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URBAN HIGHWAY STORM DRAINAGE MODEL

VOL. 1 MODEL DEVELOPMENT AND TEST APPLICATIONS

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Turner-Fairbank Highway Research Center
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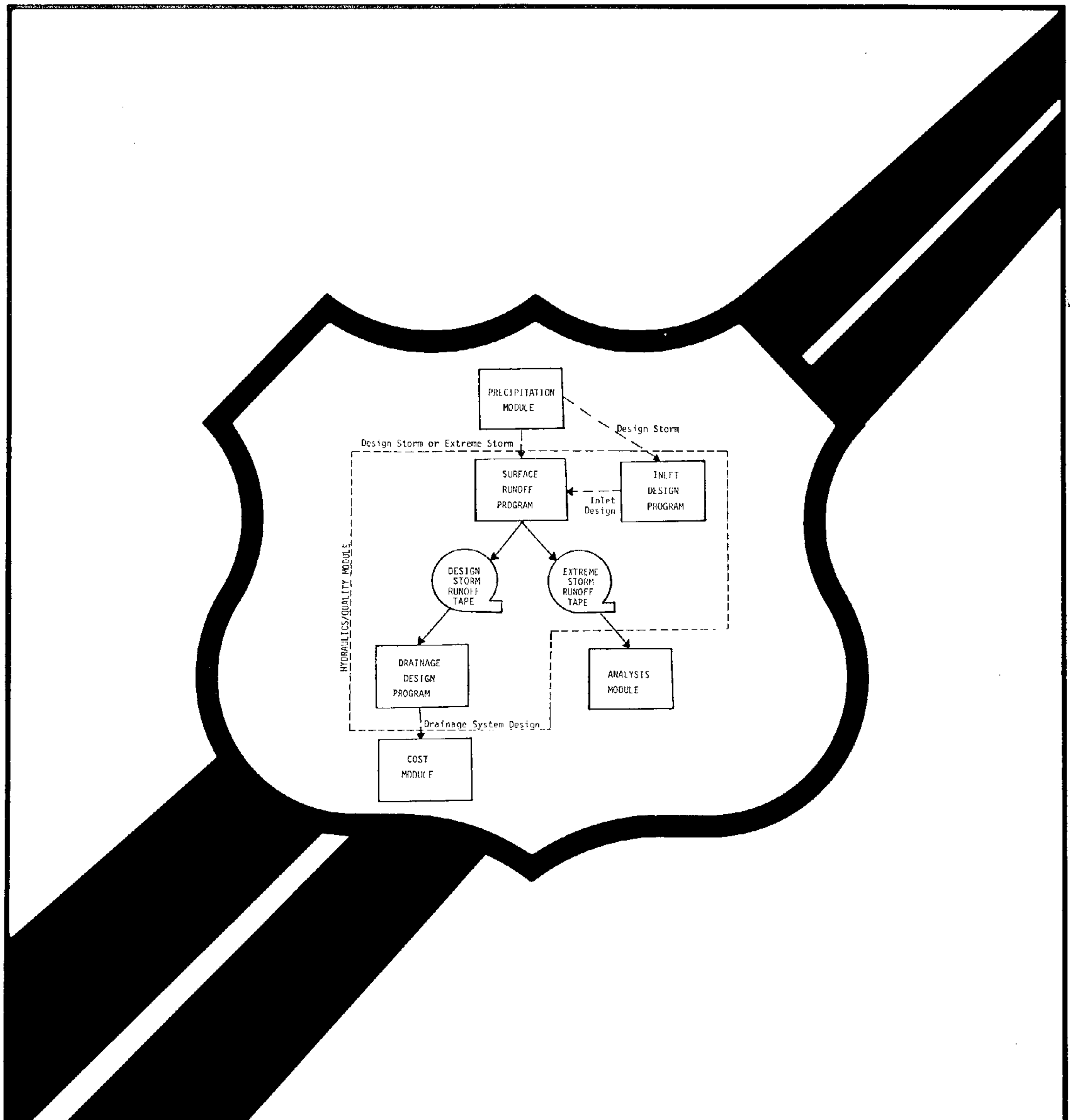

FOREWORD

This report documents the history of the study, a brief overview of the model and the results of three test applications of this computer model on proposed and existing urban highways around the country.

Research and development in urban and rural highway storm drainage is included in the Federally Coordinated Program of Highway Research, Development, and Technology Project 5H "Highway Drainage and Flood Protection." Dr. Roy E. Trent is the Project Manager and Dr. D. C. Woo is the Contracting Officer's Technical Representative for this study.

This report is being distributed on request only due to the specialized nature of the contents.

Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development
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16. Abstract

A package of six user-oriented computer programs has been developed and tested for the analysis and design of urban highway drainage systems and related nonpoint source pollution problems. These programs are organized into four related but independent Modules.

This report documents the development of these programs, giving the history of the project and a brief overview of the model. It also presents the results of several test runs of the model on various proposed and developed urban highways around the country.

This report is the first in a series. The others in the series are:

Vol. No.	FHWA No.	Short Title
-	83/040	Executive Summary
2	83/042	Precipitation Module
3	83/043	Inlet Design Program
4	83/044	Surface Runoff Program
5	83/045	Drainage Design Program
6	83/046	Analysis Module
7	83/047	Cost Estimation Module

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CHAPTER I

INTRODUCTION TO THE PROJECT

Under contract to the Federal Highway Administration (FHWA), the Water Resources Division of Camp Dresser and McKee Inc. (CDM) has developed a package of six computer programs for use in the preliminary design of urban highway drainage systems and the analysis of related stormwater management and nonpoint source pollution problems. These programs are known collectively as the Urban Highway Storm Drainage Model.

This introductory chapter has two purposes: 1) to present a brief history of this project; and 2) to present a summary of the technical products that have resulted from this project. The remainder of the report gives a more detailed description of each of the computer programs in the Model, presents results from some test applications of the programs, and gives conclusions and recommendations.

HISTORY OF THE PROJECT

This project was conducted in two phases. Phase I consisted of a detailed literature review and conceptualization of the major components of the Urban Highway Storm Drainage Model. Phase II consisted of actual development of the computer programs in the Model and test applications of the programs.

Phase I began in late 1976 and was completed in mid-1977. Four specific problem areas were addressed in the literature review and model conceptualization: 1) precipitation analysis; 2) runoff hydrology and hydraulics; 3) runoff quality; and 4) drainage system cost estimation.

The intention at that point in the project was to build a Model consisting of four independent Modules, each consisting of one or more computer programs and corresponding to one of the four problem areas listed above. The modular concept was retained in Phase II but the scope of each of the individual Modules was rearranged slightly. The results of Phase I were presented to the Federal Highway Administration in an April 1977 report (1). Phase II was initiated in late 1977 and completed in December, 1980.

All computer work during Phase II was done by remote access to the CDC 6600/6700 computer system of the Naval Ship Research and Development Center in Carderock, Maryland. The computer programs were coded in ANSI Fortran IV and tested with hypothetical problems. A report documenting the details of each program and presenting instructions to the program user was prepared for each program and reviewed by FHWA. Finally, three typical urban highway sites for program testing were selected in conjunction with FHWA and the relevant state highway departments. The programs were tested using data from these sites; the findings of these tests are presented and evaluated later in this report.

RESULTS OF THE PROJECT

The primary technical products of this study - the computer programs that make up the Urban Highway Storm Drainage Model and the associated user's manuals - were produced during Phase II. As discussed above, the model is divided into the following four Modules:

- Precipitation Module
- Hydraulics/Quality Module

- Analysis Module
- Cost Module

With the exception of the Hydraulics/Quality Module, each of these consists of a single computer program. The Hydraulics/Quality Module consists of three computer programs - the Inlet Design Program, the Surface Runoff Program, and the Drainage Design Program.

The Precipitation Module can be used to perform a variety of statistical analyses on long-term hourly precipitation data and to generate design storm hyetographs. The Hydraulics/Quality Module is the basic design tool in the package. This module can simulate time-varying runoff quantity and quality, locate stormwater inlets and size the conduits of the major drainage system. The Analysis Module can simulate unsteady gradually-varied flow in the drainage system and can be used to analyze complex hydraulic conditions, such as surcharge and backwater, that may be encountered during extreme storm events. The Cost Module can be used to estimate construction, operation and maintenance, and total annual costs associated with the drainage system; it is intended for use in relative cost comparisons for alternative systems.

Each of the six computer programs is accompanied by a separate report, called a "User's Manual and Documentation Report" (2, 3, 4, 5, 6, and 7). Each of these reports contains instructions for preparation of the input data required for the relevant program and one or more example problems. In addition, each report gives a detailed discussion of the technical approach used in the program and presents a description, a Fortran listing, and a flowchart for each subroutine of the program. It is imperative that the potential program user obtain not only the actual computer program of interest but also the accompanying User's Manual and Documentation Report.

This report presents a project overview, general program descriptions, and the results of the test applications of the Model to actual highway sites. These results should provide the potential user with insights into the proper application of these computer programs and into the limitations of these programs as they now stand.

CHAPTER II

OVERVIEW OF THE URBAN HIGHWAY STORM DRAINAGE MODEL

As explained in Chapter I, the Urban Highway Storm Drainage Model consists of four related but independent Modules, as follows:

- Precipitation Module
- Hydraulics/Quality Module
- Analysis Module
- Cost Module

These four Modules are a powerful and flexible set of tools for use in drainage system analysis and design. Their general capabilities include:

- Evaluation of existing urban highway storm drainage systems for adequacy during selected design storms;
- Preliminary highway storm drainage system design, including locating inlets, sizing pipes, and estimating construction costs;
- Hydraulic analysis of highway drainage systems under rainfall conditions more severe than those used in design; and
- Simulation of the generation and washoff of pollutants in the highway corridor to estimate storm water quality at drainage system outfalls.

