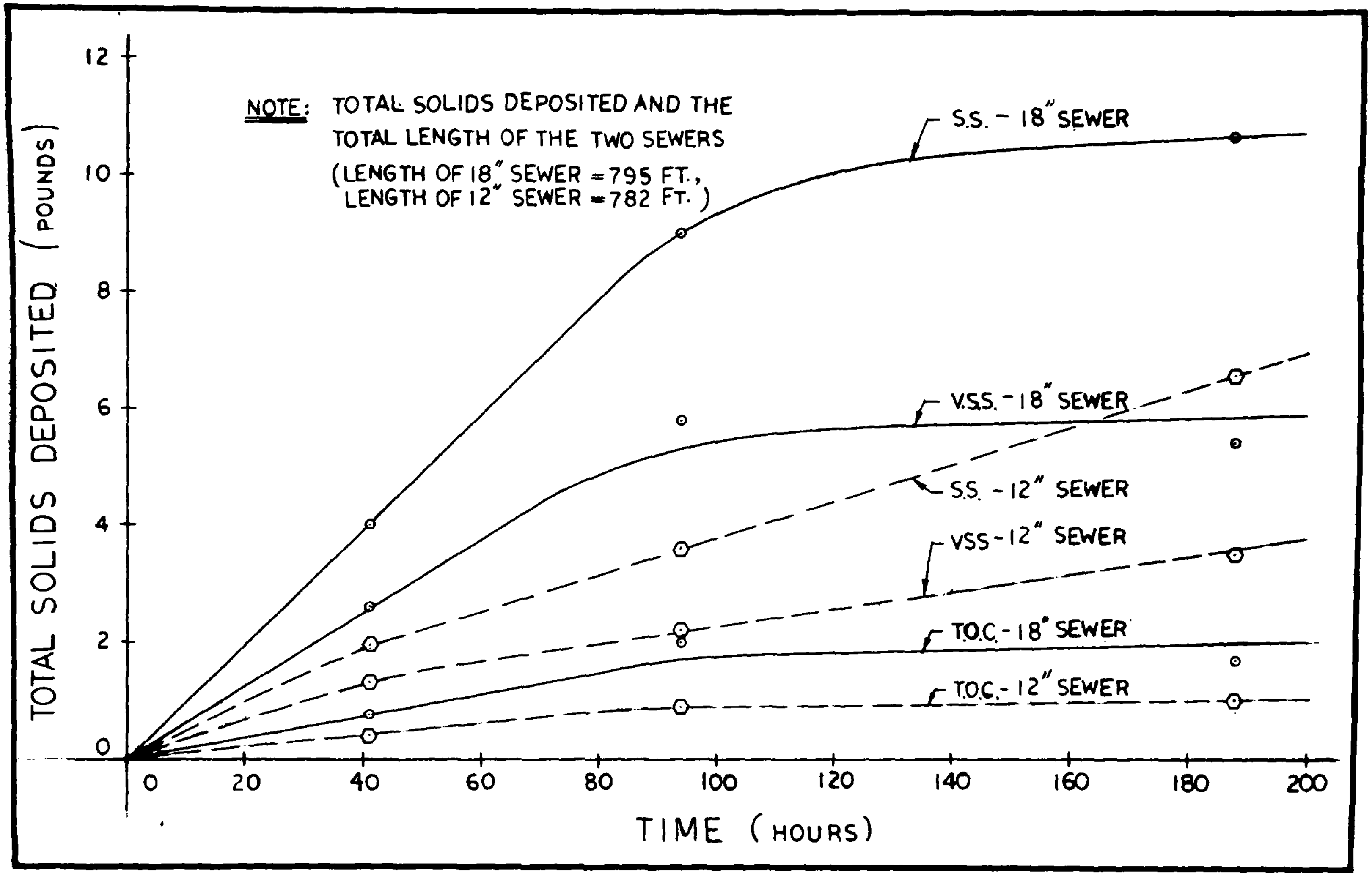


Figure 21 TIME SERIES BUILDUP OF SOLIDS

Inflatable Dam Evaluation

The inflatable dam (see Figure 9) was installed in the 18 in. test sewer and its general operation observed. The dam was inflated to several heights, ranging from 4 in. to 16 in., and the resulting flush wave observed. During these operations two major problems were found with this method of storing and releasing flush liquid. First, the solids deposits above the dam appeared to be much heavier than experienced during unobstructed sewage flows and the release of the stored sewage did not appear to decrease the deposits appreciably. The second problem encountered was with the mechanical design of the dam, in that it would not deflate rapidly enough to get the full benefit out of the volume of sewage stored behind it. The occurrence of these problems was the primary motivation for the proposed changes in the dam design which are discussed later in this section.

In spite of the above problems, discharge rates of up to 1,000 gpm were attained. Also, the solids deposited downstream of the dam appeared to be significantly decreased by the release of the sewage stored behind the dam.

SUMMARY OF RESULTS

The results of the tests run during the course of this project are quite comprehensive, but definitely not all conclusive. The reliability of the relationships that were developed from the experimental results are limited not only by the statistical variations in the results, but more important they are limited by the range of conditions included in the testing program. The statistical variations in the experimental results do not cause as great a problem as do the physical limitations of the testing program, because their effects are predictable, at least to a degree. The most serious limitation on the general equations that were developed is a result of the fact that only two diameters of pipe were used in the tests. This makes the reliability of making predictions about sewers with diameters significantly different from those tested somewhat questionable. However, since the effect of diameter was found to be relatively small in relationship to the effect of flush volume and flush rate and the effect of diameter on the relationships generated for the 12 in. and 18 in. sewers were quite small, the predictions provided by the general equations for sewers with diameters close to those tested (8 in. to 24 in.) will quite probably be within the range of standard error that was determined for each of the relationships.

Using sewage instead of clean water for flushing was found to cause a general, minor decrease in the efficiency of the cleansing operation. As shown in Figure 17, the effect is relatively small and is probably the result of the redeposition of solids by the trailing edge of the flush wave. This conclusion was made based on the fact that when clean water was used for flushing, the first portion of the wave carried nearly all of the resuspended solids and the trailing low-velocity portion of the wave was essentially clean water. When sewage was used for flushing the trailing, low-velocity portion of the wave contained relatively high concentrations of solids (equal at least to the concentration of solids in the strained sewage that was used for flushing) and significant quantities of these solids were redeposited along the length of the sewers.

The effects of the flow obstructions tested were found to be insignificant in the range of flush volumes and flush rates that would normally be expected to be used in actual practice. Also, since the flow obstructions that would be encountered in existing sewers are almost impossible to locate and even more difficult to relate to the simulated obstructions tested, a relationship to correct for these effects would not be very realistic.

The effects of flush wave sequencing were found to be insignificant as long as the flush releases were made progressively from the upstream end of the sewer. Also, the cleansing efficiencies obtained by using various combinations of flush waves were found to be quite similar to those obtained using single flushes of equivalent volumes and similar release rates. However, both of these hypotheses are based on the limited findings from tests run on relatively short sewers and therefore further testing is required to give a complete picture of the relative importance of these two factors on the overall performance of a complete flushing system.

The inflatable dam was found to have some fundamental problems associated with its use for flushing sewers. However, the in-line dam is the easiest and least expensive, of all the flushing devices investigated, to construct, install, operate, and maintain. This combined with the fact that these dams could easily be used to reduce the quantity of storm water overflows and equalize the hydraulic loadings on treatment facilities, makes further investigation of their capabilities quite desirable.

The TOC results given can be used to estimate the equivalent 5-day BOD of the deposited solids, by using the correlation relationship described in Appendix B. The discussion in Appendix B shows that the sewage used in the tests consistently had BOD_5 concentrations of 1.8 times the TOC concentration.

MATHEMATICAL MODEL DEVELOPMENT

Need for Mathematical Model

In a typical combined sewer installation a large number of periodic flush stations will be required to periodically remove the solids that are settled in the sewers. The efficiency (i.e., percent of solids removed from the sewers) of the flush system depends on:

- System Parameters - Quantity of flush water and the rate of flush discharge
- Physical Characteristics - Location, length, diameter and slope of the sewers, and amount of flush water available
- Load Characteristics - Amount of solids settled in the sewers and average base flow rate.

Given the physical and load characteristics of a combined sewer installation, there exist a large number of alternative selections of the flush system to achieve a specified cleansing efficiency. The problem of determining the best alternative is rather complex and calls for a mathematical model.

Objective of Model

The objective of the model is to select the best configuration for locating the flush stations and determine their capacities to achieve a specified cleansing efficiency. The criterion for evaluation, depending on the availability of cost information, can be either of the following:

- Minimize the total cost of the station's equipment and flush water required for operation of the flush stations.
- Minimize the quantity of flush water required.

The first approach is provided to be used when cost figures are available, whereas the second is provided so that the model can be used to determine the minimum water (or sewage) requirements even without adequate cost information.

Scope of Model

The proposed model will be applicable to the "lateral" sections of a combined sewer installation. These are the sewers carrying the sewage from households, commercial buildings, etc. to the "main" sewers. The scope of the model is limited mainly due to the limitations of the design relationships. There are, however, other important reasons, e.g.:

- The "laterals" are the sewers where the majority of solids are deposited during the low flow periods. Hence, cleansing of these sections will maintain the amount of solids in the entire sewer system at a specified level, thus reducing the concentration of solids in the bypassed flows during the storm.

- The "mains" in the sewer system can be treated independently. Given the load in sections of the main sewer (from the direct connections and from the "laterals") the same model can be applied for selecting and locating flush stations along the "mains" to achieve a specified cleansing efficiency. However further experimental testing is required before the design relationships developed in this project can be used for the larger diameter mains.

General Approach

A dynamic programming approach was used to determine optimality of each feasible combination of flush stations. The model implicitly evaluates all possible alternatives to achieve a specified efficiency within the constraints imposed and selects the best one. The selection of the best flushing system is based on values given to the following design parameters.

1. Cleansing efficiency of the flush station

    - as a function of flush volume and rate
    - as a function of pipe size, length, and slope
    - as a function of sewage load.

2. Physical parameters

- potential locations along the "lateral"
- lengths, diameters, and slopes of sewers between these locations
- engineering constraints at each location e.g., size of flushing tank, amount of flush water available, etc.
- average daily load in each sewer.

3. Costs

- of flush station for given capacity
- of flush water at each location.

The design equations used in the model are those that were developed during the experimental phase of this project. The cleansing efficiency of each flush system evaluated is determined using the clean-water suspended solids cleansing efficiency ($\overline{C}_{ESS}$) equation (Equation 10) when clean water is to be used as the flush medium and the sewage-flush suspended solids ($\overline{C}_{ESS}'$) equation (Equation 16) when sewage is used. A complete description of the analytical procedures used in the model is provided in Appendix F. Also included in Appendix F is a listing of the computer program, accompanied by complete operational documentation and examples.

Limitations

The use of the model is limited to the analysis of single laterals with physical characteristics (pipe diameters, pipe slopes, etc.) similar to those used in developing the design equations. However, the model is designed so that it can readily be adapted to virtually any sewer, by experimental verification of the design relationships.

The model, as it now exists, cannot determine the quantity of solids expected to be deposited in a given section of sewer. This parameter must be determined, by the user, based on the sewage characteristics and flow patterns of the given system, and supplied to the model as an input parameter.

No specific provision is made in the model for variations in the relative sequence of flush releases. The overall cleansing efficiencies of the selected combinations of flush stations are determined based on the assumption that the flush releases are sequenced so that the flushes will be made progressively beginning from the upstream end of the sewer.

ECONOMIC CONSIDERATIONS

A study of the materials deposited in storm water runoff areas in Tulsa, Oklahoma, indicated that an average of approximately 0.015 lb of solids were deposited daily per ft of street (2). This is approximately 5 times the quantity of solids found to be deposited in the test sewers during the solids buildup tests. However, the average BOD_5 of the solids deposited in the storm runoff areas was only about 0.000415 lb per day per ft of street (2) as compared to an average BOD_5 of the solids deposited in the test sewers of approximately 0.002 lb per day per ft of sewer (estimated using the TOC values determined in the testing and the TOC-BOD_5 correlation of $BOD_5 \cong 1.8$ TOC given in Appendix B). Comparison of these figures indicates that the solids deposited in lateral sewers during dry weather periods have a significant effect on the concentration of pollutants in the combined sewer overflows resulting from relatively intense storms following extended dry weather periods. Consequently, if the quantity of solids deposited in the lateral sewer during dry weather periods can be minimized, a significant reduction in the pollution caused by subsequent storm overflows from combined sewer will result.

The test results indicate that during the first 24 hours from 15 to 30 percent of the total quantity of suspended solids that were carried through the test sewers by the sewage flows of 10 to 50 gpm were left deposited in the 800 ft long sewers. The solids that were deposited were on the average more than 60 percent volatile material.

The results from the Flushing Evaluation Test have shown that by using reasonably small flush volumes, the solids deposits in the lateral sewers can be reduced by 60 to 75 percent each day. The results of the Solids Buildup Tests have shown that the solids deposited at the end of 5 days is at least three times the solids deposited at the end of one day. If we continue with the assumption that the percentage removal is unaffected by the amount or age of the solids deposited (within the limits of the following example) the solids removed can be calculated as indicated in Table 1. Compared to the solids deposited in 5 days with no flushing this would result in net removals of:

$$100(3 - .66) \div 3 = \underline{78\%} \text{ for } 60\% \text{ daily removal}$$

and

$$100(3 - .333) \div 3 = \underline{89\%} \text{ for } 75\% \text{ daily removal.}$$

Table 1 SOLIDS REMOVAL PREDICTIONS
(Daily Solids Deposited = 1)

Day	Solids Deposits Prior to Flushing	Percent Remaining	Solids Remaining After Flushing	Solids With No Flushing	Net Removal
1	1	40	.4	1	60%
2	1.4	40	.56	-	-
3	1.56	40	.62	-	-
4	1.62	40	.65	-	-
5	1.65	40	.66	3	78%
1	1	25	.25	1	75%
2	1.25	25	.313	-	-
3	1.313	25	.328	-	-
4	1.328	25	.332	-	-
5	1.332	25	.333	3	89%

From this example for a period of 5 days between storms it can be seen that the improvement by sewer flushing is increased for longer periods between storms. For a specific installation the predicted net removal for each possible period between storms would have to be weighted by the probability of that period occurring, based on historical records, and by the pollution load for that period to obtain the expected net removal. The expected net removal should then be comparable to performance obtained by other overflow pollution control methods being considered. The correctness of the assumptions made and the effect of removal in laterals on the pollutional load at an overflow point should be verified by a demonstration in a combined sewer system.

The mathematical model has been set up to determine the least cost of performing periodic sewer flushing to achieve a given daily removal of settled material. In order to determine the cost for a specific installation it would, of course, be necessary to enter the particular installation and operating cost factors which apply to that local situation. The resulting minimum cost and the expected net removal will provide the basis for an economic comparison with other pollution control methods.

For the case of the laterals being considered for a possible demonstration in Detroit, two system layouts are being considered to give either 61 percent daily removal or 72 percent daily removal depending on the number of flush stations used. Rough cost estimates were made as shown in Table 2.

Table 2 ESTIMATED FLUSHING COSTS

Alternate	1	2
Number of flush stations per lateral	2	4
Area per lateral - acres	9	9
Daily solids removal - percent	61	72
Installed cost of fabric flush tanks	$5,556	$11,246
Cost of telemetry and controls	not estimated	
Monthly power cost	$1.95	$4.09
Monthly maintenance cost	$100	$200.
Capital cost per acre	$617	$1,250
Monthly maintenance and power cost per acre	$11.32	$22.70

The cost for telemetering and remote control of the flushing system would be dependent on the degree of automation needed as well as the physical layout of the system in relation to the control center.

SECTION VII

DESIGN AND TESTING OF A PROTOTYPE FLUSH STATION

There are numerous possible ways to mechanically acquire, store, and release the liquid volumes necessary to flush sewers. The objective of this phase of the project was to investigate these various schemes and to select, design, construct, and test a promising arrangement.

DESIGN AND CONSTRUCTION

Several flush station designs were considered starting from the concepts shown in Figure 22. Other layouts were studied as reported in the drawing list, Appendix E. The design that was selected to be the prototype tested in this project was selected because it appeared to be one of the most functional and promised to have reasonable construction costs and low installation cost.

The prototype flush station was designed so that it can be easily installed in and/or removed from almost any standard-type manhole. The complete station is built as a single unit for maximum ease in handling and installation (see Figure 23). The unit is held rigid by a 22 in. diameter steel frame that supports the sewage supply and control equipment. The frame is surrounded by a polyurethane-coated nylon bag, which is 4 ft in diameter and is designed to fit inside a standard manhole 8 ft or more in depth. The bag was designed to push against the walls of the manhole when filled with liquid and then be completely collapsible when emptied. This allows the complete unit, including the bag, to be lifted into or out of a manhole with a minimum disassembly required.

The sewage supply and control equipment consists of a self-priming pump, two electrically actuated four-way valves, a spring loaded diaphragm-type actuator connected to a poppet-type dump valve, two level control floats, and a 24 hour timer. The equipment is arranged so that the bag can be repeatedly filled with sewage and rapidly emptied in a completely controlled fashion (see Figure 24A).

The bag is filled by positioning the four-way valves, one on the suction side and one on the discharge side of the supply pump, so that sewage is pumped from a screened intake in the sewer to the bag (Figure 24B). During this filling process, the dump valve is held closed by the spring in the diaphram-type actuator. When the level of sewage reaches the desired maximum, the level control float located near the top of the bag is activated and the pump is turned off and both four-way valves are rotated to the hold positions as shown in Figure 24C.

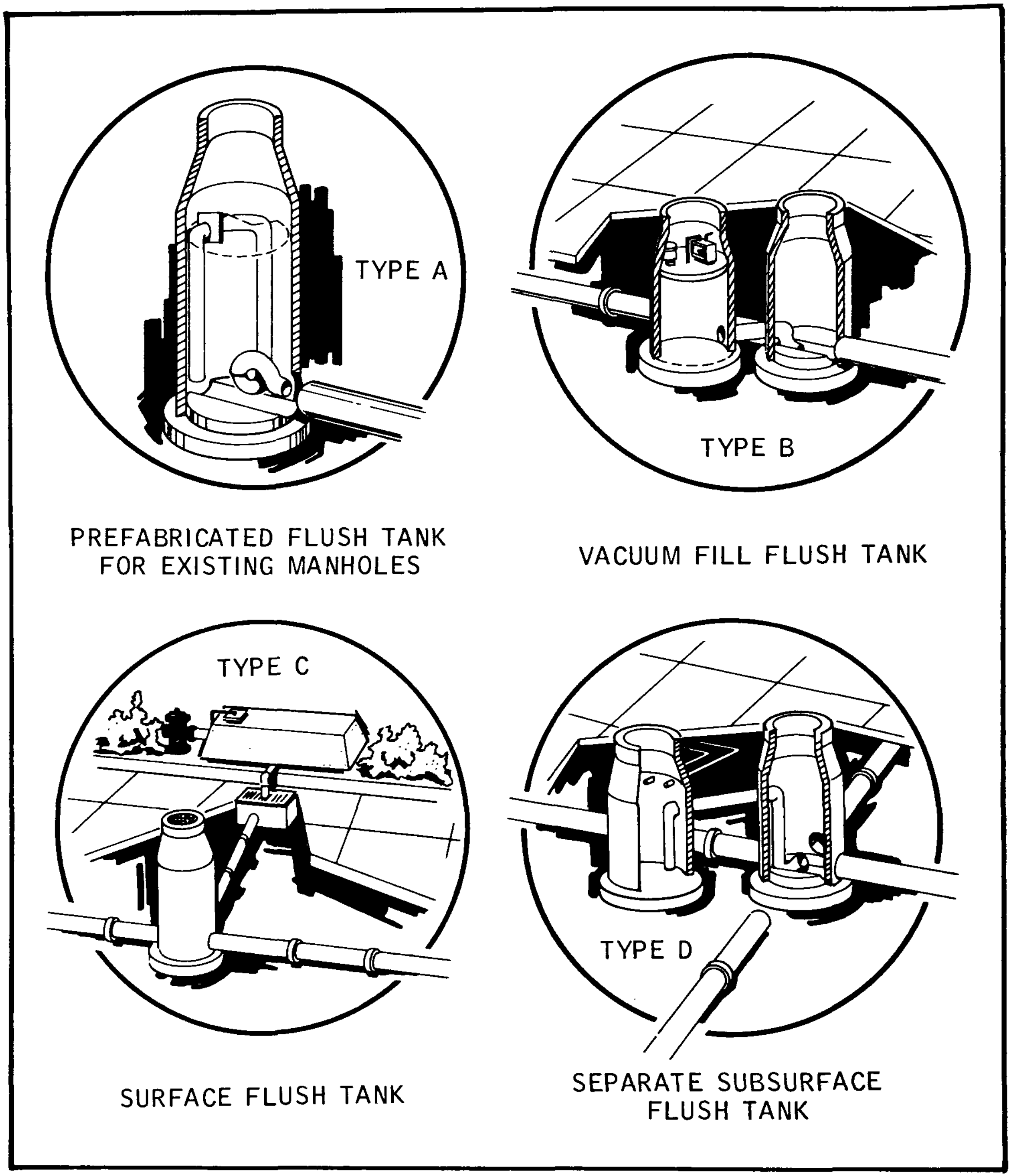
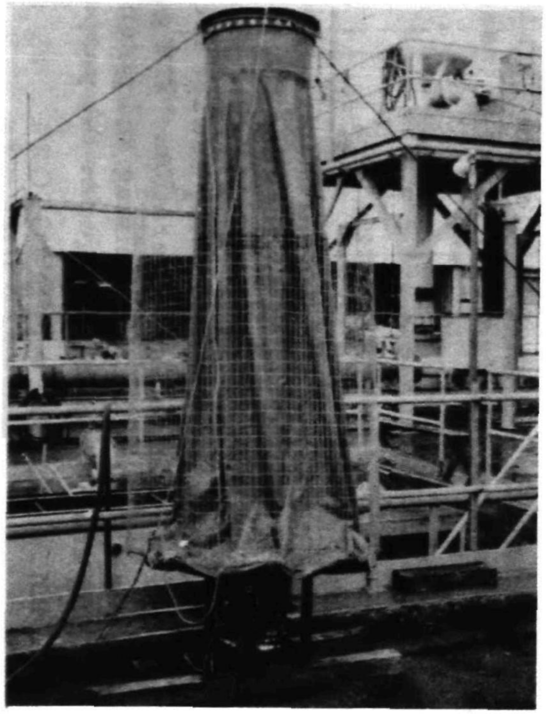
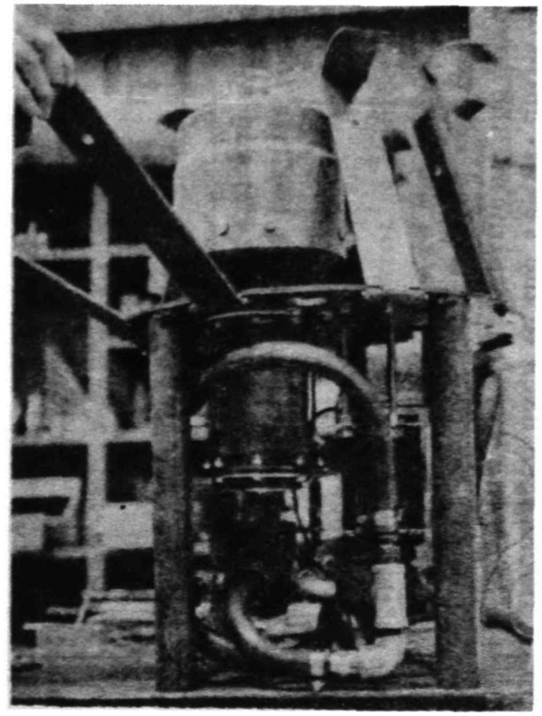


Figure 22 ALTERNATE FLUSHING STATION DESIGNS



Fabric storage tank with the pump and valves mounted underneath.



The discharge valve operator and bottom bag support arms are shown above the bottom support plate of the prototype flush station with the fabric tank removed.

Figure 23 PROTOTYPE FLUSH STATION

The bag remains full and the control valves remain in the hold position until the timer rotates the valve 90 degrees to the next position, shown in Figure 24D, and restarts the pump. The pump then pumps sewage from the bag to the dump valve actuator which opens the dump valve and allows the sewage to be discharged back to the sewer. When the level of sewage in the bag reaches the desired minimum, the level control float located near the bottom of the bag is activated and causes the pump to shut off and the four-way valves to rotate to the positions, shown in Figure 24E, where the dump valve actuator is vented through the intake screen and the dump valve is allowed to close.

When the bag is to be filled again, the timer rotates the two four-way valves 90 degrees back to the fill position (Figure 24B) and starts the pump. The complete cycle is then repeated.

PROTOTYPE TESTING

The operation of the prototype flush station was field tested to determine its reliability and feasibility. The various components of the prototype were first tested individually and then their combined performance was evaluated (Table 17, Appendix C).

After the function of the various components had been verified, the prototype was assembled and was installed over a manhole near the effluent end of the test sewers. The sequence of operation previously described, was run through several times to determine the average discharge rate and to verify the reliability of the supply and control system. Also the lifting mechanism, designed to allow the unit to be lifted in and out of manholes, was operated several times to insure correct performance.

DISCUSSION

The prototype flush station (Figure 23) was tested mechanically and found to be very functional and quite capable of performing the operations necessary to hydraulically flush sewers (see Table 17). The sewage supply and release mechanisms were tested using sewage from the test sewers and were found to provide reliable operation. The general design of the flush station was shown to be a promising and potentially inexpensive method of holding and releasing sewage for the purpose of flushing sewers.

Although the basic design of the prototype was found to be very functional, there are several improvements that can be made. Several beneficial design changes became evident during the construction and

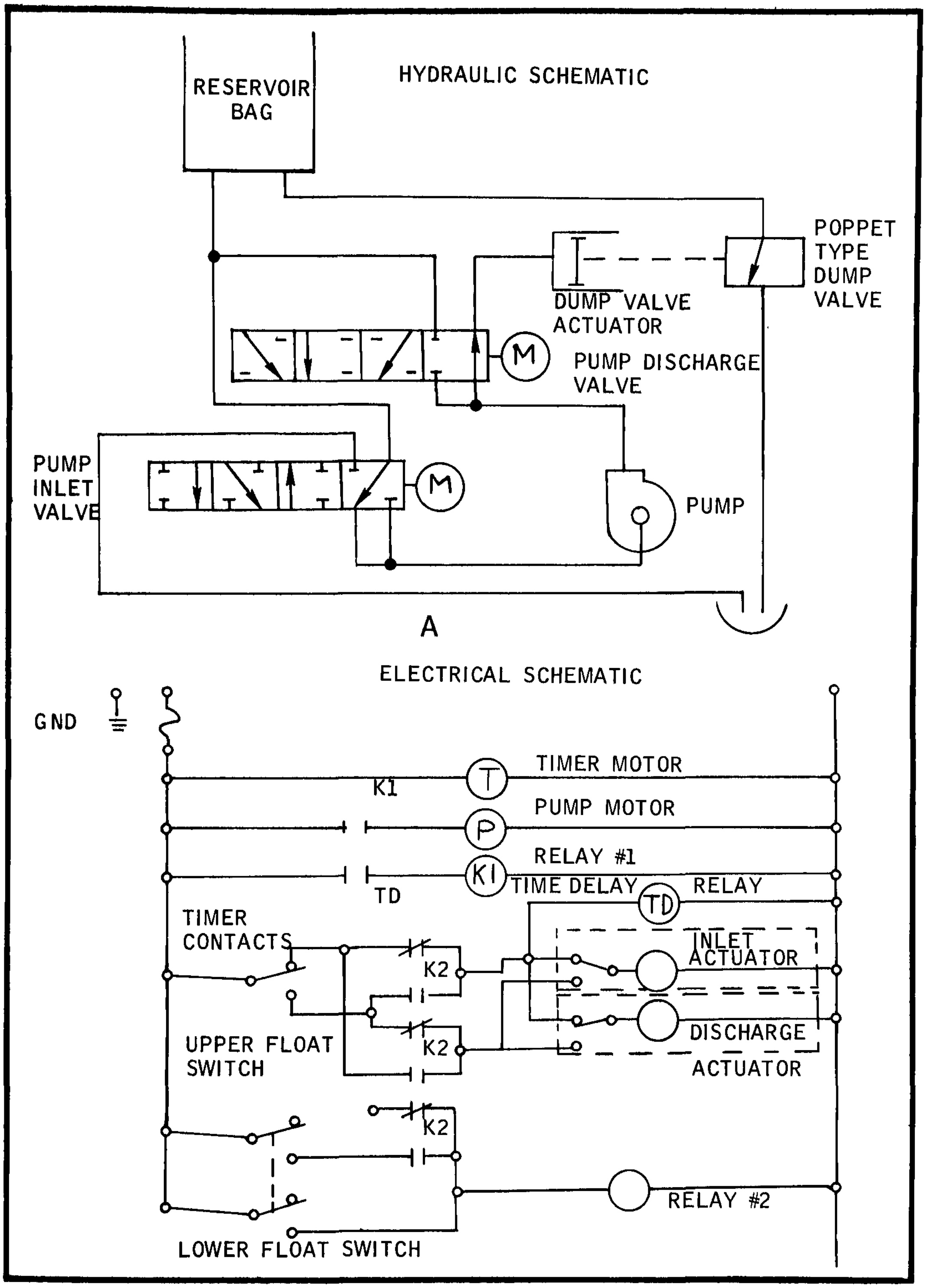


Figure 24 PROTOTYPE FLUSH STATION CONTROL AND OPERATION

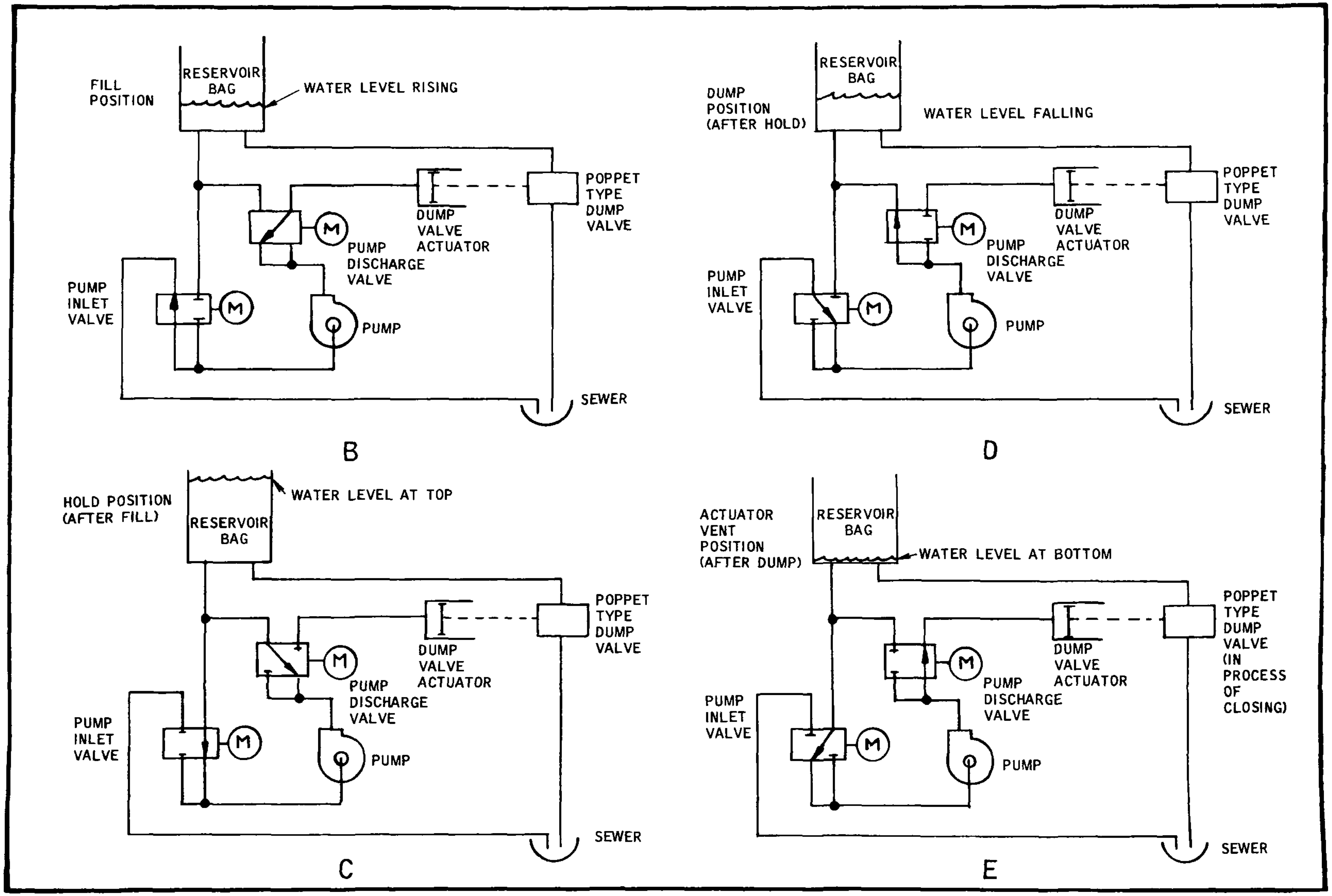


Figure 24 PROTOTYPE FLUSH STATION CONTROL AND OPERATION (CONTINUED)

testing of the prototype. These changes were incorporated into the proposed improved design shown in Figure 25. This design will allow considerable simplification in the construction and installation of the flush station and assembly of the piping. Also the number and complexity of the control circuits required has been greatly decreased by this design.

An improved design of the in-line type dam is shown in Figure 26. This design allows the excess sewage to flow out under the dam, thus reducing the solids buildup in the sewer behind the dam. Also the dam assembly is arranged so that the dam can rapidly be removed up from the sewer by applying a vacuum, thus allowing the stored sewage to be released quickly to develop maximum cleansing velocities. This also allows the dam to be pulled completely clear of the sewer during storms when the fabric of the dam might be damaged. Also the dam is proposed to be installed in the center of a manhole which allows easy installation and maintenance of the dam. The overflow weirs that are shown on either side of the sewer immediately upstream of the dam provide the necessary protection against accidental flooding of the sewer upstream of the dam.

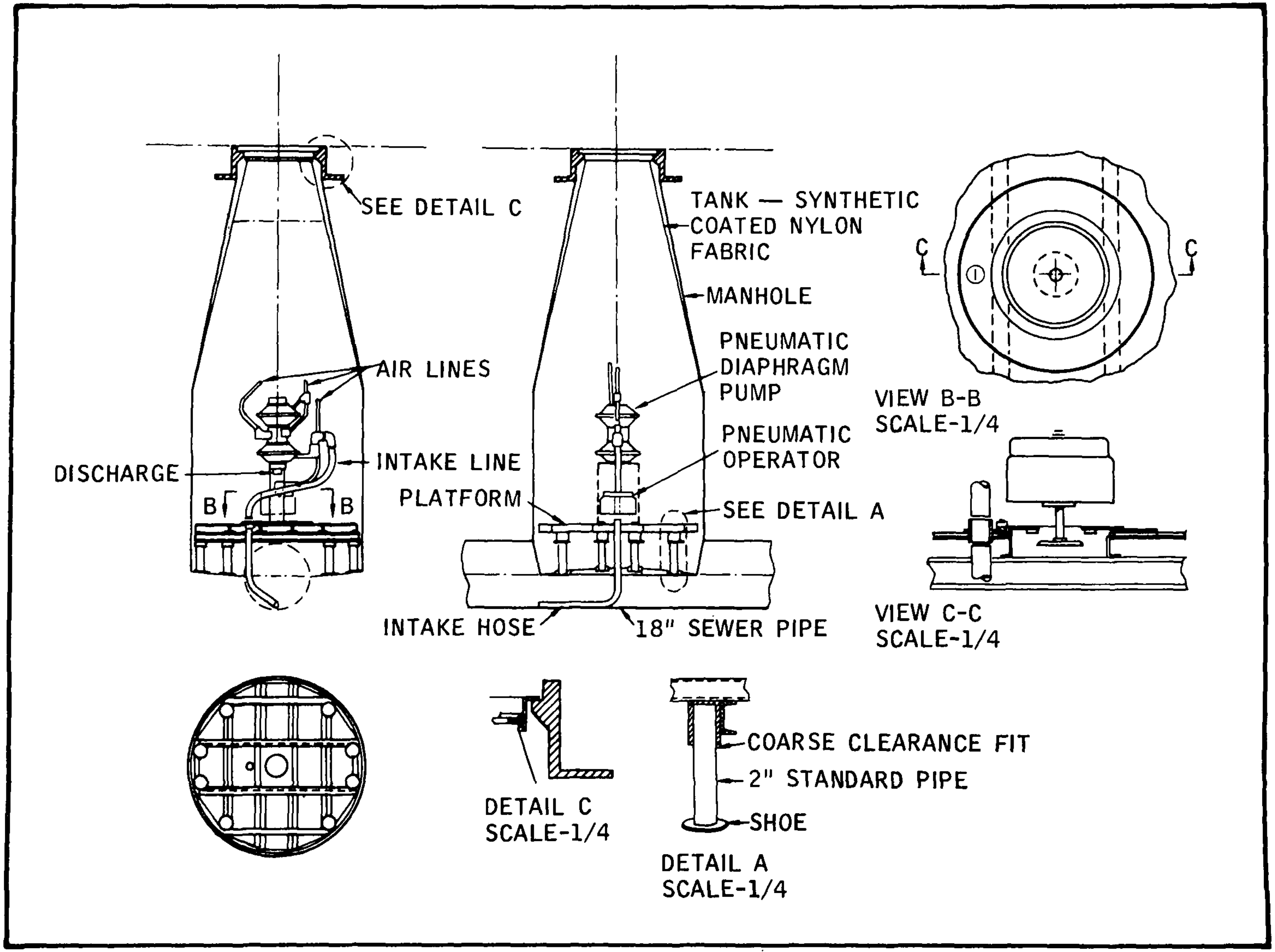


Figure 25 PROPOSED FABRIC BAG FLUSH STATION

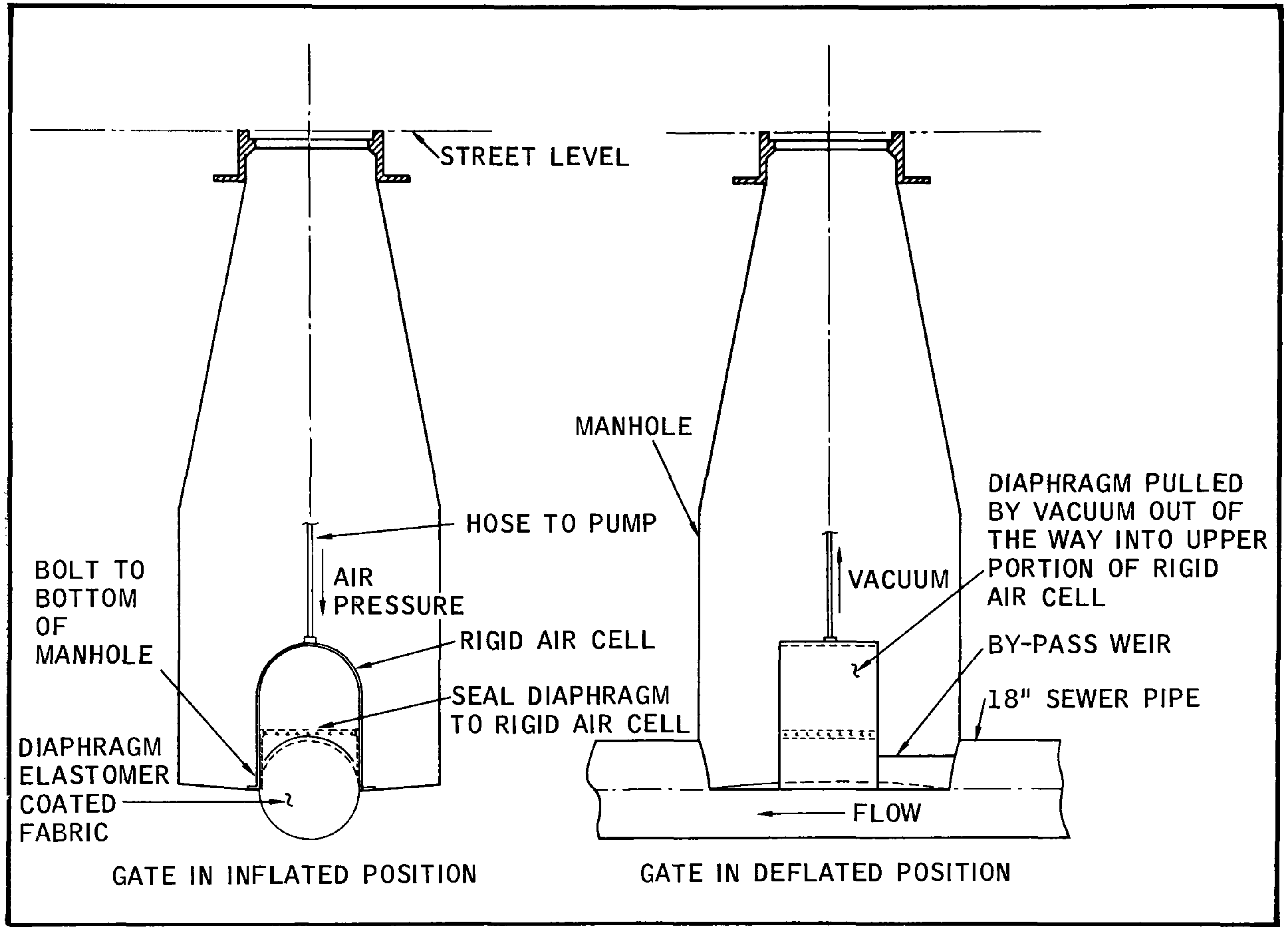


Figure 26 PROPOSED IN-LINE DAM FLUSH STATION

SECTION VIII

ARRANGEMENTS FOR FIELD DEMONSTRATION OF PERIODIC FLUSHING OF COMBINED SEWER LATERALS

Any pollution control technique must be demonstrated under practical field conditions before it can be widely accepted and used. The objective of this phase of the project was to expedite a demonstration (Phase III) of the periodic sewer flushing technique in an operating sewer system.

SOLICITATIONS FOR DEMONSTRATION LOCATIONS

1968-69 Hammond, Indiana. Worked with consulting engineers Consoer, Townsend and Associates to get an expression of interest of the Sanitary District of Hammond to explore the possibility of setting up a demonstration. Prepared two tentative flushing system layouts and demonstration plans for the Tapper Avenue area. The Sanitary District expressed a preference for the Walnut Avenue area because relief sewers had already been installed there. Prepared tentative flushing system layout for the Walnut Avenue area. The Sanitary District of Hammond finally ruled out the possibility of a periodic flushing system demonstration based on the work load in the sanitary district, the fear of legal action if any flooding were to occur, and the cost to the district.