The computer programs which make up the Model have been developed with several key features. First, each of the hydraulics programs is fully dynamic. This is in contrast to the static procedure generally used for highway drainage design, where pipes are sized based on a single peak runoff flow generated with the rational formula. Second, the Model has purposely been developed in related but independent Modules to maximize the flexibility of the package. The user may apply as many or as few of the Modules as are appropriate to his particular design or analysis problem. Third, the programs are designed to accomodate local drainage practices and design procedures. The input/output of the programs are in terms familiar to the highway drainage engineer and can include most inlet, channel, and pipe types available. Also, the programs are structured to allow the use of whatever design criteria are required locally.

The interrelationships among the computer programs are illustrated by Figure II-1. As can be seen from this figure, there are a variety of ways in which these programs can be used independently or in conjunction with each other. This flexibility should allow the engineer to apply one or more of these programs to a wide variety of common stormwater-related problems.

The remainder of this chapter is devoted to discussions of each of the four Modules. These discussions are intended to give the reader a broad overview of the Urban Highway Storm Drainage Model. To gain a detailed understanding of the potential applications, the capabilities, and the limitations of a particular program in the package, the engineer will need to study the appropriate User's Manual and Documentation Report.

PRECIPITATION MODULE

The Precipitation Module represents a completely independent part of the Urban Highway Storm Drainage Model. Its primary function is to facilitate the analysis of commonly available rainfall information and ultimately provide the user with the synthetic hyetographs needed as input to the Hydraulics/Quality Module of the Model.

The Module consists of a single computer program with three major options - two for generating single-peak synthetic hyetographs and one for performing a variety of statistical analyses on long-term precipitation data. Internally, the Module is constructed to follow one of three Program Paths, each Path corresponding to one of the three major options. Program Paths One and Two are the two options for

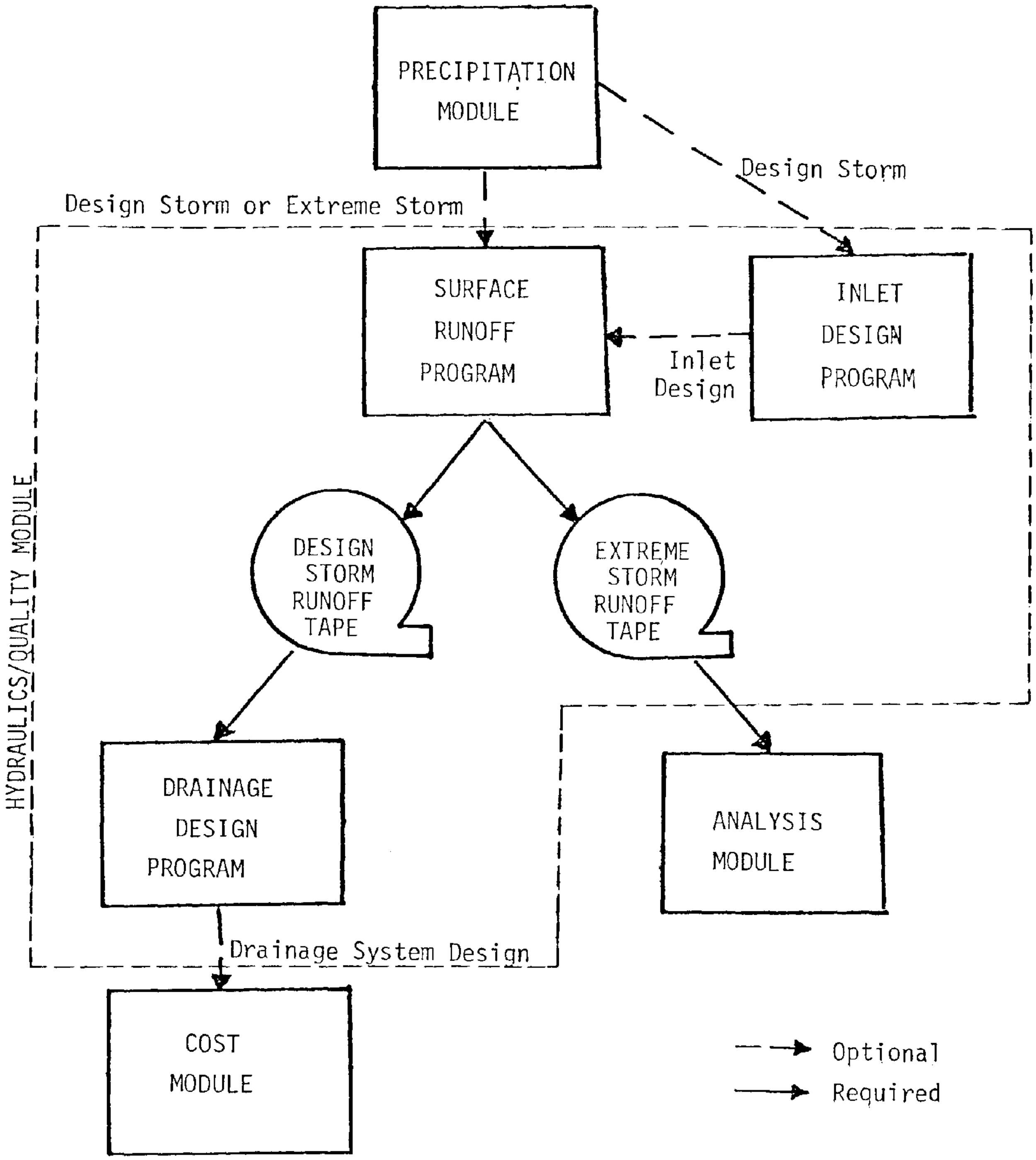

FIGURE II-1. Urban Highway Storm Drainage Model generating synthetic hyetographs. Both rely on a methodology developed by Chen (8) and require the return frequency, duration, and skew of the desired hyetograph as input. Path One requires the 10-year, 1-hour; the 10-year, 24-hour; and the 100-year, 1-hour rainfalls for the user's study area as input. Path Two makes use of an input intensity-duration-frequency curve of the same return frequency as the desired hyetograph. Both of these options can generate the rainfall hyetographs required as input for the dynamic programs of the Hydraulics/Quality Module.

Program Path Three is quite different. While Program Paths One and Two are directly oriented to the development of a design hyetograph, Program Path Three is oriented toward analyzing local rainfall data (such as those available on magnetic tape from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce). Some of the statistical analyses of which Path Three is capable are:

- Annual series analysis and partial duration series analysis, including the generation of intensity-duration frequency curves;
- Frequency of occurrence analysis for such parameters as peak rainfall intensity per storm event, storm duration, and dry period duration; and
- Analysis of storm skew (i.e., the ratio of the time to peak rainfall intensity of a given storm to the total duration of the storm).

Each of these analyses may be performed on a seasonal basis as well as an annual basis, for as many as 12 user-defined seasons.

The output from Program Path Three allows the design engineer to derive local estimates of each of the inputs required in Program Paths One and Two. Thus, if Program Path Three is run prior to Program Paths One or Two, the design engineer can develop a design hyetograph that reflects local meteorological conditions.

The major features of the Precipitation Module are summarized in Table II-1.

TABLE II-1

MAJOR FEATURES OF THE PRECIPITATION MODULE

- Derivation of Hyetographs of Selected Return Frequency, Duration, and Skew
- Statistical Analysis of Hourly Rainfall Records to Generate Intensity-Duration-Frequency Curves
- Frequency of Occurrence Analysis of Hourly Rainfall Records for Peak Rainfall Intensity, Storm Duration, and Dry Period Duration
- Statistical Analysis of Hourly Rainfall Records for Storm Skew

HYDRAULICS/QUALITY MODULE

The Hydraulics/Quality Module consists of three computer programs - the Inlet Design Program, the Surface Runoff Program, and the Drainage Design Program. Together, these programs can perform most of the major computations involved in preliminary design of highway drainage systems, as well as in evaluation of existing highway drainage systems.

Inlet Design Program

The highway storm drainage system consists of a surface runoff conveyance system and a major drainage system, as shown in Figure II-2. The design of the surface runoff conveyance system includes the location of stormwater inlets to intercept surface runoff and transmit it efficiently to the subsurface drainage system. The Inlet Design Program is a computer-based tool for performing the inlet location task.

Specifically, the purpose of the Inlet Design Program is to locate inlets in the surface runoff conveyance system of the highway right-of-way so as to maintain hydraulic conditions during the design storm event within specified criteria. The Inlet Design Program simulates time-varying runoff and routes the runoff flows through surface gutters or channels. Runoff is computed based on the kinematic wave approximation for overland flow, accounting for infiltration and depression storage. Flow is routed through gutters of triangular cross-section or channels of trapezoidal cross-section, also with the kinematic wave approximation. The program then determines the placement of inlets in gutters required to maintain flow spread within a user-specified maximum or the placement of inlets in channels to maintain flow depth within a user-specified maximum. The program also checks that the percentage of the gutter/channel flow that carries past each inlet to the next gutter/channel section does not exceed a given maximum, again specified by the user. If the user wishes to prespecify the location of selected inlets (e.g., at entrance and exit ramps), he may do so and the program will locate the remaining inlets.

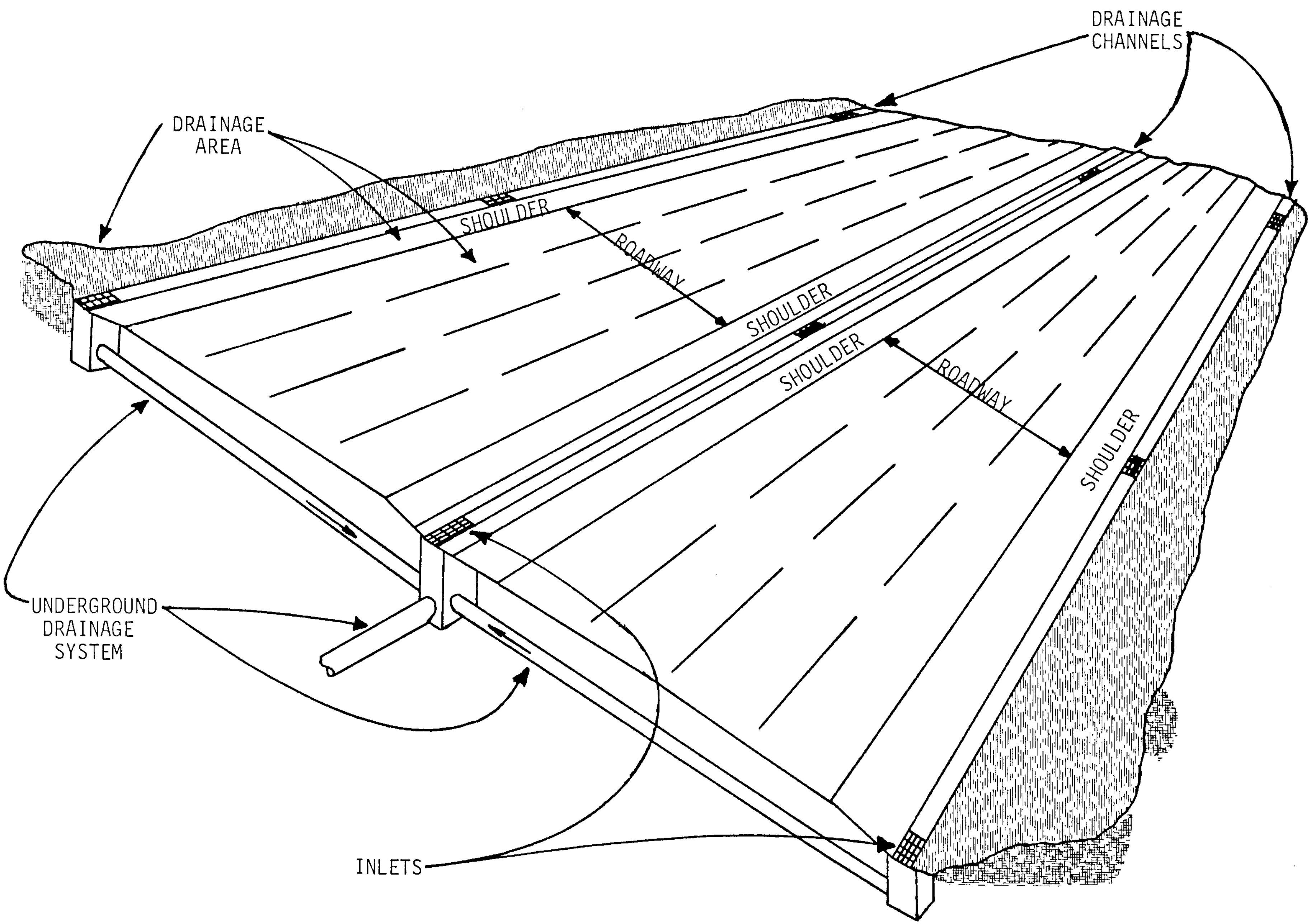

FIGURE II- 2. Typical Urban Highway Drainage System

The Inlet Design Program can simulate the hydraulics of the following six basic inlet types:

- Curb Opening Inlet
- Depressed Curb Opening Inlet
- Grate Inlet
- Depressed Grate Inlet
- Combination Inlet
- Depressed Combination Inlet

The user may select one inlet type for all the inlets on-grade in a single program run.

There are several limitations imposed on the user by the program as presently structured. These limitations include:

- Inlets may be spaced in a single continuous series of gutter or channel sections, from the top of grade to the sump, with each program run;
- The number of gutter or channel sections must be less than or equal to 200;
- The number of watersheds must be less than or equal to 200;
- The number of subareas per watershed must be less than or equal to three;
- The number of raingages must be less than or equal to ten;
- The number of infiltration types must be less than or equal to four (not including impervious surfaces);
- The number of inlets located must be less than or equal to 50; and
- The number of prespecified inlets must be less than or equal to 20.

The major features of the Inlet Design Program are summarized in Table II-2, along with the major features of the other Hydraulics/ Quality Module programs.

TABLE II-2

MAJOR FEATURES OF HYDRAULICS/QUALITY MODULE PROGRAMS

INLET DESIGN PROGRAM (INLET)

- Simulation of Time-Varying Runoff and Gutter/Channel Flow
- Spacing of Fixed-Size Inlets in Gutters or Channels
- Prespecification of Inlet Locations if Required
- Simulation of Six Basic Inlet Types

SURFACE RUNOFF PROGRAM (SRO)

- Simulation of Time-Varying Runoff and Gutter/Channel Flow
- Simulation of Accumulation and Washoff of Suspended Solids and Associated Pollutants
- Simulation of All Inlet Types Considered in Inlet Design Program
- Simulation of Four Types of Gutters/Channels
- Generation of Runoff Tape (Inlet Hydrographs and Pollutographs)

DRAINAGE DESIGN PROGRAM (DRAIN)

- Standard Pipe Sizing
- Sizing of Trapezoidal Open Channels
- Routing of Pollutants Through Drainage System
- Simulation of Treatment at Outfalls (Suspended Solids Removal)

Surface Runoff Program

The Surface Runoff Program simulates time-varying runoff quantity and quality, routes these flows and pollutants through surface gutters, channels, and detention basins, and computes inlet hydrographs and pollutographs. The inlet hydrographs and pollutographs are saved as a disc or tape file for subsequent use by the Drainage Design Program. The same basic approaches as were used in the Inlet Design Program for computation of surface runoff, open channel flow, and inlet hydraulics are also used in the Surface Runoff Program.

The Surface Runoff Program is capable of simulating the following types of surface drainage structures:

- Circular pipes
- Trapezoidal open channels
- Overbank channels (double trapezoidal channels)
- Gutters (special case of trapezoidal channels)
- Detention basins with weir outflow control
- Detention basins with channel outflow control

The hydraulics of the following six basic inlet types may be simulated:

- Curb Opening Inlet
- Depressed Curb Opening Inlet
- Grate Inlet
- Depressed Grate Inlet
- Combination Inlet
- Depressed Combination Inlet

The accumulation, washoff, and transport of total suspended solids and the following associated pollutants may be modeled, if the user so desires:

- Dissolved Oxygen
- Biochemical Oxygen Demand
- Fecal Coliforms
- Nitrate
- Organic Nitrogen
- Total Phosphorus

- Chloride
- Ammonia
- Nitrite
- Dissolved Orthophosphates
- Oil and Grease
- Heavy Metals

There are several limitations imposed on the user by the program as presently structured. These limitations include:

- The number of gutter or channel sections must be less than or equal to 200;
- The number of watersheds must be less than or equal to 200;
- The number of subareas per watershed must be less than or equal to three;
- The number of raingages must be less than or equal to 13;
- The number of infiltration types must be less than or equal to four (not including impervious surfaces);
- The number of detention basins must be less than or equal to three;
- The number of pollutants simulated must be less than or equal to 13; and
- The number of pollutant accumulation rates (for different land surface types) must be less than or equal to five.
- The detention basin computation is for evaluation of existing detention basins only. For sizing a new detention basin, several sizes will have to be assumed first and their effects evaluated.

The major features of this program are summarized in Table II-2.

Drainage Design Program

The Drainage Design Program reads the inlet hydrographs generated by the Surface Runoff Program for the selected design storm and sizes the major drainage system accordingly. Specifically, the program determines the diameter of circular conduits and the bottom width of trapezoidal channels so that each conduit and channel flows full at peak flow. The diameters of circular conduits so determined are rounded up to the nearest commercially-available pipe size.

When the accumulation and washoff of selected surface pollutants in the highway right-of-way is simulated with the Surface Runoff Program, then inlet pollutographs as well as inlet hydrographs are saved in the file used as input by the Drainage Design Program. The pollutants so generated are routed through the drainage system, after the program has completed the conduit design calculations. Pollutants are routed conservatively, i.e., with the assumption that no physical, chemical, or biological changes to the pollutant species occur from the time they are washed off the right-of-way surface to the time they reach drainage system outfalls.

If nonpoint source pollution or erosion from the highway right-of-way proves to be a problem in the user's study area, he may examine alternative control facilities with this program. Facilities for removal of suspended solids at drainage system outfalls such as detention basins can be simulated with the Drainage Design Program. As part of the input, the user must quantify the performance of the facility in terms of a flow versus removal efficiency curve. The program will then calculate the reduction in suspended solids and associated pollutants during the storm event simulated.

The Drainage Design Program as presently structured has several limitations of which the user should be aware:

- The maximum number of pipe and open channel elements that can be simulated with a single run is 200;
- The maximum number of pollutants that can be simulated is 13 (the same pollutants as in the Surface Runoff Program); and
- The maximum number of system outfalls at which treatment can be simulated is 50.