1969, Cleveland, Ohio. Cleveland responded favorably to suggestions for a sewer flushing demonstration. Information was supplied to the consulting engineers Engineering Science, Inc. to serve as a basis for including sewer flushing as one of several methods of storm water overflow pollution control to be demonstrated. The area for the sewer flushing study was to be from West 102nd Street to West 111th Street between Clifton Boulevard and Baltic Road. Part of the flushing water was to be supplied from storm water collected in a demonstration of local detention and storage.

Cleveland had taken no action on the proposal prepared for them by Engineering Science because of the press of more urgent matters. Although no time table can be given for action on the proposal, it is not necessarily dead.

1969, San Francisco, California. Requested Gene Kazmierczak, Chief Engineer, Engineering Science, Inc., Consulting Engineers, Arcadia, California, to review possibilities of interest in a Sewer Flushing Demonstration Grant Application with client, City Engineer, San Francisco, in connection with Combined Sewer Demonstration Project concerning Outfall Treatment. Kazmierczak reported no interest.

1970, Alexandria, Virginia. Reviewed possibility of a Sewer Flushing Demonstration Project as a solution for minimizing Combined Sewer Overflow pollution with Carl Rehe, Greeley and Hansen; Chicago, Illinois; consultants for Alexandria, Virginia; re: Enforcement Proceedings. Rehe reported interest would be subject to study program findings and doubted any significant pollution from storm overflows.

1970, Detroit, Michigan. Reviewed background information on periodic flushing of laterals with A. C. Davanzo and John W. Brown, Acting Sanitary Engineer. Their reaction was favorable with a particular interest in using inflatable dams for in-line storage of sewage for flushing. They supplied a sewer map of a tentative demonstration location for preliminary layout of a flushing system. A commitment to use the area for a demonstration was to be contingent on details of the system.

The tentative flush system layout was made for an area bounded by Fenkell Avenue, Lamphere Avenue, Midland Avenue, and Rockdale Avenue. Three parallel laterals will be used with identical slopes, diameters and lengths. One of the laterals will be used as a control with no flushing. Inflatable flush gates will be installed for in-line flushing liquid storage in one of the laterals. The other lateral will be flushed from sewage stored in fabric flush tanks inserted in the existing manholes similar to the prototype flush station developed under this contract.

The information on the proposed demonstration has not been in the hands of the Detroit personnel long enough for there to be a reply at the time this report is being prepared.

SECTION IX

ACKNOWLEDGEMENTS

The two inflatable dams that were tested were supplied without charge by Imbertson Engineering, Los Angeles, California.

Consulting on the structural design of the test facility was provided by the San Jose Office of Consoer, Townsend and Associates.

Mr. Milton Spiegel, FMC Corporation Staff Consultant, was responsible for much of the promotional and investigational work done in the negotiations for flushing demonstration sites.

Mr. William Kannenberg and Mr. Manher Naik of the FMC Corporation Management Information Systems group were primarily responsible for development of the mathematical model.

The equipment design, field testing, laboratory analysis, data reduction and the report preparation were all accomplished through the efforts of the Environmental Engineering Department of FMC Corporation's Central Engineering Laboratories, under the supervision of D. W. Monroe and J. P. Pelmak and the direction of F. F. Sako.

The support of the project by the Environmental Protection Agency and the guidance and help provided by the Contract Officers, Messrs. A. D. Beattie and L. L. Weinbrenner and by Messrs. G. A. Kirkpatrick and W. A. Rosenkranz is acknowledged with sincere appreciation.

SECTION X

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SECTION XI

GLOSSARY OF TERMS

Average Cleansing Efficiency - The percent of deposited solids removed from a given length of sewer.

Deposited Solids - The quantity of suspended solids that settled out of the sewage passing through the sewer and is left deposited over the given length of sewer.

Periodic Flushing - Systematic induction of stored liquid into sewers at relatively high rates of release.

Suspended Solids - Particulate materials suspended in sewage.

Volatile Suspended Solids - That portion of the suspended solids that is organic in nature.

Total Organic Carbon - The total quantity of carbon present in the suspended solids as a result of the presence of organic materials.

5-Day BOD - A measure of the oxygen required for the biochemical degradation of organic material.

Average Flush Rate - The average rate at which the flush liquid is discharged into the sewer.

Volume of Flush - The total volume of liquid added to the sewer by the flush release.

Relative Solids Distribution - The distribution of deposited solids over the length of the sewer.

Relative Correlation - A measure of the ability of a general relationship to predict the value of an experimental parameter.

Depth of Flush Wave - The maximum depth that a given flush wave reaches a specified distance downstream of the induction point.

Flush Wave - The unsteady flow condition resulting from the rapid increase in the flow rate in an open channel or gravity sewer.

Dry Weather Flows - The flows in a combined sewer that result from domestic sewage discharges with no significant contribution by storm water runoff.

Combined Storm Flow - The flows in a combined sewer that result from the combination of domestic sewage discharges and storm water runoff.

Combined Sewer Overflows - The quantities of combined storm flow that are discharged without treatment to receiving streams and lakes.

SECTION XII

APPENDICES

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APPENDIX A

RESULTS FROM SHAKEDOWN TESTING

Table 3 RESULTS FROM FRICTION COEFFICIENT TESTS

Pipe Diameter -D- (in.)	Pipe Slope -S- (ft/ft)	Average Discharge -Q- (gpm)	Average Flow Depth -d- (in.)	Average Velocity -V (fps)	Average Mannings Friction Coefficient -n-
18	0.001	819	7.56	2.58	0.0088
18	0.001	658	7.20	2.21	0.0100
18	0.001	285	4.80	1.63	0.0109
12	0.002	829	9.00	2.91	0.0104
12	0.002	693	8.40	2.63	0.0113
12	0.002	291	5.51	1.89	0.0135

Table 4 RESULTS FROM HYDRAULIC MIXING TEST USING SEWAGE

Volume of Sewage (gals.)	Mixing Time (min)	Volumes Displaced (1)	Average Suspended Solids Concentration mg/liter	
			Before Mixing	After Mixing
1200	1.2	1	178	187
2000	2.0	1	163	159
2800	2.8	1	180	171
2000	4.0	2	130	138

(1) Pumping rates were constant at approximately 1,000 gpm.

Table 5 RESULTS FROM HYDRAULIC MIXING TESTS USING FINE SAND

Volume of Water	Sand Added	Actual Concentration of Sand	0.5 Volumes Displaced (1)		1.0 Volumes Displaced (1)		2.0 Volumes Displaced (1)	
			Mixing Time	Sand Concentration in Sample	Mixing Time	Sand Concentration in Sample	Mixing Time	Sand Concentration in Sample
(gal)	(lb)	(mg/liter)	(min)	(mg/liter)	(min)	(mg/liter)	(min)	(mg/liter)
1200	0.50	50	0.6	54.2	1.2	50.5	2.4	50.2
2000	0.84	50	1.0	40.1	2.0	51.0	4.0	49.6
2800	1.17	50	1.4	39.3	2.8	49.2	5.6	50.8
1200	2.00	200	0.6	182	1.2	202	2.4	200
2000	3.34	200	1.0	215	2.0	200	4.0	198
2800	4.66	200	1.4	150	2.8	202	5.6	199
1200	6.00	600	0.6	510	1.2	202	2.4	201
2000	10.00	600	1.0	620	2.0	598	4.0	603
2800	14.00	600	1.4	585	2.8	597	5.6	597

(1) The pump rate was constant at 1,000 gpm.

APPENDIX B

FIELD AND LABORATORY PROCEDURES

SEWER FLUSHING EVALUATION
FIELD SAMPLING RECORD

DATE: 2-18-70 PAGE 1 OF 1

INVESTIGATOR: L. N. SLOPE: 18" PIPE .001

TEST NO. 46 12" PIPE .002

Test Period Description No. 1			Time — PST		Average Discharge (gpm)	Average Depth of Flow (in.)	Average Velocity (fps)	Total Elapse Time (min)	Total Discharge (gals.)	Length of Pipe Downstream of Flow Induction Point (ft)
			Begin	End						
Solids Build up	Sample Numbers	18" Pipe			50	2.1		657	39,420	
		12" Pipe			10	1.3		19.5		
Flush Evaluation	Tank No. 1 3	18" Pipe							19"	
	2	12" Pipe							18"	5 psi 900
	Tank No. 1	18" Pipe							9"/15 secs.	3 psi at 5 psig 900
		12" Pipe							5"/15 secs.	900 gals. at 5 psig
	Tank No. 3	18" Pipe								
		12" Pipe								
Storm Simulation Tests	Test No. 1 5	18" Pipe							24"	
	4	12" Pipe							24"	
	Test No. 2 7	18" Pipe							26"	
	6	12" Pipe							24"	
	Test No. 3 9	18" Pipe							38"	
	8	12" Pipe							36"	
	Test No. 4 11	18" Pipe							40"	
	10	12" Pipe							40"	
	Test No. 5	18" Pipe								
		12" Pipe								
	Test No. 6	18" Pipe								
		12" Pipe								
	Test No. 7	18" Pipe								
		12" Pipe								

SEWER FLUSHING EVALUATION
FIELD HYDRAULIC AND SOLIDS DATA SHEET

DATE: 2-18-70 Page 1 of 3

INVESTIGATOR: L. N. & DEL. TEST No. 46

Inspection Point No.	Test Pipe	Location of Point With Respect to Downstream End of Pipe (ft)	Comments (Approximate)
1	18" Pipe	3 - 4	1/32" of solid buildup, flow 2"
	12" Pipe	3 - 4	1/32" of solid buildup, flow 1"
2	18" Pipe	10 11	1/8" of solid buildup, flow 2-1/2"
	12" Pipe	10 11	1/16" of solid buildup, flow 1"
3	18" Pipe	15 16	1/16" of solid buildup, flow 2-1/4"
	12" Pipe	15 - 16	1/32" of solid buildup, flow 2"
4	18" Pipe	21 - 22	1/8" of solid buildup, flow 2"
	12" Pipe	21 - 22	1/16" of solid buildup, flow 1-1/4"
5	18" Pipe	41 42	1/32" of solid buildup, flow 2"
	12" Pipe	41 - 42	1/32" of solid buildup, flow 1-1/4"
6	18" Pipe	52 - 53	1/64" of solid buildup, flow 1"
	12" Pipe	52 - 53	1/64" of solid buildup, flow 1-1/2"
7	18" Pipe		
	12" Pipe		
8	18" Pipe		
	12" Pipe		

LABORATORY PROCEDURES

I TOTAL SUSPENDED SOLIDS ANALYSIS

A. Apparatus

1. Millipore filtering equipment
2. Whatman glass filter paper, GF/C 4.25 CMS
3. Pipets, graduated cylinder

B. Procedure

1. Weigh a filter paper on the analytical balance and place it in position on the filtering apparatus.
2. Depending on the type of sample, pipet or measure by graduated cylinder an appropriate size sample to the filter paper and apply vacuum.
3. Rinse the measuring device and filter funnel with distilled water and after the water has been extracted, remove the filter paper and place it in drying oven for 30 minutes at 103 to 105° C.
4. Cool the filter paper in a desiccator and reweigh.
5. Run a blank in the same manner using distilled water.

C. Calculation

$$\text{mg/liter Suspended Matter} = \frac{(A - B) + (C - D) \times 1000}{E}$$

where

A = Weight of filter paper and dried solids } Sample
B = Weight of filter paper only } Sample
C = Weight of filter paper only } Blank
D = Weight of filter paper dried } Blank
E = ml sample

II VOLATILE SUSPENDED SOLIDS ANALYSIS

A. Apparatus

1. Muffle Furnace, 0 to 1100°C

B. Procedure

1. Place the dried filter paper from the total suspended solids analysis in an alundum crucible and place in muffle furnace.
2. Ignite the residue on the filter paper at 600°C for approximately 1 hr.
3. Cool the crucible and its substance in a desiccator and reweigh the filter paper only.
4. Run the blank from the total suspended solids analysis in the same manner.

C. Calculation

$$\text{mg/liter Volatile Suspended Matter} = \frac{(A - B) - (C - D) \times 1000}{E}$$

where

A	=	Weight of filter paper and residue	Sample
B	=	Weight of filter paper and residue after ignition	Sample
C	=	Weight of filter paper only	Blank
D	=	Weight of filter paper after ignition	Blank
E	=	ml sample	

III TOTAL ORGANIC CARBON ANALYSIS

A. Apparatus

1. Beckman IR-315 Carbonaceous Analyzer
2. Hamilton #705 N/LT Microsyringe, 50 μl capacity
3. Waring blender

B. Reagents

1. Glacial acetic acid: ACS grade
2. Hydrochloric acid: 1 + 5

C. Standardization

1. Accurately weigh 1.000 gm of glacial acetic acid into a 1-liter volumetric flask and dilute to volume with CO_2-free distilled water. 1 ml = 1.0 mg of Acetic acid = 0.400 mg of C.

2. Prepare 5, 10, 15, 20, and 25 ml aliquots from stock solution and dilute to volume in 100 ml volumetric flasks. The above dilutions represent 20, 40, 60, 80, and 100 mg/liter of carbon respectively.
3. Starting with the highest concentrations, inject a 20 µl sample and adjust the instrument to that concentration by moving the gain control located on the front panel.
4. Continue to inject samples from the same concentration and adjusting the gain control until successive results are obtained.
5. Proceed with the remainder of the standards.
6. Plot the average peak heights obtained against the standard concentration on a graph.

D. Procedure

1. Place a portion of the sample in a Waring blender and mix thoroughly for 2 minutes.
2. If sample is to be determined for total organic carbon (TOC), add a few drops of HCl solution and remove CO_2 by bubbling Helium through the sample.
3. Prepare the necessary dilution and inject a 20 µl sample and record the peak height.
4. Repeat paragraph 3 until successive results are obtained.
5. If sample is to be analyzed for Total Carbon (TC), make the necessary dilutions and repeat steps 3 through 4.
6. Estimate the concentration in the sample by comparing the reading with the standard curve.

NOTE: For additional information, refer to instruction manual Beckman 61008.

BOD_5 - TOC RELATIONSHIPS FOR CENTRAL ENGINEERING LABORATORIES (CEL) WASTEWATERS

INTRODUCTION

During the testing of various types of activated sludge treatment at CEL over a period of 18 months, concentrations of BOD_5 and TOC were measured for many samples of sewage. These accumulated results are the basis for the correlations of BOD_5 with TOC presented in the following discussion.

CEL SEWAGE

In most wastes, the primary source of BOD_5 is the biological oxidation of organic carbonaceous material. For this reason, the BOD_5 should be directly related to the waste's TOC. As shown in Figure 27, there are two straight line relationships between BOD_5 and TOC. For a TOC below 300, the BOD_5 is equal to 1.5 times the TOC; above a TOC of 300, the BOD_5 is equal to 1.8 times the TOC. The high-range relationship should prove satisfactory for a first order estimate over the entire range.

STATISTICAL ANALYSIS

A statistical analysis was performed on the correlations of BOD_5 with TOC to determine the accuracy with which the BOD_5 can be calculated from the TOC. For each pair of BOD_5 and TOC analyses, the predicted BOD_5 was calculated using the appropriate correlation. The deviation of the predicted BOD_5 from the measured BOD_5 was calculated as a percent of the predicted BOD_5. The distribution of the error in the predicted BOD_5 was determined by plotting this error on probability paper in Figures 28 through 30. A summary of the accuracy on the correlations at the 80 percent confidence level is presented in Table 6.

CONCLUSIONS

The literature indicates that the BOD_5 of various wastewater can be correlated with their TOC. This report has shown that a correlation between BOD_5 and TOC exists for CEL sewage.

The BOD_5 of the sewage was shown to be equal to 1.5 times the TOC for a TOC $\leq$ 300 mg/liter and equal to 1.8 times the TOC for a TOC $>$ 300 mg/liter. The prediction of BOD_5 can be simplified with little loss in accuracy by using the high range relationship for all sewage strengths.

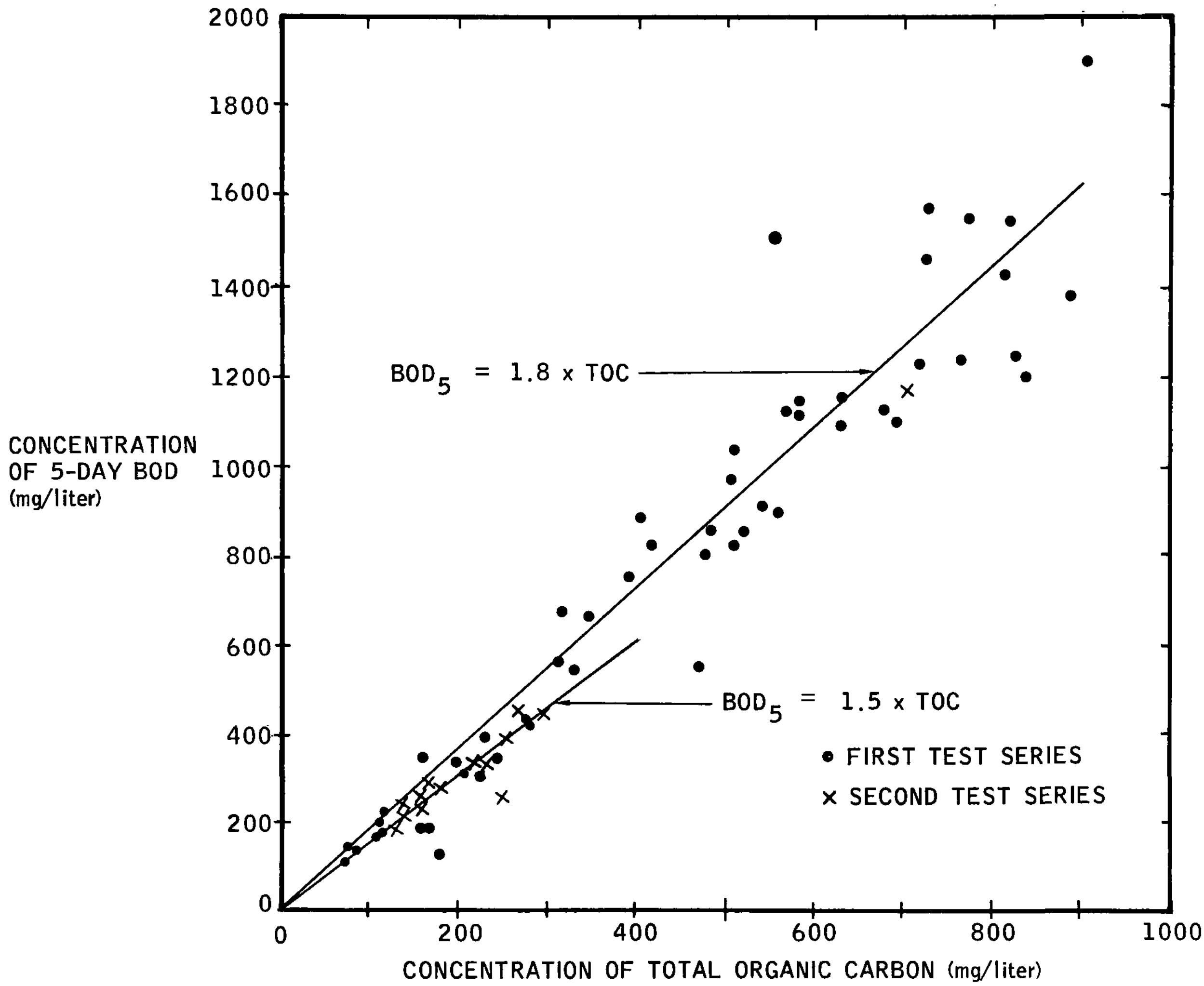


Figure 27 HIGH-RANGE AND LOW-RANGE CORRELATION OF BOD_5 WITH TOC FOR CEL SEWAGE

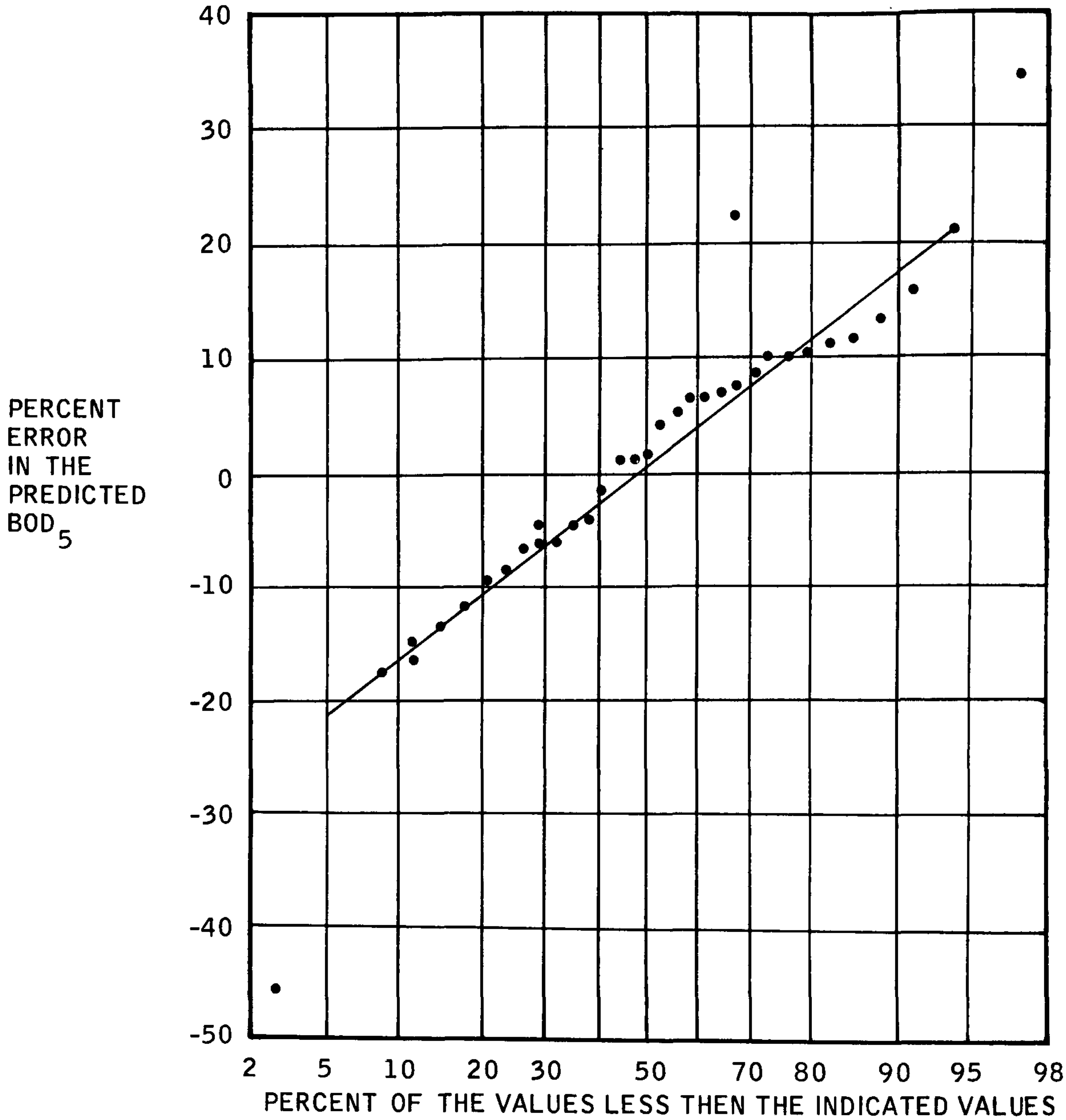


Figure 28 ACCURACY OF HIGH-RANGE CORRELATION OF BOD_5 WITH TOC FOR CEL SEWAGE

(BOD_5 = 1.8 x TOC for TOC > 300)

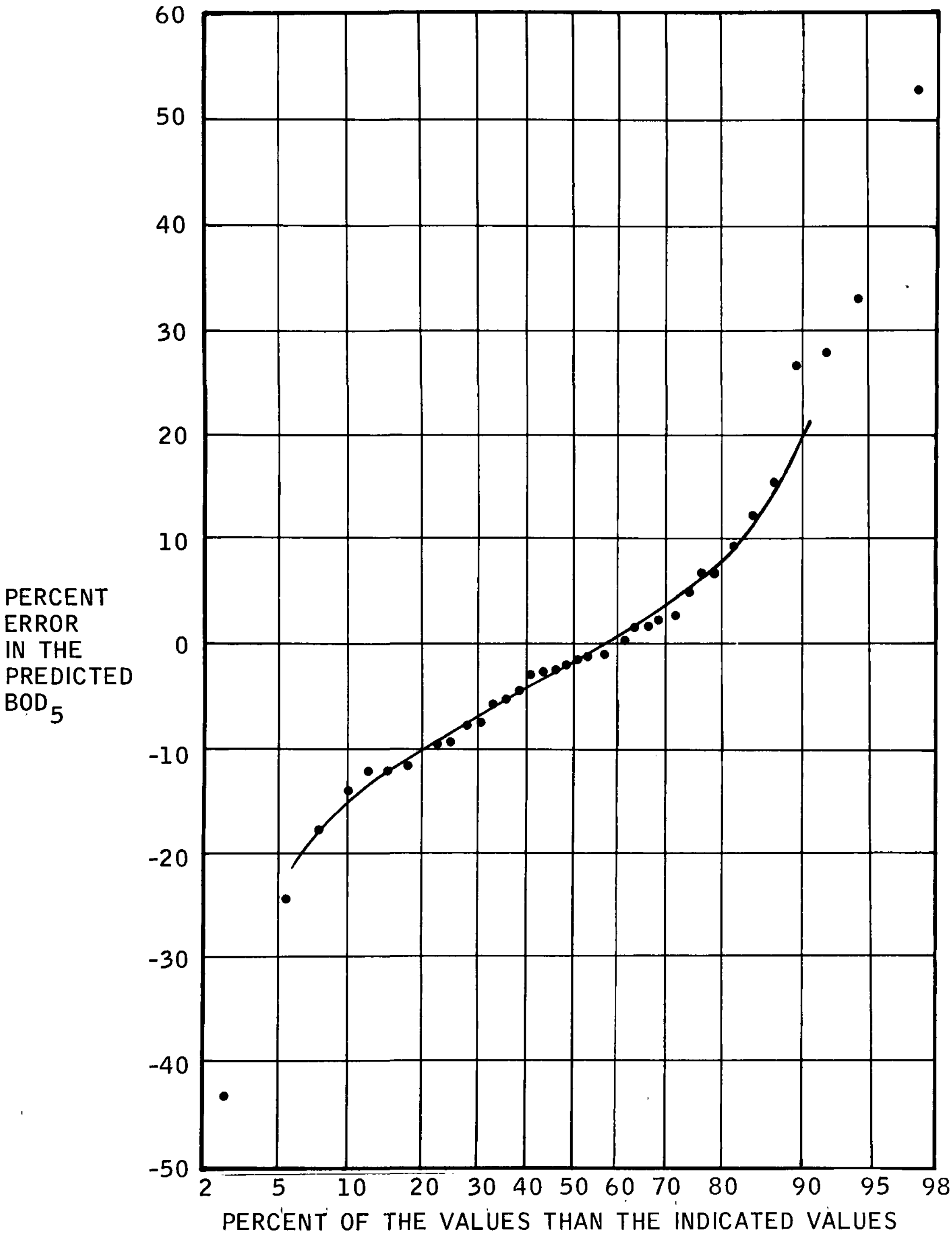


Figure 29 ACCURACY OF LOW-RANGE CORRELATION OF BOD_5 WITH TOC FOR CEL SEWAGE

(BOD_5 = 1.5 x TOC for TOC ≤ 300)

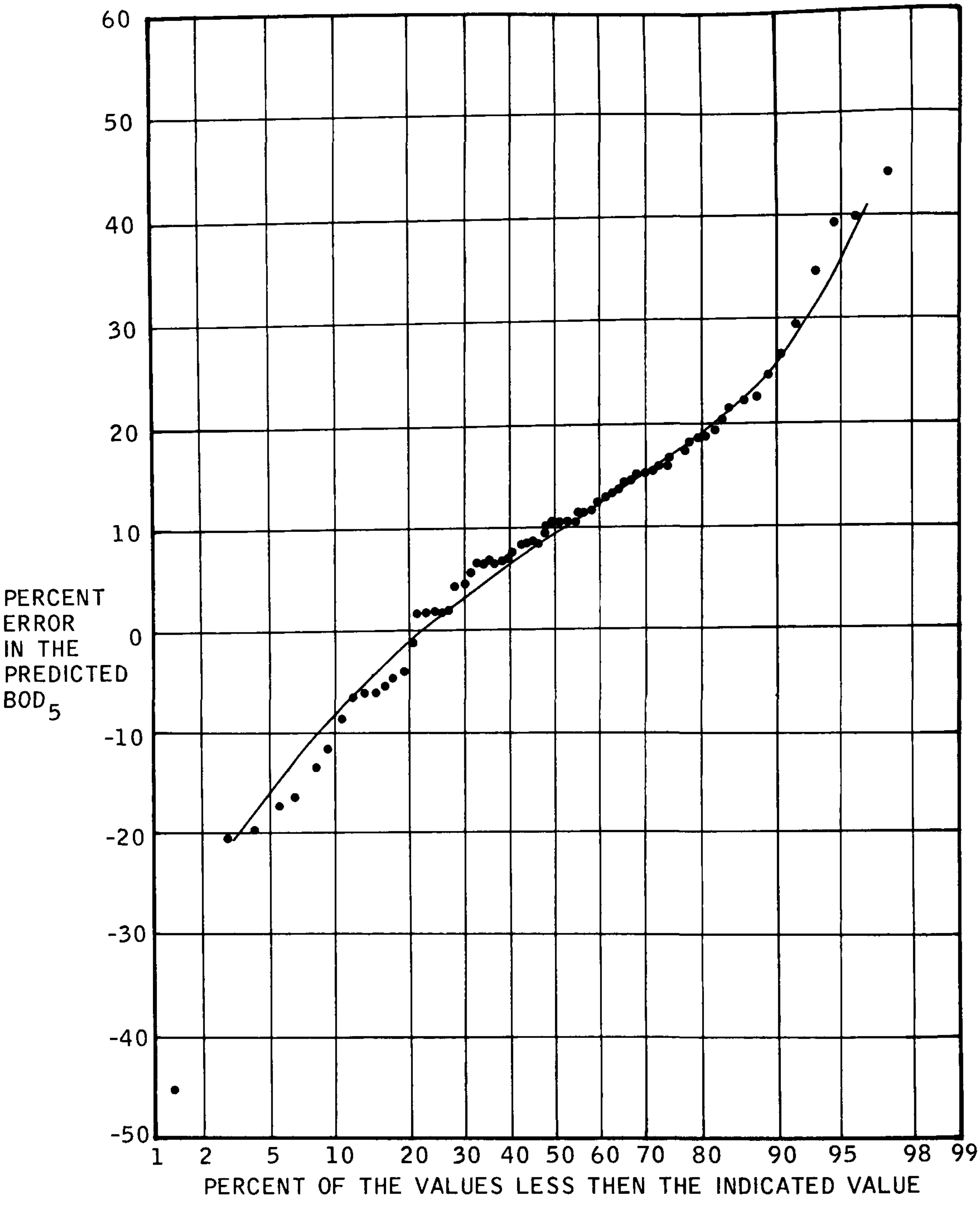


Figure 30 ACCURACY OF SIMPLIFIED CORRELATION OF BOD_5 WITH TOC FOR CEL SEWAGE

(BOD_5 = 1.8 x TOC for ALL TOC)

Table 6 SUMMARY OF ACCURACY OF BOD_5 TOC RELATIONSHIPS

Waste	Correlation	Percent Error in the Predicted BOD_5 at 80 Percent Confidence Level
CEL Sewage (High Range)	$BOD_5 = 1.8 \times TOC$ $TOC > 300$	-17 to 17
CEL Sewage (Low Range)	$BOD_5 = 1.5 \times TOC$ $TOC \leq 300$	-15 to 20
CEL Sewage (Simplified Correlation)	$BOD_5 = 1.8 \times TOC$ All TOC	-9 to 26

Table 7 SUMMARY OF RESULTS FROM SOLIDS DISTRIBUTION TESTS

Sewer Description	Number of Tests Run	Pipe Slope	Sewage Base Flow (gpm)	Average Quantity of SS Deposited in the Sewer (lbs)	Average Proportional Distribution of SS Along the Pipe Length				Average Quantity of VSS Deposited in the Sewer (lbs)	Average Proportional Distribution of VSS Along the Pipe Length				Average Quantity of TOC Deposited in the Sewer (lbs)	Average Proportional Distribution of TOC Along the Pipe Length			
					In the First 267 ft	In the Next 255 ft	In the Next 108 ft	In the Last 160 ft		In the First 267 ft	In the Next 255 ft	In the Next 108 ft	In the Last 160 ft		In the First 267 ft	In the Next 255 ft	In the Next 108 ft	In the Last 160 ft
18 Inch Sewer	3	0.001	10	4.36	0.495	0.376	0.053	0.076	2.68	0.441	0.430	0.047	0.082	1.22	0.267	0.466	0.092	0.175
	1	0.001	30	5.70	0.426	0.426	0.070	0.078	2.05	0.351	0.470	0.081	0.098	1.29	0.243	0.470	0.114	0.173
	2	0.001	50	3.75	0.356	0.476	0.088	0.080	1.97	0.261	0.510	0.114	0.115	0.97	0.219	0.474	0.136	0.171
	2	0.002	10	3.50	0.483	0.400	0.050	0.067	2.08	0.392	0.497	0.044	0.067	0.80	0.387	0.382	0.092	0.139
	2	0.002	50	5.51	0.441	0.392	0.078	0.089	1.89	0.388	0.417	0.101	0.144	0.88	0.259	0.387	0.148	0.206
	3	0.004	10	3.26	0.500	0.315	0.083	0.102	1.88	0.405	0.379	0.097	0.119	1.32	0.332	0.342	0.165	0.161
	3	0.004	50	4.44	0.481	0.296	0.105	0.118	2.42	0.385	0.339	0.128	0.148	1.41	0.340	0.313	0.167	0.180
12 Inch Sewer	2	0.002	10	1.89	0.568	0.214	0.106	0.112	1.07	0.505	0.186	0.133	0.176	0.56	0.314	0.282	0.208	0.196
	1	0.002	20	4.37	0.490	0.230	0.109	0.171	1.62	0.409	0.227	0.130	0.234	1.16	0.268	0.258	0.182	0.292
	2	0.002	30	3.54	0.413	0.245	0.112	0.230	2.15	0.312	0.268	0.128	0.292	1.09	0.222	0.233	0.156	0.389
	2	0.004	10	2.34	0.483	0.284	0.096	0.137	1.48	0.396	0.335	0.092	0.177	0.89	0.472	0.212	0.116	0.200
	2	0.004	30	2.21	0.410	0.303	0.121	0.166	0.83	0.353	0.315	0.138	0.194	0.67	0.426	0.253	0.129	0.192
	3	0.006	10	1.66	0.491	0.237	0.099	0.173	1.00	0.413	0.281	0.113	0.193	0.77	0.295	0.275	0.180	0.250
	3	0.006	30	3.01	0.423	0.299	0.098	0.180	1.61	0.408	0.318	0.123	0.151	1.11	0.303	0.300	0.157	0.240
	1	0.008	10	6.93	0.384	0.301	0.223	0.092	1.57	0.302	0.255	0.144	0.299	0.62	0.275	0.330	0.152	0.243
	1	0.008	10	0.93	0.291	0.347	0.120	0.242	0.36	0.157	0.261	0.321	0.261	0.49	0.282	0.229	0.191	0.298

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (1 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F$ (gal.)	Pipe Diameter (in)
1	35.1	35.5	0.0	267	.001	50	711	368	18
2	24.0	28.6	0.0	527	.001	50	711	368	18
3	20.4	27.8	0.0	635	.001	50	711	368	18
4	26.7	26.7	0.0	795	.001	50	711	368	18
5	79.3	84.3	0.0	267	.002	10	250	680	12
6	71.0	72.9	0.0	514	.002	10	250	680	12
7	59.7	63.8	0.0	622	.002	10	250	680	12
8	64.2	70.2	0.0	782	.002	10	250	680	12
9	57.9	73.9	51.6	267	.001	50	1519	380	18
10	11.5	7.9	43.0	527	.001	50	1519	380	18
11	15.5	16.3	37.6	635	.001	50	1519	380	18
12	15.8	19.3	35.0	795	.001	50	1519	380	18
13	71.6	75.5	46.7	267	.002	10	1053	527	12
14	68.9	71.1	51.5	514	.002	10	1053	527	12
15	64.0	67.5	49.5	622	.002	10	1053	527	12
16	57.3	63.1	47.5	782	.002	10	1053	527	12
17	61.4	87.5	69.4	267	.001	50	1639	355	18
18	45.5	68.3	63.0	527	.001	50	1639	355	18
19	45.8	70.5	62.1	635	.001	50	1639	355	18
20	44.1	64.1	63.0	795	.001	50	1639	355	18
21	78.7	93.0	63.7	267	.002	10	1102	331	12
22	70.8	88.1	66.7	514	.002	10	1102	331	12
23	66.3	86.4	65.6	622	.002	10	1102	331	12
24	58.2	72.2	61.4	782	.002	10	1102	331	12
25	27.6	44.6	31.7	267	.001	50	451	165	18
26	25.4	29.0	39.0	527	.001	50	451	165	18
27	25.0	32.6	35.8	635	.001	50	451	165	18
28	22.9	35.2	39.7	795	.001	50	451	165	18
29	61.3	74.0	63.9	267	.002	10	632	190	12
30	44.6	51.7	50.7	514	.002	10	632	190	12
31	40.6	51.6	52.9	622	.002	10	632	190	12
32	36.0	47.3	43.3	782	.002	10	632	190	12
33	9.8	0.0	2.9	267	.001	50	1543	257	18
34	15.2	0.0	18.4	527	.001	50	1543	257	18
35	9.6	0.0	20.4	635	.001	50	1543	257	18
36	16.9	0.0	34.0	795	.001	50	1543	257	18
37	77.8	77.9	30.7	267	.002	10	1269	233	12
38	67.3	65.6	14.2	514	.002	10	1269	233	12
39	60.0	58.6	17.1	622	.002	10	1269	233	12
40	64.4	66.0	33.3	782	.002	10	1269	233	12
41	55.4	59.5	21.6	267	.001	30	525	674	18
42	32.8	44.4	21.3	527	.001	30	525	674	18
43	36.2	46.9	29.4	635	.001	30	525	674	18
44	35.9	46.8	38.0	795	.001	30	525	674	18
45	75.9	76.1	54.6	267	.002	20	294	662	12
46	75.6	77.3	62.3	514	.002	20	294	662	12
47	73.8	75.4	65.2	622	.002	20	294	662	12
48	43.8	46.5	55.2	782	.002	20	294	662	12
49	66.2	74.4	64.6	267	.001	30	1904	698	18
50	50.7	63.4	65.2	527	.001	30	1904	698	18
51	50.6	63.1	60.5	635	.001	30	1904	698	18
52	51.3	63.6	62.5	795	.001	30	1904	698	18
53	67.8	77.4	45.3	267	.002	20	1063	674	12
54	70.4	77.7	63.6	514	.002	20	1063	674	12
55	70.7	77.4	68.3	622	.002	20	1063	674	12
56	68.3	73.8	69.1	782	.002	20	1063	674	12
57	89.6	91.5	81.0	267	.001	30	2768	692	18
58	67.1	76.8	76.5	527	.001	30	2768	692	18
59	61.4	71.4	68.7	635	.001	30	2768	692	18
60	64.3	74.2	74.1	795	.001	30	2768	692	18
61	90.1	90.1	37.6	267	.002	20	2094	698	12
62	85.2	86.9	52.1	514	.002	20	2094	698	12
63	77.2	79.4	51.2	622	.002	20	2094	698	12

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (2 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F$ (gal.)	Pipe Diameter (in.)
64	81.1	81.8	65.5	782	.002	20	2094	698	12
65	63.6	65.5	67.7	267	.001	30	560	355	18
66	28.4	29.2	28.2	527	.001	30	560	355	18
67	25.1	26.1	30.7	635	.001	30	560	355	18
68	22.8	25.6	32.1	795	.001	30	560	355	18
69	57.5	64.3	43.8	267	.002	20	343	355	12
70	39.8	39.7	28.9	514	.002	20	343	355	12
71	36.1	36.4	36.4	622	.002	20	343	355	12
72	33.8	37.3	39.7	782	.002	20	343	355	12
73	58.9	55.6	49.3	267	.001	50	3031	404	18
74	28.0	35.9	40.7	527	.001	50	3031	404	18
75	28.0	36.0	36.3	635	.001	50	3031	404	18
76	26.2	35.3	32.8	795	.001	50	3031	404	18
77	68.4	76.4	61.0	267	.002	10	2205	257	12
78	61.7	63.9	41.4	514	.002	10	2205	257	12
79	58.8	62.1	40.6	622	.002	10	2205	257	12
80	54.9	61.0	42.8	782	.002	10	2205	257	12
81	63.7	54.8	35.6	267	.001	50	1732	404	18
82	33.6	47.2	45.5	527	.001	50	1732	404	18
83	29.1	43.5	44.0	635	.001	50	1732	404	18
84	22.1	35.5	41.3	795	.001	50	1732	404	18
85	77.7	86.5	70.9	267	.002	10	1361	386	12
86	59.8	63.3	52.6	514	.002	10	1361	386	12
87	55.6	59.6	53.1	622	.002	10	1361	386	12
88	48.8	52.3	52.2	782	.002	10	1361	386	12
89	51.5	60.3	74.6	267	.001	50	1680	196	18
90	39.3	51.3	57.2	527	.001	50	1680	196	18
91	37.5	50.4	53.4	635	.001	50	1680	196	18
92	32.9	45.3	52.3	795	.001	50	1680	196	18
93	80.3	86.4	54.7	267	.002	10	1139	190	12
94	59.0	76.2	51.4	514	.002	10	1139	190	12
95	57.4	74.9	56.4	622	.002	10	1139	190	12
96	58.3	66.7	54.7	782	.002	10	1139	190	12
97	57.1	56.6	43.3	267	.001	30	1837	398	18
98	37.4	45.5	52.6	527	.001	30	1837	398	18
99	39.9	40.9	51.9	635	.001	30	1837	398	18
100	29.0	35.5	52.0	795	.001	30	1837	398	18
101	61.4	67.0	39.6	267	.002	20	1372	343	12
102	41.4	40.3	38.8	514	.002	20	1372	343	12
103	36.0	35.1	36.1	622	.002	20	1372	343	12
104	32.0	35.1	41.7	782	.002	20	1372	343	12
105	82.7	83.7	77.7	267	.001	30	2695	404	18
106	65.0	67.4	71.8	527	.001	30	2695	404	18
107	59.8	62.3	71.2	635	.001	30	2695	404	18
108	54.5	57.5	69.8	795	.001	30	2695	404	18
109	84.3	85.5	76.7	267	.002	20	1815	302	12
110	64.6	60.6	56.0	514	.002	20	1815	302	12
111	60.4	56.1	60.4	622	.002	20	1815	302	12
112	53.4	52.2	60.2	782	.002	20	1815	302	12
113	63.1	61.2	77.2	267	.001	30	882	300	18
114	30.1	35.5	73.2	527	.001	30	882	300	18
115	28.9	34.6	72.7	635	.001	30	882	300	18
116	25.2	32.2	73.3	795	.001	30	882	300	18
117	28.4	35.8	47.1	267	.002	20	205	300	12
118	21.7	23.3	47.0	514	.002	20	205	300	12
119	21.6	24.1	50.8	622	.002	20	205	300	12
120	18.4	23.1	52.2	782	.002	20	205	300	12
121	57.6	64.4	64.2	267	.001	30	964	300	18
122	24.5	26.1	56.9	527	.001	30	964	300	18
123	25.7	27.7	57.0	635	.001	30	964	300	18
124	25.9	29.1	56.8	795	.001	30	964	300	18
125	73.5	73.2	65.3	267	.002	20	840	300	12
126	47.0	42.6	50.2	514	.002	20	840	300	12

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (3 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Diameter (in.)
127	42.1	38.8	43.6	622	.002	20	840	300	12
128	37.5	37.9	47.7	782	.002	20	840	300	12
129	87.9	88.7	80.0	267	.001	30	3381	900	18
130	75.2	80.6	76.7	527	.001	30	3381	900	18
131	71.8	77.7	68.3	635	.001	30	3381	900	18
132	65.9	71.1	65.1	795	.001	30	3381	900	18
133	86.2	86.6	58.8	267	.002	20	2278	900	12
134	74.5	72.7	58.7	514	.002	20	2278	900	12
135	71.7	70.1	60.2	622	.002	20	2278	900	12
136	63.1	62.9	58.9	782	.002	20	2278	900	12
137	89.0	90.6	84.0	267	.001	30	2058	900	18
138	82.4	85.4	85.6	527	.001	30	2058	900	18
139	78.0	81.0	82.0	635	.001	30	2058	900	18
140	74.6	77.5	78.8	795	.001	30	2058	900	18
141	84.4	84.5	72.3	267	.002	20	1347	900	12
142	73.6	71.9	74.5	514	.002	20	1347	900	12
143	69.7	68.0	47.2	622	.002	20	1347	900	12
144	62.8	62.0	52.1	782	.002	20	1347	900	12
145	54.5	70.1	52.3	267	.001	30	441	900	18
146	47.5	56.3	50.0	527	.001	30	441	900	18
147	45.2	53.1	46.3	635	.001	30	441	900	18
148	41.7	48.4	44.0	795	.001	30	441	900	18
149	60.3	71.2	41.3	267	.002	20	264	900	12
150	55.5	62.7	41.4	514	.002	20	264	900	12
151	55.3	61.6	46.4	622	.002	20	264	900	12
152	40.5	45.1	38.5	782	.002	20	264	900	12
153	89.0	94.5	87.9	267	.001	10	2131	900	18
154	89.0	94.1	86.4	527	.001	10	2131	900	18
155	87.2	92.4	80.4	635	.001	10	2131	900	18
156	85.0	89.8	71.0	795	.001	10	2131	900	18
157	84.2	82.6	50.7	267	.002	30	1267	900	12
158	77.2	75.8	40.4	514	.002	30	1267	900	12
159	73.0	71.1	42.4	622	.002	30	1267	900	12
160	64.2	59.7	46.5	782	.002	30	1267	900	12
161	89.2	87.5	88.6	267	.001	10	3381	900	18
162	84.0	86.3	91.6	527	.001	10	3381	900	18
163	82.5	85.2	88.7	635	.001	10	3381	900	18
164	80.1	82.4	86.6	795	.001	10	3381	900	18
165	87.0	78.3	80.8	267	.002	30	1911	900	12
166	80.0	74.0	77.8	514	.002	30	1911	900	12
167	73.9	66.8	70.0	622	.002	30	1911	900	12
168	64.9	58.6	61.4	782	.002	30	1911	900	12
169	84.7	91.8	65.2	267	.001	10	420	900	18
170	80.1	87.0	75.1	527	.001	10	420	900	18
171	77.8	84.5	65.7	635	.001	10	420	900	18
172	75.3	82.1	60.1	795	.001	10	420	900	18
173	30.2	46.6	44.8	267	.002	30	323	900	12
174	41.1	46.1	37.9	514	.002	30	323	900	12
175	44.8	50.1	32.8	622	.002	30	323	900	12
176	39.5	41.5	41.5	782	.002	30	323	900	12
177	66.6	63.9	40.9	267	.001	10	367	600	18
178	71.2	67.0	52.1	527	.001	10	367	600	18
179	70.1	64.6	45.3	635	.001	10	367	600	18
180	68.6	63.2	47.4	795	.001	10	367	600	18
181	39.9	69.8	16.4	267	.002	30	294	600	12
182	33.9	68.4	25.6	514	.002	30	294	600	12
183	33.0	67.2	34.4	622	.002	30	294	600	12
184	37.7	70.4	51.4	782	.002	30	294	600	12
185	81.6	87.3	73.6	267	.001	10	1470	600	18
186	73.3	74.1	66.5	527	.001	10	1470	600	18
187	70.7	70.9	63.7	635	.001	10	1470	600	18
188	68.1	68.5	64.9	795	.001	10	1470	600	18
189	79.0	86.0	61.4	267	.002	30	1029	600	12

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (4 of 9)

Observation No.	SS Cleansing Eff. -$\overline{C}_{ESS}$- (%)	VSS Cleansing Eff. -$\overline{C}_{EVSS}$- (%)	TOC Cleansing Eff. -$\overline{C}_{ETOC}$- (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)	Pipe Diameter (in.)
190	75.0	83.4	68.4	514	.002	30	1029	600	12
191	70.2	80.2	67.4	622	.002	30	1029	600	12
192	66.9	79.1	68.8	782	.002	30	1029	600	12
193	77.1	84.0	69.5	267	.001	10	2021	600	18
194	73.1	82.4	71.4	527	.001	10	2021	600	18
195	70.3	81.0	64.4	635	.001	10	2021	600	18
196	67.3	79.4	62.3	795	.001	10	2021	600	18
197	81.9	78.9	64.7	267	.002	30	1878	600	12
198	62.4	51.8	57.7	514	.002	30	1878	600	12
199	65.1	57.1	47.2	622	.002	30	1878	600	12
200	56.2	55.8	52.6	782	.002	30	1878	600	12
201	83.3	79.0	76.5	267	.001	10	343	300	18
202	63.2	73.2	62.2	527	.001	10	343	300	18
203	50.3	69.4	56.3	635	.001	10	343	300	18
204	49.2	67.0	50.9	795	.001	10	343	300	18
205	73.5	49.7	26.6	267	.002	30	196	300	12
206	36.6	23.1	13.1	514	.002	30	196	300	12
207	27.9	29.6	18.1	622	.002	30	196	300	12
208	28.3	36.2	35.6	782	.002	30	196	300	12
209	83.1	91.8	69.8	267	.001	10	790	300	18
210	43.1	41.6	56.3	527	.001	10	790	300	18
211	41.0	40.7	57.2	635	.001	10	790	300	18
212	39.3	40.3	60.5	795	.001	10	790	300	18
213	31.5	47.0	47.8	267	.002	30	679	300	12
214	21.0	32.5	33.5	514	.002	30	679	300	12
215	18.7	28.5	36.2	622	.002	30	679	300	12
216	24.1	33.9	46.7	782	.002	30	679	300	12
217	66.1	66.4	31.6	267	.001	10	1212	300	18
218	61.9	65.7	53.5	527	.001	10	1212	300	18
219	58.1	62.6	52.0	635	.001	10	1212	300	18
220	54.1	60.2	53.9	795	.001	10	1212	300	18
221	83.8	79.4	79.7	267	.002	30	1580	300	12
222	57.1	56.3	59.0	514	.002	30	1580	300	12
223	49.1	49.3	57.0	622	.002	30	1580	300	12
224	46.5	48.2	65.1	782	.002	30	1580	300	12
225	87.6	84.7	81.9	267	.001	30	2572	900	18
226	81.4	82.6	83.3	527	.001	30	2572	900	18
227	77.2	78.2	79.3	635	.001	30	2572	900	18
228	72.2	73.5	78.2	795	.001	30	2572	900	18
229	86.8	86.8	83.6	267	.002	20	2094	900	12
230	81.8	80.1	80.7	514	.002	20	2094	900	12
231	79.2	77.4	77.9	622	.002	20	2094	900	12
232	75.5	72.8	75.7	782	.002	20	2094	900	12
233	86.5	86.5	88.2	267	.001	30	1960	900	18
234	68.1	77.2	82.0	527	.001	30	1960	900	18
235	64.2	73.3	75.5	635	.001	30	1960	900	18
236	59.1	66.9	74.1	795	.001	30	1960	900	18
237	56.5	36.0	67.4	267	.002	20	294	900	12
238	48.2	43.3	47.9	514	.002	20	294	900	12
239	43.4	42.2	52.0	622	.002	20	294	900	12
240	40.6	41.9	49.9	782	.002	20	294	900	12
241	36.7	40.0	40.3	267	.001	50	624	300	18
242	29.4	36.6	50.3	527	.001	50	624	300	18
243	19.5	26.4	43.2	635	.001	50	624	300	18
244	21.7	29.0	45.2	795	.001	50	624	300	18
245	69.2	71.6	51.7	267	.002	10	1102	300	12
246	56.5	54.9	43.3	514	.002	10	1102	300	12
247	50.5	50.4	43.7	622	.002	10	1102	300	12
248	40.5	43.4	39.4	782	.002	10	1102	300	12
249	12.3	25.0	32.5	267	.001	50	269	300	18
250	16.4	21.4	36.4	527	.001	50	269	300	18
251	19.1	25.8	36.4	635	.001	50	269	300	18
252	16.2	22.2	35.0	795	.001	50	269	300	18

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (5 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Diameter (in.)
253	71.9	81.8	68.4	267	.002	10	1078	600	12
254	66.0	73.4	68.1	514	.002	10	1078	600	12
255	62.3	70.1	66.8	622	.002	10	1078	600	12
256	56.7	65.6	57.7	782	.002	10	1078	600	12
257	46.6	45.1	46.7	267	.001	50	759	900	18
258	40.9	53.5	45.6	527	.001	50	759	900	18
259	33.4	44.4	39.5	635	.001	50	759	900	18
260	27.2	39.4	40.1	795	.001	50	759	900	18
261	92.4	90.9	75.8	267	.002	10	2058	900	12
262	85.9	85.0	71.3	514	.002	10	2058	900	12
263	82.7	82.9	72.4	622	.002	10	2058	900	12
264	73.4	76.8	63.8	782	.002	10	2058	900	12
265	61.9	63.2	76.8	267	.001	50	441	900	18
266	49.1	57.3	66.2	527	.001	50	441	900	18
267	48.8	58.0	55.4	635	.001	50	441	900	18
268	45.9	56.0	56.4	795	.001	50	441	900	18
269	65.6	74.8	82.0	267	.002	10	245	900	12
270	61.5	67.5	66.3	514	.002	10	245	900	12
271	60.3	66.9	70.1	622	.002	10	245	900	12
272	53.6	63.8	54.1	782	.002	10	245	900	12
273	82.2	88.8	12.3	267	.001	10	385	600	18
274	72.9	81.7	52.9	527	.001	10	385	600	18
275	70.6	80.2	54.0	635	.001	10	385	600	18
276	67.7	78.2	56.1	795	.001	10	385	600	18
277	64.6	58.7	66.4	267	.002	30	1176	900	12
278	59.3	59.9	67.3	514	.002	30	1176	900	12
279	59.1	60.9	58.2	622	.002	30	1176	900	12
280	56.6	62.0	63.1	782	.002	30	1176	900	12
281	82.0	86.0	65.5	267	.001	10	330	300	18
282	56.6	60.5	39.6	527	.001	10	330	300	18
283	56.0	59.8	43.4	635	.001	10	330	300	18
284	55.2	59.0	47.9	795	.001	10	330	300	18
285	77.2	74.2	47.8	267	.002	30	698	300	12
286	41.8	52.1	34.7	514	.002	30	698	300	12
287	38.2	49.6	43.4	622	.002	30	698	300	12
288	35.5	46.5	52.2	782	.002	30	698	300	12
289	86.1	86.8	88.1	267	.001	50	3234	900	18
290	77.0	81.4	81.8	527	.001	50	3234	900	18
291	75.4	79.8	70.2	635	.001	50	3234	900	18
292	71.7	75.9	69.8	795	.001	50	3234	900	18
293	85.2	92.1	92.2	267	.002	10	1127	900	12
294	81.0	87.3	81.0	514	.002	10	1127	900	12
295	78.0	84.7	82.0	622	.002	10	1127	900	12
296	72.8	80.9	77.5	782	.002	10	1127	900	12
297	85.7	91.0	40.4	267	.001	10	2499	600	18
298	77.3	86.5	70.0	527	.001	10	2499	600	18
299	72.9	83.0	65.4	635	.001	10	2499	600	18
300	70.4	80.5	65.3	795	.001	10	2499	600	18
301	63.0	44.2	33.4	267	.002	30	1065	600	12
302	51.7	50.5	50.2	514	.002	30	1065	600	12
303	45.6	46.9	42.4	622	.002	30	1065	600	12
304	46.3	52.4	53.0	782	.002	30	1065	600	12
305	81.1	89.5	90.3	267	.001	10	1323	300	18
306	63.2	74.6	58.5	527	.001	10	1323	300	18
307	60.8	71.6	56.4	635	.001	10	1323	300	18
308	58.7	69.3	58.5	795	.001	10	1323	300	18
309	30.4	43.8	0.0	267	.002	30	238	600	12
310	21.2	30.8	0.0	514	.002	30	238	600	12
311	20.2	29.1	0.0	622	.002	30	238	600	12
312	23.5	33.9	0.0	782	.002	30	238	600	12
313	51.5	57.4	58.3	267	.001	50	1506	300	18
314	41.7	47.8	50.7	527	.001	50	1506	300	18
315	41.8	47.7	53.6	635	.001	50	1506	300	18

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (6 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Diameter (in.)
316	40.3	46.7	52.2	795	.001	50	1506	300	18
317	69.4	74.5	51.0	267	.002	10	171	300	12
318	51.7	57.2	40.4	514	.002	10	171	300	12
319	49.4	55.9	51.5	622	.002	10	171	300	12
320	41.5	49.4	51.8	782	.002	10	171	300	12
321	80.0	75.8	70.6	267	.001	50	1947	900	18
322	54.6	65.4	63.9	527	.001	50	1947	900	18
323	54.3	64.8	60.5	635	.001	50	1947	900	18
324	52.3	61.8	58.5	795	.001	50	1947	900	18
325	90.7	92.6	83.9	267	.002	20	1543	600	12
326	79.6	81.2	69.7	514	.002	20	1543	600	12
327	73.1	74.7	66.6	622	.002	20	1543	600	12
328	67.1	69.6	59.4	782	.002	20	1543	600	12
329	68.2	65.8	49.6	267	.001	50	1029	600	18
330	43.1	53.3	43.1	527	.001	50	1029	600	18
331	41.8	53.0	46.0	635	.001	50	1029	600	18
332	39.2	52.0	51.4	795	.001	50	1029	600	18
333	78.0	82.6	59.7	267	.002	20	1065	600	12
334	66.7	72.5	45.9	514	.002	20	1065	600	12
335	62.6	69.7	47.8	622	.002	20	1065	600	12
336	57.4	67.0	51.9	782	.002	20	1065	600	12
337	80.1	86.7	94.8	267	.001	10	1764	300	18
338	25.7	31.5	30.4	527	.001	10	1764	300	18
339	24.2	29.4	32.4	635	.001	10	1764	300	18
340	24.5	30.3	38.5	795	.001	10	1764	300	18
341	18.3	32.5	30.5	267	.002	20	257	600	12
342	12.4	18.7	21.8	514	.002	20	257	600	12
343	13.0	18.2	30.5	622	.002	20	257	600	12
344	18.0	24.2	39.0	782	.002	20	257	600	12
345	87.8	92.1	89.0	267	.001	10	1690	300	18
346	61.1	75.1	74.2	527	.001	10	1690	300	18
347	57.4	71.9	73.3	635	.001	10	1690	300	18
348	54.1	69.2	70.7	795	.001	10	1690	300	18
349	72.8	71.7	65.7	267	.002	30	1617	300	12
350	51.7	55.4	50.1	514	.002	30	1617	300	12
351	46.1	51.4	56.4	622	.002	30	1617	300	12
352	45.1	52.2	63.4	782	.002	30	1617	300	12
353	92.6	96.7	54.9	267	.001	10	710	300	18
354	78.1	85.6	68.9	527	.001	10	710	300	18
355	75.6	83.0	66.3	635	.001	10	710	300	18
356	70.7	79.2	64.2	795	.001	10	710	300	18
357	89.8	89.7	84.2	267	.002	30	1347	300	12
358	70.4	73.3	55.4	514	.002	30	1347	300	12
359	63.0	64.7	39.4	622	.002	30	1347	300	12
360	57.6	60.7	52.5	782	.002	30	1347	300	12
361	93.4	95.9	79.2	267	.002	10	2940	900	18
362	92.0	95.6	82.4	527	.002	10	2940	900	18
363	90.2	95.1	68.4	635	.002	10	2940	900	18
364	87.1	93.0	67.4	795	.002	10	2940	900	18
365	93.6	94.9	58.7	267	.004	30	1911	900	12
366	90.8	92.2	45.8	514	.004	30	1911	900	12
367	89.3	90.8	34.8	622	.004	30	1911	900	12
368	86.5	87.0	40.3	782	.004	30	1911	900	12
369	85.5	89.4	67.0	267	.002	10	1323	300	18
370	72.2	81.3	58.2	527	.002	10	1323	300	18
371	69.2	77.6	52.9	635	.002	10	1323	300	18
372	64.9	74.4	52.2	795	.002	10	1323	300	18
373	80.8	80.5	65.9	267	.004	30	1568	300	12
374	75.4	71.6	57.4	514	.004	30	1568	300	12
375	73.4	70.2	53.4	622	.004	30	1568	300	12
376	65.2	70.8	50.9	782	.004	30	1568	300	12
377	94.1	96.7	54.1	267	.002	10	441	900	18
378	91.8	95.1	53.2	527	.002	10	441	900	18

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (7 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base $-Q_B$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Diameter (in.)
379	90.5	94.2	49.8	635	.002	10	441	900	18
380	89.2	93.1	50.9	795	.002	10	441	900	18
381	83.1	89.2	70.4	267	.004	30	294	900	12
382	73.4	81.6	46.0	514	.004	30	294	900	12
383	72.4	81.8	34.6	622	.004	30	294	900	12
384	67.7	76.2	35.0	782	.004	30	294	900	12
385	80.6	85.8	43.8	267	.002	10	343	300	18
386	61.8	66.8	36.5	527	.002	10	343	300	18
387	59.0	64.0	27.5	635	.002	10	343	300	18
388	57.3	62.4	25.0	795	.002	10	343	300	18
389	56.7	66.9	60.3	267	.004	30	196	300	12
390	48.8	56.9	43.2	514	.004	30	196	300	12
391	46.3	48.1	39.3	622	.004	30	196	300	12
392	40.8	46.1	17.9	782	.004	30	196	300	12
393	77.0	76.0	50.3	267	.002	50	2989	900	18
394	78.4	80.0	62.4	527	.002	50	2989	900	18
395	76.7	78.1	59.4	635	.002	50	2989	900	18
396	73.5	74.9	56.7	795	.002	50	2989	900	18
397	83.2	91.9	84.7	267	.004	10	1862	900	12
398	81.3	89.8	76.3	514	.004	10	1862	900	12
399	80.6	88.4	70.1	622	.004	10	1862	900	12
400	76.4	83.1	66.2	782	.004	10	1862	900	12
401	88.6	90.0	38.6	267	.002	50	1127	300	18
402	68.2	67.1	41.8	527	.002	50	1127	300	18
403	61.7	64.0	43.9	635	.002	50	1127	300	18
404	60.1	61.1	44.0	795	.002	50	1127	300	18
405	86.4	93.3	78.3	267	.004	10	1225	300	12
406	81.2	87.2	61.8	514	.004	10	1225	300	12
407	78.5	85.2	41.2	622	.004	10	1225	300	12
408	71.6	78.3	42.5	782	.004	10	1225	300	12
409	49.8	52.4	41.7	267	.002	50	441	900	18
410	61.7	63.3	53.3	527	.002	50	441	900	18
411	59.7	59.6	50.5	635	.002	50	441	900	18
412	58.5	58.7	45.9	795	.002	50	441	900	18
413	83.5	88.5	76.3	267	.004	10	245	900	12
414	81.6	85.7	67.8	514	.004	10	245	900	12
415	80.2	81.5	64.1	622	.004	10	245	900	12
416	77.2	81.9	61.0	782	.004	10	245	900	12
417	71.8	79.9	63.8	267	.002	50	343	300	18
418	66.0	74.3	44.1	527	.002	50	343	300	18
419	66.0	74.6	46.2	635	.002	50	343	300	18
420	66.7	74.2	47.2	795	.002	50	343	300	18
421	78.7	80.2	63.1	267	.004	10	245	300	12
422	76.1	79.0	55.6	514	.004	10	245	300	12
423	74.3	79.0	43.1	622	.004	10	245	300	12
424	73.7	77.3	45.4	782	.004	10	245	300	12
425	72.0	68.1	37.4	267	.002	50	882	600	18
426	65.4	66.2	38.8	527	.002	50	882	600	18
427	62.8	63.8	39.0	635	.002	50	882	600	18
428	61.0	64.1	39.4	795	.002	50	882	600	18
429	85.6	89.1	81.1	267	.004	10	980	600	12
430	80.3	83.3	65.7	514	.004	10	980	600	12
431	78.6	80.7	61.1	622	.004	10	980	600	12
432	74.7	78.2	69.4	782	.004	10	980	600	12
433	82.0	87.6	68.3	267	.002	10	980	600	18
434	75.7	84.0	67.7	527	.002	10	980	600	18
435	75.0	83.0	67.7	635	.002	10	980	600	18
436	71.6	78.5	62.0	795	.002	10	980	600	18
437	84.1	84.7	79.5	267	.004	30	882	600	12
438	76.5	76.4	71.5	514	.004	30	882	600	12
439	67.4	65.0	58.5	622	.004	30	882	600	12
440	63.4	60.9	54.1	782	.004	30	882	600	12
441	88.1	91.9	82.9	267	.002	10	931	300	18

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (8 of 9)

Observation No.	SS Cleansing Eff. -$\bar{C}_{ESS}$- (%)	VSS Cleansing Eff. -$\bar{C}_{EVSS}$- (%)	TOC Cleansing Eff. -$\bar{C}_{ETOC}$- (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)	Pipe Diameter (in.)
442	81.9	87.4	78.3	527	.002	10	931	300	18
443	80.3	85.9	77.2	635	.002	10	931	300	18
444	78.3	83.9	77.5	795	.002	10	931	300	18
445	90.4	92.3	92.9	267	.004	30	1519	300	12
446	80.5	82.7	84.7	514	.004	30	1519	300	12
447	79.9	82.7	77.2	622	.004	30	1519	300	12
448	74.8	80.1	74.8	782	.004	30	1519	300	12
449	81.0	77.6	25.3	267	.002	50	931	300	18
450	56.4	61.3	33.4	527	.002	50	931	300	18
451	55.7	59.5	32.2	635	.002	50	931	300	18
452	51.6	54.9	29.3	795	.002	50	931	300	18
453	93.0	92.3	46.1	267	.004	10	1715	300	12
454	87.6	88.1	33.9	514	.004	10	1715	300	12
455	85.7	85.5	32.6	622	.004	10	1715	300	12
456	82.7	83.4	35.5	782	.004	10	1715	300	12
457	94.0	0.0	77.4	267	.004	50	2989	900	18
458	88.3	0.0	76.3	527	.004	50	2989	900	18
459	85.2	0.0	75.4	635	.004	50	2989	900	18
460	83.0	0.0	70.4	795	.004	50	2989	900	18
461	87.6	0.0	46.2	267	.006	10	1960	900	12
462	83.5	0.0	45.3	514	.006	10	1960	900	12
463	81.2	0.0	42.7	622	.006	10	1960	900	12
464	76.6	0.0	47.6	782	.006	10	1960	900	12
465	90.1	88.1	64.9	267	.004	50	1911	300	18
466	61.4	62.4	29.6	527	.004	50	1911	300	18
467	56.7	57.1	20.2	635	.004	50	1911	300	18
468	52.6	52.4	12.9	795	.004	50	1911	300	18
469	89.2	90.5	57.2	267	.006	10	1470	300	12
470	79.4	80.4	46.9	514	.006	10	1470	300	12
471	76.9	77.0	52.4	622	.006	10	1470	300	12
472	72.9	71.9	55.7	782	.006	10	1470	300	12
473	89.9	92.3	66.0	267	.004	50	490	900	18
474	79.9	85.4	49.7	527	.004	50	490	900	18
475	78.5	83.9	46.3	635	.004	50	490	900	18
476	77.1	82.7	45.0	795	.004	50	490	900	18
477	81.7	83.3	60.1	267	.006	10	294	900	12
478	75.6	75.9	33.2	514	.006	10	294	900	12
479	72.8	73.0	19.4	622	.006	10	294	900	12
480	69.3	68.8	30.5	782	.006	10	294	900	12
481	56.1	63.6	56.3	267	.004	50	98	300	18
482	29.0	35.9	23.0	527	.004	50	98	300	18
483	25.6	31.0	19.3	635	.004	50	98	300	18
484	22.7	27.5	27.2	795	.004	50	98	300	18
485	77.9	78.1	27.9	267	.006	10	220	300	12
486	61.1	61.7	17.8	514	.006	10	220	300	12
487	55.6	56.7	23.9	622	.006	10	220	300	12
488	53.0	55.2	31.4	782	.006	10	220	300	12
489	83.3	80.4	70.5	267	.004	10	2450	900	18
490	75.2	75.7	57.9	527	.004	10	2450	900	18
491	72.0	72.9	55.5	635	.004	10	2450	900	18
492	66.1	67.8	52.0	795	.004	10	2450	900	18
493	87.1	90.2	52.9	267	.006	30	1911	900	12
494	83.8	85.8	55.8	514	.006	30	1911	900	12
495	81.5	83.6	54.2	622	.006	30	1911	900	12
496	72.8	75.5	46.5	782	.006	30	1911	900	12
497	73.1	68.9	53.2	267	.004	10	1470	300	18
498	60.2	58.7	53.7	527	.004	10	1470	300	18
499	60.0	60.2	50.7	635	.004	10	1470	300	18
500	57.5	57.8	53.5	795	.004	10	1470	300	18
501	81.2	83.7	59.4	267	.006	30	1176	300	12
502	76.2	79.8	56.9	514	.006	30	1176	300	12
503	72.5	75.5	54.4	622	.006	30	1176	300	12
504	67.5	67.7	55.4	782	.006	30	1176	300	12

Table 8 SUMMARY OF RESULTS FROM CLEAN-WATER FLUSH TESTS (9 of 9)

Observation No.	SS Cleansing Eff. $-\bar{C}_{ESS}-$ (%)	VSS Cleansing Eff. $-\bar{C}_{EVSS}-$ (%)	TOC Cleansing Eff. $-\bar{C}_{ETOC}-$ (%)	Total Length of Sewer -L- (ft)	Pipe Slope -So-	Sewage Base $-Q_B-$ (gpm)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Diameter (in.)
505	60.6	51.3	18.7	267	.004	10	343	300	18
506	48.0	46.4	25.2	527	.004	10	343	300	18
507	38.6	38.6	25.1	635	.004	10	343	300	18
508	33.7	36.8	21.6	795	.004	10	343	300	18
509	49.7	59.0	32.8	267	.006	30	196	300	12
510	31.2	39.7	32.4	514	.006	30	196	300	12
511	25.6	34.3	19.9	622	.006	30	196	300	12
512	19.7	23.4	21.1	782	.006	30	196	300	12
513	84.7	84.9	50.8	267	.004	10	196	900	18
514	83.4	87.1	65.2	527	.004	10	196	900	18
515	82.2	86.4	67.2	635	.004	10	196	900	18
516	81.3	84.1	66.4	795	.004	10	196	900	18
517	78.9	82.2	73.4	267	.006	30	245	900	12
518	55.4	60.4	57.4	514	.006	30	245	900	12
519	57.1	61.8	53.0	622	.006	30	245	900	12
520	55.9	57.2	56.1	782	.006	30	245	900	12
521	89.9	87.3	56.1	267	.004	10	784	300	18
522	79.3	77.2	53.2	527	.004	10	784	300	18
523	77.2	74.7	52.4	635	.004	10	784	300	18
524	75.2	73.3	54.0	795	.004	10	784	300	18
525	93.6	88.8	64.0	267	.006	30	1323	300	12
526	71.5	65.7	51.2	514	.006	30	1323	300	12
527	71.0	65.5	38.9	622	.006	30	1323	300	12
528	73.1	65.8	42.1	782	.006	30	1323	300	12
529	87.9	76.1	52.5	267	.004	50	1176	900	18
530	84.0	74.9	99.9	527	.004	50	1176	900	18
531	81.2	71.5	40.2	635	.004	50	1176	900	18
532	80.1	71.8	34.6	795	.004	50	1176	900	18
533	92.5	93.3	61.0	267	.006	10	1764	900	12
534	90.3	91.7	52.0	514	.006	10	1764	900	12
535	88.8	91.0	45.7	622	.006	10	1764	900	12
536	87.6	89.9	49.4	782	.006	10	1764	900	12
537	84.8	78.6	53.7	267	.004	50	1617	300	18
538	61.3	57.5	38.4	527	.004	50	1617	300	18
539	55.7	50.5	33.5	635	.004	50	1617	300	18
540	53.4	47.8	31.9	795	.004	50	1617	300	18
541	83.4	81.2	15.5	267	.006	10	1323	300	12
542	70.0	65.5	28.2	514	.006	10	1323	300	12
543	74.3	63.2	28.3	622	.006	10	1323	300	12
544	64.6	60.6	36.0	782	.006	10	1323	300	12

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (1 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
1	11.5	92	.002	30	1267	900
2	10.5	164	.002	30	1267	900
3	10.0	218	.002	30	1267	900
4	9.3	290	.002	30	1267	900
5	13.0	92	.002	30	1911	900
6	11.5	164	.002	30	1911	900
7	11.8	218	.002	30	1911	900
8	11.0	290	.002	30	1911	900
9	7.1	92	.002	30	323	900
10	6.5	164	.002	30	323	900
11	6.3	218	.002	30	323	900
12	6.5	290	.002	30	323	900
13	6.1	92	.002	30	294	600
14	6.0	164	.002	30	294	600
15	5.9	218	.002	30	294	600
16	6.3	290	.002	30	294	600
17	12.0	92	.002	30	1029	600
18	11.0	164	.002	30	1029	600
19	8.5	218	.002	30	1029	600
20	9.0	290	.002	30	1029	600
21	12.0	92	.002	30	1878	600
22	10.3	164	.002	30	1878	600
23	9.3	218	.002	30	1878	600
24	8.5	290	.002	30	1878	600
25	5.0	92	.002	30	196	300
26	4.8	164	.002	30	196	300
27	4.8	218	.002	30	196	300
28	4.8	290	.002	30	196	300
29	12.0	92	.002	30	679	300
30	9.0	164	.002	30	679	300
31	7.8	218	.002	30	679	300
32	6.5	290	.002	30	679	300
33	6.3	92	.002	30	1580	300
34	4.5	164	.002	30	1580	300
35	7.0	218	.002	30	1580	300
36	6.5	290	.002	30	1580	300
37	12.0	92	.002	20	2090	900
38	12.0	164	.002	20	2090	900
39	11.0	218	.002	20	2090	900
40	9.0	290	.002	20	2090	900
41	6.5	92	.002	20	294	900
42	6.0	164	.002	20	294	900
43	6.1	218	.002	20	294	900
44	6.5	290	.002	20	294	900
45	8.0	92	.002	10	1102	300
46	6.8	164	.002	10	1102	300
47	6.0	218	.002	10	1102	300
48	5.5	290	.002	10	1102	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (2 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
49	12.0	92	.002	10	1078	600
50	12.0	164	.002	10	1078	600
51	9.5	218	.002	10	1078	600
52	8.3	290	.002	10	1078	600
53	12.0	92	.002	10	2058	900
54	12.0	164	.002	10	2058	900
55	12.0	218	.002	10	2058	900
56	9.0	290	.002	10	2058	900
57	6.3	92	.002	10	245	900
58	5.8	164	.002	10	245	900
59	6.1	218	.002	10	245	900
60	6.1	290	.002	10	245	900
61	12.0	92	.002	30	1176	900
62	11.0	164	.002	30	1176	900
63	11.0	218	.002	30	1176	900
64	10.5	290	.002	30	1176	900
65	11.0	92	.002	30	698	300
66	8.5	164	.002	30	698	300
67	7.3	218	.002	30	698	300
68	6.3	290	.002	30	698	300
69	12.0	92	.002	10	1127	900
70	11.5	164	.002	10	1127	900
71	11.0	218	.002	10	1127	900
72	10.0	290	.002	10	1127	900
73	12.0	92	.002	30	1065	600
74	11.0	164	.002	30	1065	600
75	7.8	218	.002	30	1065	600
76	9.0	290	.002	30	1065	600
77	5.8	92	.002	30	238	600
78	5.3	164	.002	30	238	600
79	5.3	218	.002	30	238	600
80	5.5	290	.002	30	238	600
81	4.5	92	.002	10	54	300
82	4.3	164	.002	10	54	300
83	4.3	218	.002	10	54	300
84	4.0	290	.002	10	54	300
85	12.5	92	.002	20	1543	600
86	10.5	164	.002	20	1543	600
87	10.5	218	.002	20	1543	600
88	9.5	290	.002	20	1543	600
89	12.0	92	.002	20	1065	600
90	8.6	164	.002	20	1065	600
91	9.4	218	.002	20	1065	600
92	8.0	290	.002	20	1065	600
93	12.0	92	.002	20	257	600
94	10.5	164	.002	20	257	600
95	9.0	218	.002	20	257	600
96	5.8	290	.002	20	257	600

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (3 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft.)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
97	12.0	92	.002	30	1617	300
98	9.0	164	.002	30	1617	300
99	8.0	218	.002	30	1617	300
100	6.5	290	.002	30	1617	300
101	8.0	92	.002	30	1347	300
102	8.0	164	.002	30	1347	300
103	7.3	218	.002	30	1347	300
104	6.0	290	.002	30	1347	300
105	10.0	92	.004	30	1911	900
106	8.0	164	.004	30	1911	900
107	8.5	218	.004	30	1911	900
108	8.0	290	.004	30	1911	900
109	10.5	92	.004	30	1568	300
110	8.0	164	.004	30	1568	300
111	7.3	218	.004	30	1568	300
112	6.0	290	.004	30	1568	300
113	5.3	92	.004	30	294	900
114	5.8	164	.004	30	294	900
115	6.0	218	.004	30	294	900
116	6.3	290	.004	30	294	900
117	4.3	92	.004	30	196	300
118	4.5	164	.004	30	196	300
119	4.5	218	.004	30	196	300
120	4.5	290	.004	30	196	300
121	12.0	92	.004	10	1862	900
122	12.0	164	.004	10	1862	900
123	12.0	218	.004	10	1862	900
124	10.0	290	.004	10	1862	900
125	10.0	92	.004	10	1225	300
126	7.8	164	.004	10	1225	300
127	6.5	218	.004	10	1225	300
128	5.3	290	.004	10	1225	300
129	4.5	92	.004	10	245	900
130	5.5	164	.004	10	245	900
131	6.0	218	.004	10	245	900
132	6.3	290	.004	10	245	900
133	11.3	92	.004	10	980	600
134	10.3	164	.004	10	980	600
135	8.8	218	.004	10	980	600
136	7.3	290	.004	10	980	600
137	12.0	92	.004	30	882	600
138	10.5	164	.004	30	882	600
139	8.0	218	.004	30	882	600
140	7.8	290	.004	30	882	600
141	11.0	92	.004	30	1519	300
142	8.5	164	.004	30	1519	300
143	7.5	218	.004	30	1519	300
144	6.0	290	.004	30	1519	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (4 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
145	8.8	92	.004	10	548	300
146	7.5	164	.004	10	548	300
147	7.3	218	.004	10	548	300
148	5.5	290	.004	10	548	300
149	11.0	92	.006	10	1960	900
150	9.5	164	.006	10	1960	900
151	10.5	218	.006	10	1960	900
152	10.5	290	.006	10	1960	900
153	10.0	92	.006	10	1470	300
154	6.5	164	.006	10	1470	300
155	7.3	218	.006	10	1470	300
156	5.5	290	.006	10	1470	300
157	5.0	92	.006	10	294	900
158	5.0	164	.006	10	294	900
159	5.5	218	.006	10	294	900
160	6.0	290	.006	10	294	900
161	4.5	92	.006	10	220	300
162	4.8	164	.006	10	220	300
163	4.8	218	.006	10	220	300
164	4.8	290	.006	10	220	300
165	11.0	92	.006	30	1911	900
166	8.0	164	.006	30	1911	900
167	10.0	218	.006	30	1911	900
168	8.0	290	.006	30	1911	900
169	6.5	92	.006	30	1176	300
170	4.5	164	.006	30	1176	300
171	6.5	218	.006	30	1176	300
172	5.3	290	.006	30	1176	300
173	4.3	92	.006	30	196	300
174	4.3	164	.006	30	196	300
175	4.5	218	.006	30	196	300
176	5.0	290	.006	30	196	300
177	5.3	92	.006	30	245	900
178	6.0	164	.006	30	245	900
179	6.0	218	.006	30	245	900
180	6.0	290	.006	30	245	900
181	7.0	92	.006	30	1323	300
182	5.3	164	.006	30	1323	300
183	6.3	218	.006	30	1323	300
184	4.3	290	.006	30	1323	300
185	12.0	92	.006	10	1764	900
186	6.3	164	.006	10	1764	900
187	10.8	218	.006	10	1764	900
188	9.8	290	.006	10	1764	900
189	11.5	92	.006	10	1323	300
190	7.0	164	.006	10	1323	300
191	7.0	218	.006	10	1323	300
192	5.8	290	.006	10	1323	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (5 of 12)

Observation No.	Maximum Flush Wave Depth -W_D (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
193	8.3	361	.002	30	1267	900
194	5.8	442	.002	30	1267	900
195	5.3	473	.002	30	1267	900
196	6.5	535	.002	30	1267	900
197	7.5	361	.002	30	1911	900
198	6.3	442	.002	30	1911	900
199	5.5	473	.002	30	1911	900
200	5.3	535	.002	30	1911	900
201	6.1	361	.002	30	323	900
202	4.8	442	.002	30	323	900
203	4.3	473	.002	30	323	900
204	6.0	535	.002	30	323	900
205	6.8	361	.002	30	294	600
206	4.8	442	.002	30	294	600
207	3.5	473	.002	30	294	600
208	5.4	535	.002	30	294	600
209	8.0	361	.002	30	1029	600
210	4.8	442	.002	30	1029	600
211	4.0	473	.002	30	1029	600
212	6.0	535	.002	30	1029	600
213	7.5	361	.002	30	1878	600
214	5.3	442	.002	30	1878	600
215	4.3	473	.002	30	1878	600
216	5.8	535	.002	30	1878	600
217	4.1	361	.002	30	196	300
218	3.0	442	.002	30	196	300
219	3.3	473	.002	30	196	300
220	3.8	535	.002	30	196	300
221	5.0	361	.002	30	679	300
222	4.0	442	.002	30	679	300
223	3.5	473	.002	30	679	300
224	4.5	535	.002	30	679	300
225	5.1	361	.002	30	1580	300
226	4.5	442	.002	30	1580	300
227	4.0	473	.002	30	1580	300
228	4.3	535	.002	30	1580	300
229	7.3	361	.002	20	2093	900
230	5.5	442	.002	20	2093	900
231	5.4	473	.002	20	2093	900
232	6.0	535	.002	20	2093	900
233	5.0	361	.002	20	294	900
234	5.3	442	.002	20	294	900
235	4.6	473	.002	20	294	900
236	5.5	535	.002	20	294	900
237	4.0	361	.002	10	1102	300
238	3.4	442	.002	10	1102	300
239	3.0	473	.002	10	1102	300
240	3.5	535	.002	10	1102	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (6 of 12)

Observation No.	Maximum Flush Wave Depth -W_D (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
241	6.8	361	.002	10	1078	600
242	4.8	442	.002	10	1078	600
243	4.6	473	.002	10	1078	600
244	5.4	535	.002	10	1078	600
245	7.8	361	.002	10	2058	900
246	6.4	442	.002	10	2058	900
247	5.3	473	.002	10	2058	900
248	6.3	535	.002	10	2058	900
249	5.8	361	.002	10	245	900
250	4.3	442	.002	10	245	900
251	4.0	473	.002	10	245	900
252	5.5	535	.002	10	245	900
253	8.8	361	.002	30	1176	900
254	5.8	442	.002	30	1176	900
255	6.6	473	.002	30	1176	900
256	7.0	535	.002	30	1176	900
257	5.0	361	.002	30	698	300
258	3.5	442	.002	30	698	300
259	3.0	473	.002	30	698	300
260	4.5	535	.002	30	698	300
261	8.3	361	.002	10	1127	900
262	6.0	442	.002	10	1127	900
263	5.8	473	.002	10	1127	900
264	6.3	535	.002	10	1127	900
265	7.3	361	.002	30	1065	600
266	5.0	442	.002	30	1065	600
267	5.0	473	.002	30	1065	600
268	5.6	535	.002	30	1065	600
269	5.3	361	.002	30	238	600
270	4.5	442	.002	30	238	600
271	3.9	473	.002	30	238	600
272	5.0	535	.002	30	238	600
273	3.4	361	.002	10	147	300
274	3.0	442	.002	10	147	300
275	2.3	473	.002	10	147	300
276	3.0	535	.002	10	147	300
277	6.5	361	.002	20	1543	600
278	5.5	442	.002	20	1543	600
279	4.5	473	.002	20	1543	600
280	5.5	535	.002	20	1543	600
281	6.4	361	.002	20	1065	600
282	5.0	442	.002	20	1065	600
283	4.3	473	.002	20	1065	600
284	5.4	535	.002	20	1065	600
285	5.5	361	.002	20	257	600
286	4.5	442	.002	20	257	600
287	4.0	473	.002	20	257	600
288	4.0	535	.002	20	257	600