ANALYSIS MODULE

The Analysis Module consists of a single computer program that simulates unsteady, gradually-varied flow in the major drainage system of the highway right-of-way, using inlet hydrographs generated by the Surface Runoff Program as input. Its primary purpose is to analyze the performance of the drainage system under extreme storm events, a step generally included in the highway drainage design process. As such, this program can simulate complex hydraulic conditions, such as surcharge and backwater, that cannot be simulated with the simpler, uniform open-channel flow formulations of the Hydraulics/Quality Module.

The Analysis Module can simulate drainage systems consisting of one or more of the following five conduit cross-sections:

- Circular
- Rectangular
- Horseshoe
- Baskethandle
- Eggshape

The Module can also simulate several special features of drainage systems. In-line stormwater detention facilities can be modeled, as can pumping stations with variable pumping rates.

The major features of the Analysis Module are summarized in Table II-3.

COST ESTIMATION MODULE

The final Module of this package, the Cost Estimation Module, also consists of a single computer program. The purpose of this program is to estimate the capital costs, operation and maintenance costs, and total annual costs associated with the construction and maintenance of a highway drainage system. All of the cost computations are based on unit costs for materials, installation, and O&M. As part of the cost analysis, the program also estimates the excavation and backfill associated with construction of the drainage system; elevation of the highway grade line, invert elevations of the system conduits and junctions, and sizes of the conduits and junctions are employed in the excavation and backfill calculations.

TABLE II-3

MAJOR FEATURES OF THE ANALYSIS MODULE

- Analysis of Extreme Storm Event Hydraulic Conditions in the Major Drainage System Such as Surcharge, Backwater, and Surface Flooding

- Simulation of Unsteady Gradually-Varied Flow in the Major Drainage System

- Simulation of Channels and Pipes of Five Different Cross-Sections

- Simulation of Pumping Station Operation

TABLE II-4

MAJOR FEATURES OF THE COST ESTIMATION MODULE

- Calculation of Capital Costs for Construction of Major Drainage Systems

- Calculation of Operation and Maintenance Costs and Total Annual Costs for Major Drainage Systems

- Estimation of Excavation and Backfill Volumes Associated with Construction of Major Drainage Systems

The Cost Estimation Module has the capability of calculating for each junction and conduit the following information:

- The volume and cost of excavation;
- The volume and cost of backfill;
- The capital cost including installation costs;
- The O&M costs; and
- The total annual costs.

Inherent in the development of the procedures used to determine the above mentioned items are the following assumptions:

- Unit costs are up-to-date and do not need time or geographical adjustments;
- Installation costs, if available, are a percentage of the unit costs;
- O&M costs are a percentage of the unit costs;
- Labor and materials are combined in the O&M costs;
- Excavation and backfill volumes are based on the highway grade line; and
- No bedrock is encountered during excavation.

The major features of the Cost Estimation Module are summarized in Table II-4. Since the construction of a storm drainage system is part of an urban highway construction project, this Module is intended for use in relative cost comparisons for alternate drainage systems.

CHAPTER III

TEST APPLICATIONS OF THE MODEL

INTRODUCTION

An integral part of the development of the Urban Highway Storm Drainage Model was the testing of the Model using actual highway sites around the United States. Following initial development and documentation of the computer programs that make up the Model several typical highway sections for program testing were selected in conjunction with FHWA. In each case, representatives of the appropriate state highway agency supplied plans of the highway right-of-way and its surface and subsurface drainage systems and explained local design procedures and criteria.

The two primary purposes of these test applications were: 1) to identify difficulties in applying the Model to actual highway drainage analysis and design problems and to eliminate these shortcomings; and 2) to show that the Model would produce reasonable results and designs for a variety of sites. It was not expected that designs identical to the existing drainage systems at the test sites would be produced with the Model, for several reasons. First, the technical approaches used in actual design of these systems and in design of the systems with the model were different. All the drainage systems considered were originally designed based on a peak runoff flow derived from a peak rainfall intensity and the rational formula. On the other hand, the Model performs design based on a full runoff hydrograph calculated from a design storm hyetograph and the kinematic wave formulation for overland flow, accounting for depression storage and infiltration losses. Second, all the information required by the Model on drainage system characteristics and criteria used in the original design was not available for each site. Some of this information could have been obtained only with field investigations beyond the scope of this project.

These issues are discussed further in the remainder of the chapter which presents the results of each of the three test applications of the Model. Each of the three sites - one each in Wisconsin, Virginia, and Tennessee - is described. The application of the computer programs tested at each site is discussed, including assumptions made and results obtained. The major findings from each application are presented.

Due to the lack of field data, the water quality part of the Model was not applied to these three sites.

WISCONSIN TEST SITE

The first site used to test the Model was a limited-access highway in Milwaukee County, Wisconsin. This highway, built in the early 1960's, was formerly called the West Expressway and now apparently is referred to as the Zoo Freeway (because it provides access to Milwaukee's famous zoo). The section of highway selected is approximately 1.7 miles in length, three traffic lanes in either direction running from the vicinity of Blue Mound Road to Underwood Creek. Much of this stretch consists of superelevated curves in a fill section.

The original surface drainage system consisted of standard curb-and-gutters with grate inlets. This system has apparently been modified since it was first installed; however, it was decided to base this test application on the original drainage system since detailed plans and profiles from the original construction work were available. The subsurface drainage system consists of circular concrete storm sewers, the main trunk line ranging in diameter from 21 inches at the upstream end of the system to 72 inches at the system outfall to Underwood Creek. The contributory drainage area for this section of the system is approximately 35 acres.

Four programs from the Urban Highway Storm Drainage Model were applied to all or part of this highway section - the Precipitation Module and the three programs of the Hydraulics/Quality Module. Each of these program applications is described in turn below.

Precipitation Module

The Precipitation Module was used to derive two design storm hyetographs - the 2-year, 15-minute storm for inlet design and the 10-year, 3-hour storm for major drainage system design. (The 2-year storm and the 10-year storm are the storm events used in design in Wisconsin, according to conversations with the Wisconsin Department of Transportation.) The required input data to derive each of these hyetographs were: 1) the intensity-duration-frequency curve for the selected return frequency; 2) the storm duration; and 3) the storm skew. The required intensity-duration-frequency curves for the Milwaukee area were available from the Wisconsin Department of Transportation. The storm durations used were as noted above; a storm skew of 0.4 was selected as being representative of this part of the country.

The two hyetographs are summarized in Table III-1 and III-2. The two hyetographs so derived were used as input for the Inlet Design Program and the Surface Runoff Program, described below.

Inlet Design Program

A 1,650 ft. long section of the Wisconsin test site was chosen for an application of the Inlet Design Program. As discussed in earlier chapters of this report, the Inlet Design Program, one of the three programs that make up the Hydraulics/Quality Module, is designed to locate stormwater inlets in the highway right-of-way so as to satisfy specified hydraulic criteria during a design storm event.

TABLE III-1

2-YEAR, 15-MINUTE STORM
MILWAUKEE COUNTY, WISCONSIN

Time (minutes)	Rainfall Intensity (in/hr)
1	1.67
2	1.99
3	2.44
4	3.07
5	4.04
6	5.60
7	4.47
8	3.67
9	3.07
10	2.62
11	2.27
12	1.99
13	1.77
14	1.58
15	1.42

TABLE III-2

10-YEAR, 3-HOUR STORM
MILWAUKEE COUNTY, WISCONSIN

Time (minutes)	Rainfall Intensity (in/hr)
10	0.21
20	0.25
30	0.31
40	0.41
50	0.60
60	1.11
70	4.64
72	8.88
80	2.37
90	1.11
100	0.71
110	0.52
120	0.41
130	0.34
140	0.29
150	0.25
160	0.22
170	0.20
180	0.18

Specifically, the program was applied to the curb-and-gutter section along the eastbound traffic lanes, from top of grade (crest vertical curve) to the sump (sag vertical curve). This section is superelevated and only the road surface itself drains to the gutter. The road cross-slope varies from 0.5% to 5.0% through this section. All the drainage area was impervious, so no infiltration was simulated. An average depression storage of 0.06 inches, a typical value for impervious areas, was assumed. A Manning roughness coefficient for overland flow of 0.014 was used for the drainage area; a Manning coefficient of 0.014 was also used for the gutters.

Three existing grate inlets serve to intercept the gutter flow. However, the length of these inlets was not available (without a field inspection) and the manner in which inlet capacity had been calculated during the original design work some twenty years ago was not definitely known. Therefore, it was decided to use the typical grate inlet length of four feet and to calculate the capacity of these with a series of efficiency curves available for parallel bar grate inlets of this size (9).

The design storm used was the 2-year, 15-minute storm derived with the Precipitation Module, as described above. The basic design criterion was the maximum gutter flow spread during the design storm event. The Wisconsin DOT indicated that a maximum flow spread of six feet, measured from the curb face, was the appropriate criterion to use.

The Inlet Design Program was run with the input described above. The program located six inlets in the gutter along this stretch of highway, as opposed to the three inlets actually in place. These results are summarized in Table III-3. It should be noted that the inlet spacings produced by the program are reasonable and consistent with drainage design practice, ranging from mimimum of 75 feet near the sump to a maximum of 515 feet. The results will be discussed further below.

TABLE III-3

EXISTING AND COMPUTED INLET LOCATIONS
MILWAUKEE COUNTY TEST SITE

Existing		Computed	
Inlet No.	Station	Inlet No.	Station
		1	75 + 25
		2	77 + 00
1	78 + 00		
		3	79 + 25
2	84 + 00	4	84 + 00
		5	89 + 25
3	90 + 00	6	90 + 00

Surface Runoff Program

The Surface Runoff Program was applied to the entire 1.7 mile length of the test site right-of-way. This program, the second in the Hydraulics/Quality Module, can compute surface runoff quantity and quality, route the runoff through surface gutters and channels, calculate the flow and pollutant loads intercepted by inlets, and save these inlet hydrographs and pollutographs for input to the Drainage Design Program. (The quality computations are optional.)