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (7 of 17)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
289	5.0	361	.002	30	1617	300
290	3.5	442	.002	30	1617	300
291	3.5	473	.002	30	1617	300
292	4.3	535	.002	30	1617	300
293	5.0	361	.002	30	1347	300
294	3.0	442	.002	30	1347	300
295	3.5	473	.002	30	1347	300
296	3.5	535	.002	30	1347	300
297	9.0	361	.004	30	1911	900
298	7.5	442	.004	30	1911	900
299	7.0	473	.004	30	1911	900
300	6.5	535	.004	30	1911	900
301	5.0	361	.004	30	1568	300
302	4.0	442	.004	30	1568	300
303	3.8	473	.004	30	1568	300
304	4.3	535	.004	30	1568	300
305	6.0	361	.004	30	294	900
306	5.0	442	.004	30	294	900
307	4.5	473	.004	30	294	900
308	5.5	535	.004	30	294	900
309	4.0	361	.004	30	196	300
310	3.5	442	.004	30	196	300
311	3.5	473	.004	30	196	300
312	3.8	535	.004	30	196	300
313	8.0	361	.004	10	1862	900
314	6.5	442	.004	10	1862	900
315	5.8	473	.004	10	1862	900
316	6.5	535	.004	10	1862	900
317	4.5	361	.004	10	1225	300
318	3.5	442	.004	10	1225	300
319	3.3	473	.004	10	1225	300
320	4.0	535	.004	10	1225	300
321	5.8	361	.004	10	245	900
322	4.8	442	.004	10	245	900
323	4.5	473	.004	10	245	900
324	5.3	535	.004	10	245	900
325	6.5	361	.004	10	980	600
326	5.5	442	.004	10	980	600
327	5.0	473	.004	10	980	600
328	5.5	535	.004	10	980	600
329	7.3	361	.004	30	882	600
330	6.0	442	.004	30	882	600
331	5.5	473	.004	30	882	600
332	5.5	535	.004	30	882	600
333	5.3	361	.004	30	1519	300
334	4.3	442	.004	30	1519	300
335	3.8	473	.004	30	1519	300
336	4.3	535	.004	30	1519	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (8 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
337	4.8	361	.004	10	1475	300
338	3.3	442	.004	10	1475	300
339	3.8	473	.004	10	1475	300
340	4.0	535	.004	10	1475	300
341	7.0	361	.006	10	1960	900
342	8.0	442	.006	10	1960	900
343	7.8	473	.006	10	1960	900
344	7.0	535	.006	10	1960	900
345	5.0	361	.006	10	1470	300
346	4.0	442	.006	10	1470	300
347	3.5	473	.006	10	1470	300
348	4.0	535	.006	10	1470	300
349	4.8	361	.006	10	294	900
350	4.3	442	.006	10	294	900
351	4.5	473	.006	10	294	900
352	4.8	535	.006	10	294	900
353	4.0	361	.006	10	220	300
354	2.5	442	.006	10	220	300
355	3.3	473	.006	10	220	300
356	3.8	535	.006	10	220	300
357	8.0	361	.006	30	1911	900
358	7.3	442	.006	30	1911	900
359	7.0	473	.006	30	1911	900
360	6.8	535	.006	30	1911	900
361	4.8	361	.006	30	1176	300
362	4.0	442	.006	30	1176	300
363	4.5	473	.006	30	1176	300
364	4.3	535	.006	30	1176	300
365	3.8	361	.006	30	196	300
366	3.5	442	.006	30	196	300
367	3.3	473	.006	30	196	300
368	3.5	535	.006	30	196	300
369	4.8	361	.006	30	245	900
370	4.5	442	.006	30	245	900
371	4.8	473	.006	30	245	900
372	5.0	535	.006	30	245	900
373	5.0	361	.006	30	1323	300
374	4.0	442	.006	30	1323	300
375	4.3	473	.006	30	1323	300
376	4.0	535	.006	30	1323	300
377	8.5	361	.006	10	1764	900
378	7.5	442	.006	10	1764	900
379	8.0	473	.006	10	1764	900
380	6.8	535	.006	10	1764	900
381	5.3	361	.006	10	1323	300
382	4.5	442	.006	10	1323	300
383	4.5	473	.006	10	1323	300
384	4.5	535	.006	10	1323	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (9 of 12)

Observation No.	Maximum Flush Wave Depth -W_D (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
385	6.0	614	.002	30	1267	900
386	5.7	680	.002	30	1267	900
387	5.6	732	.002	30	1267	900
388	5.1	770	.002	30	1267	900
389	6.3	614	.002	30	1911	900
390	6.0	680	.002	30	1911	900
391	6.0	732	.002	30	1911	900
392	6.0	770	.002	30	1911	900
393	5.5	614	.002	30	323	900
394	5.8	680	.002	30	323	900
395	5.8	732	.002	30	323	900
396	5.8	770	.002	30	323	900
397	4.9	614	.002	30	294	600
398	5.0	680	.002	30	294	600
399	4.8	732	.002	30	294	600
400	4.9	770	.002	30	294	600
401	5.3	614	.002	30	1029	600
402	5.0	680	.002	30	1029	600
403	5.3	732	.002	30	1029	600
404	5.3	770	.002	30	1029	600
405	5.0	614	.002	30	1878	600
406	5.0	680	.002	30	1878	600
407	5.0	732	.002	30	1878	600
408	3.3	770	.002	30	1878	600
409	3.5	614	.002	30	196	300
410	3.5	680	.002	30	196	300
411	3.5	732	.002	30	196	300
412	2.8	770	.002	30	196	300
413	4.3	614	.002	30	679	300
414	4.3	680	.002	30	679	300
415	4.0	732	.002	30	679	300
416	4.5	770	.002	30	679	300
417	4.3	614	.002	30	1580	300
418	4.3	680	.002	30	1580	300
419	4.3	732	.002	30	1580	300
420	4.3	770	.002	30	1580	300
421	5.5	614	.002	20	2096	900
422	5.0	680	.002	20	2096	900
423	4.8	732	.002	20	2096	900
424	5.0	770	.002	20	2096	900
425	5.0	614	.002	20	294	900
426	5.0	680	.002	20	294	900
427	4.8	732	.002	20	294	900
428	4.5	770	.002	20	294	900
429	3.0	614	.002	10	1102	300
430	3.1	680	.002	10	1102	300
431	3.5	732	.002	10	1102	300
432	3.6	770	.002	10	1102	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (10 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
433	4.8	614	.002	10	1078	600
434	5.0	680	.002	10	1078	600
435	4.8	732	.002	10	1078	600
436	4.8	770	.002	10	1078	600
437	5.8	614	.002	10	2058	900
438	5.5	680	.002	10	2058	900
439	5.4	732	.002	10	2058	900
440	5.8	770	.002	10	2058	900
441	5.3	614	.002	10	245	900
442	5.0	680	.002	10	245	900
443	5.0	732	.002	10	245	900
444	5.1	770	.002	10	245	900
445	6.1	614	.002	30	1176	900
446	6.0	680	.002	30	1176	900
447	6.3	732	.002	30	1176	900
448	6.3	770	.002	30	1176	900
449	4.0	614	.002	30	698	300
450	4.0	680	.002	30	698	300
451	3.5	732	.002	30	698	300
452	3.0	770	.002	30	698	300
453	5.5	614	.002	10	1127	900
454	5.5	680	.002	10	1127	900
455	5.5	732	.002	10	1127	900
456	5.5	770	.002	10	1127	900
457	5.0	614	.002	30	1065	600
458	5.3	680	.002	30	1065	600
459	5.1	732	.002	30	1065	600
460	5.3	770	.002	30	1065	600
461	4.1	614	.002	30	238	600
462	4.5	680	.002	30	238	600
463	4.5	732	.002	30	238	600
464	4.8	770	.002	30	238	600
465	2.8	614	.002	10	226	300
466	2.9	680	.002	10	226	300
467	3.0	732	.002	10	226	300
468	3.1	770	.002	10	226	300
469	4.8	614	.002	20	1543	600
470	4.6	680	.002	20	1543	600
471	4.8	732	.002	20	1543	600
472	4.8	770	.002	20	1543	600
473	4.8	614	.002	20	1065	600
474	5.0	680	.002	20	1065	600
475	4.8	732	.002	20	1065	600
476	4.8	770	.002	20	1065	600
477	4.3	614	.002	20	257	600
478	4.5	680	.002	20	257	600
479	4.0	732	.002	20	257	600
480	4.8	770	.002	20	257	600

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (11 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
481	4.0	614	.002	30	1617	300
482	4.0	680	.002	30	1617	300
483	4.3	732	.002	30	1617	300
484	4.3	770	.002	30	1617	300
485	3.8	614	.002	30	1347	300
486	3.5	680	.002	30	1347	300
487	3.5	732	.002	30	1347	300
488	4.0	770	.002	30	1347	300
489	6.0	614	.004	30	1911	900
490	6.5	680	.004	30	1911	900
491	7.0	732	.004	30	1911	900
492	6.8	770	.004	30	1911	900
493	4.3	614	.004	30	1568	300
494	4.3	680	.004	30	1568	300
495	4.3	732	.004	30	1568	300
496	4.0	770	.004	30	1568	300
497	5.8	614	.004	30	294	900
498	5.8	680	.004	30	294	900
499	5.5	732	.004	30	294	900
500	5.8	770	.004	30	294	900
501	3.8	614	.004	30	196	300
502	3.8	680	.004	30	196	300
503	3.8	732	.004	30	196	300
504	3.5	770	.004	30	196	300
505	6.3	614	.004	10	1862	900
506	6.3	680	.004	10	1862	900
507	6.5	732	.004	10	1862	900
508	6.0	770	.004	10	1862	900
509	4.0	614	.004	10	1225	300
510	3.8	680	.004	10	1225	300
511	3.8	732	.004	10	1225	300
512	3.5	770	.004	10	1225	300
513	5.5	614	.004	10	245	900
514	5.5	680	.004	10	245	900
515	5.5	732	.004	10	245	900
516	5.3	770	.004	10	245	900
517	5.0	614	.004	10	980	600
518	5.5	680	.004	10	980	600
519	5.3	732	.004	10	980	600
520	5.3	770	.004	10	980	600
521	5.5	614	.004	30	882	600
522	5.3	680	.004	30	882	600
523	5.8	732	.004	30	882	600
524	5.5	770	.004	30	882	600
525	4.5	614	.004	30	1519	300
526	4.5	680	.004	30	1519	300
527	4.5	732	.004	30	1519	300
528	4.3	770	.004	30	1519	300

Table 9 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 12-INCH SEWER (12 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
529	4.0	614	.004	10	2268	300
530	4.0	680	.004	10	2268	300
531	4.0	732	.004	10	2268	300
532	3.8	770	.004	10	2268	300
533	6.5	614	.006	10	1960	900
534	5.8	680	.006	10	1960	900
535	6.5	732	.006	10	1960	900
536	6.0	770	.006	10	1960	900
537	4.0	614	.006	10	1470	300
538	4.0	680	.006	10	1470	300
539	4.5	732	.006	10	1470	300
540	4.3	770	.006	10	1470	300
541	4.8	614	.006	10	294	900
542	4.5	680	.006	10	294	900
543	5.8	732	.006	10	294	900
544	4.8	770	.006	10	294	900
545	3.8	614	.006	10	220	300
546	3.5	680	.006	10	220	300
547	3.5	732	.006	10	220	300
548	3.3	770	.006	10	220	300
549	6.5	614	.006	30	1911	900
550	6.3	680	.006	30	1911	900
551	6.3	732	.006	30	1911	900
552	6.3	770	.006	30	1911	900
553	4.3	614	.006	30	1176	300
554	4.0	680	.006	30	1176	300
555	5.0	732	.006	30	1176	300
556	4.8	770	.006	30	1176	300
557	3.5	614	.006	30	196	300
558	3.3	680	.006	30	196	300
559	3.8	732	.006	30	196	300
560	3.8	770	.006	30	196	300
561	5.0	614	.006	30	245	900
562	4.8	680	.006	30	245	900
563	5.8	732	.006	30	245	900
564	5.3	770	.006	30	245	900
565	4.0	614	.006	30	1323	300
566	4.3	680	.006	30	1323	300
567	4.3	732	.006	30	1323	300
568	4.0	770	.006	30	1323	300
569	5.5	614	.006	10	1764	900
570	6.5	680	.006	10	1764	900
571	6.5	732	.006	10	1764	900
572	6.5	770	.006	10	1764	900
573	4.3	614	.006	10	1323	300
574	4.3	680	.006	10	1323	300
575	4.3	732	.006	10	1323	300
576	4.0	770	.006	10	1323	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (1 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F (gal.)
1	13.0	92	.001	10	2131	900
2	11.5	164	.001	10	2131	900
3	10.0	218	.001	10	2131	900
4	8.5	290	.001	10	2131	900
5	13.0	92	.001	10	3381	900
6	12.5	164	.001	10	3381	900
7	8.0	218	.001	10	3381	900
8	10.0	290	.001	10	3381	900
9	6.8	92	.001	10	420	900
10	6.8	164	.001	10	420	900
11	5.5	218	.001	10	420	900
12	5.5	290	.001	10	420	900
13	6.0	92	.001	10	367	600
14	6.5	164	.001	10	367	600
15	5.8	218	.001	10	367	600
16	5.6	290	.001	10	367	600
17	12.0	92	.001	10	1470	600
18	11.0	164	.001	10	1470	600
19	9.5	218	.001	10	1470	600
20	6.8	290	.001	10	1470	600
21	15.5	92	.001	10	2021	600
22	11.5	164	.001	10	2021	600
23	9.0	218	.001	10	2021	600
24	7.0	290	.001	10	2021	600
25	5.8	92	.001	10	343	300
26	5.1	164	.001	10	343	300
27	4.3	218	.001	10	343	300
28	3.8	290	.001	10	343	300
29	7.5	92	.001	10	790	300
30	6.3	164	.001	10	790	300
31	5.5	218	.001	10	790	300
32	3.8	290	.001	10	790	300
33	8.3	92	.001	10	1212	300
34	7.5	164	.001	10	1212	300
35	5.1	218	.001	10	1212	300
36	4.0	290	.001	10	1212	300
37	13.0	92	.001	30	2572	900
38	12.0	164	.001	30	2572	900
39	12.0	218	.001	30	2572	900
40	11.0	290	.001	30	2572	900
41	12.0	92	.001	30	1960	900
42	13.0	164	.001	30	1960	900
43	13.0	218	.001	30	1960	900
44	10.0	290	.001	30	1960	900
45	7.5	92	.001	50	624	300
46	5.8	164	.001	50	624	300
47	5.5	218	.001	50	624	300
48	4.5	290	.001	50	624	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (2 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
49	5.3	92	.001	50	269	300
50	5.0	164	.001	50	269	300
51	4.0	218	.001	50	269	300
52	4.3	290	.001	50	269	300
53	8.5	92	.001	50	759	900
54	8.5	164	.001	50	759	900
55	7.1	218	.001	50	759	900
56	7.0	290	.001	50	759	900
57	6.8	92	.001	50	441	900
58	6.6	164	.001	50	441	900
59	5.6	218	.001	50	441	900
60	5.6	290	.001	50	441	900
61	6.3	92	.001	10	385	600
62	6.0	164	.001	10	385	600
63	5.0	218	.001	10	385	600
64	4.8	290	.001	10	385	600
65	5.1	92	.001	10	330	300
66	4.5	164	.001	10	330	300
67	3.5	218	.001	10	330	300
68	2.8	290	.001	10	330	300
69	18.0	92	.001	50	3234	900
70	14.0	164	.001	50	3234	900
71	12.0	218	.001	50	3234	900
72	10.0	290	.001	50	3234	900
73	15.0	92	.001	10	2499	600
74	11.0	164	.001	10	2499	600
75	8.5	218	.001	10	2499	600
76	6.5	290	.001	10	2499	600
77	11.0	92	.001	10	1323	300
78	7.1	164	.001	10	1323	300
79	5.9	218	.001	10	1323	300
80	4.1	290	.001	10	1323	300
81	13.0	92	.001	50	1506	300
82	10.0	164	.001	50	1506	300
83	7.3	218	.001	50	1506	300
84	5.8	290	.001	50	1506	300
85	14.0	92	.001	50	1947	900
86	14.0	164	.001	50	1947	900
87	11.0	218	.001	50	1947	900
88	8.8	290	.001	50	1947	900
89	8.9	92	.001	50	1029	600
90	8.4	164	.001	50	1029	600
91	7.0	218	.001	50	1029	600
92	6.5	290	.001	50	1029	600
93	12.0	92	.001	10	1764	300
94	7.5	164	.001	10	1764	300
95	7.3	218	.001	10	1764	300
96	7.0	290	.001	10	1764	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (3 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
97	12.0	92	.001	10	1690	300
98	9.0	164	.001	10	1690	300
99	6.0	218	.001	10	1690	300
100	4.5	290	.001	10	1690	300
101	7.0	92	.001	10	710	300
102	7.0	164	.001	10	710	300
103	5.3	218	.001	10	710	300
104	5.3	290	.001	10	710	300
105	11.0	92	.002	10	2940	900
106	8.5	164	.002	10	2940	900
107	8.3	218	.002	10	2940	900
108	8.5	290	.002	10	2940	900
109	8.5	92	.002	10	1323	300
110	6.5	164	.002	10	1323	300
111	5.3	218	.002	10	1323	300
112	4.5	290	.002	10	1323	300
113	6.8	92	.002	10	441	900
114	6.0	164	.002	10	441	900
115	5.8	218	.002	10	441	900
116	5.8	290	.002	10	441	900
117	5.3	92	.002	10	343	300
118	4.5	164	.002	10	343	300
119	4.3	218	.002	10	343	300
120	3.8	290	.002	10	343	300
121	13.0	92	.002	50	2989	900
122	13.0	164	.002	50	2989	900
123	13.0	218	.002	50	2989	900
124	9.0	290	.002	50	2989	900
125	9.5	92	.002	50	1127	300
126	8.5	164	.002	50	1127	300
127	8.0	218	.002	50	1127	300
128	6.0	290	.002	50	1127	300
129	6.5	92	.002	50	441	900
130	6.0	164	.002	50	441	900
131	5.5	218	.002	50	441	900
132	5.5	290	.002	50	441	900
133	8.0	92	.002	50	882	600
134	6.5	164	.002	50	882	600
135	6.5	218	.002	50	882	600
136	6.3	290	.002	50	882	600
137	7.0	92	.002	10	980	600
138	7.0	164	.002	10	980	600
139	6.5	218	.002	10	980	600
140	6.3	290	.002	10	980	600
141	7.5	92	.002	10	931	300
142	7.0	164	.002	10	931	300
143	6.0	218	.002	10	931	300
144	4.8	290	.002	10	931	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (4 of 12)

Observation No.	Maximum Flush Wave Depth -W_D (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
145	7.5	92	.002	50	931	300
146	6.5	164	.002	50	931	300
147	6.0	218	.002	50	931	300
148	4.5	290	.002	50	931	300
149	18.0	92	.004	50	2989	900
150	16.0	164	.004	50	2989	900
151	10.5	218	.004	50	2989	900
152	11.0	290	.004	50	2989	900
153	13.0	92	.004	50	1911	300
154	5.3	164	.004	50	1911	300
155	6.3	218	.004	50	1911	300
156	5.5	290	.004	50	1911	300
157	6.0	92	.004	50	490	900
158	5.5	164	.004	50	490	900
159	5.8	218	.004	50	490	900
160	6.0	290	.004	50	490	900
161	7.5	92	.004	50	98	300
162	6.0	164	.004	50	98	300
163	5.3	218	.004	50	98	300
164	4.5	290	.004	50	98	300
165	13.0	92	.004	10	2450	900
166	7.0	164	.004	10	2450	900
167	11.0	218	.004	10	2450	900
168	6.0	290	.004	10	2450	900
169	7.5	92	.004	10	1470	300
170	6.0	164	.004	10	1470	300
171	6.0	218	.004	10	1470	300
172	5.0	290	.004	10	1470	300
173	4.5	92	.004	10	343	300
174	4.5	164	.004	10	343	300
175	4.3	218	.004	10	343	300
176	4.3	290	.004	10	343	300
177	6.5	92	.004	10	196	900
178	4.3	164	.004	10	196	900
179	4.3	218	.004	10	196	900
180	4.5	290	.004	10	196	900
181	7.3	92	.004	10	784	300
182	6.0	164	.004	10	784	300
183	5.5	218	.004	10	784	300
184	5.0	290	.004	10	784	300
185	8.8	92	.004	50	1176	900
186	8.0	164	.004	50	1176	900
187	9.0	218	.004	50	1176	900
188	7.5	290	.004	50	1176	900
189	10.5	92	.004	50	1617	300
190	7.5	164	.004	50	1617	300
191	6.5	218	.004	50	1617	300
192	4.5	290	.004	50	1617	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWER (5 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
193	7.0	361	.001	10	2131	900
194	4.8	432	.001	10	2131	900
195	4.5	490	.001	10	2131	900
196	4.8	548	.001	10	2131	900
197	8.5	361	.001	10	3381	900
198	5.3	432	.001	10	3381	900
199	5.8	490	.001	10	3381	900
200	5.0	548	.001	10	3381	900
201	5.0	361	.001	10	420	900
202	4.8	432	.001	10	420	900
203	4.5	490	.001	10	420	900
204	4.4	548	.001	10	420	900
205	5.6	361	.001	10	367	600
206	3.5	432	.001	10	367	600
207	5.5	490	.001	10	367	600
208	5.0	548	.001	10	367	600
209	5.3	361	.001	10	1470	600
210	3.8	432	.001	10	1470	600
211	4.0	490	.001	10	1470	600
212	3.8	548	.001	10	1470	600
213	5.5	361	.001	10	2021	600
214	4.0	432	.001	10	2021	600
215	3.8	490	.001	10	2021	600
216	3.5	548	.001	10	2021	600
217	3.5	361	.001	10	343	300
218	3.0	432	.001	10	343	300
219	3.0	490	.001	10	343	300
220	2.8	548	.001	10	343	300
221	3.5	361	.001	10	790	300
222	3.0	432	.001	10	790	300
223	2.5	490	.001	10	790	300
224	2.8	548	.001	10	790	300
225	3.0	361	.001	10	1212	300
226	3.0	432	.001	10	1212	300
227	3.3	490	.001	10	1212	300
228	2.6	548	.001	10	1212	300
229	8.8	361	.001	30	2572	900
230	7.5	432	.001	30	2572	900
231	7.3	490	.001	30	2572	900
232	7.0	548	.001	30	2572	900
233	7.6	361	.001	30	1960	900
234	5.5	432	.001	30	1960	900
235	6.0	490	.001	30	1960	900
236	5.5	548	.001	30	1960	900
237	4.0	361	.001	50.	624	300
238	3.0	432	.001	50	624	300
239	3.5	490	.001	50	624	300
240	3.5	548	.001	50	624	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (6 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Down-stream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
241	3.8	361	.001	50	269	300
242	3.5	432	.001	50	269	300
243	3.5	490	.001	50	269	300
244	3.5	548	.001	50	269	300
245	6.3	361	.001	50	759	900
246	5.5	432	.001	50	759	900
247	5.8	490	.001	50	759	900
248	5.4	548	.001	50	759	900
249	5.3	361	.001	50	441	900
250	5.5	432	.001	50	441	900
251	5.1	490	.001	50	441	900
252	5.0	548	.001	50	441	900
253	4.0	361	.001	10	385	600
254	4.0	432	.001	10	385	600
255	3.8	490	.001	10	385	600
256	3.4	548	.001	10	385	600
257	2.5	361	.001	10	330	300
258	2.8	432	.001	10	330	300
259	2.5	490	.001	10	330	300
260	2.3	548	.001	10	330	300
261	7.5	361	.001	50	3234	900
262	6.0	432	.001	50	3234	900
263	6.0	490	.001	50	3234	900
264	5.6	548	.001	50	3234	900
265	5.0	361	.001	10	2499	600
266	4.3	432	.001	10	2499	600
267	4.0	490	.001	10	2499	600
268	3.6	548	.001	10	2499	600
269	3.3	361	.001	10	1323	300
270	3.3	432	.001	10	1323	300
271	3.1	490	.001	10	1323	300
272	2.3	548	.001	10	1323	300
273	5.0	361	.001	50	1506	300
274	4.5	432	.001	50	1506	300
275	4.0	490	.001	50	1506	300
276	3.3	548	.001	50	1506	300
277	7.0	361	.001	50	1947	900
278	6.0	432	.001	50	1947	900
279	5.8	490	.001	50	1947	900
280	5.4	548	.001	50	1947	900
281	5.5	361	.001	50	1029	600
282	4.9	432	.001	50	1029	600
283	4.8	490	.001	50	1029	600
284	4.3	548	.001	50	1029	600
285	5.0	361	.001	10	1764	300
286	2.8	432	.001	10	1764	300
287	4.3	490	.001	10	1764	300
288	3.5	548	.001	10	1764	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (7 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
289	3.5	361	.001	10	1690	300
290	3.0	432	.001	10	1690	300
291	3.3	490	.001	10	1690	300
292	2.8	548	.001	10	1690	300
293	3.5	361	.001	10	710	300
294	2.5	432	.001	10	710	300
295	2.5	490	.001	10	710	300
296	2.5	548	.001	10	710	300
297	7.3	361	.002	10	2940	900
298	5.0	432	.002	10	2940	900
299	5.0	490	.002	10	2940	900
300	5.3	548	.002	10	2940	900
301	3.5	361	.002	10	1323	300
302	3.3	432	.002	10	1323	300
303	3.3	490	.002	10	1323	300
304	3.0	548	.002	10	1323	300
305	5.8	361	.002	10	441	900
306	5.0	432	.002	10	441	900
307	5.0	490	.002	10	441	900
308	5.0	548	.002	10	441	900
309	3.5	361	.002	10	343	300
310	3.0	432	.002	10	343	300
311	2.0	490	.002	10	343	300
312	3.3	548	.002	10	343	300
313	7.3	361	.002	50	2989	900
314	4.8	432	.002	50	2989	900
315	4.0	490	.002	50	2989	900
316	5.0	548	.002	50	2989	900
317	5.5	361	.002	50	1127	300
318	4.8	432	.002	50	1127	300
319	4.3	490	.002	50	1127	300
320	4.5	548	.002	50	1127	300
321	5.3	361	.002	50	441	900
322	4.8	432	.002	50	441	900
323	4.8	490	.002	50	441	900
324	4.5	548	.002	50	441	900
325	5.5	361	.002	50	882	600
326	4.8	432	.002	50	882	600
327	4.3	490	.002	50	882	600
328	4.5	548	.002	50	882	600
329	5.3	361	.002	10	980	600
330	4.0	432	.002	10	980	600
331	3.8	490	.002	10	980	600
332	4.3	548	.002	10	980	600
333	3.5	361	.002	10	931	300
334	3.5	432	.002	10	931	300
335	3.0	490	.002	10	931	300
336	3.3	548	.002	10	931	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (8 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
337	4.0	361	.002	50	931	300
338	3.5	432	.002	50	931	300
339	2.5	490	.002	50	931	300
340	3.8	548	.002	50	931	300
341	9.0	361	.004	50	2989	900
342	7.0	432	.004	50	2989	900
343	7.0	490	.004	50	2989	900
344	6.5	548	.004	50	2989	900
345	4.5	361	.004	50	1911	300
346	3.8	432	.004	50	1911	300
347	3.5	490	.004	50	1911	300
348	4.0	548	.004	50	1911	300
349	5.3	361	.004	50	490	900
350	5.3	432	.004	50	490	900
351	5.0	490	.004	50	490	900
352	6.0	548	.004	50	490	900
353	4.3	361	.004	50	98	300
354	2.5	432	.004	50	98	300
355	3.5	490	.004	50	98	300
356	3.8	548	.004	50	98	300
357	5.5	361	.004	10	2450	900
358	5.3	432	.004	10	2450	900
359	5.8	490	.004	10	2450	900
360	6.0	548	.004	10	2450	900
361	4.3	361	.004	10	1470	300
362	3.5	432	.004	10	1470	300
363	2.5	490	.004	10	1470	300
364	3.8	548	.004	10	1470	300
365	3.5	361	.004	10	343	300
366	2.8	432	.004	10	343	300
367	3.3	490	.004	10	343	300
368	3.3	548	.004	10	343	300
369	4.5	361	.004	10	196	900
370	4.0	432	.004	10	196	900
371	4.3	490	.004	10	196	900
372	4.8	548	.004	10	196	900
373	4.3	361	.004	10	784	300
374	3.8	432	.004	10	784	300
375	3.3	490	.004	10	784	300
376	2.5	548	.004	10	784	300
377	7.0	361	.004	50	1176	900
378	4.5	432	.004	50	1176	900
379	6.5	490	.004	50	1176	900
380	5.5	548	.004	50	1176	900
381	4.8	361	.004	50	1617	300
382	4.0	432	.004	50	1617	300
383	2.5	490	.004	50	1617	300
384	4.0	548	.004	50	1617	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (9 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
385	4.3	614	.001	10	2131	900
386	4.0	691	.001	10	2131	900
387	3.8	744	.001	10	2131	900
388	3.8	780	.001	10	2131	900
389	4.8	614	.001	10	3381	900
390	4.5	691	.001	10	3381	900
391	4.3	744	.001	10	3381	900
392	3.8	780	.001	10	3381	900
393	4.1	614	.001	10	420	900
394	4.0	691	.001	10	420	900
395	3.9	744	.001	10	420	900
396	3.8	780	.001	10	420	900
397	4.8	614	.001	10	367	600
398	4.8	691	.001	10	367	600
399	4.5	744	.001	10	367	600
400	3.9	780	.001	10	367	600
401	3.5	614	.001	10	1470	600
402	3.4	691	.001	10	1470	600
403	3.3	744	.001	10	1470	600
404	3.3	780	.001	10	1470	600
405	3.4	614	.001	10	2021	600
406	3.3	691	.001	10	2021	600
407	3.0	744	.001	10	2021	600
408	3.0	780	.001	10	2021	600
409	2.8	614	.001	10	343	300
410	2.5	691	.001	10	343	300
411	2.5	744	.001	10	343	300
412	2.5	780	.001	10	343	300
413	2.5	614	.001	10	790	300
414	2.3	691	.001	10	790	300
415	2.0	744	.001	10	790	300
416	2.5	780	.001	10	790	300
417	2.3	614	.001	10	1212	300
418	2.3	691	.001	10	1212	300
419	2.0	744	.001	10	1212	300
420	2.3	780	.001	10	1212	300
421	5.8	614	.001	30	2572	900
422	6.0	691	.001	30	2572	900
423	5.3	744	.001	30	2572	900
424	4.3	780	.001	30	2572	900
425	4.8	614	.001	30	1960	900
426	4.6	691	.001	30	1960	900
427	4.4	744	.001	30	1960	900
428	4.0	780	.001	30	1960	900
429	3.1	614	.001	50	624	300
430	3.0	691	.001	50	624	300
431	3.0	744	.001	50	624	300
432	3.0	780	.001	50	624	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (10 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F- (gpm)	Flush Volume -V_F- (gal.)
433	3.3	614	.001	50	269	300
434	3.1	691	.001	50	269	300
435	3.3	744	.001	50	269	300
436	3.1	780	.001	50	269	300
437	4.8	614	.001	50	759	900
438	4.5	691	.001	50	759	900
439	4.3	744	.001	50	759	900
440	4.0	780	.001	50	759	900
441	4.5	614	.001	50	441	900
442	4.5	691	.001	50	441	900
443	4.5	744	.001	50	441	900
444	4.0	780	.001	50	441	900
445	3.0	614	.001	10	385	600
446	3.0	691	.001	10	385	600
447	3.0	744	.001	10	385	600
448	3.0	780	.001	10	385	600
449	2.0	614	.001	10	330	300
450	2.0	691	.001	10	330	300
451	2.0	744	.001	10	330	300
452	2.0	780	.001	10	330	300
453	5.0	614	.001	50	3234	900
454	4.8	691	.001	50	3234	900
455	4.5	744	.001	50	3234	900
456	4.4	780	.001	50	3234	900
457	3.3	614	.001	10	2499	600
458	3.3	691	.001	10	2499	600
459	3.0	744	.001	10	2499	600
460	3.3	780	.001	10	2499	600
461	2.3	614	.001	10	1323	300
462	2.3	691	.001	10	1323	300
463	2.3	744	.001	10	1323	300
464	2.5	780	.001	10	1323	300
465	3.3	614	.001	50	1506	300
466	2.4	691	.001	50	1506	300
467	2.4	744	.001	50	1506	300
468	3.3	780	.001	50	1506	300
469	4.8	614	.001	50	1947	900
470	4.8	691	.001	50	1947	900
471	4.4	744	.001	50	1947	900
472	4.0	780	.001	50	1947	900
473	4.0	614	.001	50	1029	600
474	4.0	691	.001	50	1029	600
475	3.3	744	.001	50	1029	600
476	3.5	780	.001	50	1029	600
477	3.0	614	.001	10	1764	300
478	2.0	691	.001	10	1764	300
479	2.0	744	.001	10	1764	300
480	2.8	780	.001	10	1764	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (11 of 12)

Observation No.	Maximum Flush Wave Depth -W_D- (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B- (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F- (gal.)
481	2.8	614	.001	10	1690	300
482	2.8	691	.001	10	1690	300
483	2.5	744	.001	10	1690	300
484	2.5	780	.001	10	1690	300
485	2.5	614	.001	10	710	300
486	2.5	691	.001	10	710	300
487	2.3	744	.001	10	710	300
488	2.3	780	.001	10	710	300
489	4.8	614	.002	10	2940	900
490	4.8	691	.002	10	2940	900
491	4.5	744	.002	10	2940	900
492	4.5	780	.002	10	2940	900
493	3.0	614	.002	10	1323	300
494	2.8	691	.002	10	1323	300
495	2.8	744	.002	10	1323	300
496	2.8	780	.002	10	1323	300
497	4.5	614	.002	10	441	900
498	4.5	691	.002	10	441	900
499	4.3	744	.002	10	441	900
500	3.8	780	.002	10	441	900
501	2.8	614	.002	10	343	300
502	2.8	691	.002	10	343	300
503	3.0	744	.002	10	343	300
504	2.8	780	.002	10	343	300
505	4.8	614	.002	50	2989	900
506	4.5	691	.002	50	2989	900
507	4.5	744	.002	50	2989	900
508	4.0	780	.002	50	2989	900
509	3.8	614	.002	50	1127	300
510	4.3	691	.002	50	1127	300
511	4.3	744	.002	50	1127	300
512	3.8	780	.002	50	1127	300
513	4.3	614	.002	50	441	900
514	4.3	691	.002	50	441	900
515	4.3	744	.002	50	441	900
516	3.8	780	.002	50	441	900
517	4.3	614	.002	50	882	600
518	4.0	691	.002	50	882	600
519	4.0	744	.002	50	882	600
520	4.0	780	.002	50	882	600
521	3.8	614	.002	10	980	600
522	3.8	691	.002	10	980	600
523	3.8	744	.002	10	980	600
524	3.8	780	.002	10	980	600
525	3.0	614	.002	10	931	300
526	2.8	691	.002	10	931	300
527	2.8	744	.002	10	931	300
528	3.0	780	.002	10	931	300

Table 10 SUMMARY OF MAXIMUM FLUSH WAVE DEPTHS OBSERVED IN 18-INCH SEWERS (12 of 12)

Observation No.	Maximum Flush Wave Depth -W_D (in.)	Distance Downstream of Flush Release (ft)	Pipe Slope -So-	Sewage Base Flow -Q_B (gpm)	Flush Rate -Q_F (gpm)	Flush Volume -V_F (gal.)
529	3.8	614	.002	50	931	300
530	3.0	691	.002	50	931	300
531	3.3	744	.002	50	931	300
532	3.0	780	.002	50	931	300
533	5.5	614	.004	50	2989	900
534	5.5	691	.004	50	2989	900
535	5.5	744	.004	50	2989	900
536	5.5	780	.004	50	2989	900
537	3.5	614	.004	50	1911	300
538	3.5	691	.004	50	1911	300
539	3.5	744	.004	50	1911	300
540	3.3	780	.004	50	1911	300
541	5.0	614	.004	50	490	900
542	4.8	691	.004	50	490	900
543	5.0	744	.004	50	490	900
544	4.8	780	.004	50	490	900
545	3.5	614	.004	50	98	300
546	3.5	691	.004	50	98	300
547	3.5	744	.004	50	98	300
548	3.3	780	.004	50	98	300
549	4.8	614	.004	10	2450	900
550	4.8	691	.004	10	2450	900
551	4.8	744	.004	10	2450	900
552	4.5	780	.004	10	2450	900
553	3.3	614	.004	10	1470	300
554	3.5	691	.004	10	1470	300
555	3.5	744	.004	10	1470	300
556	3.3	780	.004	10	1470	300
557	3.0	614	.004	10	343	300
558	2.8	691	.004	10	343	300
559	2.8	744	.004	10	343	300
560	2.8	780	.004	10	343	300
561	4.5	614	.004	10	196	900
562	4.0	691	.004	10	196	900
563	4.3	744	.004	10	196	900
564	4.0	780	.004	10	196	900
565	3.3	614	.004	10	784	300
566	3.3	691	.004	10	784	300
567	3.3	744	.004	10	784	300
568	3.3	780	.004	10	784	300
569	5.5	614	.004	50	1176	900
570	4.8	691	.004	50	1176	900
571	5.0	744	.004	50	1176	900
572	4.5	780	.004	50	1176	900
573	3.8	614	.004	50	1617	300
574	3.8	691	.004	50	1617	300
575	3.5	744	.004	50	1617	300
576	3.5	780	.004	50	1617	300

Table 11 SUMMARY OF STEEP-SLOPE EQUATION VERIFICATION

Pipe Diameter -D- (in.)	Pipe Slope -So-	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Pipe Length -L- (ft)	Sewage Base Flow -Q- (gpm)	SS Clean Effluent $-\overline{C}_{ESS}-$ (%)		VSS Clean Effluent $-\overline{C}_{EVSS}-$ (%)		TOC Clean Effluent $-\overline{C}_{ETOC}-$ (%)	
						① Observed Value	② Estimated Value	① Observed Value	③ Estimated Value	① Observed Value	④ Estimated Value
12	.008	1421	300	267	10	94.1	97.4	93.9	97.5	71.3	68.8
12	.008	1421	300	514	10	87.2	86.2	88.8	87.6	72.3	64.1
12	.008	1421	300	622	10	87.5	82.9	80.0	84.7	47.0	62.7
12	.008	1421	300	782	10	73.5	76.3	71.4	76.2	46.7	61.1
12	.008	1715	900	267	10	98.0	100.0	97.1	100.0	53.9	75.2
12	.008	1715	900	514	10	98.5	100.0	93.4	100.0	54.2	70.5
12	.008	1715	900	622	10	93.5	98.3	89.3	100.0	32.1	69.1
12	.008	1715	900	782	10	91.8	94.4	86.3	96.5	39.6	67.5
12	.008	1813	900	267	30	98.0	100.0	94.1	100.0	79.7	70.4
12	.008	1813	900	514	30	90.9	90.0	89.1	90.9	53.3	65.7
12	.008	1813	900	622	30	80.0	86.7	86.5	88.0	54.8	64.3
12	.008	1813	900	782	30	76.4	82.8	82.2	84.6	55.0	62.7
12	.008	1372	300	267	30	86.3	82.9	84.9	84.7	65.5	62.7
12	.008	1372	300	514	30	68.3	71.7	74.0	74.8	62.2	58.0
12	.008	1372	300	622	30	67.0	68.4	70.5	71.9	58.0	56.7
12	.008	1372	300	782	30	63.9	64.5	66.2	68.4	56.0	55.0

NOTES: ① Observed values were taken from test data, Tests 123 through 126.
② Estimated values were taken from Equation No. 10.
③ Observed values were taken from Equation No. 11.
④ Estimated values were taken from Equation No. 12.

Table 12 STEEP-SLOPE CHECK OF WAVE DEPTH EQUATION (Equation 13A)

Pipe Diameter -D- (in.)	Pipe Slope -So-	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal.)	Sewage Base Flow $-Q_B-$ (gpm)	Flush Wave Depth At Various Locations From Influent End (inches)											
					92'	164'	218'	290'	361'	442'	473'	535'	614'	680'	732'	770'
12 ①	.008	1715	900	10	12.00	9.50	9.00	8.50	8.50	7.75	8.25	6.50	7.50	7.50	6.00	5.25
12 ②	.008	1715	900	10	10.67	9.83	9.32	8.73	8.21	7.68	7.49	7.13	6.70	6.36	6.11	5.93
12 ①	.008	1421	300	10	9.50	8.25	7.25	7.50	6.00	5.50	5.75	5.00	5.25	5.00	5.00	4.75
12 ②	.008	1421	300	10	9.30	8.46	7.95	7.36	6.84	6.31	6.12	5.76	5.33	4.99	4.74	4.56
12 ①	.008	1813	900	30	10.50	10.50	10.50	9.50	9.00	9.50	8.25	8.00	8.25	7.50	7.50	7.50
12 ②	.008	1813	900	30	11.68	10.84	10.33	9.74	9.22	8.69	8.50	8.14	7.71	7.37	7.12	6.94
12 ①	.008	1372	300	30	9.25	8.85	7.95	7.25	7.00	6.25	5.75	5.75	5.50	5.25	5.25	5.00
12 ②	.008	1372	300	30	9.76	8.92	8.41	7.82	7.30	6.77	6.58	6.22	5.79	5.45	5.20	5.02

NOTES: ① Observed Values were taken from test data, Tests 123, 124, 125 and 127.
② Estimated values determined using Equation No. 13A.

Table 13 RESULTS FROM SEWAGE FLUSH CORRELATION TESTS (1 of 2)

Observation No.	Predicted ① Clean-Water Cleansing Efficiency $-\overline{C}_{ESS}-$ (%)	Observed Sewage Flush Cleansing Efficiency $-\overline{C}_{ESS}'-$ (%)	Percent ② Reduction In $\overline{C}_{ESS}$ Resulting From Sewage Flush $-\Delta\overline{C}_{ESS}-$ (%)	Length of Sewer Flushed -L- (ft)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gals.)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Pipe Diameter -D- (in.)
1	68.9	70.9	2.90	267	220	300	.004	10	12
2	57.6	53.9	+ 6.42	514	220	300	.004	10	12
3	54.4	44.2	+18.75	622	220	300	.004	10	12
4	50.4	41.8	+17.06	782	220	300	.004	10	12
5	85.4	79.3	+ 7.14	267	1225	300	.004	10	12
6	74.2	79.3	6.87	514	1225	300	.004	10	12
7	70.9	73.9	4.23	622	1225	300	.004	10	12
8	67.0	63.5	+ 5.22	782	1225	300	.004	10	12
9	84.2	86.3	2.49	267	220	900	.004	10	12
10	72.9	74.7	2.47	514	220	900	.004	10	12
11	69.7	72.6	4.16	622	220	900	.004	10	12
12	65.7	62.6	+ 4.72	782	220	900	.004	10	12
13	100.0	89.9	+10.10	267	1838	900	.004	10	12
14	93.4	85.0	+ 8.99	514	1838	900	.004	10	12
15	90.1	79.9	+11.32	622	1838	900	.004	10	12
16	86.2	70.5	+18.21	782	1838	900	.004	10	12
17	67.6	65.7	+ 2.81	267	194	300	.004	10	12
18	56.4	56.0	+00: 71	514	194	300	.004	10	12
19	53.1	53.4	0.56	622	194	300	.004	10	12
20	49.2	46.2	+ 6.10	782	194	300	.004	10	12
21	86.0	79.7	+ 7.33	267	1298	300	.004	10	12
22	74.8	68.4	+ 8.56	514	1298	300	.004	10	12
23	71.5	65.0	+ 9.09	622	1298	300	.004	10	12
24	67.6	54.3	+19.67	782	1298	300	.004	10	12
25	85.2	86.4	1.41	267	245	900	.004	10	12
26	74.0	73.2	+ 1.08	514	245	900	.004	10	12
27	70.7	67.5	+ 4.53	622	245	900	.004	10	12
28	66.8	59.9	+10.33	782	245	900	.004	10	12
29	100.0	94.2	+ 5.80	267	1960	900	.004	10	12
30	94.0	88.4	+ 5.96	514	1960	900	.004	10	12
31	90.8	83.1	+ 8.48	622	1960	900	.004	10	12
32	86.8	71.4	+17.74	782	1960	900	.004	10	12
33	100.0	91.9	+ 8.10	267	1886	900	.004	10	12
34	93.7	86.5	+ 7.68	514	1886	900	.004	10	12
35	90.4	84.0	+ 7.08	622	1886	900	.004	10	12
36	86.5	74.3	+14.10	782	1886	900	.004	10	12
37	83.6	50.7	+39.35	267	208	900	.004	10	12
38	72.4	43.6	+39.78	514	208	900	.004	10	12
39	69.1	41.9	+39.36	622	208	900	.004	10	12
40	65.2	32.9	+45.54	782	208	900	.004	10	12
41	85.6	68.3	+20.21	267	1250	300	.004	10	12
42	74.4	61.6	+17.20	514	1250	300	.004	10	12

NOTES: ① Computed using Equation 10.
② Computed using Equation 15.

Table 13 RESULTS FROM SEWAGE FLUSH CORRELATION TESTS (2 of 2)

Observation No.	Predicted (1) Clean-Water Cleansing Efficiency $-\bar{C}_{ESS}$ (%)	Observed Sewage Flush Cleansing Efficiency $-\bar{C}_{ESS}'-$ (%)	Percent (2) Reduction In $\bar{C}_{ESS}$ Resulting From Sewage Flush $-\Delta\bar{C}_{ESS}-$ (%)	Length of Sewer Flushed -L- (ft)	Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gals.)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Pipe Diameter -D- (in.)
43	71.1	56.0	+21.24	622	1250	300	.004	10	12
44	67.2	52.2	+22.32	782	1250	300	.004	10	12
45	47.6	56.0	-17.65	267	270	300	.002	50	18
46	45.9	42.2	+ 8.06	527	270	300	.002	50	18
47	32.7	37.8	-15.60	635	270	300	.002	50	18
48	28.8	32.3	-12.15	795	270	300	.002	50	18
49	61.3	70.1	-14.36	267	1127	300	.002	50	18
50	49.7	70.2	-41.25	527	1127	300	.002	50	18
51	46.5	64.2	-38.06	635	1127	300	.002	50	18
52	42.6	55.1	-29.34	795	1127	300	.002	50	18
53	62.8	62.5	+ 0.48	267	268	900	.002	50	18
54	51.1	64.1	-25.44	527	268	900	.002	50	18
55	47.9	53.7	-12.11	635	268	900	.002	50	18
56	44.1	41.2	+ 6.58	795	268	900	.002	50	18
57	82.8	83.5	0.85	267	2132	900	.002	50	18
58	71.1	59.2	+16.74	527	2132	900	.002	50	18
59	67.9	46.6	+31.37	635	2132	900	.002	50	18
60	64.1	30.4	+52.57	795	2132	900	.002	50	18
61	47.1	33.3	+29.30	267	258	300	.002	50	18
62	35.5	32.0	+ 9.86	527	258	300	.002	50	18
63	32.3	24.9	+22.91	635	258	300	.002	50	18
64	28.4	18.5	+34.86	795	258	300	.002	50	18
65	61.3	75.3	-22.84	267	1127	300	.002	50	18
66	49.7	75.5	-51.91	527	1127	300	.002	50	18
67	46.5	65.5	-40.86	635	1127	300	.002	50	18
68	42.6	56.2	-31.92	795	1127	300	.002	50	18
69	65.2	61.8	+ 5.21	267	343	900	.002	50	18
70	53.5	56.7	5.98	527	343	900	.002	50	18
71	50.3	51.5	2.39	635	343	900	.002	50	18
72	46.5	45.6	+ 1.94	795	343	900	.002	50	18
73	86.4	89.7	3.82	267	3112	900	.002	50	18
74	74.8	76.3	2.01	527	3112	900	.002	50	18
75	71.6	71.0	+ 0.84	635	3112	900	.002	50	18
76	67.7	63.7	+ 5.91	795	3112	900	.002	50	18
77	64.1	67.3	4.99	267	306	900	.002	50	18
78	52.4	63.8	-21.76	527	306	900	.002	50	18
79	49.2	61.6	-25.20	635	306	900	.002	50	18
80	45.4	58.4	-28.63	795	306	900	.002	50	18
81	60.5	76.7	-26.78	267	1029	300	.002	50	18
82	48.8	64.9	-34.09	527	1029	300	.002	50	18
83	45.6	59.6	-30.70	635	1029	300	.002	50	18
84	41.8	53.2	-27.27	795	1029	300	.002	50	18

NOTES: (1) Computed using Equation 10.
(2) Computed using Equation 15.

Table 14 RESULTS FROM PIPE MISALINEMENT TESTS

Tests	Pipe Diameter -D- (in.)	Pipe Slope -So-	Sewage Base Flow $-Q_B-$ (gpm)	Flush Volume $-V_F-$ (gals.)	Flush Rate $-Q_F-$ (gpm)	Average S.S. Cleansing Efficiency, $\bar{C}_{ESS}$ (Percent) For the First 267' of Sewer	For the First 520' of Sewer	For the First 630' of Sewer	For the Full Length of Sewer (790')
Pipe Misalinement	12 ①	.004	10	900	1838	90.4	85.4	82.5	76.8
	12 ①	.004	10	900	196	65.5	65.4	64.0	57.0
	12 ①	.004	10	300	1372	79.8	72.2	69.0	63.7
	12 ①	.004	10	300	208	64.4	63.1	60.1	54.4
	18 ②	.002	50	900	2450	88.5	82.1	78.0	72.8
	18 ②	.002	50	900	343	42.0	46.0	42.5	38.5
	18 ②	.002	50	300	1127	87.0	57.0	50.7	44.5
	18 ②	.002	50	300	270	17.4	15.3	8.6	10.9
	12 ③	.004	10	900	1862	91.2	87.4	84.0	78.1
	18 ④	.002	50	900	2254	89.1	82.7	78.1	74.5
Grade Misalinement	12 ⑤	.004	10	900	1666	82.7	80.3	77.7	74.2
	12 ⑤	.004	10	900	1666	95.7	92.4	90.2	86.2
	12 ⑤	.004	10	300	1421	91.6	84.7	81.3	73.9
	18 ⑥	.002	50	900	2303	84.1	82.6	77.2	73.6
	18 ⑥	.002	50	900	1960	96.6	87.0	79.9	74.6
	18 ⑥	.002	50	300	931	70.4	58.2	52.1	44.9

NOTES:
① Six 1/2-inch steel rings at approximately 130-foot intervals, simulating pipe misalinement.
② Three 1/2-inch steel rings at approximately 260-foot intervals, simulating pipe misalinement.
③ Six 1-inch steel rings at approximately 130-foot intervals, simulating pipe misalinement.
④ Three 1-inch steel rings at approximately 260-foot intervals, simulating pipe misalinement.
⑤ Forty-three 1/2-inch grade misalinement at approximately 18-foot intervals.
⑥ Forty-three 1-inch grade misalinement at approximately 18-foot intervals.

Table 15 RESULTS FROM FLUSH WAVE SEQUENCING TESTS

Pipe Diameter -D- (in.)	Pipe Slope $-S_o-$	Sewage Base Flow $-Q_B-$ (gpm)	Average Flush Rate $-Q_F-$ (gpm)	Flush Volume $-V_F-$ (gal)			Values of $\bar{C}_{ESS}$ Observed at the Various Sequences ① $-\bar{C}_{ESS}-$			Equivalent ② Single Flush Volume $-V_F-$ ① (gal)	SS Cleansing Efficiency Predicted from Equation 10 (%)
				Tank No. 1	Tank No. 2	Tank No. 3	Flush Sequence ① A	B	C		
12	.004	10	230	300	300	300	57.7	59.6	62.1	600	58.8
12	.004	10	1220	300	300	300	65.8	82.2	66.3	600	76.6
12	.004	10	1370	900	300	300		80.6		1200	87.5
12	.004	10	150	600		300		53.5		700	63.0
12	.004	10	1500	600		300		73.4		700	81.0
18	.002	50	640	300	300	300	44.8	68.2	60.6	600	46.1
18	.002	50	1200	300	300	300	71.9	74.6	76.4	600	52.9
18	.002	50	1470	900	300	300		75.5		1200	64.7
18	.002	50	340	600		300		41.8		700	41.5
18	.002	50	1620	600		300		61.6		700	58.2

NOTES: ① Flush Release Sequences:

Sequence A — The flush tanks were activated separately beginning with the downstream flush tank (Tank No. 3).

Sequence B — The upstream flush tank (Tank No. 1) was activated first and then Tanks No. 2 and 3 were released, when the flush wave generated upstream reached its maximum depth at their respective positions.

Sequence C — The flush tanks were activated separately, beginning with the upstream tank (Tank No. 1), so that each of the three flush waves generated passed separately through the entire length of the sewer.

② This parameter was determined by taking the summation of the products of the total quantity of water that passed through each of the three sections of pipe and the length of each section, and dividing by the total length of the sewer.

Table 16 RESULTS FROM SOLIDS BUILDUP TESTS

Pipe Diameter -D- (in.)	Pipe Slope $-S_o-$	Duration of the Sewage Flow $-D_T-$ (hrs)	Total SS Deposited (lbs)				Total VSS Deposited (lbs)				Total TOC Deposited (lbs)			
			In First 267 ft of Pipe	In First 520 ft of Pipe	In First 630 ft of Pipe	In Total Length of Sewer, 790 ft	In First 267 ft of Pipe	In First 520 ft of Pipe	In First 630 ft of Pipe	In Total Length of Sewer, 790 ft	In First 267 ft of Pipe	In First 520 ft of Pipe	In First 630 ft of Pipe	In Total Length of Sewer, 790 ft
12	.004	42	1.130	1.534	1.695	1.982	0.832	1.130	1.184	1.339	0.149	0.253	0.325	0.405
12	.004	94	2.560	2.975	3.104	3.629	1.420	1.708	1.798	2.208	0.251	0.368	0.533	0.853
12	.004	188	4.750	5.470	5.650	6.590	2.930	2.920	3.560	0.250	1.490	1.580	1.760	1.760
18	.002	42	1.270	3.350	3.636	3.988	0.640	2.210	2.380	2.573	0.206	0.566	0.672	0.744
18	.002	94	3.220	8.130	8.658	8.993	1.375	5.075	5.517	5.803	0.667	1.482	1.740	2.040
18	.002	188	2.330	9.490	10.100	10.56	0.700	4.980	5.210	5.360	0.430	0.770	0.930	0.980

Table 17 RESULTS FROM PROTOTYPE FLUSH STATION TESTS

Station Type	Function Evaluated	Findings
Fabric Storage Bag in Manhole	Fill Cycle	The pump was run for approximately 2 hours, at which time the bag was filled. Some problems were experienced with clogging of the intake screen but were eliminated by making it flatter.
	Dump Cycle	The dump cycle was tested with the bag half full and completely full. The average rate of discharge ranged from 800 gpm with the bag full to 670 gpm with the bag half full.
	Lifting Mechanism	The lifting mechanism was evaluated and found to function quite well. The bag was lifted while void of water and was found to lift easily through a 20-inch opening.
	Continuous Operation	The flush station was operated for 3 successive days and was found to perform very dependably during this period. The control valve functioned very well and no major clogging problems were experienced.
In-line Inflatable Dam	Inflatability and Installation	The bag was found to be easily inflated, once installed. However, the installation was quite difficult because of the awkward design. It was noted that when the dam is inserted directly into the sewer, it is hard to seal around and could possibly cause problems with upstream flooding at the sewer.
	Rate of Release	The average release rate was found to be less than that which would be desirable (ranging from approximately 500 to 1000 gpm depending on the degree of initial inflation) due to air entrapment and slow deflation near the end of the cycle.
	Flow Interference	There was no evidence that the deflated dam produced any significant interference with the normal sewage flows through the sewer.
	Solids Removal	Despite the low release rate, the flush wave downstream of the dam was visually observed and found to remove much of the visable deposited material. However, upstream of the dam, the solids deposits were very heavy and were not significantly reduced after release of the stored sewage.

APPENDIX D

STATISTICAL ANALYSIS OF DESIGN EQUATIONS

Table 18 SUMMARY OF STATISTICS FOR EQUATION 9 (SS CORRELATION)

Statistical Parameter	Statistics For Each of the Independent Variables					Statistics for the Complete Relationship
	$(V_F x Q_F)^{0.1}$	$(Q_B)^{-0.5}$	$(L)^{-0.1}$	$(S_o)^{0.5}$	$(D)^{1.8}$	
Sum of the Squares Reduced (of 228,904)	51,680	37,953	25,802	24,669	2,052	142,157
Proportion of Variance of $\bar{C}_{ESS}$ Reduced	0.2258	0.1658	0.1127	0.1078	0.0090	0.6210
F (DF= 1,538)	155.1	144.7	120.5	147.0	12.5	173.0
Correlation Coefficient	0.4752	0.4070	0.3355	0.3280	0.0948	0.7881
Regression Coefficient	66.74	5.07	312.61	57.72	111.01	
Standard Error of Regression Coefficient	3.365	0.3717	25.20	4.654	31.411	
Computed T for Regression Coefficient	19.834	13.646	12.405	12.404	3.534	
Standard Error of Estimate						12.8178
$\bar{C}_{ESS}$ Intercept						-379.8

Table 19 SUMMARY OF STATISTICS FOR EQUATION 10
(SS Correlation)

STATISTICS FOR ALL 544-OBSERVED VALUES OF $\overline{C}_{ESS}$

Proportion of Variance of $\overline{C}_{ESS}$ Reduced	0.6414
Partial F (DF = 1, 542)	969.4868
Cumulative Sum of Squares Reduced	147691.000
Cumulative Proportion Reduced	0.6414 (of 230258.9000)
Multiple Correlation Coefficient	0.8060
F For Analysis of Variable (DF = 1, 542)	969.4868
Standard Error of Estimate	12.1326

Variable	Regression Coefficient	Standard Error-Coefficient	Computed T
$Log_{10}(H)$	24.0116	.771171	31.1366

Intercept ($\overline{C}_{ESS}$) — 13.30284

STATISTICS AFTER DELETIONS OF 12 OBSERVATIONS (532)

Proportion of Variance of $\overline{C}_{ESS}$ Reduced	0.6847
Partial F (DF = 1, 530)	1150.9930
Cumulative Sum of Squares Reduced	148131.7000
Cumulative Proportion Reduced	0.6847 (of 216342.2000)
Multiple Correlation Coefficient	0.8275
F For Analysis of Variable (DF = 1, 530)	11.3446

Variable	Regression Coefficient	Standard Error-Coefficient	Computed T
$Log_{10}(H)$	24.6802	.727465	33.9263

Intercept ($\overline{C}_{ESS}$) — 13.7134

Table 20 SUMMARY OF STATISTICS FOR EQUATION 11
(VSS Correlation)

Proportion of Variance of $\bar{C}_{EVSS}$ Reduced	0.5597
Partial F (DF = 1,530)	673.8613
Cumulative Sum of Squares Reduced	108994.6000
Cumulative Proportion Reduced	0.5597 (of 194720.2000)
Multiple Correlation Coefficient	0.7482
F For Analysis of Variable (DF = 1,530)	673.8613
Standard Error of Estimate	12.7180

Variable	Regression Coefficient	Standard Error-Coefficient	Computed T
Log_{10} (H)	21.7178	.836625	25.9589

Intercept ($\bar{C}_{EVSS}$) — .344437

Table 21 SUMMARY OF STATISTICS FOR EQUATION 12
(TOC Correlation)

Proportion of Variance of Y Reduced	0.1645
Partial F (DF = 1,530)	104.3881
Cumulative Sum of Squares Reduced	25594.4100
Cumulative Proportion Reduced	0.1645 (of 155542.6000)
Multiple Correlation Coefficient	0.4056
F For Analysis of Variable (DF = 1,530)	104.3881
Standard Error of Estimate	15.6584

Variable	Regression Coefficient	Standard Error-Coefficient	Computed T
Log_{10} (H)	10.2977	1.00789	10.2171

Intercept $\bar{C}_{ETOC}$ — 22.3553

Table 22 SUMMARY OF STATISTICS FOR EQUATION 13A
($\overline{W}_D$) Correlation for the 12-inch Sewer)

Statistical Parameter	Statistics For Each of the Independent Variables					Statistics for the Complete Relationship
	$L^{0.5}$	V_F	Q_F	So	Q_B	
Sum of the Squares Reduced (of 2,977)	1207.0	463.0	316.0	17.4	1.32	2006.8
Proportion of Variance $\overline{W}_D$ Reduced	0.4057	0.1556	0.1064	0.0059	0.0004	0.6740
F (DF = 1,574)	391.8	203.3	183.2	10.2	0.75	235.7
Correlation Coefficient	0.637	0.3940	0.3260	0.0768	0.020	0.8210
Regression Coefficient	-0.261	0.023	0.534	-1.00	2.36	
Standard Error of Regression Coefficient	0.00968	0.00158	0.0387	0.340	2.717	
Computed T for Regression Coefficient	-26.96	14.57	13.83	-2.95	0.868	
Standard Error of Estimate						1.3049
$\overline{W}_D$ Intercept						8.454

Table 23 SUMMARY OF STATISTICS FOR EQUATION 13B
($Wave Depth (\overline{W}_D)$ Correlation for the 18-inch Sewer)

Statistical Parameter	Statistics For Each of the Independent Variables					Statistics for the Complete Relationship
	$L^{0.5}$	Q_F	V_F	Q_B	S_o	
Sum of the Square Reduced (of 4,007)	1944.2	683.1	274.7	52.9	0.38	2955.3
Proportion of Variance $\overline{W}_D$ Reduced	0.4852	0.1705	0.0685	0.0132	0.0001	0.7374
F (DF = 1,574)	540.9	283.6	142.1	28.7	0.2035	320.2
Correlation Coefficient	0.6965	0.4130	0.1620	0.1150	0.0100	0.8587
Regression Coefficient	-0.322	0.408	0.0189	7.286	-0.215	
Standard Error of Regression Coefficient	0.00994	0.0306	0.00170	1.361	0.4777	
Computed T of Regression Coefficient	-32.45	13.37	11.10	5.353	-0.451	
Standard Error of Estimate						1.3586
$\overline{W}_D$ Intercept						8.839

Table 24 SUMMARY OF STATISTICS FOR EQUATION 15
(Sewage-Flush Correlation, $\Delta\overline{C}_{ESS}$)

Statistical Parameter	Statistics For Each of the Independent Variables			Statistics for the Complete Relationship
	V_F	L	Q_F	
Sum of the Square Reduced (of 36,175)	2693.4	152.7	15.5	2721.6
Proportion of Variance of $\Delta\overline{C}_{ESS}$ Reduced	0.0745	0.0042	0.0004	0.0791
F (DF = 1.82)	6.60	0.371	0.0372	2.2906
Correlation Coefficient	0.2729	0.0648	0.0200	0.2813
Regression Coefficient	-0.140	-0.00710	-0.242	
Standard Error of Regression Coefficient	0.0570	0.0117	1.256	
Computed T of Regression Coefficient	-2.449	-0.605	-0.193	
Standard Error of Estimate				20.41
$\Delta\overline{C}_{ESS}$ Intercept				14.30

Table 25 SUMMARY OF STATISTICS FOR EQUATION 16
(Correlation of $\overline{C}_{ESS}$, to LOG_{10} H)

Intercept	-13.6990
Regression Coefficient	23.6974
Standard Error of Regression Coefficient	1.602
Computed T Value	10.691
Correlation Coefficient	0.763
Standard Error of Estimate	10.940

ANALYSIS OF VARIANCE FOR THE REGRESSION

Source of Variation	D.F.	Sum of Square	Mean Square	F Value
Attributable to Regression	1	13677.410	13677.410	114.288
Deviation from Regression	82	9813.332	119.675	
Total	83	23490.742		

APPENDIX E

LIST OF DESIGN DRAWINGS

LIST OF DRAWINGS FOR THE PROTOTYPE FLUSH STATION

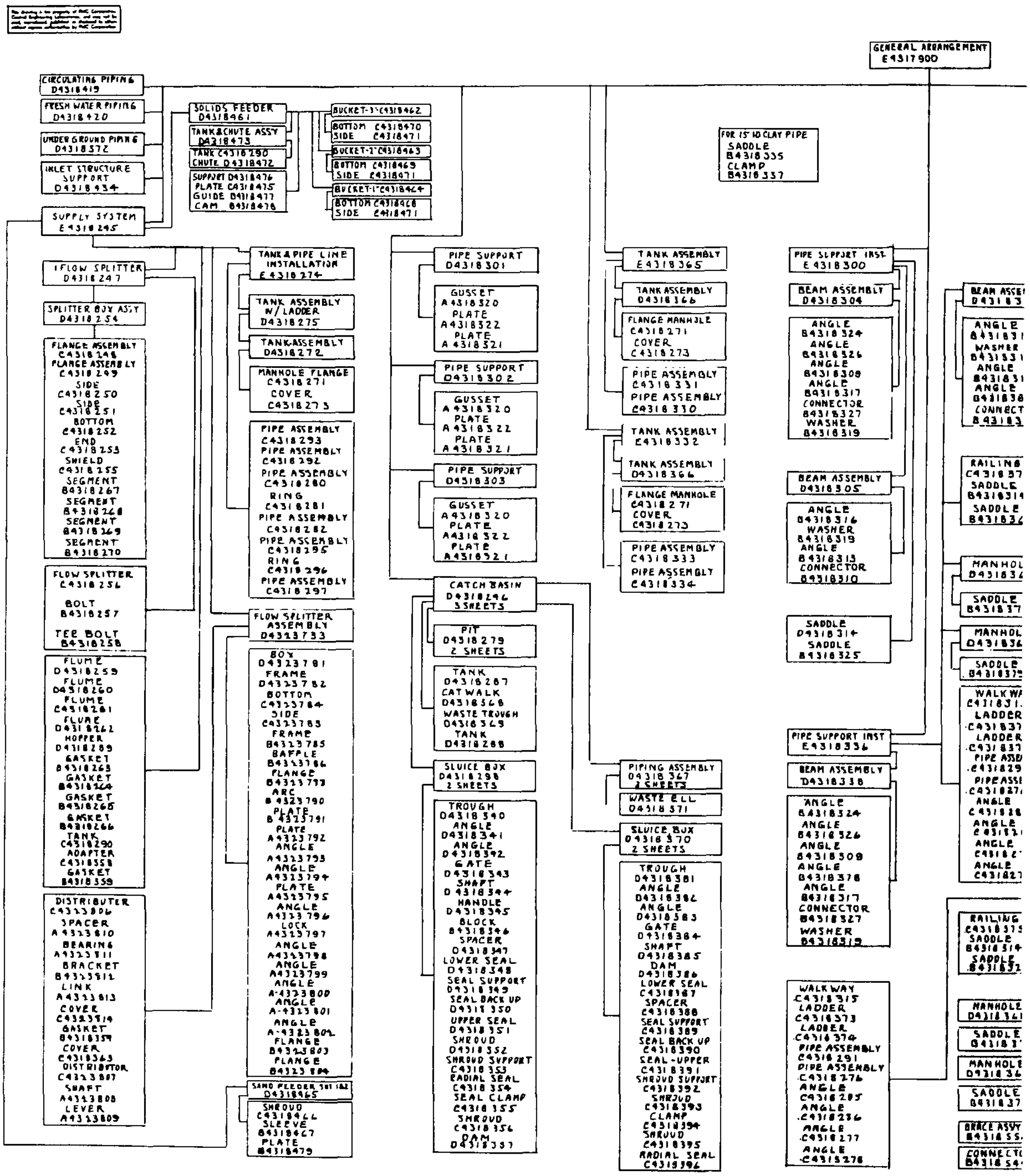
LAYOUTS:

E4318852
D4318853
D4318856, 3 Sheets
E4318945
E4319113
E4319114
E4319115

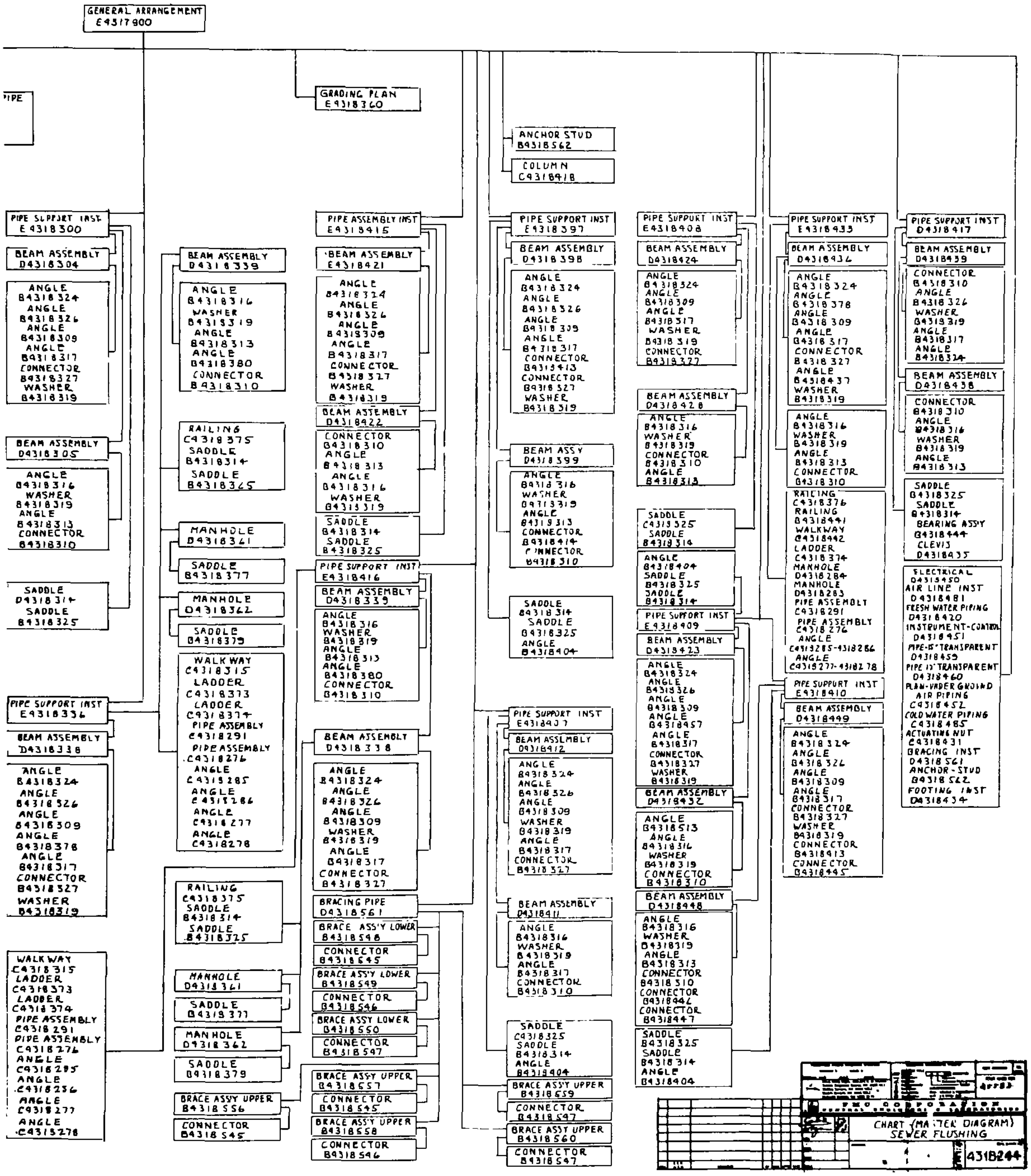
FABRIC FLUSH TANK (as built):

- D4319173
  - D4319192
    - D4319174
      - C4319178, C4319179, B4319188
    - B4319180, B4319189, B4319190, B4319292, C4319176, B4319177, B4319175
  - C4319187, C4319186, B4319194, B4319184, D4319185, D4319181, C4319182, D4319183, C4319195, B4319292

LIST OF DRAWINGS FOR THE TEST FACILITY (1 of 2)



LIST OF DRAWINGS FOR THE TEST FACILITY (2 of 2)



APPENDIX F

DESCRIPTION OF MATHEMATICAL MODEL FOR DESIGN OF SEWER FLUSHING SYSTEMS

INTRODUCTION

Since there are a variety of flush station types available, each with different solids removal characteristics and costs, an efficient method of selecting types and locations for installation is required. The following discussion addresses itself to this problem. The problem is to develop a mathematical model to select the best configuration for locating the flush stations and determine their capacities to achieve a specified cleansing efficiency. The criterion for evaluation can be either of the following:

- Minimize the total cost of the station's equipment and flush water required for operation of the flush stations.

- Minimize the quantity of flush water required.

An approach known as a dynamic programming technique is used to determine the optimal location and type of flushing stations. Under this approach, the analysis proceeds stepwise from the first upstream location to the last and identifies the most cost effective installation at each location.

The discussion which follows gives a detailed description of the development and use of the model and the computer program. A sample problem is also included as well as a discussion of ways that the existing model can be extended to be used for larger, more complex problems.

DESCRIPTION OF FLUSHING STATIONS

A flushing station is designed to release a hydraulic wave of sufficient magnitude and duration to cause deposited solids to become suspended and be flushed down the lateral. The idea is to install a series of these facilities along a lateral and operate them periodically so as to reduce the amount of solids which settle out during low flow periods.

The manner in which this wave may be generated is varied: it might be a discharge of clean water directly into the sewer lateral or possibly a small check dam to contain sewage and then periodically release it. The method of generating the flushing wave is unimportant as long as the efficiency of removal can be quantified as a function of the relevant physical parameters.

The parameters affecting the station efficiency are of three types:

- Flush Station Parameters; type of flushing installation, quantity of flush water, and rate of flush discharge
- Physical Characteristics; the length, diameter, and slope of sewer pipe and the distance between station installations
- Load Characteristics: The average rate of base sewage flow and the quantity of solids deposited in the flow.

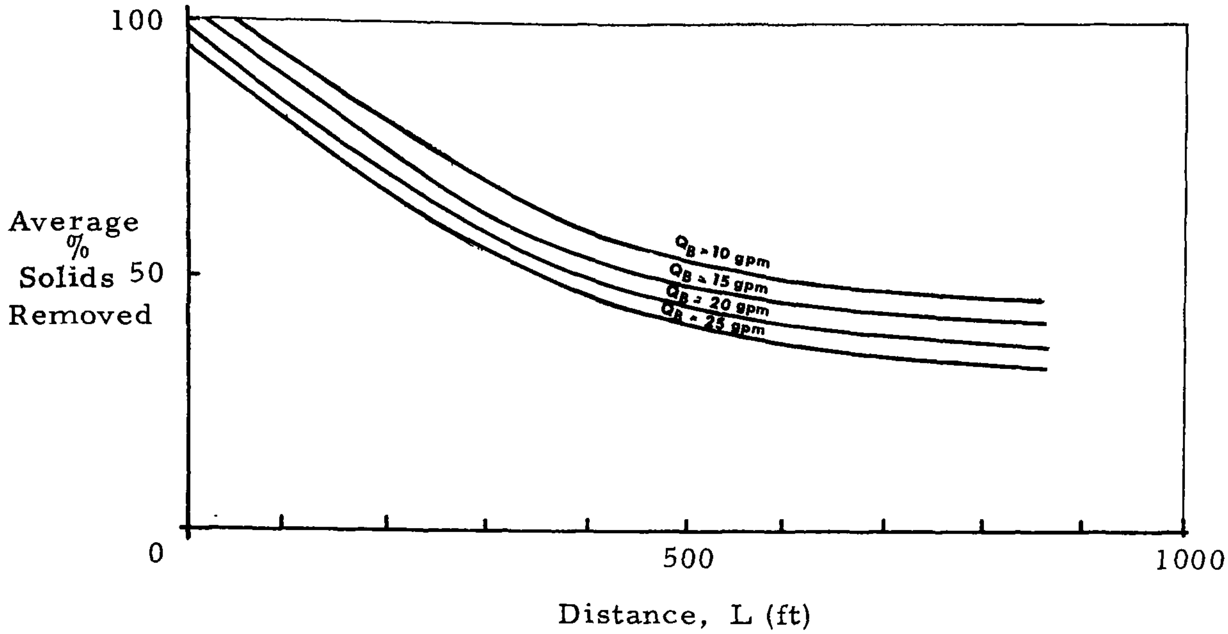
The Central Engineering Laboratories have performed extensive experiments to determine the efficiency of a flushing station as a function of the cited parameters. The equation as developed by the Central Engineering Laboratories gives the functional relationship of average cleansing efficiency ($\overline{C}_{ESS}$) in percent over the length (L) as a function of the length from the installation (L), the volume (V_F) and rate (Q_F) of the flush release, the slope (S_o), diameter (D), and the rate (Q_B) of base flow. The experiments show that the percent solids removal is independent of the amount of solids in the base flow; of course, the amount in pounds of solids removed is proportionally greater for larger solids loads.

The average cleansing efficiency is determined using the equation of the following general form:

$$\overline{C}_{ESS} = A + B \log_{10} \left[\frac{V_F^C \, Q_F^D \, S_o^E}{L^F \, Q_B^G} \right]$$

where A, B, C, D, E, F, and G are constants determined by a regression analysis of the experimental results (Equation 10).

Graphically, for constant slope and diameter and a particular flush rate and volume, the relationship between average efficiency and distance from point of installation for a variety of base flows is shown on the following page.



The above equation is expedient for performing the analysis of the experiment but is difficult to work with for the model developed in this document. For purposes of this model it is necessary to convert the curves for average efficiency to a curve for the point efficiency at a distance u from the installation (C_E). That is, if a 60 percent efficiency is stated for the distance of 500 ft., the implication of average efficiency is that over the entire length of 500 ft., on the average, 60 percent of the solids are removed; under the interpretation of point efficiency the implication is that at the distance 500 ft. from the point of installation, 60 percent of the deposited solids are removed. The expression for point efficiency may be derived from the average efficiency expression by using the general relationship

$$\bar{y}(L) = \frac{1}{L}\int_{o}^{L} y(u)\, du,$$

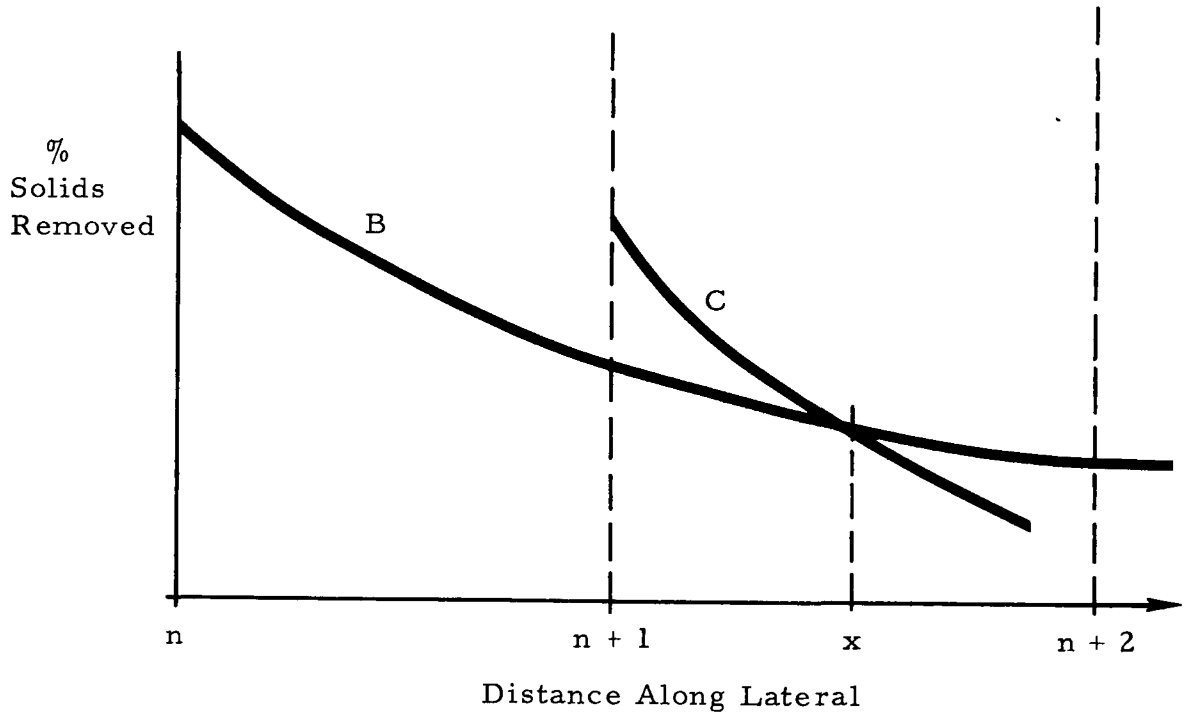
where $\bar{y}(L)$ is the average efficiency over L, and y(u) is the point efficiency as a function of distance u from the origin, and differentiating both sides. The result is,

$$C_E = \bar{C}_{ESS} - FB/\log_e (10)$$

where F and B are from the above average efficiency expression.

There are several assumptions about the operation of flushing stations which should be established before the computational procedure is discussed. The first stipulation is that no negative efficiencies (point efficiency) are allowed. A negative point efficiency implies that solids would be deposited rather than removed. It is obvious that over particularly long reaches from the installation, the solids would settle out. There are two tacit assumptions inherent in the stipulation of no negative efficiencies: first, that once in suspension, the solid particles stay in suspension (this is fairly reasonable since the plucking velocity is greater than that required to maintain the solids in suspension); and secondly, that installations will be sufficiently close together so as to provide additional assistance in keeping the particles in suspension (for typical levels of flushing efficiencies this assumption should be satisfied).

A second assumption which significantly impacts the computational procedures arises when the efficiencies of two or more stations overlap. An example of this problem is illustrated below. Here a flush station of type B is installed at location n and a station type C is installed at location n + 1.



As is seen in the plot, station type B has efficiencies which carry over into the reach beyond the next installation (the stations are assumed not to act simultaneously). The question is how to handle these overlapping efficiencies. There are several approaches for which good arguments can be made. For the purposes of the model developed here, however, it is assumed that the efficiency at any point follows the maximum efficiency of either curve. In the above example then, the efficiency follows the curve of station type B from location n to n+1, the curve of station type C from n+1 to X and the curve of station type B again from X to n+2. The argument for this type of removal pattern is based on grading the solids into an order based on ease of removal. If the least difficult particles to remove are first on the graded list, then conceptually, the model assumes that if some particular station type under given conditions will remove 40 percent of the solids, then the upper 40 percent will be flushed. This is equivalent to saying that the station under the conditions given cannot remove the bottom 60 percent of the solids. Such flushing behavior would be dependent upon the nature of the hydraulic wave that the flushing station emits. If this is representative of the behavior of a flushing station then the assumed pattern of cleansing for overlapping efficiency curves is valid. As long as the stations are operated independently (so that the wave of each is not acting simultaneously), then together they would flush no more solids than each would have flushed by itself.

The last assumption implicit to the computational procedure is that the sequence of stations along a lateral are operated in harmony. That is, that there is no interference in the flushing action of any station by any of the others. Certainly if there is constructive interference (e.g., additive effects of flushing by multiple stations operating together) the model will give conservative cleansing efficiencies. Basically this assumption stipulates that, at the least, the operation of flushing stations will pass to successively downstream locations.

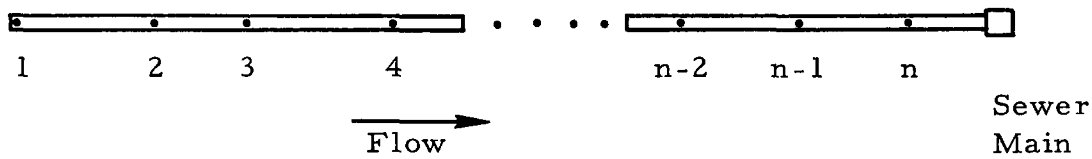
This establishes the necessary operational preliminaries to proceed to the computational procedure for selecting and locating flushing stations along a lateral.

THE FLUSHING STATION LOCATION MODEL

In equation form, the model employed to select the locations and station types for flushing station installations is difficult to interpret and appreciate. Hence, an intuitive approach through a more-or-less narrative, discussion is the best way to introduce the model. A more precise presentation is found on page 188. The actual mathematical formulation is not presented but can be found in the texts referenced.

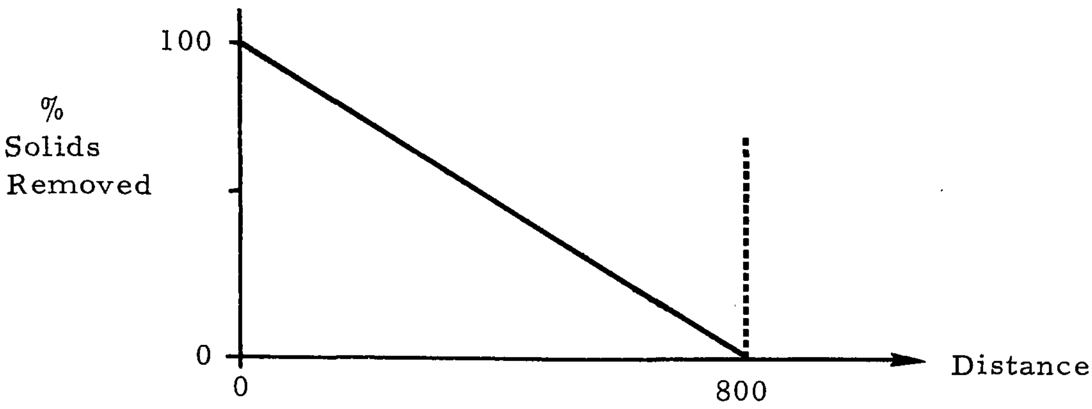
The solution technique is referred to in the literature as dynamic programming. This approach to problem solving is frequently employed in the optimization of sequential decision problems; that is, in problems in which a periodic (either over time or distance) decision must be made. Before discussing the actual mechanics of the model, however, it is necessary to establish a couple of points; one is fairly obvious, the second point is more subtle and introduces an important crutch to the actual computation.

Consider a simple lateral with defined acceptable locations for flushing stations as indicated below. There are n possible locations for flushing station installations along the lateral. In actual practice, these locations may be manholes or otherwise convenient locations to install a station.