The Surface Runoff Program was applied to calculate the inlet hydrographs, from the appropriate design storm, to be used in design of the underground drainage system of the test site (described in the next section of this chapter). The contributory drainage area of this section of right-of-way was approximately 35 acres, most of this the road surface itself. The parameters used in calculating runoff from the impervious areas of the test site and routing flow through the surface gutters were the same as described above for the Inlet Design Program application.

The areas and average slopes of the pervious portion of the test site were known, but information on soil type and land cover for these areas was not available without investigations beyond the scope of this study. However, since the impervious areas accounted for over 60% of the test watershed, it was assumed that the use of typical infiltration, depression storage and roughness parameters for the pervious areas would not introduce a serious error. Therefore, a depression storage of 0.2 inches, a typical value for pervious areas, was used. A Manning roughness coefficient for overland flow of 0.20, representative of a pervious area with light turf cover, was used. The infiltration curve selected was typical of a bone-dry, grass-covered, moderately fine-textured soil of slow infiltration rate. A schematic of a typical section of the drainage area is shown in Figure III-1. The subsurface drainage system, described in the next section, is also shown on this figure.

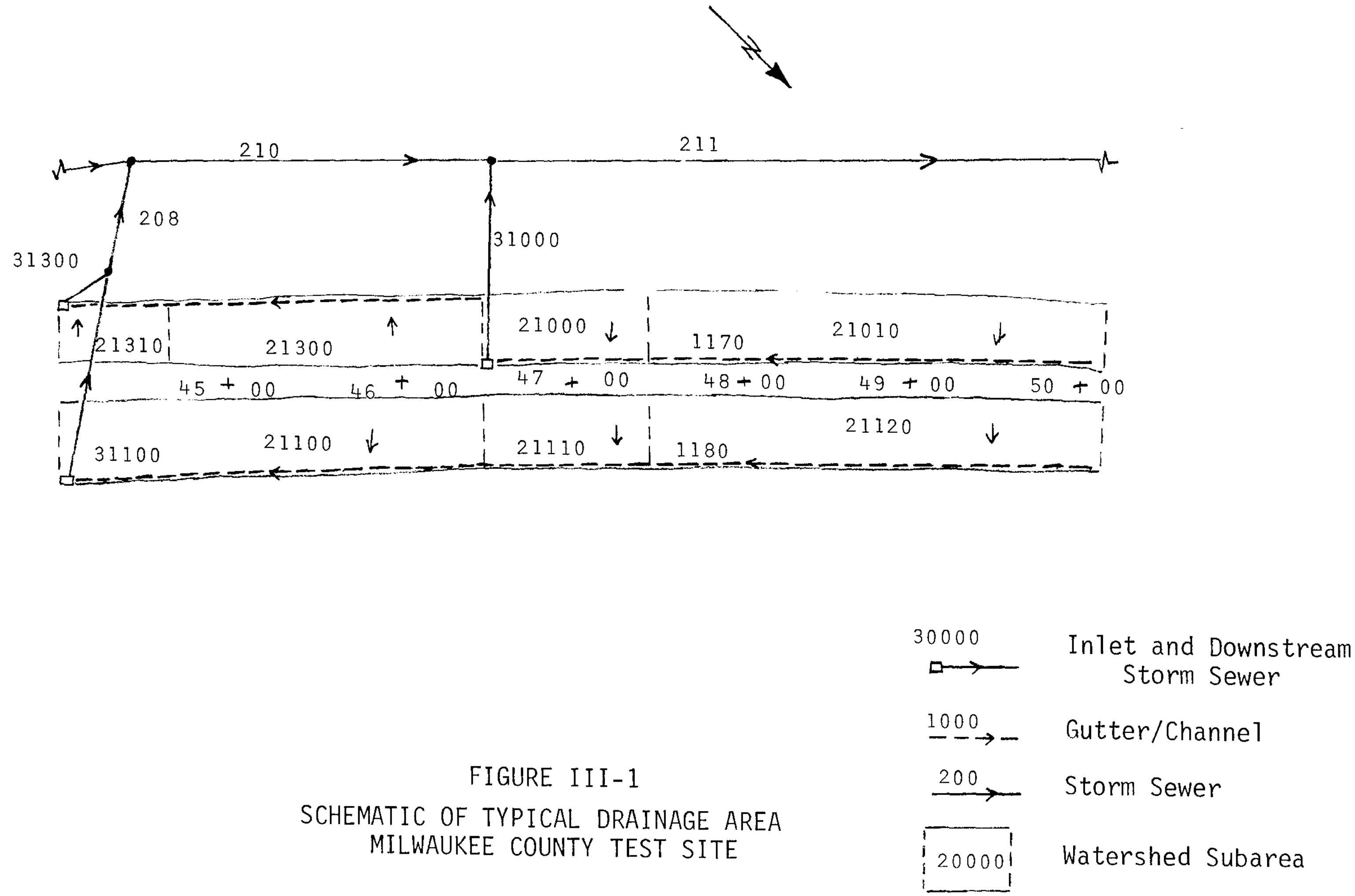

FIGURE III-1

SCHEMATIC OF TYPICAL DRAINAGE AREA
MILWAUKEE COUNTY TEST SITE

In this computation, the actual 55 inlets of the test site was used. The 10-year, 3-hour storm was simulated and the resulting inlet hydrographs saved in a disc file for use in the Drainage Design Program.

The continuity summary from this simulation is reproduced as Table III-4. As can be seen, approximately 70% of the rainfall became runoff captured by the inlets, while approximately 30% of the rainfall infiltrated the pervious areas of the watershed. The remaining minor amounts of the total rainfall were accounted for by depression storage, surcharge or gutter storage. There is an error in continuity in this simulation of approximately 7%, which is acceptable.

The inlet hydrographs so calculated were next used as input to the Drainage Design Program, described below.

Drainage Design Program

The Drainage Design Program was also applied to the entire 1.7 mile length of the test site right-of-way. As mentioned above, a single main trunk sewer runs this entire length, with a number of lateral pipes connecting inlets on either side to the main trunk. The Drainage Design Program was applied to size this entire drainage system.

For purposes of the simulation, the trunk line was divided into a series of 39 pipe sections. Representing the lateral lines and other secondary parts of the drainage system required an additional 71 pipe sections. A typical section of the drainage system is shown in Figure III-1. Note that the pipe sections that receive inlet hydrographs have the same identifying numbers as the inlets did in the Surface Runoff Program run.

TABLE III-4

SURFACE RUNOFF CONTINUITY SUMMARY
10-YEAR, 3-HOUR STORM
MILWAUKEE COUNTY TEST SITE

	Input	Output
Rainfall (ft^3)	344,090[1]	
Inlet Flow (ft^3)		225,406
Infiltration (ft^3)		85,381
Depression Storage (ft^3)		3,555
Surcharge (ft^3)		3,458
Gutter Storage (ft^3)		598
	344,090	318,398

[1] Given the drainage area of 35.3 acres, this is equivalent to approximately 2.7 inches total rainfall.

The slopes of these pipe sections range from 0.3% to 3.0%. The entire system consists of circular concrete pipes; a Manning coefficient of 0.013 was used for the roughness of these pipes. An initial diameter of one foot was specified for all the pipes and the pipe sizing option of the program was run. The design storm input consisted of the inlet hydrographs saved by the Surface Runoff Program simulation of the 10-year, 3-hour storm, as described above.

The results of the simulation are summarized in Table III-5 (only the results for the main trunk sewer are shown). As can be seen, the computed pipe sizes are slightly smaller than those of the existing system in most cases.

There are two apparent anomalies in the pipe sizes shown in Table III-5. Pipe 106 and pipe 202 are each one commercial pipe size smaller than the pipes immediately upstream (105 and 201, respectively). One would expect each pipe to be of a size equal to or greater than the upstream pipe. The explanation in both these cases lies in the slopes of the pipe sections. Both of the pipes in question have slopes approximately twice as steep as the pipes immediately upstream and downstream. (Pipes 105, 106 and 107 have slopes of 0.4%, 0.7% and 0.4%, respectively; pipes 201, 202 and 204 have slopes of 0.4%, 0.8% and 0.3%, respectively.) Thus, the two pipes in question can carry a given flow at a smaller diameter than pipes of lesser slopes, such as the upstream pipes. In practice, the design engineer would probably increase the sizes of these two pipes by one commercial pipe size.

Discussion of Results

As described above, the results of the Milwaukee County test application of the Model were quite good. In particular, the two design programs applied--the Inlet Design Program and the Drainage Design Program--both produced results that were reasonable. The lack of accurate information on the inlets of the test site may have adversely affected the results of both design programs to some extent.

TABLE III-5

DRAINAGE DESIGN PROGRAM RESULTS
MILWAUKEE COUNTY TEST SITE

Pipe Number	Upstream Station	Downstream Station	Existing Diameter (inches)	Computed Diameter (inches)
100	3+50	5+00	21	15
101	5+00	8+00	30	18
102	8+00	9+25	30	21
103	9+25	11+80	30	21
105	11+80	14+60	36	30
106	14+00	16+75	36	27
107	16+75	19+00	48	33
108	19+00	21+75	48	33
109	21+75	22+00	48	42
110	22+00	23+00	48	48
111	23+00	27+00	54	48
113	27+00	30+50	54	48
114	30+50	33+00	54	48
200	33+00	34+00	54	48
201	34+00	38+25	54	48
202	38+25	39+25	60	42
204	39+25	40+50	60	54
207	40+50	44+00	60	54
210	44+00	46+50	60	54
211	46+50	52+00	66	54
212	52+00	54+00	66	54
213	54+00	56+25	66	60
214	56+25	57+25	66	60
215	57+25	60+00	66	60
216	60+00	61+00	66	60
219	61+00	62+00	66	60
222	62+00	66+00	66	60

TABLE III-5
(Continued)

Pipe Number	Upstream Station	Downstream Station	Existing Diameter (inches)	Computed Diameter (inches)
223	66+00	66+50	66	60
224	66+50	69+50	66	60
225	69+50	70+50	66	60
226	70+50	71+00	66	60
227	71+00	72+00	66	60
301	72+00	77+50	66	60
302	77+50	78+00	72	66
303	78+00	81+00	72	66
304	81+00	84+00	72	66
305	84+00	90+00	72	66
307*	90+00	90+25	-	-
308	90+25	93+00	72	66

*Drop structure

The two apparent anomalies in the Drainage Design Program results discussed in the previous section bring out another point of interest. The programs in this package are computational tools to assist the design engineer in his work; they are not intended to be "black boxes" that produce complete design with no review by the engineer. The final judgement on all elements of the design must be made by the engineer himself.

VIRGINIA TEST SITE

Virginia Interstate Route 66 was selected as a test application site for the Urban Highway Storm Drainage Model. The highway, located in northern Virginia, provides a four to eight lane limited access route from Route 81 west of Front Royal, Virginia to the Washington, D.C. Capital Beltway (Interstate Route 495). The section of the highway selected for model testing is within a continuation of the Interstate, currently under construction, that will provide direct entrance into the Capital Beltway.

The site is an 0.8 mile-long segment of the highway in Arlington County between Williamsburg Boulevard and North Roosevelt Street involving a drainage area of approximately 53 acres. The median of the highway was designed to provide an above-ground right-of-way for one line of the Washington, D.C. Metro subway system. As such, drainage beyond standard design procedures was designed for the median.

The drainage system for I-66 was represented according to procedures described in the appropriate User's Manual and Documentation Reports. Drainage features used in the test applications were obtained from the State of Virginia Department of Highways and Transportation plans and profiles for the area. Additional sources of data included the Virginia Department of Highways drainage design manual (10) and road design manual (11).

Before proceeding to descriptions of the specific applications of the programs in this package, some general discussion of data preparation for the Virginia test site for the Inlet Design Program and the Surface Runoff Program needs to be given.

For these two programs, the watershed area was divided into individual basins feeding specific gutter lengths. Subdivisions of each basin were made if significant discontinuities existed in the slopes of the basins or if the basin had distinct regions of defineable infiltration characteristics. Each basin subarea was classified according to area, width, average slope, Manning roughness coefficient, and infiltration type. The gutters were represented by the hydraulic and geometric characteristics required for program input. Generally, each gutter was a continuous section beginning at an upstream inlet or origin and ending at the next inlet downstream. When existing inlet spacing exceeded 500 feet, the gutter was divided into additional sections to maintain a maximum gutter length of 500 feet.

Three general gutter or channel types were included in the test applications of the Inlet Design Program and the Surface Runoff Program. Highway runoff is collected by standard curb and gutters on the Interstate and underpasses feeding the subsurface drainage network. The second category is a one-foot wide trapezoidal channel in an impervious gravel-covered portion of the median, as taken from the design plans. The plans also include grass channels in portions of the watershed, the third type used.

The test site for I-66 includes four inlet types, but only one inlet type can be simulated at a time in the two programs mentioned above. Therefore, Virginia grate inlet DI-7A was used in the program applications because it is the predominantly used inlet in the entire test site and is the only inlet used in the portion of the site to which the Inlet Design Program was applied.

The programs run for the Virginia site were the Precipitation Module, the Inlet Design Program, the Surface Runoff Program, and the Drainage Design Program. A discussion of applying each of these to the Virginia test site follows.

Precipitation Module

Two rainfall hyetographs were synthesized using the Program Path 2 procedures of the Precipitation Module to provide input for the Inlet Design Program and the Surface Runoff Program. Using a rainfall skew of 0.4 and the intensity-frequency-duration curves shown in Figure III-2 for Arlington County, Virginia (10), the 2-year 15-minute storm and the 10-year 1-hour storm were computed. The resulting hyetographs are shown in Tables III-6 and III-7.

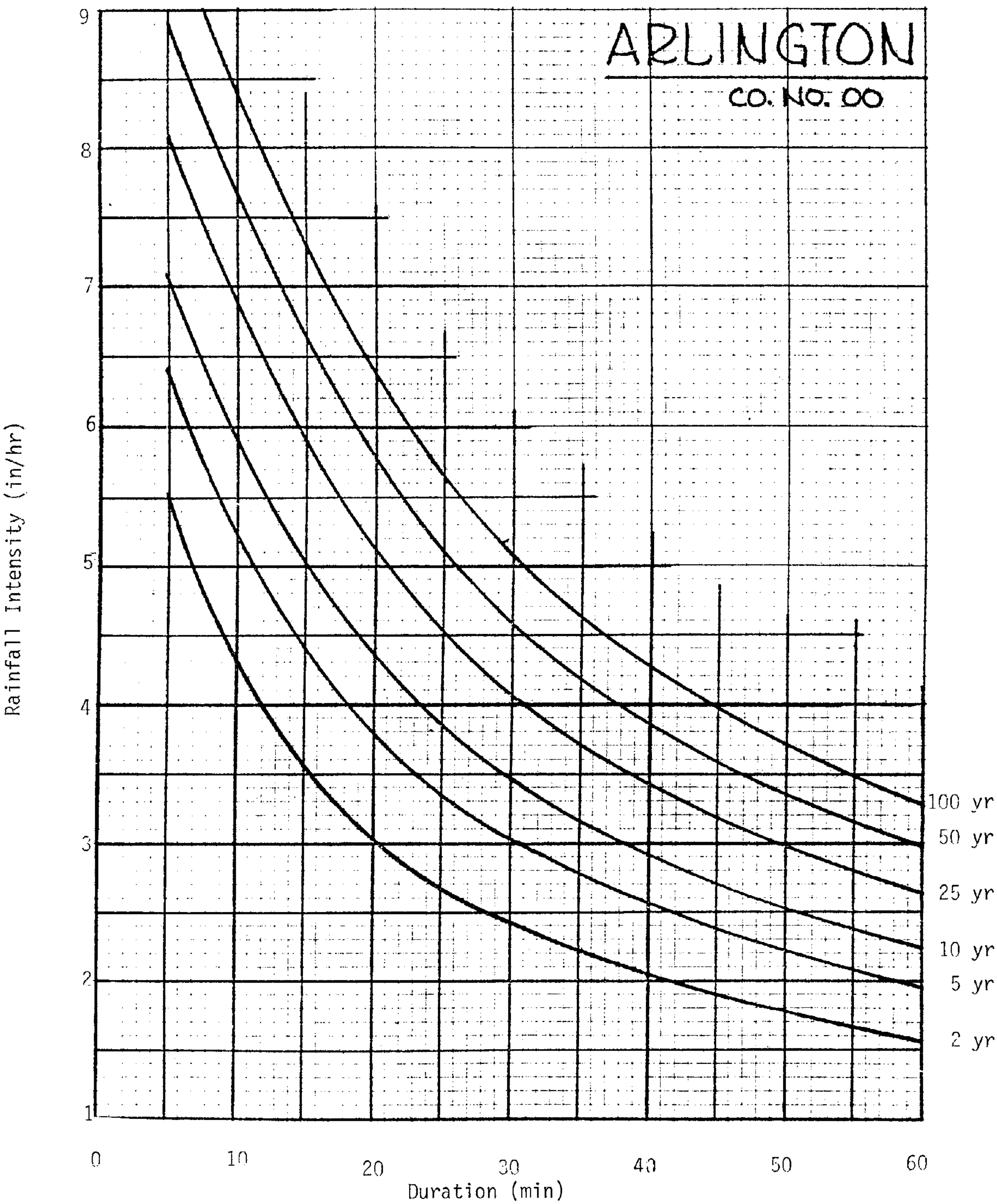

FIGURE III-2. Intensity-Duration-Frequency Curves, Arlington County

TABLE III-6

2-YEAR, 15-MINUTE STORM
ARLINGTON COUNTY, VIRGINIA

Time (minutes)	Rainfall Intensity (in/hr)
1	2.23
2	2.63
3	3.15
4	3.84
5	4.82
6	6.23
7	5.89
8	4.90
9	4.14
10	3.55
11	3.05
12	2.71
13	2.40
14	2.14
15	1.92

TABLE III-7

10-YEAR, 1-HOUR STORM
ARLINGTON COUNTY, VIRGINIA

Time (minutes)	Rainfall Intensity (in/hr)
4	0.82
8	1.03
12	1.38
16	1.99
20	3.26
24	6.88
25	8.91
28	5.71
32	3.40
36	2.32
40	1.71
44	1.33
48	1.08
52	0.90
56	0.77
60	0.67

Inlet Design Program

The test site of the Inlet Design Program consisted of the passing lane of east-bound I-66 from Station 867+25 to 889+50. Selection of this lane of the highway as the drainage basin allowed an accurate representation of the watershed for several reasons. First, because the site begins at a crest and ends at a sump, full account of inlet to gutter carryover could be maintained. Second, a single inlet type (DI-7A) was used in the design of this gutter section which allowed one set of inlet capacity curves to be used in the program. Third, the drainage area consisted of only the highway and shoulder. As a result, there was no problem in determining the watershed geometry because both the shoulder and the driving lane longitudinal slopes, cross slopes, and widths could be obtained directly from the design plans. Finally, because the entire drainage area was of impervious material, there was less error in estimating infiltration, roughness, and depression storage properties of the drainage area than if a previous area had been selected.