The first point to note is that a flushing station will have effects only downstream of its point of installation. That is, a station installed at say location 3, may have consequences (either through the removal or deposition of solids) from location 3 through the last downstream reach of the lateral, in no case will there be any effects upstream of location 3.

The second point concerns the specification of cleansing efficiency along the lateral. The usual approach in assuring that sufficient solids have been removed for acceptable system operation is to specify an average efficiency of total solids removal for the entire lateral. For example, if engineering analysis has indicated that along some particular lateral there would be 200 lbs of solid material deposited in a day and an acceptable amount of solids remaining in the lateral were 60 lbs, the required efficiency would be specified at 70 percent removal. There is no direct way in this type of problem to solve for the minimum cost policy and still be assured of meeting the specified efficiency. To force the average efficiency to the specified level it is necessary to introduce an artificial or shadow savings of solids removal. To motivate the need for this shadow savings consider the following argument. The primary criterion for evaluation of a configuration is its cost. The least cost sequence of flush stations is the configuration with no installation which incurs a zero cost, but also a zero efficiency. If there is some installation configuration, then, there has to be a savings implied by the removal of solids. This savings implied by the removal of solids is the total shadow savings, referenced above. As an example, suppose for some station the installation, operation, and maintenance costs are $50 per month. It is assumed that the unit shadow savings are $1.50 per pound of solids removed and the amount of settled solids are .1 lb/ft. Then if the point flushing efficiency over 800 ft is as graphically illustrated below,



the net cost, including the savings of removing solids, of such an installation is easily calculated:

Average efficiency ($\overline{C}_{ESS}$)	= 50%
Total solids removed	= (.1 lb/ft)(.50)(800 ft) = 40 lbs
Total savings due to removal	= ($1.50/lb)(40 lb) $60
Net cost of installation	= $50 - $60 = -$10

The net cost of an installation of the above type is -$10 and hence, is preferable to no installation at this location.

A problem characteristic of this approach is the difficulty in selecting the unit value of the shadow savings that will yield the required level of efficiency. The only information known about the shadow savings is that small values imply low cleansing efficiencies while larger values yield high cleansing efficiencies. The relative magnitude in relation to the installation and operating costs is not known but a little practice and a trial-and-error approach to the solution technique should allow a fairly rapid determination of the shadow savings implying the required level of efficiency. The computer program uses a search technique to automatically determine the shadow savings. This is done by recursively solving the model with a new estimate of the shadow savings. The estimates are generated by doubling previous estimates (starting at $.01 per unit removed) until successive estimates bracket the desired efficiency. Once bracketed, the shadow savings is more accurately determined (and the desired efficiency more closely attained) by a search technique known as a "golden section search." Details of the technique are found in Foundations of Optimization by Wilde and Beightler. Essentially the approach is to successively redefine the interval in which the shadow savings implying the desired efficiency lies until sufficient accuracy is attained. More specifically, the model is evaluated at a fraction of .618 of the interval and either the 61.8 percent interval or the 38.2 percent interval is discarded depending on which of the intervals bracket the desired efficiency. The fraction .618 is recursively applied to the remaining interval. A manner in which successive estimates of the shadow savings may be used to give useful information of investment levels is discussed.

With these preliminaries and the assumptions about flushing station operation established in the preceding section, sufficient groundwork has been laid to present the computational procedure for locating flushing stations along a lateral. The approach is to cost out each successive location selecting that configuration of flushing stations which yields the minimum cost to the location under consideration. When the last location has been reached the sequence of costs leading to the absolute minimum cost is retraced to determine the particular station type at each location. This is the general approach, but now consider the actual procedure in more detail.

Begin at the most upstream location; in the example (page 168) this is designated at Location 1. Suppose the installation alternatives are either no station or one of three distinct station types. It is a fairly straightforward problem to calculate the net cost of any of the particular alternative installations at Location 1.

First determine the costs associated with the purchase installation, maintenance, and operation of each station at Location 1, and then subtract the savings generated by solids removal by applying the unit shadow savings to the amount of solids removed. Once this is done for the first location (including the no station alternative of zero cost) the procedure with slight variation is carried to Location 2 and subsequent locations. The variation in approach at Location 2 (and subsequent locations) is to include the costs and any cleansing associated with the installation at Location 1 (and all upstream locations). Suppose the station types are designated A, B, C, and no station is D. Computationally then, at Location 2, beginning with Station type A, each station type is considered and the costs and savings associated with this station type at Location 2 is evaluated by conditioning on each of the immediately preceding station types (A, B, C, or D at Location 1). Care must be taken to assure that downstream effects of an installation are considered. For each station type at 2, the minimum of the conditioned costs and the downstream cleansing pattern are retained for subsequent calculations.

These retained costs are the minimum costs to the current location for each station type. These minimum costs are the only costs which need to be considered in subsequent calculations. For example, suppose station type B were under consideration at Location 2 and the following conditioned costs were generated:

Station Type at Location 1	Cost with Type B Installation at Location 2 ($)
Station type A	-19.50
Station type B	-34.60
Station type C	not feasible
Station type D	-31.00

Then under the dynamic programming scheme it is necessary to carry along the cost of -$34.60 and a preceding station type of B for subsequent calculations. This may be interpreted that if through subsequent calculations it is determined that there should be a station type of B at Location 2, then the optimal preceding station type will always be a B at Location 1. For each of the possible station types there will be the minimum cost and preceding station type; for example, the following list might be obtained:

Station Type at Location 2	Minimum Cost ($)	Preceding Station Type
Station type A	-41.40	B
Station type B	-34.60	A
Station type C	not feasible	-
Station type D	-27.00	B

These costs and policies are retained for subsequent calculations.

Proceed to Location 3 for further illustration of the procedure. If any particular station type were considered, say type C, the most efficient means to determine the cost to Location 3 with a type C installation, is to evaluate the costs and savings of installing a type C station conditioned on the cost and downstream effects of each possible station type at Location 2. No direct consideration of installations at Location 1 is required since these are accounted for in the minimum cost and preceding station type information carried with the station types at Location 2. Again after the calculations for cost are completed for each station type, the minimum cost and preceding station type are retained for purposes of the subsequent calculations.

The feasible station types at each location are evaluated in the above manner beginning at the first and preceding location by location to the last location on the lateral. At the final location, the minimum costs associated with each of the station types at this location are perused to find the absolute minimum cost over the entire lateral. With this absolute minimum cost, the problem becomes to identify the sequence of station types leading to this cost. This is easily accomplished by working backward from the last location to successively preceding locations. Using the preceding station type information carried with each station type at each location it is fairly direct to recursively identify that station type at the preceding location which implies the cost at the current location. When the sequence has been defined, the computational procedure is completed.

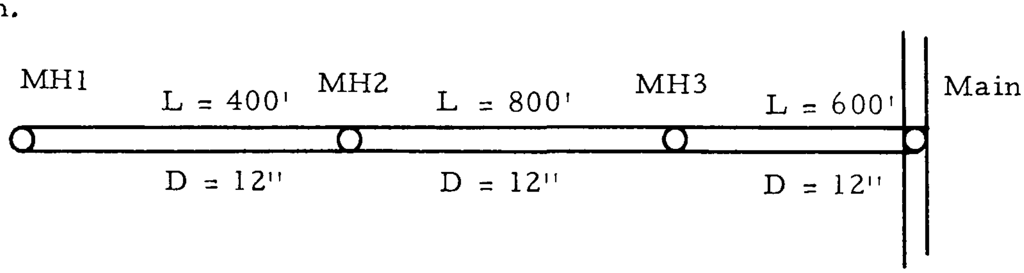
Manually this method becomes quite tedious, but it can be efficiently programmed for execution on a computer. At first the approach seems little better, if at all, than direct enumeration; there are, however, significant efficiencies. Under direct enumeration for a lateral with say four possible station types for installation at five potential locations, there are 1,024 ($=4^5$) station configurations to calculate. Using the technique of dynamic programming the number of calculations (usually of a much simpler nature) is 68 $[= 4+4\ (4^2)]$. Although it is not as direct as might be hoped, it is the most efficient method in the solution of this problem.

EXAMPLE

In order to illustrate the solution technique which was described rather abstractly in the preceding section, a sample problem is presented below. This problem has been greatly simplified to minimize the basic computational requirements. However, the problem satisfactorily demonstrates the function and flexibility of the optimization technique used in the mathematical model.

Problem Statement

For the purposes of this example, assume that it is desired to select the most economical flushing system to periodically remove 60 percent of the solids deposited in the lateral sewer described by the following diagram.



Information Required

Before the problem can be solved, the engineer must supply specific information about the sewer and the flushing equipment that is being considered. The following discussions describes the information required and the reasons for its need.

Physical Description of Sewer. The physical characteristics and geometric configuration of the sewer in question must be completely described. To accomplish this, the engineer must begin by determining the locations along the sewer where flush equipment of one type or another can feasibly be installed (this would most often be at the location of manholes.) He then must number the access locations consecutively beginning with the number 1 at the location nearest the upstream end of the sewer. These identification numbers can then be used to describe the relative position of each access location and the physical characteristics of the sewer between the successive locations.

The lateral sewer under investigation in this example would be described in the following manner:

Sewer Section	Sewer Length -L- (ft)	Average Slope -S_o- (%)	Pipe Diameter -D- (ft)
1 - 2	400	1.0	1.0
2 - 3	800	1.0	1.0
3 - M	600	1.0	1.0

Hydraulic Characteristics. The engineer must also analyze the sewer and the area which it serves and describe the expected dry weather hydraulics. He must either make statistical estimates or field determinations to define the average solids concentration expected to pass through each of the sections of the sewer. Also, he must determine what is a reasonable time between successive flushings and what the expected buildup of solids deposits would be in each of the sections of the sewer during this time interval.

In this example, the following hydraulic characteristics will be used:

Sewer Section	Average Flow Rate $-Q_B-$ (cfs)	Solids Deposited $-D_S-$ (lbs/ft/day)	Frequency of Flush $-F_F-$ (No. /Days
1 - 2	0.05	0.01	1.0
2 - 3	0.05	0.01	1.0
3 - M	0.05	0.01	1.0

Flush Equipment Characteristics. The engineer must determine the characteristics and limitations of the various types of flush devices which are available and then decide which ones can realistically be used in his situation. He must also analyze each of the access locations along the sewer in question and determine which of these devices cannot be used due to the physical location of the access point and the limitations caused by obstructions in the surrounding area.

Having accomplished the above, he must then list all of the types of flush devices that can be used on the lateral and determine the following physical characteristics and cost information for each:

1. Determine the purchase cost, expected life, storage volume, and average release rate of the smallest available size of each type of flush device to be used.

2. Estimate the total installation cost and monthly maintenance cost of each of the flush devices at each of the locations where the specific type can be used.

3. Determine which of the flush devices to be investigated will use clean water as the flush media, and which will use sewage. Also estimate the unit cost of handling the flush media ($\$/ft^3$) that is associated with each of the flush devices.

4. Determine the maximum size (largest storage volume) of each device that can be used at each of the access locations.

5. Determine the variable cost of purchasing and installing at each location, sizes of each device which are larger than the minimum sizes available in $\$/ft^3$ of volume in excess of the storage volume allowed by the smallest available size of each type of flush device.

For this example, the physical characteristics and estimated costs to be used for the flush equipment are described as follows:

1. The general characteristics to be used for the smallest available size of each type of flush device to be investigated, are as follows:

Station Type	Storage Volume -V min.- (ft³)	Average Release Rate -Q_F- (cfs)	Purchase Cost -C_p- ($)	Variable[b] Purchase Cost -ΔC_p- ($/ft³)	Expected Life -P- (years)	Monthly Cost -C_m- ($)	Cost[c] Flush Media -ΔC_o- ($/ft³)	Cost[d] Volume Exponent -K_e-
A	30	1.0	500	10.0	20	200	0.001	1.0
B	30	2.0	800	15.0	20	200	0.001	1.0
C[a]	-	-	-	-	-	-	-	-

Notes:

(a) The Type C flush station represents the alternative which must always be investigated, that of not installing flushing equipment at any of the given locations.

(b) This is the additional cost ($/ft³) of purchasing the specific type of flush device per cubic foot of volume in excess of the storage capacity of the smallest size unit available.

(c) This is the average cost of handling and storing each cubic foot of the flush media as governed by the operation characteristics of each specific type of flush device (operation cost).

(d) This exponent allows the engineer to express "Variable Costs" as a function of increased volume (volume in excess of that associated with the smallest available size of flush device in a nonlinear fashion, K_e = 1.0 gives a linear variable cost function).

2. The cost of installing each type flush device at each of the proposed access locations:

	Location 1		Location 2		Location 3	
Station Type	Minimum[a] Installation Cost -C_i- ($)	Variable[b] Installation Cost -ΔC_i- ($/ft³)	Minimum[a] Installation Cost -C_i- ($)	Variable[b] Installation Cost -ΔC_i- ($/ft³)	Minimum[a] Installation Cost -C_i- ($)	Variable[b] Installation Cost -ΔC_i- ($/ft³)
A	100	1.00	150	1.50	50	0.50
B	50	0.50	100	1.00	50	0.50
C	-	-	-	-	-	-

Notes:

(a) This is the cost of installing the smallest available size of a given type of flush device at the given location.

(b) This is the additional cost, per cubic foot of increased volume, of installing, at each given location, flush devices with storage capacities greater than that allowed by the smallest unit.

3. The limits on the maximum sizes of flush devices which can be used at the various access locations, as governed by the physical characterestics of the access locations.

Station Type	Ratio of the Maximum Allowable Storage Volume to the Storage Volume of the Smallest Unit -R_V-		
	Location 1	Location 2	Location 3
A	2.0	3.0	4.0
B	3.0	2.0	3.0
C	-	-	-

As can be seen by the simplicity of the hypothetical sewer being used for this example, and the uniformity of the physical and hydraulic characteristics and cost relationships selected for the sewer and flush equipment, the computational procedures involved are much less complicated and the number of alternatives to be investigated are considerably less than will normally be the case when a flush system is to be designed for an actual existing sewer. However, this example has been simplified to this extent in order to allow the reader to more readily understand the overall operation of the model and the optimization technique used.

Application of Model

Once the above information has been established and supplied to the computer program, the computer performs a series of computational operations which are described in detail in the following discussion.

Volume Determinations. First, the maximum allowable size (storage volume) is determined for each type of flush station at each of the prospective access locations. This is accomplished by multiplying the volume of the minimum size of each type of station (V min) by the ratio of the maximum allowable volume to the minimum volume for each type of flush station at each access location (R_V). For instance, the maximum size of station Type A that can be installed at Location 1 is,

$$V_{max} = V_{min} \times R_v$$
$$= (30 \text{ ft}^3) \times (2.0)$$
$$= 60 \text{ ft}^3$$

Next, two intermediate storage volumes (V_i) are selected for each type of flush station at each of the locations. This is accomplished as follows:

$$\Delta V_i = (V_{max} - V_{min})/3.0$$
$$V_i = V_{min} + \Delta V_i$$
$$V_1 = V_{min} + \Delta V_i$$
$$V_2 = V_{min} + 2\Delta V_i$$

For example, the intermediate volumes for station Type A at Location 1 would be,

$$\Delta V_i = (60 - 30)/3 = 10 \text{ ft}^3$$
$$V_i = 30 + 10 = \underline{\underline{40 \text{ ft}^3}}$$
$$V_2 = 30 + 2(10) = \underline{\underline{50 \text{ ft}^3}}$$

The flush station volumes that would be investigated by the model are:

Volumes at Each Location - Cubic Feet

Station Type	Location 1				Location 2				Location 3			
	V_{min}	V_1	V_2	V_{max}	V_{min}	V_1	V_2	V_{max}	V_{min}	V_1	V_2	V_{max}
A	30	40	50	60	30	50	70	90	30	60	90	120
B	30	50	70	90	30	40	50	60	30	50	70	90
C	-	-	-	-	-	-	-	-	-	-	-	-

However, in order to minimize the computations, only the maximum and minimum volumes will be used in the remainder of this example.

Cost Determinations. The total monthly cost of purchasing, installing, operating and maintaining each size (volume) of each type of station at each access location must now be determined. This is done in the manner described below.

- Purchase Cost (P_C). The monthly purchase cost is determined by the amortization of the purchase price over the expected life of the equipment, P, and at an annual discount rate of 6 percent.

$$P_c = \frac{1}{12}\left[C_p + \Delta C_p \left(\text{Volume to be used} - V_{min}\right)^{K_e}\right].$$

$$\times \text{ (amortization factor at 6\% for P years)}$$

For example, the monthly purchase cost of the maximum size (volume) of a Type A flush station to be installed at Location 1 is:

$$P_c = \frac{1}{12}\left[\$500 + (\$10/ft^3)\left(60\ ft^3 - 30\ ft^3\right)^{1.0}\right]$$

$$\times \text{ [amortization factor (6\%, 20 years)]}$$

$$= \frac{1}{12}\left[(\$800) \times (0.08718)\right]$$

$$= \underline{\underline{\$5.18 \text{ per month}}}.$$

The monthly purchase costs for this example are as follows:

Station Type	Location 1 Size (ft^3)	Location 1 P_c ($/Mo.)	Location 2 Size (ft^3)	Location 2 P_c ($/Mo.)	Location 3 Size (ft^3)	Location 3 P_c ($/Mo.)
A	30	3.63	30	3.63	30	3.63
	60	5.18	90	7.99	120	10.17
B	30	5.81	30	5.81	30	5.81
	90	12.35	60	9.08	90	12.35
C	-	-	-	-	-	-

NOTE: (a) Maximum and minimum sizes only are included in this example.

- Installation Cost (I_c). The monthly installation cost is determined in much the same manner as the monthly purchase cost.

$$I_c = \frac{1}{12}\left[C_i + \Delta C_i \left(\text{Volume used} - V_{min}\right)^{K_e}\right]$$

For example, the installation cost at the largest Type A station at Location 1 is:

$$I_c = \frac{1}{12}\left[\$100 + \$1.00/ft^3 \ (60 - 30)^{1.0}\right]$$

$$\times \left[\text{amortization factor } (6\% - 20 \text{ years})\right]$$

$$= \frac{1}{12}\left[(\$130) \times (0.08718)\right]$$

$$= \underline{\underline{\$0.94/Mo.}}$$

The monthly installation costs for this example are as follows:

	Location 1		Location 2		Location 3	
Station Type	Size (ft^3)	I_c ($/Mo.)	Size (ft^3)	I_c ($/Mo.)	Size (ft^3)	I_c ($/Mo.)
A	30	0.73	30	0.73	30	0.73
	60	0.94	90	1.74	120	0.69
B	30	0.36	30	0.36	30	0.36
	90	0.58	60	0.94	90	0.58
C	-	-	-	-	-	-

- Operating Cost (C_o). The monthly operating cost is determined by taking the product of the cost per cubic foot of flush media (ΔC_o), the volume of each flush (V_F), and the flush frequency (F_F), times 365 days/year divided by 12 months per year. For example, the monthly operating costs at a Type A station of maximum size at Location 1 is:

$$C_o = (\Delta C_o \times V_F \times F_F \times 365)/12$$

$$= (0.001 \times 60 \times 1.0 \times 365)/12$$

$$= \underline{\underline{\$1.58/Mo.}}$$

The operating costs for this example are:

	Location 1		Location 2		Location 3	
Station Type	Size (ft^3)	C_o ($/Mo.)	Size (ft^3)	C_o ($/Mo.)	Size (ft^3)	C_o ($/Mo.)
A	30	0.91	30	0.91	30	0.91
	60	1.82	90	2.74	120	3.65
B	30	0.91	30	0.91	30	0.91
	90	2.74	60	1.32	90	2.74
C	-	-	-	-	-	-

- Total Monthly Cost (M_c). The total monthly cost of each type of station is determined by summing up all of the individual costs. For example, the total monthly cost of a Type A station of maximum volume at Location 1 is:

$$M_c = P_c + I_c + C_o + C_m$$

C_m is the monthly maintenance cost and was one of the given cost input parameters.

$$M_c = \$5.18 + \$0.94 + \$1.82 + \$2.00$$
$$= \$9.94$$

The total monthly costs for this example are:

	Location 1		Location 2		Location 3	
Station Type	Size (ft^3)	M_c ($/Mo.)	Size (ft^3)	M_c ($/Mo.)	Size (ft^3)	M_c ($/Mo.)
A	30	7.27	30	7.27	30	7.27
	60	9.94	90	14.47	120	16.51
B	30	9.08	30	9.08	30	9.08
	90	17.67	60	13.84	90	17.67
C	-	-	-	-	-	-

- Maximum Cleansing Determination. The maximum cleansing efficiency that can be attained within the limits and specifications established above is determined, without regard to optimization of cost, by allowing the value of shadow savings to approach infinity. With the value of saving associated with removal of the solids deposited in the sewer being very high (the effect and meaning of the shadow savings is discussed more fully later in this section), the emphasis is shifted completely from optimization of the system with respect to cost to maximization of the solids removal. The maximum cleansing efficiency is determined in the same basic manner as described in the next section for the selection of the optimum (cost) flush system, except that only one pass is made with an extremely high value of the shadow savings, say, $10,000 per pound of solids removed.

  The maximum cleansing efficiency is determined at the very beginning for two reasons; first, so that the user will know what the maximum limit of the proposed system is and, second, to make sure that the desired system efficiency (specified by the user) is possible within the specified limits. Once the maximum cleansing efficiency has been established, it is checked against the value specified by the user. If the maximum value is less than the desired value, the computations are terminated and the maximum allowable efficiency is printed out so that the user knows that the limits he has specified for the system are too small and must be increased if the desired efficiency is to be realized. If the maximum value is greater than the desired value, the value of the shadow savings is adjusted downward and the process of optimizing the system with respect to cost is started and proceeds as described in the following section.

Optimum System Selection. The cost optimization of the system is accomplished using a dynamic programming technique which involves the use of a corrected multiplier which in this case will be referred to as the shadow savings. This multiplier can be thought of as representing the dollar value of removing a pound of deposited solids from the given sewer. The program is constructed such that the user can estimate the dollar value of removing a pound of the solids deposited in the sewer each day, based on the costs of alternate methods of accomplishing the same function, or the penalty for not removing the solids, and the model will determine the most economical flushing system and corresponding cleansing efficiency such that the monthly costs of the system do not exceed the total value of removing the deposited solids, as limited by the value of shadow savings given. Or the user can supply the model with the desired cleansing efficiency (average over the length) and the model will, by trial and error, establish the most economical flush system that can be used to accomplish this specified level of cleansing.

Because the basic computational procedures are the same when either of the above described approaches is used and because in most cases the user will probably know most exactly the cleansing efficiency he desires, this example will approach the problem by taking an assumed value of the shadow savings and correcting it to obtain the specified cleansing efficiency. As previously described in the description of The Flushing Station Location Model, the model begins with a value of shadow savings and correcting it to obtain the specified cleansing efficiency. As previously described, the model begins with a value of shadow savings of $0.01 per pound and then doubles the value repeatedly until the desired cleansing efficiency is reached or exceeded and then further refines the estimate using the "golden section search" technique. However, for the purpose of this example, the initial repetitive computation will be eliminated by assuming a value of shadow savings of $5.00 per pound of solids removed, which will give a more realistic cleansing efficiency based on the costs and limits that have been arbitrarily selected in this case.

The first step in the system optimization is to determine the total cost (including the shadow savings) of each size of each type of flush station that can be installed at the upstream most access location (Location 1). Since the monthly cost of each of the various sizes and types of flush stations has previously been determined for this example, the only major determination that is left to be made is that of the savings that can be accomplished, based on the solids removal in each case and the value of the shadow savings. In this example, the flush media will be taken as clean water, in all cases, in order to simplify the computations. However, if sewage is to be used as the flush media, the computations are much the same except that the clean water cleansing efficiency must be corrected using Equations 14 and 15 and the procedures previously described in the Discussion section of this report.

The average clean-water cleansing efficiency over a given length of sewer, $\bar{C}_{ESS}$, can be determined using Equation 10 as long as the value of L used is taken from the point at which the flush release is made. However, the computations involved in this model require that the average cleansing efficiency be determined for sections of sewer downstream of the point of flush release, the upstream ends of which do not coincide with the point of flush release. Therefore the differential form (with respect to L) of Equation 10 is more useful (point efficiency equation, C_E). The development of this point efficiency equation in its general form was described in the preceding section. The specific equation used in this model is:

$$C_E(L) = -30.87 + 24.68 \log_{10} \frac{V_F^{1.3} \, Q_F^{0.9} \, S_o^{1.4} \, D^{1.8}}{L^{1.6} \, Q_B^{1.2}} \times 10^4 \, .$$

The above equation for C_E can be used to determine the average cleansing efficiency for any section of sewer downstream of the point of flush release by integrating it with respect to L between the specified limits of L (L is always the distance from the point of release). For example,

$$\bar{C}_{ESS} \text{ (for Section 2-3)} = \int_{L_2}^{L_3} C_E \, (L) \, d^L \, .$$

Where L_2 is the distance from the point of flush release to the upstream end of the section, L_3 is the distance from the point of flush release to the downstream end of the section, and C_E (L) is the point efficiency equation which is a function of L. The quantity of solids removed by the flush wave from the section of sewer between Location 2 and Location 3 (S_R) can be determined,

$$S_R \text{ (from Section 2-3)} = S_D \frac{1}{100} \int_{L_2}^{L_3} C_E (L) \, d^L$$

where S_D is the total quantity of solids deposited in Section 2-3.

The model begins at the upstream most location (Location 1) and determines the total cost (including savings) for each type of station that can be installed at that location. For this example, the total cost of the largest Type A station at Location 1 is determined as described below.

First, the total quantity of solids deposited in each section of sewer, S_D, during the interval between flushes is determined. The total quantity of solids deposited in the section of sewer between Locations 1 and 2 is,

$$S_D = D_S \, L/F_F$$

$$= (0.01 \text{ lbs/ft/day}) (400 \text{ ft})/(1.0/\text{day})$$

$$= \underline{\underline{4.0 \text{ lbs}}}$$

The quantity of solids deposited between flushes in each of the sewer sections is given below.

Section No.	Section Length -L- (ft)	Deposited Solids -D_S (lbs/ft/day)	Frequency of Flush -F_F- (No. /day)	Total Solids Deposited Between Flushes -S_D (lbs)
1-2	400	0.01	1.0	4.0
2-3	800	0.01	1.0	8.0
3-Main	600	0.01	1.0	6.01

Beginning at the upstream most location (Location 1), the quantity of deposited solids removed from each section of sewer by each size and type of flush device that can be installed at this location is determined. Then the solids removal quantities are used to determine the saving and costs associated with each of the installations. The quantity of deposited solids removed from each section of the sewer is determined for each type and size of flush station by integrating the point efficiencies over the length of each section and multiplying the average cleansing efficiency obtained for each section by the total quantity of solids deposited in each section.

In the actual model, the integral in the above relationship for S_R is evaluated more exactly using small increments of L, over the length of each section. However, for the purposes of this example, the point efficiency function will be assumed to be linear along the length of each section. For example, the solids removed from each of the sections of sewer by the smallest Type A station installed at Location 1, is determined as follows:

For Section 1-2,

$$\overline{C}_{ESS} = -13.70 - 24.68 \log_{10}\left[\frac{(30)^{1.3}(1.0)^{0.9}(1.0)^{1.4}(1.0)^{1.8}}{(400)^{1.6}(0.05)^{1.2}} \times 10^4\right]$$

$$= -13.70 + 24.68 \log_{10}(2080)$$

$$= \underline{\underline{68.6\%}}$$

$$S_R = 4.0(0.686) = \underline{\underline{2.74 \text{ lbs}}}$$

For Section 2-3,

$$\overline{C}_{ESS} = \frac{1}{2}(C_E @ 2 + C_E @ 3)$$

$$C_E @ 2 = -30.87 + 24.68 \log_{10}\left[\frac{(30)^{1.3}(1.0)^{0.9}(1.0)^{1.4}(1.0)^{1.8}}{(400)^{1.6}(0.05)^{1.2}} \times 10^4\right]$$

$$= 51.4\%$$

$$C_E @ 3 = -30.87 + 24.68 \log_{10}\left[\frac{3.02 \times 10^7}{(1200)^{1.6}}\right]$$

$$= 32.3\%$$

$$\overline{C}_{ESS} = \frac{1}{2}(51.4 + 32.3) = \underline{\underline{41.8\%}}$$

$$S_R = (8 \text{ lbs})(41.8\%)/100$$

$$= \underline{\underline{3.34 \text{ lbs}}}$$

For Section 3 - Main,

$$\overline{C}_{ESS} = \frac{1}{2}(C_E @ 3 + C_E @ \text{Main})$$

$$C_E @ 4 = -30.87 + 24.68 \log_{10}\left[\frac{(30)^{1.3}(1.0)^{0.9}(1.0)^{1.4}(1.0)^{1.8}}{(1800)^{1.6}(0.05)^{1.2}} \times 10^4\right]$$

$$= 25.1\%$$

$$\overline{C}_{ESS} = \frac{1}{2}(32.3 + 25.13) = \underline{\underline{28.7\%}}$$

$$S_R = (6.0 \text{ lbs})(28.7\%)/100$$

$$= \underline{\underline{1.72 \text{ lbs}}}$$

The solids removals accomplished in the three sections of the sewer by each size of each type of flush station installed at Location 1 are given below:

Station Type @ 1	Volume of Flush $-V_F-$ (ft^3)	Solids Removed, S_R, (lbs) Section 1-2	Section 2-3	Section 3-M	Total Removed From Sewer
A	30	2.74	3.34	1.72	7.80
	60	3.11	3.98	2.27	9.36
B	30	3.00	3.75	2.05	8.80
	90	3.61	4.97	3.02	11.60
C	-	-	-	-	-

The total cost of using each size and type of flush station at Location 1 to clean the section of sewer between Locations 1 and 2 can now be determined by applying the shadow savings (in this case assumed to be \$5.00 per pound of solids removed) to the solids removed in this section of sewer by each flush station and then deducting this savings from total month cost, M_c, of each station. For example, the cost of using the largest Type A station at Location 1 to clean Section 1-2 is,

$$\text{Total Cost} = M_c - [(\text{Shadow Savings}) \times (\text{Solids Removal, } S_R, \text{ in Section 1-2}]$$

$$= \$9.94 - [(\$5.00/\text{lb})(3.11 \text{ lbs})]$$

$$= \underline{\underline{\$5.61}}$$

The total costs and solids removals associated with each size and type of flush station at Location 1 are as follows:

Station Type @ 1	Flush Volume $-V_F-$ (ft^3)	Total Month Cost $-M_c-$ ($)	Section of Sewer Cleaned	Solids Removed (S_R) (lbs)	Savings ($)	Total Cost ($)
A	30	7.27	1-2	2.74	13.70	-6.43
	60	9.94	1-2	3.11	15.55	-5.61
B	30	9.08	1-2	3.00	15.00	-5.92
	90	17.67	1-2	3.61	18.05	-0.38
C	-	-	-	-	-	-

The total costs given above are all less than zero, indicating that with a value of shadow savings of $5.00 per pound, any of the proposed flush stations is preferable to not installing a flush station at Location 1 (Type C station). Also since the smallest Type A station has the lowest cost, it is obviously the best alternative to combine with the proposed flush stations at Location 2. However, when the proposed flush stations at Location 1 are compared to the Type C or "no-installation" alternative at Location 2, the above cost values must be recalculated to account for the additional savings associated with the solids removed by each in Section 2-3, as will be shown later.

Now the deposited solids removed from each downstream section of sewer by each of the types and sizes of flush stations to be investigated at Location 2 are determined. They are determined in the same manner as previously used for the flush stations at Location 1 and are given below.

Station Type @ 2	Flush Volume $-V_F-$ (ft^3)	Solids Removed, S_R, (lbs)		Total Length of Sewer
		Section 2-3	Section 3-Main	
A	30	4.48	2.05	6.53
	90	5.73	2.95	8.68
B	30	5.04	2.43	7.47
	60	5.81	3.01	8.82
C	-	-	-	-

The total cost of each flush station to be investigated at Location 2 can be determined in the same manner as that used for Location 1. The results are as follows:

Station Type @ 2	Flush Volume $-V_F-$ (ft^3)	Total Month Cost $-M_c-$ ($)	Section of Sewer Cleaned	Solids Removed $-S_R-$ (lbs)	Savings ($)	Total Cost ($)
A	30	7.27	2-3	4.48	22.40	-15.13
	90	14.47	2-3	5.73	28.70	-14.23
B	30	9.08	2-3	5.04	25.20	-16.12
	60	13.84	2-3	5.81	29.10	-15.26
C	-	-	-	-	-	-

The best combination of flush stations at Locations 1 and 2 can be determined, simply by adding the total cost given above for each flush station at Location 2 to the total cost of the least-cost alternative at Location 1. However, before the Type C or no-installation alternative at Station 2 can be evaluated, the costs of all the types and sizes of flush stations at Location 1 must be corrected to include the additional savings associated with the solids removed by each in Section 2-3. For example, the adjusted cost of the largest Type A at Location 1 with a Type C station at Location 2 is,

Adjusted Solids Removed = (solids removed from Section 1-2) + (solids removed from Section 2-3)
= 3.11 lbs + 3.98 lbs = 7.09 lbs

Adjusted Total Cost = Total Monthly Cost - Savings
= \$9.94 -(\$5.00/lb)(7.09 lb)
= \$25.51

The adjusted costs and solids removals for each of the sizes and types of flush station at Location 1 are given below:

Station Type @ 1	Flush Volume $-V_F-$ (ft^3)	Total Month Cost $-M_C-$ ($)	Section of Sewer Cleaned	Adjusted Solids Removed (lbs)	Adjusted Savings ($)	Adjusted Total Cost ($)
A	30	7.27	1-3	6.08	30.40	-23.13
	60	9.94	1-3	7.09	35.45	-25.51
B	30	9.08	1-3	6.75	33.75	-24.67
	90	17.67	1-3	8.58	42.90	-25.23
C	-	-	-	-	-	-

The lowest cost combination of flush stations at Locations 1 and 2 can now be determined in the following manner. First the total cost and solids removal must be determined for each possible combination. For example, the total cost and solids removal associated with the installation of the smallest Type A station at Location 1 and the largest Type A station at Location 2 is,

Total Solids Removed = (solids removed from Section 1-2 by the flush station at Location 1)
+ (solids removed from Section 2-3 by the flush station at Location 2)
= 3.00 lbs + 5.73 lbs
= 8.73 lbs

Total Cost = (total cost of flush station at Location 1)
+ (total cost of flush station at Location 2)
= \$6.43 + (-\$14.23)
= -\$20.66

The cost and solids removals for the various combinations of flush stations at Locations 1 and 2 are given below.

Station at Location 1[a]			Station at Location 2			Combined Stations		
Type	Volume	Section Cleaned	Type	Volume	Section Cleaned	Solids Removed (lbs)	Section Cleaned	Total Cost ($)
A	30	1-2	A	30	2-3	7.22	1-3	-21.56
				90	2-3	8.47	1-3	-20.66
A	30	1-2	B	30	2-3	7.78	1-3	-22.55
				60	2-3	8.55	1-3	-21.69
A	60	1-3	C	-	-	7.09	1-3	-25.51

Note: (a) These station types and sizes were selected because they were previously found to be the least costly for the given section of sewer to be cleaned.

The cost figures given above indicate that the most economical combination of flush stations at Locations 1 and 2 is a Type A with a 60 ft^3 storage capacity at Location 1 and a Type C (no-installation) at Location 2. This combination with the corresponding cost and solids removal information is now used to determine the best type and size of flush station for Location 3.

As was the case at the upstream locations, the quantity of solids removed and the associated costs must first be determined for each type and size of flush station at Location 3, when each is used to clean the next adjacent downstream section of sewer. These figures are:

Station Type @ 3	Flush Volume $-V_F-$	Total Month Cost ($)	Section of Sewer Cleaned	Solids Removed $-S_R-$ (lbs)	Savings ($)	Total Cost ($)
A	30	7.27	3-Main	3.68	18.40	-11.13
	120	16.51	3-Main	4.82	24.10	-7.59
B	30	9.08	3-Main	4.07	20.35	-11.27
	90	17.67	3-Main	4.76	24.30	-6.63
C	-	-	-	-	-	-

Now as was done at Location 2 for the flush stations at Location 2, the solids removals and costs for the flush stations at Location 2 should be adjusted to allow proper evaluation of the Type C station (no-installation) at Location 3. However, since a Type C station (no-installation) is indicated at Location 2, the adjustments must be made again to the costs and solids removals for the flush stations at Location 1. The adjustment is made by simply adding the solids removals and associated savings that each station at Location 1 effects in Section 3-Main to the corresponding adjusted solids removals and savings determined previously at Location 2. The adjusted values are given below:

Station Type @ 1	Flush Volume $-V_F-$ (ft^3)	Total Month Cost $-M_C-$ (\$)	Section of Sewer Cleaned	Adjusted Solids Removed $-S_R-$ (lbs)	Adjusted Savings (\$)	Adjusted Total Cost (\$)
A	30	7.27	1-Main	7.80	39.00	-31.73
	60	9.94	1-Main	9.36	46.70	-36.76
B	30	9.08	1-Main	8.80	44.00	-34.92
	90	17.67	1-Main	11.60	58.00	-40.33
C	-	-	-	-	-	-

The above figures show that the Type B station with a 90 ft^3 capacity is the best selection for the evaluation of the Type C (no-installation) station at Location 3. The solids removals and costs of the various combinations of flush stations along the length of the sewer are as follows:

Upstream Stations							Combined Stations		
@ Location 1		@ Location 2		Station at Location 3					
Type	Volume (ft^3)	Type	Volume (ft^3)	Type	Volume (ft^3)	Section Cleaned	Section Cleaned	Total Solids Removed (lbs)	Total Cost
A	60	C		A	30	3-Main	1-Main	10.77	-36.69
					120	3-Main	1-Main	11.91	-33.10
AB	60	C	-	B	30	3-Main	1-Main	11.16	-36.78
					90	3-Main	1-Main	11.85	-32.14
B	90	C	-	C	-	-	1-Main	11.60	-40.33

The figures given above indicated that the best periodic flushing system for this particular lateral sewer, within the limits given and for a shadow savings of \$5.00 per pound of solids removed, is one consisting only of a Type B flush station with a volume of 90 ft^3 installed at Location 1. The average cleansing efficiency, $\bar{C}_{ESS}$, over the total length of the sewer is determined by dividing the total quantity of deposited solids removed from the sewer by each flush (11.60 lbs) by the total quantity of solids deposited in the sewer between flushes (18.0 lbs). Thus the average cleansing efficiency, $\bar{C}_{ESS}$, for the proposed flushing system is,

$$\bar{C}_{ESS} = \frac{11.60 \text{ lbs} \times 100\%}{18.00 \text{ lbs}}$$

$$= \underline{\underline{64.0\%}}$$

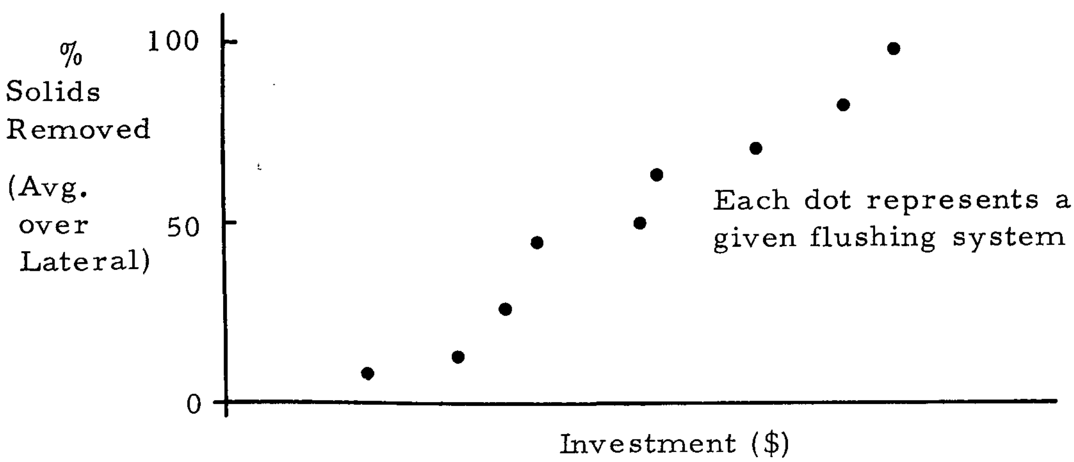
This value of $\overline{C}_{ESS}$ is quite close to the value of 60% which was originally specified, so no further refinement is necessary. However, if the actual value of $\overline{C}_{ESS}$ had been significantly higher than the desired value, the estimate could be refined by reducing the value of shadow savings a small amount (say from \$5.00/lb to \$4.50/lb) and repeating the above procedures until the actual value of $\overline{C}_{ESS}$ becomes sufficiently close to the desired value.

EXTENSIONS OF MODEL

Flushing Efficiency Versus Investment Relationship

The first impression of using the shadow savings for solids removal is that it is an awkward, artificial technique. There is, however, significant power in the utilization of this artificial cost. Although the average effectiveness of flushing is usually of prime interest, another and possibly more realistic question is: What is the best system that can be installed for X dollars? Whereas, keeping the level of pollutants within some specified amount is the major engineering concern, the communities installing a flushing network might typically be interested in considering the various investment alternatives for control. These communities may in fact, be evaluating whether to install flushing stations or an alternative such as temporary storage facilities.

To satisfy these interests a flushing efficiency versus investment relation would be beneficial. An investigation of this is easily motivated by the shadow savings approach. By performing the optimization repeatedly beginning with the artificial shadow savings at a small value and continuously increasing the value until either the maximum investment or maximum feasible efficiency is attained, a curve of flushing efficiency versus investment can be generated. By proceeding in this manner, there is always the assurance that the installation is kept cost effective. The resulting plot would have a form somewhat as that shown below.



Approach For Sewer System Analysis

The model presentation and discussion to this point has been oriented toward the analysis of a particular lateral in a sewer system. The orientation may be expanded to include the entire system if the flow in the main sewer conduit is sufficient to remove the solid materials which might be deposited in it, or may be analyzed independently. In such a case, the model may be applied to each lateral individually using one specific value of the shadow savings over the entire system. For example, if the value of . 15 per unit solids removed were applied to each lateral, some might be flushed to an efficiency of 75 percent while others sould be 40 percent or 55 percent. The differing flushing efficiencies indicate that on some laterals the quantity of solids removed is not sufficient to justify expenditures on flushing stations. In general, higher efficiencies for a given shadow savings would be associated with laterals with high solids loads. Once the entire system is evaluated with a given shadow savings, the overall efficiency is assessed. If necessary, the unit shadow savings is adjusted and the procedure repeated. This approach could consume considerably more computation time, but the savings and advantages of balancing overall effectiveness would justify the additional expense. The computer model as developed and presented here would require the manual input and adjustment of shadow savings (even this requires a special code - see computer model write-up) to obtain either the system analysis or the efficiency versus investment relationship. The model could be altered without too much additional difficulty to allow for automatic development of either or both of these features.