Both design storms generated by the Precipitation Module were used as input to the program. An incremental routing length of 25 feet was used in both runs as was a time step of five minutes. The 15 minute storm and one hour storm were simulated over periods of 30 minutes and 90 minutes, respectively, to allow sufficient time to compute entire hydrographs.

The watershed was represented by two parallel drainage areas on either side of the gutter. The area on the highway side consisted of two subareas, the passing lane and the shoulder. Because the Inlet Design Program requires areas on both gutter sides, the other area used was a half-foot wide catchment area of the gutter itself. The gutter was a standard curb-and-gutter with reciprocal side slopes of 19.2 ft/ft and 0.6 ft/ft.

Inlet efficiency curves for inlets on grade were calculated as per program requirements and according to Virginia procedures for grate inlets on grade (10). Sump inlet capacity in Virginia is calculated treating the inlet as a weir for water depths under 0.4 feet and as an orifice when the depth exceeds 1.4 feet. For depths in between, the phenomenon is not clearly defined and a combined approach must be used. For the orifice equation, a discharge coefficient of 0.67 is given and the area used is reduced to accommodate partial clogging. The effective opening is based on a three-foot length and 1.75 feet of total space between bars. A 1.5 foot length and width was specified in the input to account for clogging of the sump inlet.

When designing inlets in a sump, it is Virginia design procedure to place an additional inlet upstream where the gutter slope becomes one percent. Therefore, in the Inlet Design Program one inlet upstream of the sump was prespecified at Station 868+25.

Virginia design criteria for spacing inlets on grade is to achieve 100 percent interception of the two-year storm and to limit flow spread so as not to inundate the shoulders for the ten-year storm. To achieve these criteria in the two storm simulations, a maximum carryover of 0.0% was used for the two-year storm simulation and a design spread of the width of the shoulder (12.0 feet) was used for the ten-year storm simulation. The results of each simulation are shown in Table III-8 and are compared to existing inlet locations.

Based upon the results using the two separate design criteria, the inlet spacing as determined by the two-year storm should be selected. The results so determined are reasonable, are consistent with good drainage practice . The average inlet spacing computed here was 250 feet compared to 400 feet for the actual design. A sample page from the program output, showing the summary information printed otu for one of the inlets located, is reproduced as Exhibit III-1.

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-------------------------------------------------------------------------------------------------------------------
FEDERAL HIGHWAY ADMINISTRATION        ****  URBAN HIGHWAY DRAINAGE MODEL  ****     WATER RESOURCES DIVISION
DEPARTMENT OF TRANSPORTATION          ****                                ****     CAMP DRESSER + MCKEE
WASHINGTON D.C.                       ****     INLET DESIGN PROGRAM       ****     ANNANDALE,VIRGINIA

 EXAMPLE PROBLEM
 VIRGINIA INTERSTATE 66 PROJECT 0066-000-101, GRATE INLET WITH 2 YEAR STORM

--------------------------------------------INLET  5 DESIGN SPECIFICATIONS-----------------------------------------

                                        INLET LOCATED AT STATION   878+00  ----- ON GRADE -----
                                            DEPRESSED   COMBINATION

                                            DESIGN CARRYOVER0.00 OF PEAK FLOW

                                            MAXIMUM CARRYOVER RATIO0.00


                                            GUTTER/CHANNEL CHARACTERISTICS AT INLET

                                        SLOPE                                         .0090
                                        WIDTH                                          0.00 FT
                                        SIDE SLOPE 1 RECIPROCAL                      19.2000
                                        SIDE SLOPE 2 RECIPROCAL                        .5774