DISCUSSION OF DYNAMIC PROGRAMMING

Dynamic programming is a computational technique which finds application in the solution of sequential decision problems. The particular types of problem to which the approach is most easily applied are those in which benefits yielded at one stage of the problem are additive to benefits accrued in prior stages. A corollary of this is that decisions only have consequences in successive stages of the problem. This is precisely the type of problem presented in location flush station facilities.

The theory of dynamic programming is more intuitive than analytic and is more easily grasped by example than through a mathematical approach. The reader interested in a more precise development and further areas for application is referred to any of the standard texts on the subject (particularly good presentations are found in G. L. Nemhauser, Introduction to Dynamic Programming, and G. Hadley, Nonlinear and Dynamic Programming). The fundamental property upon which the theory of dynamic programming is developed is called "the principle of optimality" and is stated as:

> "An optimal sequence of decisions in a multi-stage decision problem has the property that whatever the final decision and state preceding the terminal one, the prior decision must constitute an optimal sequence of decisions leading from the initial state to that state preceding the terminal one."

The validity of this property may be verified by contradiction.

Expanding on the computational procedure to include five possible locations will show the model to be an application of the principle of optimality. To illustrate this more explicitly, begin at the last stage of the decision problem, the sewer main. The efficiencies generated by installation of any of the station types between Location 5 and the sewer main constitute the various states that can be assumed under the different decisions of installation. Then by the principle of optimality that sequence of decisions (station types) and states (resulting efficiencies) from the initial state (the result from a decision at Location 1) to the state preceding the terminal state (efficiencies accrued to Location 5, including the installation at 4) must be optimal for a final optimal decision as to station type at Location 5. And how is this optimality to the state preceding the terminal state assured? By redefining the terminal state to be that state from Location 4 to the end of the lateral and applying the principle of optimality to the state preceding the installation at 4. To assure that the state preceding the installation at 4 is optimal, the terminal state is redefined to be that state from Location 3 to the sewer main. Hence, following this argument, the principle of optimality is applied recursively with the terminal state becoming that state from Location 2 to the sewer main and then from Location 1 to the sewer main. This may be done because the principle of optimality must be valid over any particular definition of initial and terminal states.

At first this may seem backward from the approach taken in the solution technique; it is in fact the same approach. The above paragraph indicates that it is necessary to successively calculate the optimum sequence of decisions from the initial state to the terminal state by recursively redefining the terminal state. This is the manner in which the computational technique proceeded: The initial state was the consequence of a decision at Location 1 to the end; in effect, the terminal state and initial state were the same. The terminal state was then redefined so as to be the consequences from Location 2 to the sewer main where the various states were determined by the decisions at 2 conditioned on the various states preceding 2 (the states implied by the decisions at 1). When the states associated with a decision at Location 2 have been evaluated, the terminal state is redefined to be from Location 3 to the sewer main. By the principle of optimality the optimal return for this reduced problem is found by conditioning on the preceding states (which are themselves optimal). This procedure is performed until the last location in the problem is reached.

There is a mathematical representation for dynamic programming. Whereas, for completeness it would be nice to present this form, the definitions necessary for precise formulation make it impractical to do so. The interested reader will find formulations in the referenced texts.

COMPUTER PROGRAM

Introduction and Use of Program

The program allows the automatic determination of the flushing station configuration yielding the minimum cost for a specified average cleansing efficiency. As presented, the program is designed for use with the station types developed by the Central Engineering Laboratories. The particular impact of this is in the equations expressing cleansing efficiencies.

The intent of this discussion is to detail the requirements for use of the program in designing a flushing system. No attempt is made to present any type of programmer's guide, but the program is documented well enough internally to allow an analyst to make minor changes if necessary for a particular application. The analytic features of the program are discussed in the previous sections of this report.

The inputs for the program may be classified as two types: those data describing the lateral and the various flow parameters in it, and those characteristics of the flushing station which effect either the cost or performance of the station. These descriptive data plus a specified efficiency are sufficient to allow the program to determine the minimum cost station configuration.

Before detailing the precise form of inputs and outputs, a summary of the assumptions on which model is based would be in order to assure proper application. The pertinent assumptions are:

- The stations flushing efficiency may be expressed by the equations developed by the Central Engineering Laboratories. The equation for average efficiency over the length L using clean water as the flushing fluid,

$$\bar{C}_{ESS} = -13.7 + 24.680 \log_{10} \left[\frac{V_F^{1.3} Q_F^{0.9} S_o^{1.4} D^{1.8}}{L^{1.6} Q_B^{1.2}} \times 10^4 \right]$$

where

$\bar{C}_{ESS}$ = average cleansing efficiency over a given length of sewer L(%)

V_F = volume of flush (ft^3)

Q_F = rate of flush (cfs)

S_o = average slope of pipe (%)

D = diameter of pipe (ft)

Q_B = rate of base flow (cfs)

L = distance from installation (ft)

If the flushing fluid is sewage, it is necessary to apply a correction factor to the above expression. If $\bar{C}_{ESS}$ is the average efficiency using sewage for flushing, the change is,

$$\bar{C}_{ESS} = \bar{C}_{ESS}\left(1.0 - \frac{\Delta\bar{C}_{ESS}}{100}\right)$$

where

$$\Delta\bar{C}_{ESS} = 14.3 - .14\, V_F - .242\, Q_F + .00711\, L$$

- The efficiency (in percent of solids removed) is independent of the solids load in the base flow.
- Stations and locations are sufficiently close together so that the point efficiency never falls below zero.
- Any flushing station will only have effects downstream of its installation.
- When the efficiency curves of two or more stations overlap, the efficiency at any point is taken as the maximum of the overlapping efficiencies taken individually at that point.

- The stations act in concert with one another. At the least, the flushing action will pass to successively downstream locations.

If these assumptions cannot be met or at least generally satisfied, the model should be applied with judgement.

Restrictions

There are various dimensional restrictions on the size of the problem that can be evaluated as the program is now written. The number of station types that can be considered along a lateral is limited to six. A station type is as specified on a station type card as detailed later in this discussion. Locations along an individual lateral are limited to 30 sites. A location includes manholes and any other readily accessible locations. Of course, modifications can be made to the program to permit the evaluation of larger problems.

Timing

Execution time is primarily dependent on four parameters; number of station types, division of the limits on the volume, number of manhole locations along the lateral, and the starting value of the shadow savings. Execution time seems to increase roughly by the square of the number of station types and the division size, and linearly with the number of locations. The initial value of the shadow savings influences the execution time in a somewhat linear manner but the precise effect is dependent on the relative magnitudes of the initial value and final solution value.

Whereas the number of station types and installation locations are defined by the problem and hence fixed as far as reducing execution time, the division limits and starting value of the shadow savings can be manipulated to achieve some processing economies. By using an arbitrary shadow savings and a relatively small number of divisions in the initial stages of analysis and increasing the number of divisions and more closely approximating the shadow savings during more refined analysis, a significant reduction in computer costs can be achieved. There are notes in the program as to where the modifications can be made.

The example presented later in this appendix required 5 minutes for execution with the values as defined in the program as listed.

Inputs

The following is a list and explanation of the data required to execute the program. All numeric data are right justified and, if necessary, carry a decimal point in the appropriate position. There are three groups of cards: a title card of which there is one; location cards consisting of two cards for each manhole location along the lateral, the first of the two cards contains lateral characteristics data and the second, data on installation costs at the manhole; and station cards, one for each station type detailing operational and cost data about each station. A blank card separates the location cards from the station type cards.

Title Card

Card Columns	Explanation
1 - 40	Title to be printed on the output
41 - 48	Date computer run performed
50	Code indicating whether the required efficiency or a shadow savings value will be specified by the analyst. 0 or blank — required efficiency specified and program will automatically determine shadow savings 1 — shadow savings input
51 - 60	Required efficiency of cleansing, $\overline{C}_{ESS}$, to be attained along the lateral in percent or if unit value of shadow savings is to be an input it is entered in this field.

Location Cards

Card Columns	Explanation
Card 1 - Physical Characteristics	
1 - 5	Lateral number of the pipe being evaluated.
6 - 10	Manhole number of the location under consideration (number beginning at upstream end of lateral).
11 - 20	Distance to next manhole or to main or interceptor in feet.
21 - 30	Average base flow in the reach to the next manhole in cfs.

Card Columns	Explanation
31 - 40	Average quantity of solids deposited in the next reach in pounds of solids deposited per foot of sewer. This is dependent on the parameters of the lateral and the frequency of flush.
41 - 50	Diameter of pipe in feet.
51 - 60	Average slope over the reach to the next manhole (%).
61 - 63	Multiple of low volume limit yielding high volume limit at this location for station described on first station type card.
64 - 66	Multiple of low volume limit yielding high volume limit at this location for station described on second station type card.
67 - 69	Multiple of low volume limit yielding high volume limit at this location for station described on third station type card.
70 - 72	Multiple of low volume limit yielding high volume limit at this location for station described on fourth station type card.
73 - 75	Multiple of low volume limit yielding high volume limit at this location for station described on fifth station type card.
76 - 78	Multiple of low volume limit yielding high volume limit at this location for station described on sixth station type card.

Card 2 - Installation and Variable Costs

1 - 5	Lateral number from the above Physical Characteristics card.
6 - 10	Manhold number from the above Physical Characteristics card.
11 - 14	Minimum cost installation (excluding purchase cost) for station on first station type card ($).
15 - 18	Variable cost for increasing volume for station on first station type card ($\$/ft^3$). The added cost of purchasing and installing a flush station of a given type that is larger than the minimum sized unit, per cubic foot of increased volume.

Card Columns	Explanation
19 - 21	Exponent on volume for non-constant purchase and installation costs (for station on first station type card). [These three cards define the parameters of the installation and variable cost expression. Cost = minimum cost + (variable cost) x (volume - minimum volume)exponent]
22 - 25 26 - 29 30 - 32	Minimum and variable costs, and exponent for station on second station type card.
33 - 36 37 - 40 41 - 43	Minimum and variable costs and exponent for station on third station type card.
44 - 47 48 - 51 52 - 54	Minimum and variable costs and exponent for station on fourth station type card.
55 - 58 59 - 62 63 - 65	Minimum and variable costs and exponent for station of fifth station type card.
66 - 69 70 - 73 74 - 76	Minimum and variable costs and exponent for station of sixth station type card.

NOTE: If a station type is not feasible for the particular manhole, the corresponding field should be left blank or contain zeros. If it is desired to minimize only the operation costs, the feasible station types be indicated by a 1 in the right most position of the appropriate minimum cost field; the infeasible types should, as before, be left blank.

Station Type Cards

Card Columns	Field	Explanation
1 - 4	4	Code to identify station type.
5	1	Flushing fluid code: 0 if clean water is the flushing agent and 1 if sewage is to be employed.
6 - 9	4	Expected life of the station in years.
10 - 15	6	Flushing rate of the station in cfs.
16 - 21	6	Low volume limit in ft^3 on the quantity of flush.
28 - 33	6	Frequency of flushing expressed by the number of hours between flushes. Normally the frequency is 24 hours. Note that the average solids load in the sewer will decrease as the time between flushes (frequency) is reduced.
34 - 39	6	Unit cost ($\$/ft^3$) to purchase a ft^3 of flushing agent for operation of the station.
40 - 45	6	Monthly maintenance cost of station ($).
46 - 51	6	Purchase cost ($) to procure a station of this type with minimum capacity.

These are the inputs required to execute the program. If more basic data were used a preprocessor could, of course, be programmed to create a file which this program could then read to obtain the necessary data.

Output

A sample output is shown near the end of this discussion. The interpretation of these forms is straightforward, but a detailed description is contained herein so as to avoid any ambiguity. On the first page the title entered on the title card is printed at the top of the page; the date on the title card is also printed, appearing below the title. The lateral number entered in the first field of the Location Cards is output on the next line.

MANHOLE NUMBER	Identifying number of the manhole for which the associated line indicates the installation. This is the number indicated in the second field of the location cards and the output list begins at the most upstream end and works down the lateral.
STATION TYPE	Station type to be installed at the manhole location indicated. The station type number is as defined in the first field of the station type cards.
FLUSH RATE CFS	Flush rate of the station to be installed. This will be as defined in the flushing rate field of the station type cards.
FLUSH VOLUME CU FT	Flushing volume required by the particular station type to achieve sufficient cleansing.
INSTALL COST DOLLARS	Cost to install the station type specified. Included in this is the purchase price plus the direct cost of installation.
OPERATE COST DOLLARS	Monthly cost to purchase flushing fluid and operate at the specified frequency.
MAINT. COST DOLLARS	Monthly maintenance costs of station. Obtained from input.
SOLIDS REMOVED POUNDS	The number of pounds of solid material removed over the reach to the next manhole location.
SOLIDS REMOVED PERCENT	The average percentage of solid material removed over the reach to the next manhold location.

There are totals for the appropriate columns. An average percent of solids removed over the entire length of the lateral is tabulated as AVERAGE EFFICIENCY. It is this value that is compared to the input required efficiency to be certain of attaining sufficient cleansing. The value tabulated under MAXIMUM EFFICIENCY is the maximum efficiency that can be obtained independent of the cost of the system. No cleansing efficiency greater than this amount can be attained without increasing the maximum volume specifications.

The second page of the illustrated output contains more detailed information on the flushing performance. The particular cleansing efficiency for various points along the lateral is tabulated. The points at which the efficiency is calculated are:

- at each 100 ft along the lateral
- at each manhole or station location, and
- at any points at which efficiency curves cross.

The first column of the output gives the distance from the most upstream manhole. The second column is the point flushing efficiency at the corresponding distance. Also printed is the value of shadow savings corresponding to the particular report.

One report will be generated for each value of the shadow savings tested. The program will terminate when the required level of efficiency (in percent solids removal) is attained.

Error Messages

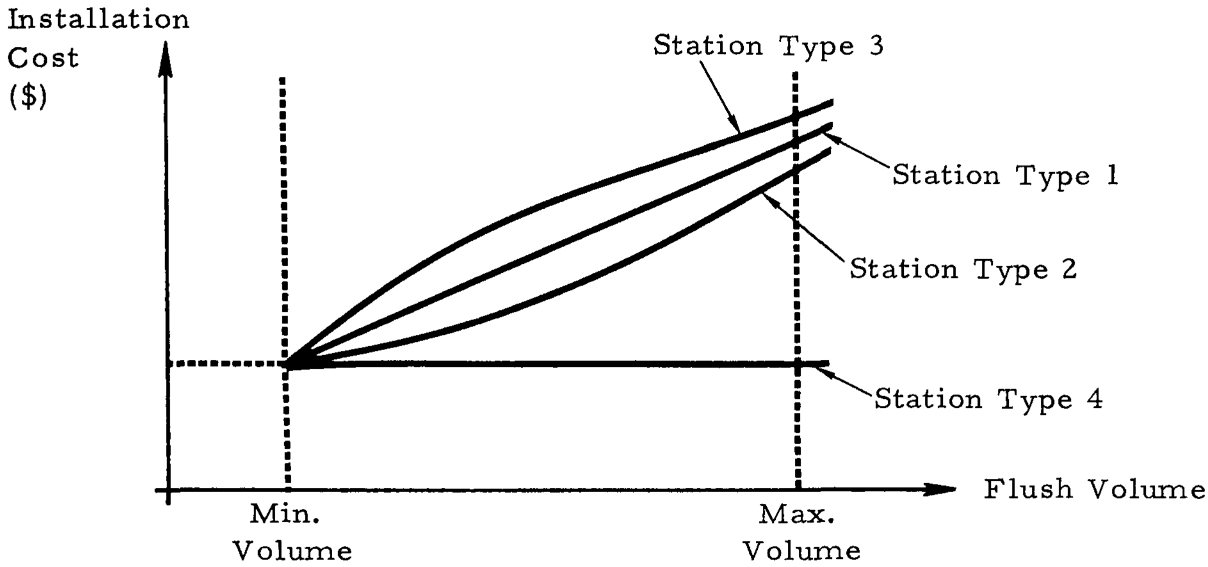
There are no informative diagonistic messages output by the program. The FORTRAN and loading messages normally furnished by the computer will still be available but no additional tests explicitly for erroneous or inconsistent data will be made. Interspersed within the program are statements of the form

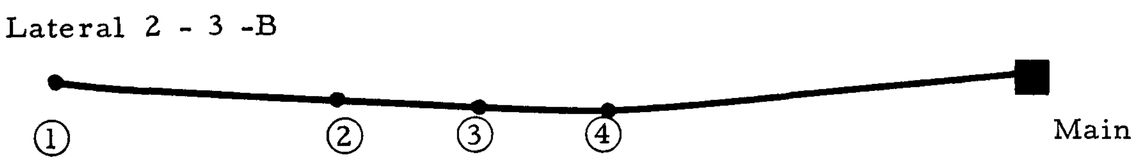
STOP XXX.

XXX is an integer and is unique to each STOP statement. These statements may cause the program to terminate execution for a variety of reasons; none of which is normal. The corrective action when a termination of this sort occurs is to locate the STOP statement within the program by means of the identifier XXX (this number will be printed on the output) and rectify the problem (which most likely will be in the data) by examining the program logic immediately preceding the termination.

Example

The following is presented as a rather typical application of the program. For the lateral illustrated and described on the following page it is required to remove 70 percent of the solids. The lateral carries the designation 2 - 3 -B. There are four possible station types. The installation costs for the different types are schematically illustrated below. The particular specifications for the station types and manhole locations are on the following pages.





	①	②	③	④
Length	310 ft	200 ft	230 ft	650 ft
Diameter	8 in.	8 in.	10 in.	12 in.
Avg. Base Flow	.0026 cfs	.0067 cfs	.0102 cfs	.0174 cfs
Avg. Load	.00115 lb/ft	.00303 lb/ft	.00460 lb/ft	.00781 lb/ft
Avg. Slope	.6%	.4%	.32%	.22%

Sample Problem

Station Type

	F03C	F27C	F36C	F03S
Flush Fluid	Clean	Clean	Clean	Sewage
Life	15 yrs.	10 yrs.	10 yrs.	10 yrs.
Flush Rate	2.00 cfs	1.33 cfs	4.45 cfs	2.00 cfs
Min. Flush Vol.	30 ft^3	80 ft^3	30 ft^3	30 ft^3
Frequency	24 hrs.	24 hrs.	24 hrs.	24 hrs.
Unit Cost	.0012$/$ft^3$	.0012$/$ft^3$	.0012$/$ft^3$	.0012$/$ft^3$
Monthly Maint. Cost	$5.00	$8.00	$8.00	$12.00
Purchase	$1000	$800	$2500	$1000

Installation and Variable Costs:

Location	Component	F03C	F27C	F36C	F03S
1	Min. Install.	-	300	500	-
	Var. Cost	-	30	.071	-
	Exponent	-	.5	1.5	-
2	Min. Install.	500	-	700	500
	Var. Cost	10	-	.071	0
	Exponent	1.0	-	1.5	0
3	Min. Install.	750	300	900	850
	Var. Cost	10	40	.071	0
	Exponent	1.0	.5	1.5	0
4	Min. Install.	1000	300	-	900
	Var. Cost	10	45	-	0
	Exponent	1.0	.5	-	0

Maximum Limit on Volume

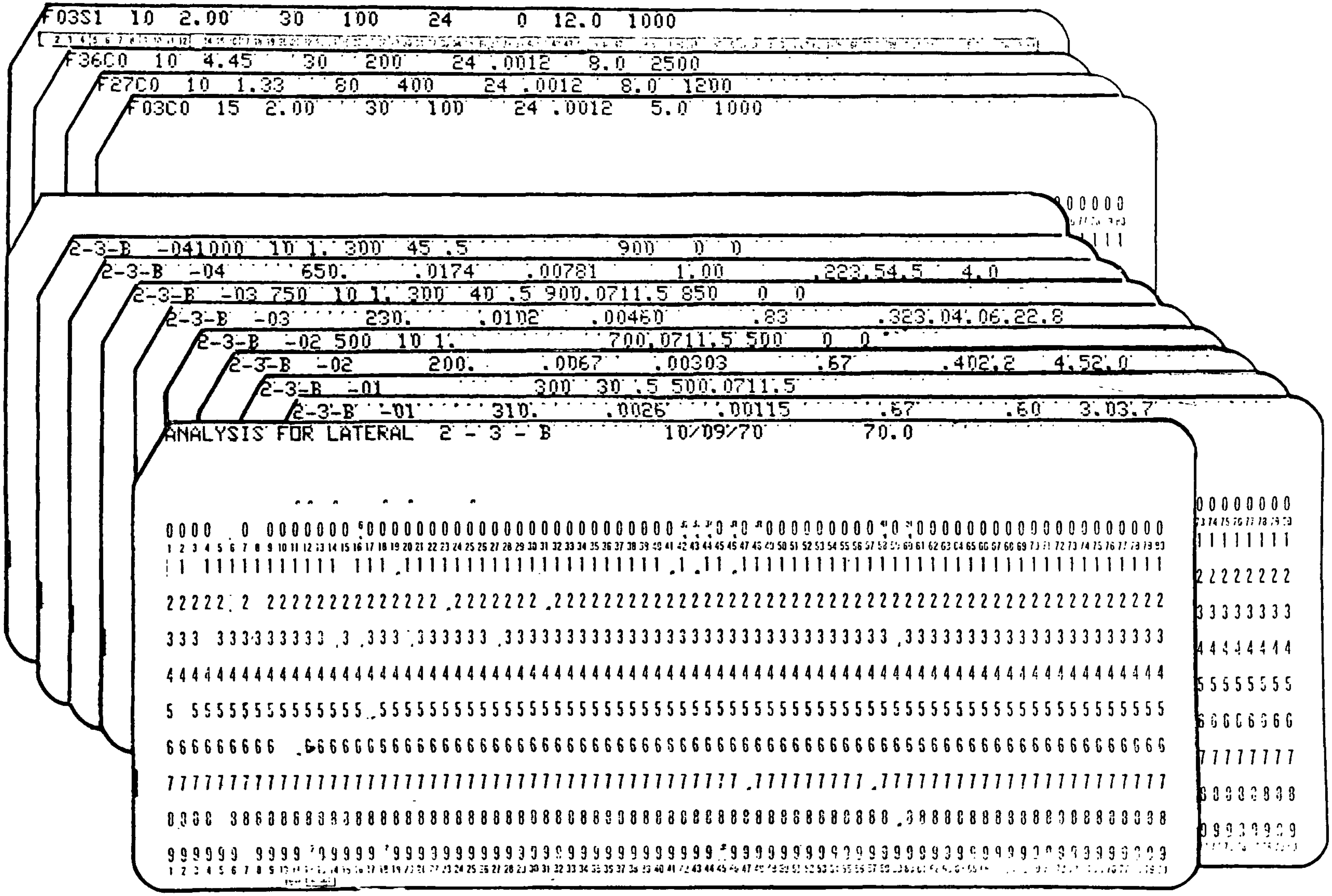
The following table lists the maximum volume of water that can be stored and utilized for flushing. Normally the limit will be a function of the size of the manhole and depth of pipe at that location; hence, the limit must be expressed at each location for each station type. Also the maximum limit as input to the program is expressed as multiples of minimum flush volume.

Station Type

Location	Measure	F03C	F27C	F36C	F03S
1	cubic feet	-	240	110	-
	multi. low	-	3.0	3.7	-
2	cubic feet	65	-	135	60
	multi. low	2.2	-	4.5	2.0
3	cubic feet	90	320	185	85
	multi. low	3.0	4.0	6.2	2.8
4	cubic feet	105	360	-	120
	multi. low	3.5	4.5	-	4.0

The prepared card input and final results of the computer run are found on the following pages.

SAMPLE DATA CARDS



SUMMARY -- INPUT DATA
ANALYSIS FOR LATERAL 2 - 3 - B

DATE 10/09/70

LATERAL NO.2-3-B REQUIRED EFFICIENCY 70 .%

LATERAL CHARACTERISTICS

LOCATION	DISTANCE TO NEXT MANHOLE (FT)	AVERAGE BASE FLOW (CFS)	AVERAGE BASE LOAD (LB/FT)	AVERAGE SLOPE (%)	DIAMETER (FT)
-01	310.	.00260	.00115	0.600	0.670
-02	20C.	.00670	.00303	0.400	0.670
-03	230.	.01020	.00460	0.320	0.830
-04	65C.	.01740	.00781	0.220	1.000

STATION TYPE CHARACTERISTICS

STATION CODE	F03C	F27C	F36C	F03S
FLUSH FLUID CODE	0	0	0	1
STATION LIFE (YRS)	15	1C	10	10
FLUSH RATE (CFS)	2.00	1.33	4.45	2.00
FLUSH VOL-LOW (CUFT)	30.	80.	30.	30.
FREQUENCY (HRS)	24.	24.	24.	24.
MAINTENANCE COST ($)	5.0	8.0	8.0	12.0
PURCHASE COST ($)	1000.	1200.	2500.	1000.
COST OF WATER ($/CUFT)	.00120	.00120	.00120	.0

INSTALLATION COSTS / HIGH VOLUME LIMIT

LOCATION		STATION TYPE F03C	F27C	F36C	F03S
-01	MINIMUM COST	0.0	300.000	500.000	0.0
	VARIABLE COST	0.0	30.000	0.071	0.0
	EXPONENT	0.0	0.50	1.50	0.0
	HIGH VOL MULT	0.0	3.00	3.70	0.0
-02	MINIMUM COST	5CC.000	0.0	700.000	500.000
	VARIABLE COST	1C.000	C.0	0.071	0.0
	EXPONENT	1.C0	C.0	1.50	0.0
	HIGH VOL MULT	2.20	0.0	4.50	2.00
-03	MINIMUM COST	75C.000	300.000	900.000	850.000
	VARIABLE COST	10.000	40.000	0.071	0.0
	EXPONENT	1.0C	0.50	1.50	0.0
	HIGH VOL MULT	3.00	4.00	6.2C	2.80
-04	MINIMUM COST	1CC0.000	300.000	0.0	900.000
	VARIABLE COST	10.000	45.000	0.0	0.0
	EXPONENT	1.00	0.50	0.0	0.0
	HIGH VOL MULT	3.50	4.50	0.0	4.00

ANALYSIS FOR LATERAL 2 - 3 - B

DATE 10/09/70

LATERAL NO. 2-3-B

MANHOLE NUMBER	STATION TYPE	FLUSH RATE CFS	FLUSH VOLUME CU FT	INSTALL COST DOLLARS	MONTHLY OPERATE COST DOLLARS	MONTHLY MAINTEN COST DOLLARS	SOLIDS REMOVED POUNDS	SOLIDS REMOVED PERCENT
-01	F27C	1.33	240.	1879.	8.64	8.00	0.356	100.00
-02	NONE						0.436	72.02
-03	NONE						0.836	79.01
-04	NONE						3.186	62.77
			240.	1879.	8.64	8.00	4.815	

AVERAGE EFFICIENCY 67.85

MAXIMUM EFFICIENCY 89.22

EFFICIENCY CURVE

LOCATION	PERCENT
0.0	100.00
100.00	100.00
200.00	100.00
300.00	100.00
310.00	100.00
310.00	76.55
410.00	71.76
510.00	68.01
510.00	82.36
610.00	79.29
710.00	76.69
740.00	75.98
740.00	68.72
840.00	66.55
940.00	64.62
1040.00	62.89
1140.00	61.31
1240.00	59.87
1340.00	58.54
1390.00	57.91
1390.00	0.0

VALUE OF MATERIAL REMOVAL DOL / LB 38.44

PROGRAM LISTING

```
C      OPTIMUM SELECTION AND LOCATION OF PERIODIC FLUSHING STATIONS
C      FOR COMBINED SEWER CLEANSING
C
C      W H PAULSEN
C      28 JULY 1970
C      OED FMC
C
C
C      ACOST     ACCUM COST OF THIS STATION - DOLLARS / MONTH
C      AEFF      EFFICIENCY TABLE FOR SELECTED STATION STRING
C      AMOUNT    AMOUNT OF MATERIAL REMOVED BY FLUSHING
C      AREA      AREA UNDER EFFICIENCY CURVE - PERCENT * FT
C      AVEFF     AVERAGE EFFICIENCY FOR THIS STRING OF STATIONS
C      BLANK     '   '
C      CODE      CODE FOR TYPE OF PROCESSING
C                CODE = 1   INPUT SAVE
C                CODE = 2 INPUT REQUIRED EFFICIENCY
C      CODE1     CODE FOR FIRST TIME THROUGH ITERATION CONTROL ROUTINE
C      COST      COST OF STATION - DOLLARS / MONTH
C      COSTN     NET COST OF SELECTED STATION
C      COSTP     COST OF PURCHASE AND INSTALLATION - DOLLARS
C      COSTPT    TOTAL COST OF PURCHASE AND INSTALLATION - DOLLARS
C      COUNT     COUNT OF THE NUMBER OF ITERATIONS
C      CRF       CAPITAL RECOVERY FACTOR
C      CR        CAPITAL RECOVERY FACTOR
C      C1        COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C2        COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C3        COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C4        COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C5        COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C1I       COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C2I       COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C3I       COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C4I       COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      C5I       COEFFICIENT OR EXPONENT OF THE EFFICIENCY CURVE
C      D         DISTANCE - FT
C      DATE      REPORT DATE
C      DELV      VOLUME INCREMENT FOR A FLUSHING STATION - GAL
C      DIA       DIAMETER OF PIPE - FT
C      EFF       POINT EFFICIENCY AT D FROM STATION
C      EFFAVE    AVERAGE EFFICIENCY OVER THIS SEGMENT - PERCENT
C      EFFERR    ERROR FACTOR FOR ZEROING IN ON EFFREQ
C      EFFHI     EFFICIENCY ON HIGH SIDE OF REQUIRED EFFICIENCY - PERCENT
C      EFFINT    INTEGRAL OF EFF AGAINST DISTANCE
C      EFFLO     EFFICIENCY ON LOW SIDE OF REQUIRED EFFICIENCY - PERCENT
C      EFFMAX    MAXIMUM EFFICIENCY ATTAINABLE
C      EFFREQ    EFFICIENCY REQUIRED FOR THIS STRING OF FLUSH STATIONS
C      EFFSTA    INTEGERAL OF EFFICIENCY FOR THIS STATION
C      EFFTRP    EFFICIENCY AT LAST ITERATION CYCLE  PERCENT
C      EFFY      SUBROUTINE TO FIND THE EFFICIENCY CURVES
C      EFF1      EFFICIENCY AT STATION
C      EFF2      EFFICIENCY AT END OF SEGMENT - PERCENT
C      FREQ      NO. OF HOURS BETWEEN FLUSHINGS
C      GPM       AVERAGE BASE FLOW IN A PIPE - CU FT / SEC
C      ICOST     INSTALLATION COST - DOLLARS / MONTH
C      ICOSTI    INSTALLATION COST OF THIS TYPE OF FLUSHING STATION AT
C                THIS LOCATION
```

```
C      INC        NO CF VOLUMES FCR A STATION TYPE
C      ITRP       NO OF ITERATION CYCLES WHICH HAVE SAME EFFICIENCY
C      K
C      KKKOD      CODE FOR TYPE CF FLUSHING WATER  0-CLEAN  1-DIRTY
C      KNAME      2 CHAR LATERAL NAME
C      KODE       TABLE TO INDICATE CPTIMUM SELECTICN
C      KODET      NO OF THE LAST STATION THAT GIVES LOWEST ACCUM COST  WITH
C                 THIS STATICN
C      KODEX      NO OF THE STRING CF STATIONS GIVING THE LCWEST ACCUM CCST
C      LIFE       LIFE OF A FLUSHING STATION - YR
C      LNAME      3 CHAR LATERAL NAME
C      LOAD       AVERAGE LOAD OF DEPCSITS OVER SEGMENT  LB / FT
C     LOADT       TOTAL POUNDS CF SOLIDS OVER LATERAL
C      M
C      MAXCNT     MAXIMUM NC OF ITERATIONS
C      MAXTRP     MAX NO. OF ITERATION CYCLES WHICH HAVE SAME EFFICIENCY
C      MCOST      MONTHLY MAINTENANCE COST  -  DOL
C      MCOSTI     MONTHLY MAINTENANCE COST  -  DOL
C      MCOSTT     TCTAL MONTHLY MAINTENANCE CCST - DOLLARS / MONTH
C      MNAME      2 CHAR LATERAL NAME
C      NLOC       NO CF LOCATICNS
C      NNAME      3 CHAR LATERAL NAME
C      NSTA       NO OF STATICNS
C      NSTAT      NO OF STATICNS
C      NSTYP      NO CF STATICN TYPES
C      OCOST      OPERATING COST - DCLLATS / MCNTH
C      OCOSTP     COST OF MCNTHLY CPERATICN - DOLLARS / MONTH
C      OCOSTT     TOTAL MONTHY OPERATING CCST - DOLLARS / MONTH
C      OPT        CODE FOR METHCD CF CPTIMUMIZATION
C                 OPT = 1   MINIMIZE CPERATICNAL COST
C                 OPT = 2   MINIMIZE TCTAL COST
C      PCOST      PURCHASE CCST PER MONTH - DCLLARS / MONTH
C      PCOSTI     TOTAL PURCHASE CCST OF A TYPE OF FLUSHING STATION - DOL
C      QF         RATE OF FLUSH FLCW - CU FT / SEC
C      QFI        MAXIMUM FLUSHING FLCW RATE - CU FT / SEC
C      RATE       INTEREST RATE - 6 PERCENT CCMPOUNDED ANNUALLY
C      SAVE       VALUE OF REMOVING MATERIAL  DCLLARS / PCUND
C      SAVEFF     SUBROUTINE TC SAVE THE EFFICIENCY CURVE CF SELECTED STRING
C      SAVEHI     VALUE OF SHADCW SAVINGS ON HIGH SIDE OF EFFREQ
C      SAVELO     VALUE OF SHADOW SAVINGS ON LOW SIDE OF EFFREQ
C      SAVING     SAVINGS OF SELECTED STATION
C      SHI        A HIGH VALUE FOR REMOVAL OF MATERIAL TO FIND THE
C                 HIGHEST MAXIMUM EFFICIENCY  -  DOL / LB
C      SLOPE      AVERAGE SLCPE OF PIPE - PERCENT
C      SOLIDS     AMOUNT OF SCLIDS REMOVED BY THIS STATION - LB
C      SOLT       TOTAL AMOUNT CF SOLIDS REMOVED - LB
C      SRP        SOLIDS REMCVED BETWEEN LATERALS - LB
C      STYP       4 CHAR NAME FCR TYPE OF FLUSH STATION
C      STYPI      4 CHAR NAME FCR TYPE OF FLUSH STATION
C      TCOST      ACCUM COST FOR THIS LOCATION
C      TCOSTI     TOTAL MONTHLY INSTALLATICN COST  DOLLARS
C      TCOST1     SAVE AREA FOR FINDING LOWEST ACCUM COST  DOLLARS
C      TITLE      REPORT TITLE
C      TMSAVE     TOTAL MONTHLY SAVINGS
C      TNCOST     TOTAL NET COST
C      TOCOST     TOTAL MONTHLY CPERATING COST
C      UCOST      UNIT COST CF FLUSHING WATER - DOLLARS / GAL
C      UCOSTI     UNIT COST OF FLUSHING WATER - DOLLARS / GAL
C      VALUE      VALUE OF THE SAVINGS CAUSED BY THE INSTALLATION OF THE
C                 STATION - DOLLARS / MONTH
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C      VHDUM     DUMMY
C      VH        LARGEST MAXIMUM VOLUME OF WATER DISCHARGED BY A TYPE OF
C                FLUSHING STATION
C      VL        SMALLEST MAXIMUM VOLUME OF WATER DISCHARGED BY A TYPE OF
C                FLUSHING STATION
C      VOL       VOLUME OF WATER DISCHARGED BY FLUSHING STATION - CU FT
C      VOLT      TOTAL VOUME OF FLUSH TO OPERATE EACH MONTH
C      X         DISTANCE BETWEEN STATIONS - FT
C      XN,YN     EFFICIENCY TABLE FOR CURRENT SELECTION CANDIDATES
C      XO,YO     EFFICIENCY TABLE FOR PREVIOUS SUBOPTIMUMIZED SELECTION
C      XTT,YTT   TABLE FOR HOLDING THE EFFICIENCY CURVE TEMPERARILY
C      XX        DISTANCE FROM BEGINNING OF THE LINE
C      Z         DISTANCE FROM STATION AT WHICH EFFICIENCY DROPS TO ZERO
C                USE WHEN B AND C ARE ZERO - FT
C      ZMIN      MINIMUM INSTALLATION COST  - DOL
C      ZXP       INSTALLATION COST EXPONNENT
C      ZVAR      VARIABLE INSTALLATION COST  - DOL / FT ** EXP
C      ZZ        DISTANCE FROM FLUSHING STATION TO ZERO EFFICIENCY
C      ZZZZ      ACCUM COST - DOLLARS
C
C      L         ROW - TYPE OF STATION
C      J         COL - LOCATION
C      I         TYPE OF THE PREVIOUS STATION
C
C


      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),CF(36)
      REAL LOAD,LOADT
      REAL ICOSTI
      REAL ICOST
      REAL MCOSTI(6), MCOST(31),MCOSTT
      INTEGER KKKD (7)
      INTEGER CODE
      INTEGER OPT
      INTEGER COUNT
      INTEGER LNAME, BLANK
      INTEGER STYPI
C
C
      EQUIVALENCE (NSTA, NSTAT)
C
C
      DIMENSION SAVING (30)
      DIMENSION COSTN (30)
      DIMENSION KCODEX (30)
      DIMENSION SOLIDS(30)
      DIMENSION KODE (36, 30), ACOST (36, 30), ICOST (36, 30)
      DIMENSION              CCST (36)
      DIMENSION TITLE(10), DATE (2)
      DIMENSION KNAME(20),LNAME(20),MNAME(20),NNAME(20)
```

```
      DIMENSION STYPI(7), LIFE(7), QFI(7), VL(7),          FREQI(7),CR(7)
      DIMENSION UCCSTI(7), PCCSTI(7)
      DIMENSION ZZ(7)
      DIMENSION FREQ (36), DELV(36)
      DIMENSION COSTP (36), CCOSTP (36)
      DIMENSION C5I(7), ICOSTI(7, 30)
      DIMENSION UCCST(36), PCOST(36), STYP(36)
      DIMENSION ZMIN (6, 30), ZVAR (6, 30), ZXP (6, 30),VH(6,30)
      DATA BLANK /'     '/
C
C
  101 FORMAT (8I10)
  102 FORMAT (8F10.0)
  103 FORMAT (10E8.0)
  104 FORMAT (2(A2,A3),6(2F4.0,F3.0))
  108 FORMAT (10A4, 2A4, 1X, I1, F10.0)
  109 FORMAT (2(A2,A3),5F10.0,6F3.0)
  110 FORMAT (A4, I1, I4, 7F6.0)
C
C
C
  201 FORMAT ('1', 25X, 'MONTHLY', 4X, 'MONTHLY' /
     1          5X, 'LOCATION  STATION', 4X, 'INSTALL', 4X, 'OPERATE',
     2          4X, 'MONTHLY', 8X, 'NET' /
     3          11X, 'NO', 5X, 'TYPE', 7X, 'COST', 7X, 'COST', 4X,
     4          'SAVINGS', 7X, 'COST' // )
  202 FORMAT (I13, I9, 4F11.2)
  203 FORMAT (/// ' TOTAL MONTHLY INSTALLATION COST', 3X, F10.2)
  204 FORMAT (' TOTAL MONTHLY OPERATING COST', 6X, F10.2)
  205 FORMAT (' TOTAL MONTHLY SAVINGS', 13X, F10.2)
  206 FORMAT (' TOTAL NET COST', 20X, F10.2)
  207 FORMAT (//' AVERAGE EFFICIENCY',F10.2)
  210 FORMAT (/,' MAXIMUM EFFICIENCY',F10.2)
  211 FORMAT ('1', 24X, 10A4 //)
  212 FORMAT (13X, 'DATE', 4X, 2A4 //)
  213 FORMAT (13X, 'LATERAL NO.',1X,A2,A3)
  214 FORMAT (62X, 'MONTHLY', 3X, 'MONTHLY' /
     1    34X, 'FLUSH', 5X, 'FLUSH', 3X, 'INSTALL',
     2    3X, 'OPERATE', 3X, 'MAINTEN', 4X, 'SOLIDS', 4X, 'SOLIDS' /
     3    13X, 'MANHOLE  STATION', 6X, 'RATE', 4X, 'VOLUME', 6X, 'COST',
     4    6X, 'COST', 6X, 'COST', 3X, 'REMOVED', 3X, 'REMOVED' /
     5    14X, 'NUMBER', 5X, 'TYPE', 7X, 'CFS', 5X, 'CU FT',
     6    3(3X, 'DOLLARS'), 4X, 'POUNDS' 3X, 'PERCENT' / )
  215 FORMAT (15X,A2,A3,5X,A4,F10.2,2F10.0,2F10.2,F10.3,F10.2)
  216 FORMAT (39X,5(1X,9('-')) / 39X,2F10.0,2F10.2,F10.3)
  217 FORMAT (15X,A2,A3, 5X, 'NONE', 50X, F10.3, F10.2)
  218 FORMAT (2F20.2)
  219 FORMAT ('1', 12X, 'EFFICIENCY CURVE' ///
     1          12X, 'LOCATION', 13X, 'PERCENT' /)
  220 FORMAT (// ' VALUE OF MATERIAL REMOVAL  DOL / LB', F20.2 //)
  225 FORMAT (I5, 4(I10, F15.2))
  801  FORMAT ('1' ,/ / ,30X,'SUMMARY -- INPUT DATA',/,24X,10A4,//)
  802 FORMAT (13X,'DATE ',2A4,/)
  803 FORMAT (13X,'LATERAL NO.',A2,A3,T60,'REQUIRED EFFICIENCY',F4.0,
     1      '%',/)
  804 FORMAT (13X,'LATERAL CHARACTERISTICS',/,29X,'DISTANCE TO',T47,
     1       'AVERAGE BASE   AVERAGE BASE   AVERAGE SLOPE   DIAMETER',/,
     2       16X,'LOCATION  NEXT MANHOLE (FT)     FLOW (CFS)    LOAD ',
     3       '(LB/FT)',T82,'(%)',T96,'(FT)')
```

```
  805 FORMAT (/,18X,A2,A3,T31,F5.C,T49,F6.5,T64,F6.5,T80,F6.3,T95,F5.3)
  806 FORMAT (//,13X,'STATION TYPE CHARACTERISTICS',//,16X,
    1         'STATICN CODE',T44,6(A4,11X))
  807 FORMAT (16X,'FLUSH FLLIC CCDE',T46,6(I1,14X))
  8C8 FORMAT (16X,'STATION LIFE (YRS)',T45,6(I2,13X))
  809 FORMAT (16X,'FLUSH RATE (CFS)',T44,6(F5.2,10X))
  810 FORMAT (16X,'FLUSH VCL-LCW (CUFT)',T42,6(F5.0,10X))
  812 FORMAT (16X,'FREQUENCY (HRS)',T44,6(F3.0,12X))
  813 FORMAT (16X,'CCST CF WATER ($/CUFT)',T42,6(F6.5,9X))
  814 FORMAT (16X,'MAINTENANCE CCST ($)',T43,6(F5.1,10X))
  815 FORMAT (16X,'PLRCHASE CCST ($)',T42,6(F5.0,10X))
  816 FORMAT(  //,13X'INSTALLATICN COSTS / HIGH VOLUME LIMIT',/,50X,
    1         'STATION TYPE',/,16X,'LCCATION',T44,6(A4,11X))
  817 FORMAT(/15X,A2,A3,T26,'MINIMUM COST',T40,6(F9.3,6X))
  818 FORMAT (T26,'VARIABLE CCST',T41,6(F8.3,7X))
  819 FORMAT (T26,'EXPONENT',T44,6(F4.2,11X))
  82C FORMAT (T26,'HIGH VCL MULT',T44,6(F4.2,11X))
C
C
C
  900 CONTINUE
      COUNT = 0
      EFFTRP = 1E18
      MAXTRP = 4
      ITRP = C
C
C     INC IS THE NUMBER OF DIVISICNS IN THE HIGH - LOW SPECIFICATION
C     ON THE VOLUME. MORE THAN ANY CTHER VARIABLE THIS EFFECTS THE TIME
C     REQUIRED FOR EXECUTICN, HENCE, THIS SHOULD BE AS SMALL AS PRAC-
C     TICAL.  A PARTITION OF 3 --HIGH, LCW, AND AVERAGE -- SEEMS REA-
C     SONABLE FOR PRELIMINARY WORK AND 5 OR 7 FOR MORE REFINEC ANALYSIS.
C     EXECUTION TIME GOES UP BY THE RATIO CF SQUARES OF THE NUMBER OF
C     INTERVALS.
C
      INC = 3
      INC = 5
      EFFLO = 0
      LOADT = 0.
      SHI = 1E6
      SAVELO = 0
      SAVEHI = 10CC.
      EFFHI = 100.0
      CODE1 = 1
      RATE = C.C6
      MAXCNT = 15
      EFFERR = 0.C5
      DO 1 J = 1, 3C
      X (J) = 0
      GPM (J) = 0
      DO 1 I = 1, 36
      KODE (I, J) = 0
      ACOST (I, J) = 0
      ICOST (I, J) = 0
    1 CONTINUE
      DO 27 I = 1, 100
      DO 27 J = 1, 36
      XO (I, J) = 1E20
      XTT (I, J) = 1E20
      YTT (I, J) = 0
```

```
   27 YO (I, J) = 0
      DO 580 I = 1, 36
      Z(I) = 5000
      XTT (1, I) = 0
  580 XO(1, I) = 0
C
C
C
C     READ INPUT DATA
C
      READ (5, 108) TITLE, DATE, CODE, SAVE
      J = 0
   10 J = J + 1
      LNAME(J)=BLANK
      READ (5,109) KNAME(J),LNAME(J),MNAME(J),NNAME(J),X(J),GPM(J),
     1             LOAD(J),DIA(J),SLOPE(J),(VH(I,J),I=1,6)
      IF (LNAME(J)-BLANK) 11,4,11
   11 READ (5,104) KNAME(J),LNAME(J),MNAME(J),NNAME(J),(ZMIN(I,J),
     1             ZVAR(I,J),ZXP(I,J),I=1,6)
      GOTO 10
    4 NLOC=J-1
      WRITE (6,801) TITLE
      WRITE (6,802) DATE
      WRITE (6,803) KNAME(1),LNAME(1),SAVE
      WRITE (6,804)
      DO 888 J=1,NLOC
  888 WRITE (6,805) MNAME(J),NNAME(J),X(J),GPM(J),LOAD(J),
     1              SLOPE(J),DIA(J)
      I = 0
   13 CONTINUE
      I = I + 1
      READ (5, 110,END=18) STYPI (I), KKKD(I), LIFE(I), QFI(I), VL(I),
     1VHDUM,          FREQI(I), UCOSTI(I), MCOSTI(I), PCOSTI(I)
      GO TO 13
   18 CONTINUE
      NSTYP = I - 1
      WRITE (6,806)(STYPI(I) ,I=1,NSTYP)
      WRITE (6,807)(KKKD(I)  ,I=1,NSTYP)
      WRITE (6,808)(LIFE(I)  ,I=1,NSTYP)
      WRITE (6,809)(QFI(I)   ,I=1,NSTYP)
      WRITE (6,810)(VL(I)    ,I=1,NSTYP)
      WRITE (6,812)(FREQI(I) ,I=1,NSTYP)
      WRITE (6,814)(MCOSTI(I),I=1,NSTYP)
      WRITE (6,815)(PCOSTI(I),I=1,NSTYP)
      WRITE (6,813)(UCOSTI(I),I=1,NSTYP)
      WRITE (6,816) (STYPI(I),I=1,NSTYP)
      DO 890 J=1,NLOC
      WRITE (6,817) MNAME(J),NNAME(J),(ZMIN(I,J),I=1,NSTYP)
      WRITE (6,818) (ZVAR(I,J),I=1,NSTYP)
      WRITE (6,819) (ZXP(I,J),I=1,NSTYP)
  890 WRITE (6,820) (VH(I,J),I=1,NSTYP)
C
      IF (CODE - 1) 56, 48, 56
C
C     SAVE DETERMINES THE STARTING VALUE OF THE VALUE OF SOLIDS REMOVAL
C     (SHADOW OR ARTIFICAL SAVINGS).  AS SET UP THE VALUE IS $100.0
C     AS EXPERIENCE ON A PARTICULAR PROBLEM IS GAINED SOME EFFICIENCY
C     OF EXECUTION CAN BE ACHIEVED BY CHANGING THIS TO THE APPROXIMATE
C     EXPECTED VALUE
```

```
C
   56 CONTINUE
      EFFREQ = SAVE
      SAVE = 100.0
      SAVES = SAVE
      SAVE = SHI
   48 CONTINUE
      XX (1) = 0
      DO 12 J = 1, NLOC
      LOADT = LOADT + LOAD(J)*X(J)
   12 XX (J+1) = XX(J) + X (J)
C
C     SET UP TABLES
C
      NSTA = 1 + NSTYP * INC
      KKKOD (1) = 0
      QF (1) = 0
      FREQ (1) = FREQI (2)
      UCOST (1) = 0
      PCOST (1) = 0
      MCOST (1) = 0
      DO 44 J = 1, NLOC
      VOL(1,J) = 0.
   44 ICOST (1, J) = 0
      M = 1
      DO 9 I = 1, NSTYP
      CRF = RATE * (1 + RATE) ** LIFE(I) / ((1 + RATE) ** LIFE(I) -1)/12
      CR(I) = CRF
      DO 9 I5 = 1, INC
      M = M + 1
      UCOST (M) = UCOSTI (I)
      KKKOD (M) = KKKD (I)
      QF (M) = QFI (I)
      FREQ (M) = FREQI (I)
      PCOST (M) = PCOSTI (I) * CRF
      MCOST (M) = MCOSTI (I)
      DO 799 J = 1, NLOC
      DELV(J) = (VH(I,J) * VL(I) - VL(I))/ (INC - 1.)
      IF (VH(I,J).LT.1.) DELV(J) = 1.
      VOL (M,J) = VL   (I) + (I5 - 1) * DELV(J)
      IF (I5 - 1) 242, 243, 244
  242 STOP 242
  243 CONTINUE
      ICOST (M, J) = CRF * ZMIN (I, J)
      GO TO 245
  244 CONTINUE
      ICOST (M, J) = CRF * (ZMIN (I, J) + ZVAR (I, J) * ((I5 - 1) *
     1   DELV(J))
  245 CONTINUE
  799 CONTINUE
      DO 28 J = 1, NLOC
      IF (ZMIN  (I, J)) 17, 14, 17
   14 CONTINUE
      ICOST (M, J) = 1E20
      GO TO 28
   17 CONTINUE
      IF (ZMIN  (I, J) - 1) 28, 29, 28
   29 CONTINUE
      ICOST (M, J) = 0
```

```
   28 CONTINUE
    9 CONTINUE
   80 CONTINUE
C
C
      DO 5 J = 1, NLOC
      DO 35 L = 1, NSTAT
      DO 6 I = 1, NSTAT
C
C     FIND THE AMOUNT OF SOLIDS REMOVED BY THIS STATION
C
      IF (ICOST (L, J) - 1E18) 723, 722, 722
  722 VALUE = -1E20
      GO TO 724
  723 CONTINUE
      CALL EFFY (I, J, L, AMOUNT)
C
C     FIND THE VALUE OF THE SAVINGS OF THIS STATION
C
      VALUE = SAVE * AMOUNT
  724 CONTINUE
C
C     FIND THE COST
C
      OCOST = UCOST (L) * VOL (L,J) * 30 * 24 / FREQ (L) + MCOST (L)
      COST (I) = ICOST (L, J) + PCOST (L) + OCOST - VALUE
      IF (J - 1) 8, 8, 6
    6 CONTINUE
    8 CONTINUE
C
C     FIND MIN ACCUM COST
C
      IF (J - 1) 15, 15, 16
   15 CONTINUE
      ACOST (L, 1) = COST (1)
      GO TO 7
   16 CONTINUE
      KODET = 1
      TCOST = ACOST (1, J-1) + COST (1)
      DO 19 I = 2, NSTA
      TCOST1 = ACOST (I, J-1) + COST (I)
      IF (TCOST - TCOST1) 19, 19, 20
   20 TCOST = TCOST1
      KODET = I
   19 CONTINUE
      ACOST (L, J) = TCOST
      KODE  (L, J) = KODET
    7 CONTINUE
      I = KODE (L, J)
      CALL SAVEFF (J, L, I)
   35 CONTINUE
    5 CONTINUE
C
C     FIND STRING OF STATIONS WITH MINIMUM ACCUM COST
C
      KODET - 1
      TCOST - ACOST (1, NLOC)
      DO 21 I = 2, NSTA
      IF (TCOST - ACOST (I, NLOC)) 21, 21, 22
```

```
   22 KODET = I
      TCOST = ACOST (I, NLCC)
   21 CONTINUE
      KODEX (NLOC) = KODET
      DO 23 J = 2, NLOC
      I = NLCC - J + 1
      KODEX (I) = KCDE (KCDET, I + 1)
      KODET = KODEX (I)
   23 CONTINUE
      I = KODEX (1)
      COSTN (1) = ACOST (I, 1)
      DO 24 J = 2, NLOC
      I1 = KODEX (J)
      I2 = KODEX (J-1)
   24 COSTN (J) = ACOST (I1, J) - ACOST (I2, J-1)
C
C     PRINT REPORT
C
   46 CONTINUE
      WRITE (6, 211) TITLE
      WRITE (6, 212) DATE
      WRITE (6,213) KNAME(1),LNAME(1)
      WRITE (6, 214)
      VOLT = 0
      COSTPT = 0
      OCOSTT = 0
      SOLT = 0
      MCOSTT= 0.
      DO 705 J = 1, NLOC
      M = KODEX (J)
      IF (M - 1) 706, 706, 707
  706 CONTINUE
      IJ = 0
      DO 246 I = 1, J
      IJ = IJ + KODEX (I)
  246 CONTINUE
      IF (IJ - J) 247, 247, 248
  247 CONTINUE
      SOLID = 0
      GO TO 249
  248 CONTINUE
      CALL SOLD (J, KODEX(NLCC), SCLID)
  249 CONTINUE
      SRP = SCLID / LOAD (J) * 100 / X(J)
      SOLT = SOLT + SOLID
      WRITE (6,217) MNAME(J),NNAME(J),SOLIC,SRP
      GO TO 705
  707 CONTINUE
      I = (M - 2) / INC + 1
      COSTP(M) = ICOST(M,J) /CR(I) + PCCSTI(I)
      OCOSTP (M) = LCOST (M) * VCL (M,J) * 30 * 24 / FREQ (M)
      CALL SOLD (J, KODEX(NLCC), SCLID)
      SRP = SOLID / LCAD (J) * 100 / X(J)
      WRITE (6,215) MNAME(J),NNAME(J),STYPI(I),QFI(I),VCL(M,J),COSTP(M),
     1              OCOSTP (M), MCOST (M), SCLID, SRP
      VOLT = VCLT + VOL(M,J)
      COSTPT = COSTPT + CCSTP(M)
      OCOSTT = OCOSTT + OCCSTP(M)
      MCOSTT= MCOSTT + MCOST(M)
```

```
      SOLT = SOLT + SOLID
  705 CONTINUE
      WRITE (6,216) VOLT, COSTPT,OCOSTT,MCOSTT,SOLT
      AVEFF = SOLT/LOADT * 100.
      IF (SAVE - SHI) 250, 251, 251
  251 CONTINUE
      WRITE (6, 210) AVEFF
      EFFMAX=AVEFF
      GO TO 252
  250 CONTINUE
      WRITE (6, 207) AVEFF
      WRITE (6,210) EFFMAX
  252 CONTINUE
      EFFAVE = AVEFF
      WRITE (6, 219)
      I = KODEX (NLCC)
      J = 1
  253 CONTINUE
      WRITE (6, 218) XO (J, I), YO (J, I)
      J = J + 1
      IF (XO (J, I) - 1E18) 253, 254, 254
  254 WRITE (6,220) SAVE
      IF (SAVE - SHI) 255, 256, 256
  256 CONTINUE
      SAVE = SAVES
      GO TO 80
  255 CONTINUE
C
C     CONTROL ROUTINE FOR ITERATIONS
C
      IF (EFFAVE - EFFTRP) 302, 301, 302
  301 ITRP = ITRP + 1
      IF (ITRP - MAXTRP) 303, 304, 304
  304 WRITE (6, 305) MAXTRP, EFFTRP
  305 FORMAT ('1', 10X, 'SAME EFFICIENCY', I3, 2X, 'TIMES', F20.2,
     1          'PERCENT' / '1')
      STOP 304
  302 CONTINUE
      EFFTRP = EFFAVE
      ITRP = 0
  303 CONTINUE
      COUNT = COUNT + 1
      IF (COUNT - MAXCNT) 703, 704, 704
  704 STOP 704
  703 CONTINUE
      IF (CODE - 1) 69, 57, 69
   57 STOP 57
   69 IF (CODE1 - 1) 73, 70, 73
   70 CONTINUE
      IF (EFFAVE - EFFREQ) 71, 76, 76
C  71 STOP 71
   71 CONTINUE
      SAVELO = SAVE
      SAVE = 2 * SAVE
      EFFLO = EFFAVE
      GO TO 80
   76 CONTINUE
      CODE1 = 2
   73 CONTINUE
      IF (ABS (EFFAVE - EFFREQ) / EFFREQ - EFFERR) 9999, 9999, 77
```

```
   77 CONTINUE
      IF (EFFAVE - EFFREC) 557, 557, 556
  557 CONTINUE
      SAVELO = SAVE
      EFFLO = EFFAVE
      SAVE = SAVELO + 0.62 * (SAVEHI - SAVELO)
      GO TO 8C
  556 CONTINUE
      SAVEHI = SAVE
      EFFHI = EFFAVE
      SAVE = SAVELO + 0.62 * (SAVEHI - SAVELO)
      GO TO 80
 9999 STOP 9999
      END
```

```
      SUBROUTINE EFFY (I, J, LL, AMCUNT)
C
C     AMOUNT    AMOUNT OF MATERIAL REMOVED BY FLUSHING
C     AREA      AREA OF EFFICIENCY CURVE FOR CURRENT CANDIDATE
C     AREAO     AREA OF EFFICIENCY CURVE WHICH IS OVERLAPPING
C     D         DISTANCE - FT
C     D1        DISTANCE FROM STATICN TC NEXT MANHCLE
C     D2        DISTANCE FROM STATION TO NEXT POINT ON SAVED EFF CURVE
C     D4        DISTANCE FRCM LAST PCINT TC ZERO EFFICIENCY - FT
C     EFF       EFFICIENCY AT D
C     EFFSTA    EFFICIENCY INCREMENT GAINED BY ADDING THIS STATION
C     EFFVAL    EFFICIENCY SUBRCUTINE
C     EFF1      EFFICIENCY AT D1 - PERCENT
C     EFF2      EFFICIENCY AT C2 - PERCENT
C     EFF3      EFFICIENCY AT D1 (JUST PAST THE NEXT MANHOLE)
C     I         TYPE OF THE PREVICUS STATICN
C     J         LOCATION OF THE STATION
C     K         COUNTER FCR LCCATICNS
C     KK        LOCATION OF THE STATION
C     L         TYPE CF THE PREVICUS STATICN
C     LL        TYPE CF THE CURRENT STATION
C     M         COUNTER FCR LCCATICN CF PCINTS IN THE XN,YN TABLE
C     MM        COUNTER FCR PCINTS IN THE SAVED EFF TABLE
C     N         LOCATION CF THIS STATION IN THE XO,YO TABLE
C     NLOC      NO CF LOCATICNS
C     XN,YN     EFFICIENCY TABLE FOR CURRENT SELECTICN CANDIDATES
C     XO,YO     EFFICIENCY TABLE FCR PREVIOUS SUBOPTIMUMIZED SELECTION
C     X1,Y1     INTERSECTICN PCINT CF THE EFFICIENCY CURVES
C     XX        DISTANCE FROM START CF THE LATERAL
C     Z         DISTANCE FROM STATICN TC POINT OF ZERO EFFICIENCY
C
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YC(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VCL (36,30),QF(36)
      REAL LOAD
      REAL LOADA, LCADO
C
C
      DELTX = 100
      L = I
      DO 34 N = 1, 50
      YN (N, I) = 0
   34 XN (N, I) = 1E19
      XN (1, I) = 0
C     LL=1 MEANS NO STATION AT THIS LOCATION
      IF (LL - 1) 49, 50, 51
   49 STOP 49
   50 AMOUNT = 0
      RETURN
   51 CONTINUE
      DO 36 N = 1, 100
      IF (XX (J) - XO (N, L)) 37, 36, 36
```

```
   36 CONTINUE
      N = 2
   37 CONTINUE
C
C     FIND EFFICIENCY TABLE OF CURRENT CANCIDATE
C
      M = 0
      K = J
      KK = J
      KK3 = KK + 1
      MM = N - 1
      D1 = XX(K) - XX(J)
  5C2 CONTINUE
      D2 = XO(MM, L) - XX(J)
      IF (D2) 601, 503, 503
  601 D2 = 0
  5C3 CONTINLE
      IF (J - 1) 504, 505, 5C6
  504 STOP 5C4
  506 CONTINUE
      IF (D1 - D2) 505, 5C5, 5C7
  5C5 CONTINLE
      IF (D1 - Z(LL)) 508, 3C, 30
  508 CONTINLE
      CALL EFFVAL (LL, KK, C1, EFF1)
      IF (EFF1) 521, 521, 522
  522 CONTINLE
      M = M + 1
      YN (M, I) = EFF1
      XN (M, I) = XX(J) + D1
      IF (M - 1) 515, 509, 517
  515 STOP 515
  517 CONTINUE
      IF (KK - KK3) 721, 5C9, 721
  721 CONTINLE
      CALL EFFVAL (LL, KK3 , D1, EFF3)
      IF (EFF3) 519, 519, 520
  52C CONTINLE
      IF (EFF1 - EFF3) 510, 5C9, 510
  510 CONTINUE
      M = M + 1
      YN (M, I) = EFF3
      XN (M, I) = XX(J) + D1
  5C9 CONTINUE
      IF (J - 1) 523, 512, 524
  523 STOP 523
  524 CONTINUE
      IF (D1 - D2) 512, 511, 513
  513 STOP 513
  511 CONTINUE
      MM = MM + 1
      D2 = XO(MM, L) - XX(J)
  512 CONTINUE
      KK = K
      KK3 = KK + 1
      D1 - XX(K + 1) - XX(J)
      D5 = XN (M, I) + DELTX - XX (J)
      IF (D1 - D5) 73C, 73C, 731
```

```
  731 D1 = D5
      KK3 = K
      GO TO 503
  730 CONTINUE
      IF (K - NLOC) 732, 38, 39
  732 CONTINUE
      K = K + 1
      GO TO 503
   39 STOP 39
   38 CONTINUE
      IF (D1 - Z(LL)) 702, 30, 30
  702 CONTINUE
      D = D1
      GO TO 32
  507 CONTINUE
      IF (D2 - Z(LL)) 514, 30, 30
  514 CONTINUE
      CALL EFFVAL (LL, KK, D2, EFF2)
      IF (EFF2) 518, 518, 516
  516 CONTINUE
      M = M + 1
      YN (M, I) = EFF2
      XN (M, I) = XX(J) + D2
      MM = MM + 1
      GO TO 502
  518 CONTINUE
      D = D2
      EFF = EFF2
      GO TO 31
  519 EFF = EFF3
      D = D1
      GO TO 31
  521 EFF = EFF1
      D = D1
      GO TO 31
   30 CONTINUE
      D = Z (LL)
   32 CONTINUE
      CALL EFFVAL (LL, KK, D, EFF)
      IF (EFF) 31, 31, 18
   18 CONTINUE
      M = M + 1
      YN (M, I) = EFF
      XN (M, I) = XX (J) + D
      YN (M+1, I) = 0
      XN (M+1, I) = XX (J) + D
      GO TO 33
   31 CONTINUE
      M = M + 1
      YN (M, I) = 0
      D4 = XN (M-1, I) - XX (J)
      XN (M, I) = (D - D4             ) * YN (M-1, I) / (YN(M-1, I) - EFF)
     1                + XN (M-1, I)
   33 CONTINUE
C
C     FIND THE EFFICIENCY GAINED BY ADDING THIS STATION
C
C
C     FIND AREA OF EFFICIENCY CURVE (TABLE) FOR CURRENT CANDIDATE
```

```
C
      LOADA = 0
      AREA = 0
      M = 1
   52 CONTINUE
      M = M + 1
      IF (YN(M,I)) 551, 54, 53
  551 STOP 551
   53 CONTINUE
      DAREA =        (YN(M-1,I) + YN(M,I)) * (XN(M,I) - XN(M-1,I)) * 0.5
      AREA = AREA + DAREA
      CALL LOADX (XN(M,I), DAREA, LOADA)
      GO TO 52
   54 CONTINUE
      DAREA =        (YN(M-1,I)) * (XN(M,I) - XN (M-1,I)) * 0.5
      AREA = AREA + DAREA
      CALL LOADX (XN(M,I), CAREA, LCADA)
C
C     FIND AREA OVERLAPPED BY PREVIOUS STATION
C
      LOADO = 0
      AREAO = 0
      IF (J - 1) 555, 566, 558
  555 STOP 555
  558 CONTINUE
      M = 1
      K = N - 1
  559 CONTINUE
      M = M + 1
      IF (XN(M-1,I) - XN(M,I)) 530,531,906
  906 IF (XN(M-1,I) - XN(M,I) * 1.00001) 531,531,806
  806 STOP 806
  531 CONTINUE
      IF (XN(M, I) - 1E18) 602, 566, 566
  602 CONTINUE
      IF (YN(M  ,I)) 559, 566, 559
  530 CONTINUE
      K = K + 1
      IF (XO(K-1,L) - XO(K,L)) 532, 533, 907
  907 IF (XO(K-1,L) - XO(K,L) * 1.00001) 533, 533, 807
  807 STOP 807
  533 CONTINUE
      IF (XO(K, L) - 1E18) 603, 566, 566
  603 CONTINUE
      IF (YO(K  ,L)) 530, 566, 530
  532 CONTINUE
      IF (XN(M, I) - XO(K, L)) 534, 560, 570
  534 CONTINUE
      CALL X1Y1 (XO(K-1,L),YO(K-1,L), XN(M,I),YN(M,I), XN(M,I),0.0,
     1           XO(K,L),YO(K,L), X1,Y1)
      M1 = K + 1
      DO 539 I539 = M1, 100
      M2 = 100 + M1 - I539
      XO (M2, L) = XO (M2 - 1, L)
      YO (M2, L) = YC (M2 - 1, L)
  539 CONTINUE
      XO (K, L) = X1
      YO (K, L) = Y1
      GO TO 560
```

```
  570 CONTINUE
      CALL X1Y1 (XN(M-1,I),YN(M-1,I),
     1          XO(K,L),YO(K,L), XO(K,L),0.0, XN(M,I),YN(M,I), X1,Y1)
      M1 = M + 1
      DO 55 I55 = M1, 50
      M2 = 50 + M1 - I55
      XN (M2, I) = XN (M2 - 1, I)
      YN (M2, I) = YN (M2 - 1, I)
   55 CONTINUE
      XN (M, I) = X1
      YN (M, I) = Y1
      GO TO 560
  560 CONTINUE
      IF (YN(M, I) - YO(K, L)) 561, 561, 562
  561 CONTINUE
      IF (YN(M-1, I) - YO (K-1, L)) 563, 564, 564
  563 CONTINUE
      DAREO =         (YN(M-1, I) + YN(M, I)) * (XN(M,I) - XN(M-1,I))*.5
      AREAO = AREAO + DAREO
      CALL LOADX (XN(M,I), DAREO, LOADO)
      GO TO 565
  564 CONTINUE
      CALL X1Y1 (XN(M-1, I), YN(M-1, I), XO(K-1, L), YO(K-1, L),
     1          XO(K, L), YO(K, L), XN(M, I), YN(M, I), X1, Y1)
      DAREO =         (YO(K-1, L) + Y1) * (X1 - XO(K-1, L)) * 0.5
     1              + (Y1 + YN(M, I)) * (XN(M, I) - X1) * 0.5
      AREAO = AREAO + DAREO
      CALL LOADX (XN(M,I), DAREO, LOADO)
  565 CONTINUE
      IF (YN(M, I)) 572, 566, 559
  572 STOP 572
  562 CONTINUE
      IF (YN (M-1, I) - YO (K-1, L)) 568, 568, 567
  567 CONTINUE
      DAREO =         (YO(K, L) + YO(K-1, L)) * (XO(K, L) - XO(K-1, L))
     1              * 0.5
      AREAO = AREAO + DAREO
      CALL LOADX (XO(K,L), DAREO, LOADO)
      GO TO 569
  568 CONTINUE
      CALL X1Y1 (XO(K-1, L), YO(K-1, L), XN(M-1, I), YN(M-1, I),
     1          XN(M, I), YN(M, I), XO(K, L), YO(K, L), X1, Y1)
      DAREO =         (YN(M-1, I) + Y1) * (X1 - XN(M-1, I)) * 0.5
     1              + (Y1 + YO(K, L)) * (XO(K, L) - X1) * 0.5
      AREAO = AREAO + DAREO
      CALL LOADX (XO(K,L), DAREO, LOADO)
  569 CONTINUE
      IF (YO(K, L)) 573, 566, 559
  573 STOP 573
C
C
  566 CONTINUE
      AMOUNT = LOADA - LOADO
      IF (AMOUNT + 0.00001) 801, 802, 802
  801 WRITE (6, 803) AMOUNT, LOADA, LOADO
      DO 805 K = 1, 50
  805 CALL XOYO (K, L)
      DO 804 M = 1, 50
  804 CALL XNYN (M, I)
```

```
      STOP 801
  802 CONTINUE
  803 FORMAT (2F20.6)
      RETURN
      END
```

```
      SUBROUTINE EFFVAL (I, J, D, EFF)
C
C     SUBROUTINE EFFVAL CALCULATES THE EFFICIENCY VALUES REQUIRED.
C     IF CHANGES ARE TO BE MADE TO THE EQUATIONS THE CHANGES NEED
C     ONLY ENTERED HERE.  NOTE THAT THESE ARE EXPRESSIONS FOR POINT
C     EFFICIENCY WHICH HAVE BEEN DERIVED FROM THE AVERAGE EFFICIENCY
C     EXPRESSIONS SUPPLIED BY CEL.
C
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
      DATA ALPHA /1.0/
      DATA A1 /-13.7/
      DATA    A2 /24.68/
      DATA C2 /-.0000711/
      DATA  BETA /1.6/
C     D          DISTANCE FROM STATION
C     DIA        DIAMETER OF PIPE - FT
C     EFF        POINT EFFICIENCY AT D FROM STATION
C     GPM        AVERAGE BASE FLOW IN A PIPE - CU FT / SEC
C     I          TYPE OF STATION
C     J          LOCATION
C     KKKOD      CODE FOR TYPE OF FLUSHING WATER  0-CLEAN  1-DIRTY
C     QF         RATE OF FLUSH FLOW - CU FT / SEC
C     SLOPE      AVERAGE SLOPE OF PIPE - PERCENT
C     VOL        VOLUME OF WATER DISCHARGED BY FLUSHING STATION - CU FT
      IF (D) 7, 7, 9
    7 EFF = 100
      RETURN
    9 CONTINUE
      A3 = VOL(I,J) **1.3 * QF(I) ** 0.9 * SLOPE(J) ** 1.4 * 1E4 /
     1     GPM(J) ** 1.2 * DIA(J) ** 1.8
      EFF = A1 + A2 * ALOG10 (A3 / D ** BETA) - BETA * A2 / ALOG (10.0)
      EFF = AMIN1 (EFF, 100.0)
      IF (KKKOD(I)) 1, 1, 2
    1 RETURN
    2 CONTINUE
      C1=100 - 14.3 + .14*VOL(I,J) + .242*QF(I)
      C1 = C1 / 100
      EFF = EFF * (C1 + C2 * D ** ALPHA * (1 + ALPHA)) +
     1             (BETA * C2 * A2 * ALPHA * D ** ALPHA/ ALOG(10.0))
      EFF = AMIN1 (EFF, 100.0)
      RETURN
      END
```

```
      SUBROUTINE SAVEFF (J, LLL, L)
C
C
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
C
C
      DIMENSION YT(100), XT(100)
C
C
C     I          TYPE OF CURRENT STATION
C     J          LOCATION OF STATION
C     L          TYPE OF STATION TO BE SAVED
C     LL         TYPE OF PREVIOUS STATION
C     LLL        TYPE OF PREVIOUS STATION
C     LOWYN      YN<YO LOWYN=1   YO>YN LOWYN=2
C     M          LOCATION IN NEW EFFICIENCY TABLE
C     MM         LOCATION IN TEMPORARY EFFICIENCY TABLE
C     N          LOCATION IN SAVED EFFICIENCY TABLE
C     NSTAT      NO OF STATION TYPES
C     SN,YN      NEW EFFICIENCY CURVES
C     XO,YO      OLD EFFICIENCY CURVE
C     XT,YT      TEMPORARY TABLE TO HOLD THE EFFICIENCY CURVE
C     XTT,YTT    HOLD AREA FOR SAVING THE EFFICIENCY CURVES
C     X1,Y1      INTERSECTION POINT FOR NEW AND OLD EFFICIENCY CURVES
C
      I = L
      LL = LLL
      IF (J - 1) 525, 526, 527
  525 STOP 525
  526 CONTINUE
      I = LLL
      N = 0
  528 CONTINUE
      N = N + 1
      YO (N, I) = YN (N, 1)
      XO (N, I) = XN (N, 1)
      YTT(N, I) = YN (N, 1)
      XTT(N, I) = XN (N, 1)
      IF (XN(N, 1) - 1E18) 528, 528, 61
C
C
C
  527 CONTINUE
      IF (LL - 1) 554, 552, 553
  554 STOP 554
  552 CONTINUE
      DO 550 N = 1, NSTAT
      XTT (1, N) = 0
      YTT (1, N) = 0
      DO 550 M = 2, 100
```

```
      XTT (M, N) = 1E19
      YTT (M, N) = 0
  550 CONTINUE
      N = 0
   59 CONTINUE
      N = N + 1
      YTT (N, 1) = YO (N, I)
      XTT (N, 1) = XO (N, I)
      IF (XO (N, I) - 1E18) 59, 64, 64
  553 CONTINUE
C
C     FIND LOCATION IN XO,YO TABLE
C
      DO 78 N = 1, 100
      IF (XN(1 ,I) - XO (N, L)) 79, 58, 58
   58 CONTINUE
      XTT (N, LLL) = XO (N, L)
      YTT (N, LLL) = YO (N, L)
   78 CONTINUE
      N = 2
   79 CONTINUE
C
C     FIND HIGH ENVELOPE
C
      M = 1
      MM = 0
      K = N - 1
      IF (YN(M, I) - YO(K, L)) 535, 535, 536
  535 CONTINUE
      LOWYN = 1
      GO TO 537
  536 CONTINUE
      LOWYN = 2
  537 CONTINUE
      MM = MM + 1
  763 CONTINUE
      IF (XN(M, I) - XO(K, L)) 540, 538, 748
  538 CONTINUE
      IF (YN(M, I) - YO(K, L)) 541, 541, 542
  541 CONTINUE
      IF (LOWYN - 1) 543, 544, 543
  543 CONTINUE
      CALL X1Y1 (XN(M-1, I), YN(M-1, I), XO(K-1, L), YO(K-1, L),
     1           XO(K, L), YO(K, L), XN(M, I), YN(M, I), X1, Y1)
      XT(MM) = X1
      YT(MM) = Y1
      LOWYN = 1
      IF (XT(MM) - 1E18) 537, 749, 749
  544 CONTINUE
      XT(MM) = XO(K, L)
      YT(MM) = YO(K, L)
      K = K + 1
      M = M + 1
      LOWYN = 1
      IF (XT(MM) - 1E18) 537, 749, 749
  542 CONTINUE
      IF (LOWYN - 2) 546, 545, 546
  545 CONTINUE
      XT(MM) = XN (M, I)
```

```
      YT(MM) = YN(M, I)
      K = K + 1
      M = M + 1
      LOWYN = 2
      IF (XT(MM) - 1E18) 537, 749, 749
  546 CONTINUE
      CALL X1Y1 (XO(K-1, L), YO(K-1, L), XN(M-1, I), YN(M-1, I),
     1           XN(M, I), YN(M, I), XO(K, L), YO(K, L), X1, Y1)
      XT(MM) = X1
      YT(MM) = Y1
      LOWYN = 2
      IF (XT(MM) - 1E18) 537, 749, 749
  540 CONTINUE
      IF (YN(M, I)) 750, 751, 760
  760 IF (YO (K, L)) 766, 755, 756
  766 STOP 766
  750 STOP 750
  751 CONTINUE
      XT (MM) = XO (K, L)
      YT (MM) = YO (K, L)
      IF (XT (MM) - 1E18) 753, 749, 749
  753 CONTINUE
      MM = MM + 1
      K = K + 1
      GO TO 751
  752 CONTINUE
      IF (XO(K-1,L) - XO(K,L)) 764, 761, 971
  971 IF (XO(K-1,L) - XO(K,L) * 1.00001) 761, 761, 771
  771 STOP 771
  761 CONTINUE
      IF (XT(MM - 1) - XX(NLCC + 1)) 775, 773, 773
  775 CONTINUE
      K = K + 1
      GO TO 763
  762 CONTINUE
      CALL X1Y1 (XO(K-1,L),YO(K-1,L), XN(M,I),0.0, XN(M,I),100.0,
     1           XO(K,L),YO(K,L), X1,Y1)
      IF (YN(M, I) - Y1) 541, 541, 542
  748 CONTINUE
      IF (YO (K, L)) 754, 755, 758
  758 IF (YN (M, I)) 759, 751, 752
  759 STOP 759
  754 STOP 754
  755 CONTINUE
      XT (MM) = XN (M, I)
      YT (MM) = YN (M, I)
      IF (XT (MM) - 1E18) 757, 749, 749
  757 MM = MM + 1
      M = M + 1
      GO TO 755
  756 CONTINUE
      IF (XN(M-1,I) - XN(M,I)) 762, 765, 972
  972 IF (XN(M-1,I) - XN(M,I) * 1.00001) 765, 765, 772
  772 STOP 772
  765 CONTINUE
      IF (XT(MM - 1) - XX(NLOC + 1)) 774, 773, 773
  774 CONTINUE
      M = M + 1
      GO TO 763
```

```
  764 CONTINUE
      CALL X1Y1 (XN(M-1,I),YN(M-1,I), XO(K,L),0.0, XO(K,L),100.0,
     1           XN(M,I),YN(M,I), X1,Y1)
      IF (Y1 - YO (K, L)) 541, 541, 542
  773 XT (MM) = XX (NLOC + 1)
      YT (MM) = 0
  749 CONTINUE
C
C     SAVE THE BETTER EFFICIENCY TABLES
C
      MM = 0
      K = N - 1
   60 CONTINUE
      MM = MM + 1
      K = K + 1
      XTT (K, LLL) = XT (MM)
      YTT (K, LLL) = YT (MM)
      IF (YT(MM)) 62, 61, 60
   62 WRITE (6, 101) (XT(I), YT(I), I = 1, MM)
      WRITE (6, 102) J, LLL, L
  101 FORMAT (2F20.2)
  102 FORMAT (3I20)
   61 CONTINUE
      IF (LL - NSTAT) 64, 63, 65
   65 STOP 65
   64 RETURN
   63 CONTINUE
      DO 67 LL = 1, NSTAT
      I = 0
   68 CONTINUE
      I = I + 1
      XO(I,LL) = XTT(I,LL)
      YO(I,LL) = YTT(I,LL)
      IF (XO(I,LL) - 1E18) 68, 68, 67
   67 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE X1Y1 (XA1, YA1, XB1, YB1, XB2, YB2, XA2, YA2, X1, Y1)
C     MA         SLOPE OF LINE A
C     MB         SLOPE OF LINE B
C     XA1, YA1 FIRST POINT OF LINE A
C     XA2,YA2   SECOND POINT ON LINE A
C     XB1,YB1   FIRST POINT ON LINE B
C     XB2,YB2   SECOND POINT ON LINE B
C     X1,Y1      INTERSECTION POINT OF LINES A & B
      REAL MA, MB
      IF (XB1 - XB2) 553, 554, 553
  554 CONTINUE
      IF (XA2 - XA1) 572, 574, 572
  574 CONTINUE
      IF (XA1 - XB1) 576, 575, 576
  576 STOP 576
  575 CONTINUE
      IF (YA1 - YA2) 578, 577, 578
  577 CONTINUE
      X1 = XA1
      Y1 = YA1
      GO TO 579
  578 CONTINUE
      X1 = XA1
      Y1 = YB1
      GO TO 579
  572 CONTINUE
      X1 = XB1
      Y1 = YA1 + (YA2 - YA1) * (X1 - XA1) / (XA2 - XA1)
      RETURN
  553 CONTINUE
      IF (XA1 - XA2) 550, 552, 550
  552 CONTINUE
      X1 = XA1
      GO TO 555
  550 CONTINUE
      MA = (YA2 - YA1) / (XA2 - XA1)
      MB = (YB2 - YB1) / (XB2 - XB1)
      IF (MA - MB) 571, 577, 571
  571 CONTINUE
      X1 = (YB1 - YA1 + MA * XA1 - MB * XB1) / (MA - MB)
  555 CONTINUE
      Y1 = YB1 + (YB2 - YB1) * (X1 - XB1) / (XB2 - XB1)
  579 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE XOYO (I, J)
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON     X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON     XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
      WRITE (6, 1) I, J, XO(I,J), YO(I,J)
    1 FORMAT (' XOYO', 2I10, 2F20.6)
      RETURN
      END
```

```
      SUBROUTINE XNYN (I, J)
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
      WRITE (6, 1) I, J, XN(I, J), YN (I, J)
    1 FORMAT (' XNYN', 2I10, 2F20.6)
      RETURN
      END
```

```
      SUBROUTINE AREOX (K, L, AREAC)
      COMMCN LOAD (30)
      CCMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      CCMMON    XX (31), Z(36)
      COMMON XO(100, 31), YC(100,31)
      COMMON XN (5C, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
      WRITE (6, 1) K, L, XC(K,L), YO(K,L), AREAO
    1 FORMAT (' AREAO', 2I10, 3F20.6)
      RETURN
      END
```

```
      SUBROUTINE LOADX (XXX, AREA, LOADA)
C
C     AREA      AREA UNDER EFFICIENCY CURVE - PERCENT * FT
C     LOAD      AMOUNT OF DEPOSITED MATERIAL - LB / FT
C     LOADA     AMOUNT OF MATERIAL REMOVED - LB
C     XXX       LOCATION OF RIGHT HAND END OF AREA SEGMENT
C
      COMMON LOAD (30)
      COMMON KKKOD (36)
      COMMON NSTAT, NLOC
      COMMON    X(30), GPM (30), DIA (30), SLOPE (30)
      COMMON XTT(100, 36), YTT(100,36)
      COMMON    XX (31), Z(36)
      COMMON XO(100, 31), YO(100,31)
      COMMON XN (50, 36), YN (50, 36)
      COMMON VOL (36,30),QF(36)
      REAL LOAD
      REAL LOADA
C
      DO 1 I = 1, NLOC
      IF (XXX - XX(I+1)) 2, 2, 1
    1 CONTINUE
      I = NLOC
    2 J = I
      LOADA = LOADA + AREA * LOAD (J) * 0.01
      RETURN
      END
```

```
      SUBROUTINE SOLD (J, M, SCLID)
C
C     J          LOCATION
C     M          NO OF THE EFFICIENCY CURVE
C     XOYO       EFFICIENCY CURVE
C     SOLID      AMCUNT OF SCLIDS CN THIS REACH  -  LB
C
      COMMCN LOAD (30)
      COMMON KKKCD (36)
      COMMON NSTAT, NLCC
      COMMON    X(30), GPM (3C), DIA (30), SLOPE (30)
      COMMON XTT(1CC, 36), YTT(10C,36)
      CCMMCN    XX (31), Z(36)
      COMMCN XO(100, 31), YC(100,31)
      COMMON XN (5C, 36), YN (5C, 36)
      COMMON VCL (36,30),QF(36)
      REAL LCAD
C
      SOLID = 0
      DO 1 I = 1, 100
      IF (XC (I, M) - XX (J)) 1, 1, 2
    1 CONTINUE
      STOP 7788
    2 CONTINUE
      DAREA = (XO(I,M) - XO(I-1,M)) * (YO(I-1,M) + YO(I,M)) * 0.5
      SOLID = SOLID + DAREA * LCAD (J) * 0.01
      IF (XC (I, M) - XX (J + 1)) 3, 4, 4
    3 I = I + 1
      GC TO 2
    4 CCNTINUE
      RETURN
      END
```

1 Accession Number	2 Subject Field & Group	
W	Ø5D	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

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*Periodic Flushing, Average Cleansing Efficiency, Solids Removal

27 *Abstract*

Because solids deposits in lateral sewers are considered to contribute a significant quantity of pollutional material to storm water overflows from combined sewers, the use of a periodic flushing operation was evaluated as a means of maintaining lower levels of these deposited materials during low-flow, dry weather periods.

Full scale tests were conducted on two variable-slope test sewers (12- and 18-inch diameters). During the tests, solids were first allowed to build up in both test sewers by passing domestic sewage through the sewers for durations of 12 to 40 hours and then were removed by hydraulic flushing. The results from the tests showed that flush waves generated using flush volumes ranging from 300 to 900 gallons at average release rates ranging from 200 to 3000 gpm were found to remove from 20 to 90 percent of the solids deposited in the 800-foot long test sewers.

The cost of installing a periodic flushing system in a typical system of lateral sewers was estimated to be $620 to $1,275 per acre.

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Abstractor	Institution

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