                                            PEAK HYDRAULIC CONDITIONS AT INLET

                                        FLOW SPREAD                                    5.09 FT
                                        DEPTH                                           .26 FT
                                        FLOW                                           1.78 CFS
                                        VELOCITY                                       2.71 FPS
```

EXHIBIT III-1

SAMPLE OUTPUT, INLET DESIGN PROGRAM
VIRGINIA TEST SITE

TABLE III-8

EXISTING AND COMPUTED INLET LOCATIONS
ARLINGTON COUNTY TEST SITE

Existing		Computed			
		2 Year Storm		10 Year Storm	
Inlet No.	Station	Inlet No.	Station	Inlet No.	Station
1	867+25	1	867+25	1	867+25
2	868+25	2	868+25		
3	872+25	3	870+00		
4	876+50	4	872+50	2	875+00
5	880+50	5	875+50		
6	884+50	6	878+00		
		7	880+50		
		8	883+00		
		9	885+25		
		10	887+50		

Discrepancies in the results between the existing and computed inlet locations could be attributed in part to different techniques for calculating inlet interception. Also the current (1980) Virginia Drainage Manual procedures used in developing the inlet efficiency curves, may have differed from the procedures used in the original 1956 design of the test site drainage system.

Surface Runoff Program

The Surface Runoff Program was applied to compute surface runoff from the 10-year, 1-hour design storm for the Virginia test site. The simulation occurred over a two-hour period and used a one minute time step. Some special considerations in preparing the data for this test are discussed below.

Because of program limitations mentioned earlier, only one inlet type was included in the simulation. Although all existing inlets, regardless of type, were included, the inlet efficiency computations were based on the single inlet type input.

Required model input for pervious areas includes parameters for Horton's infiltration equation. Parameters selected were an initial infiltration rate of 7.0 inches per hour, final rate of 0.4 inches/hour, decay rate of 2.0 per hour, and maximum infiltration of 3.0 inches (12). This represents a bone-dry, fine-textured soil of slow to moderate infiltration rate, with grass cover.

Because the available plans did not show the complete drainage system in the median, certain assumptions were made in modeling the drainage in this part of the highway right-of-way. Runoff from the median is routed into a gravel-lined concrete channel on the low side of the median. It was assumed that this channel would feed inlets tying into the storm sewers at locations adjacent to inlets in the parallel gutters along the highway. Because final grading contours for the median were not

TABLE III-9

DRAINAGE DESIGN PROGRAM RESULTS
VIRGINIA TEST SITE

Pipe Number	Upstream Station	Downstream Station	Existing Diameter (inches)	Computed Diameter (inches)
102	3 + 00	1 + 25	18	21
104	1 + 25	0 + 75	18	18
106	0 + 75	0 + 00	24	21
110	853 + 25	855 + 00	24	21
120	855 + 00	858 + 50	30	27
130	858 + 50	862 + 50	30	24
140	862 + 50	866 + 00	36	36
150	866 + 00	867 + 00	36	36
210	867 + 00	868 + 00	48	48
220	868 + 00	870 + 00	54	54
230	870 + 00	872 + 25	54	54
240	872 + 25	876 + 50	54	54
250	876 + 50	880 + 50	60	60
310	880 + 50	884 + 50	60	66
320	884 + 50	886 + 50	72	66
330	886 + 50	888 + 00	72	66
340	888 + 00	890 + 50	72	66

The Surface Runoff Program and Drainage Design Program were executed using the 10-year storm. The results showed an excellent preservation of flow continuity.

Although Virginia design practices were utilized whenever possible, differences in the basic technical approaches as discussed at the beginning of this chapter should be kept in mind. Virginia calculates overland flow for highway drainage design based upon the rational formula and a peak rainfall intensity. The simulations made here used time-varying rainfall and the kinematic wave approach for watershed flow, accounting for slope, roughness, depression storage, and infiltration.

In addition to testing the accuracy and sensitivity of the programs in the Model, a second purpose of the test applications was to identify and correct problems in the programs. During the Virginia test application, two such problems were found with the Surface Runoff Program and corrected. First, an error in the program routines that connected watersheds, gutters, channels and inlets internally was discovered and corrected. This error was only encountered in certain cases and would probably not have been detected without this test application. Second, it was found that in certain steep gutters or channels immediately downstream of an inlet, flow could drop to zero in a very short time near the end of the hydrograph. If this happened in a time less than the time step, a rare problem in the numerical solution in the program could be encountered and unrealistic solutions produced. As a result, advice to the user on selecting the proper time step to avoid this problem was included in the User's Manual and Documentation Report.

included with the plans, the slope of the median surface was calculated from elevation differences between the median edge of the east and west bound lanes. The median surface was covered by a plastic liner, which was covered in turn by gravel. Therefore, the drainage area was considered impervious, with a depression storage of 0.2 inches and a Manning roughness coefficient of 0.035.

The results of the Surface Runoff Program simulation were excellent, with an error of continuity of only 0.03%. A total of 2.2 inches (4.34×10^5 cubic feet) of rainfall fell on the watershed, from which approximately 46% was infiltrated, 52% (2.24×10^5 cubic feet) entered inlets, and the remainder was accounted for by minor losses.

Less than ten percent of the gutters reached full depth, while the majority did not exceed 80 percent of full depth. The peak flow in all gutters fell between 25 and 40 minutes from the start of the one hour rainfall event. Flow had ceased in the surface system at approximately 35 minutes from the end of rainfall.

The inlet hydrographs from this run were saved as a disc file and used by the Drainage Design Program, described below.

Drainage Design Program

For the Drainage Design Program application, the actual inlet locations, and the lengths and elevations of the circular concrete storm sewers were obtained directly from the plans and profiles of the test sites. A Manning coefficient of 0.013 was used as required by Virginia design practice.

A two hour time period was simulated using a one minute time step. All pipes were initially specified having a diameter of 1.0 feet. The pipe diameters as resized by the program were compared to the actual I-66 design diameters.

The Drainage Design Program specified a total inflow into the pipe network of 2.24×10^5 cubic feet which corresponds with the results of the Surface Runoff Program. After resizing 71 of the 172 pipes in the network, an error in continuity of 0.06% of the inflow had been achieved.

The pipe diameters of the actual design compare well with those in the computed design. Tributary lines tying into the main trunk lines were all within three inches of the computed diameters. The computed main trunk line had a few diameters smaller than the actual design, as can be seen in Table III-9.

A peak flow of approximately 267 cfs occurred at the outfall at approximately 32 minutes from the beginning of the storm. Flow at the outfall returned to zero by approximately 30 minutes after the end of the storm.

Discussion of Results

The Urban Highway Storm Drainage Model was applied to Virginia Interstate-66 as discussed above. A 2-year, 15-minute storm and 10-year, 1-hour storm were synthesized with the Precipitation Module and used as input to the Inlet Design Program and the Surface Runoff Program.

The Inlet Design Program was used to space inlets on a portion of I-66. Inlets were spaced using the two relevant Virginia design criteria: 1) 100% capture with the 2-year storm; and 2) flow spread limited to the highway edge using the 10-year storm. The first of these produced the closer spacing. Discrepancies in the results, can be attributed to differences in methods for computing inlet capacity.

TENNESSEE TEST SITE

Tennessee Interstate 40 was selected as the final test application site. I-40 is an east-west limited access highway spanning the nation from California to North Carolina. The section of the interstate selected for study is a divided six lane segment located within the city of Nashville between Arlington Avenue and Spence Boulevard at the Murfreesboro Pike Interchange. The drainage basin simulated entails 0.8 miles of highway on the west-bound side with a total watershed area of approximately 23 acres and a difference in relief of 88 feet. The actual inlets were used in this test.

The three programs applied to the test site were the Precipitation Module, the Surface Runoff Program, and the Drainage Design Program. A discussion on model input and results for each program follows.

Precipitation Module

The Program Path 1 procedure of the Precipitation Module was executed to obtain a design storm with a 10 year recurrence interval and 1 hour duration, as specified by the Tennessee Department of Highways. The 10-year 1-hour, 10-year 24-hour, and 100-year 1-hour storm values were obtained from the Weather Bureau's "Rainfall Frequency Atlas of the United States" (13) as input to produce the design storm using a 0.45 skew. The resulting hyetograph values are specified in Table III-10.

Surface Runoff Program

The 10-year 1-hour storm produced by the Precipitation Module provided input for the Surface Runoff Program. The program was executed for a 120 minute period using a 1.0 minute time step.

TABLE III-10

10-YEAR, 1-HOUR STORM
NASHVILLE, TENNESSEE

Time (minutes)	Rainfall Intensity (in./hr.)
4	0.82
8	0.99
12	1.25
16	1.69
20	2.56
24	4.86
26	8.00
28	6.69
32	3.44
36	2.23
40	1.63
44	1.28
48	1.05
52	0.89
56	0.77
60	0.68

Drainage features of the highway were obtained from the State of Tennessee Department of Highways plans and profiles for the test site. Tennessee design standards were obtained from correspondence with the State. A schematic of part of the site is shown in Figure III-3.

Two land surface types were represented in the model - the impervious surface of the highway and the pervious grassy right-of-way along the highway side. No soil characteristics for the pervious areas were readily available. The Horton infiltration equation parameters selected were a maximum and minimum rate of 4.0 and 0.6 inches per hour, respectively, a decay of 4.0 per hour, and a maximum amount of 2.0 inches.

The watershed boundaries were delineated from the final grading contours on the plans. Each watershed was represented according to its area, infiltration type, width, average slope, and downstream gutter or channel. Roughness coefficients used for the turf and highway were 0.20 and 0.014, respectively. The respective depression storage depths used were 0.2 and 0.05 inches.

Two types of gutters or channels were used in the design plans. A circular arc open channel collects runoff from contributing areas along the highway and a curb and gutter collects highway runoff.

The concrete channel arc has a radius of 24 inches with a maximum depth of six inches and a three foot horizontal span. Two alternatives were considered for modeling these channels. The channel could be modeled as a circular pipe, but this would be incorrect if the maximum depth of flow exceeded six inches. The second alternative was to approximate the geometry of the area by a trapezoidal channel with a maximum depth of six inches. The trapezoidal channel was selected with a base width of 1.1 feet and reciprocal side slopes of 1.9 ft/ft.

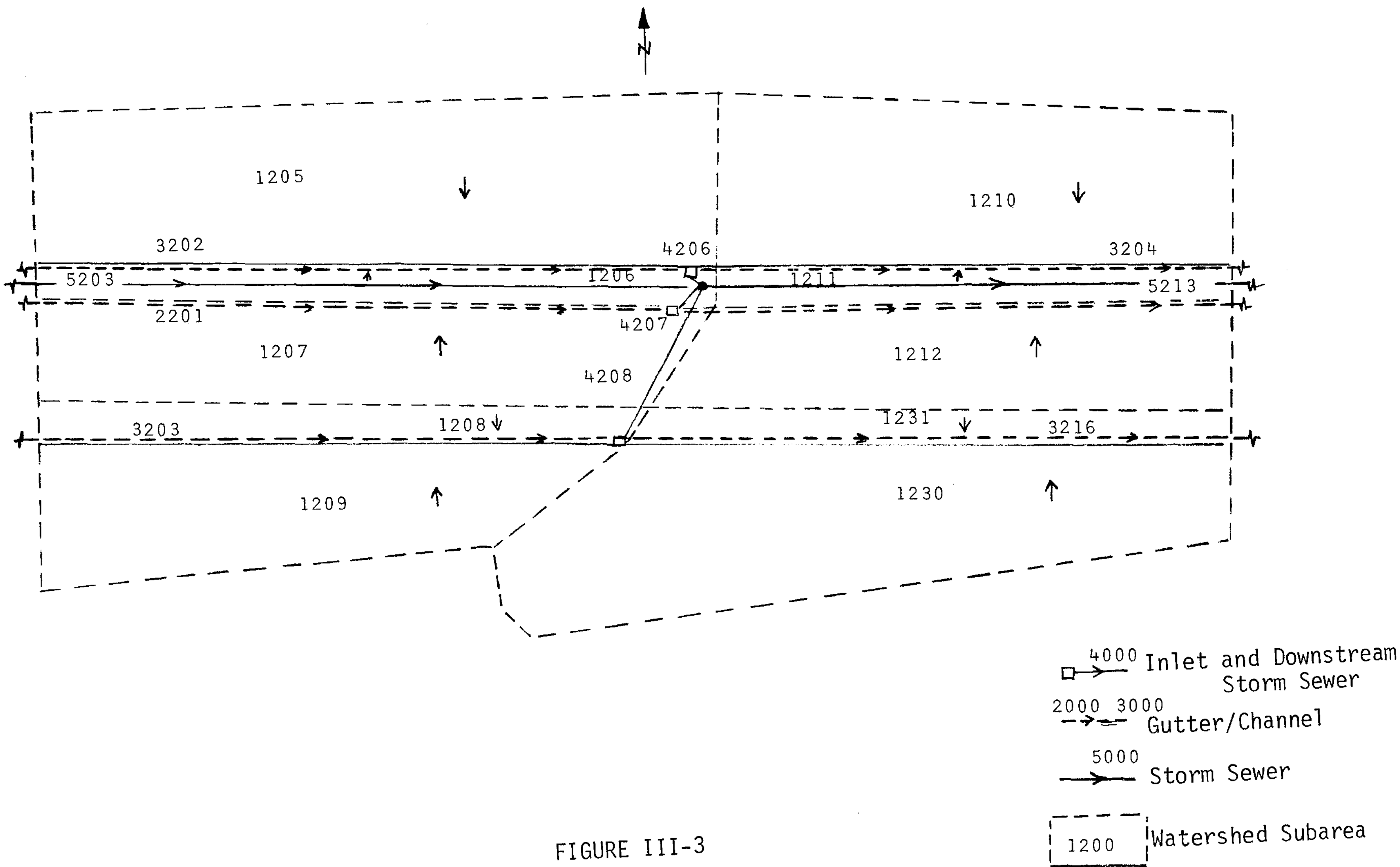

FIGURE III-3

SCHEMATIC OF TYPICAL DRAINAGE AREA
TENNESSEE TEST SITE

The curb and gutter was represented by its two side slopes. The curb side is convex and was represented as having a 60 degree slope with the horizontal. The highway side slope was taken from the plans as having a reciprocal side slope of 12.0 ft/ft.

Two inlet types were presented in the highway design. It was possible to include inlet capacity characteristics for both types because one inlet was used exclusively with the concrete circular channel and the other was used in the standard curb and gutter. (The final version of the Surface Runoff Program allows one inlet type for all inlets in gutters and one type for all inlets in channels.)

The inlet type used in the curb and gutter was Tennessee standard catch-basin 28A. The inlet is a grate inlet having overall dimensions of approximately two feet wide by three feet long. Tennessee uses the standard orifice equation to determine the capacity of these inlets as follows:

$$Q = CA\ (2gH)^{\frac{1}{2}}$$

in which Q is the capacity in cubic feet per second, A is the area of the effective opening in square feet, C is the orifice discharge coefficient (0.3), g is the acceleration due to gravity, and H is the average depth of water in feet. This equation was used to calculate inlet efficiency curves for different curb-and-gutter geometries.

The calculated area of the opening of the inlet was multiplied by a reduction factor of 0.8 to obtain an effective area while computing the efficiency curves. Apparently , this reduction factor is routinely applied as part of Tennessee inlet capacity calculations. Inlet efficiency curves for inlets in the circular channels were computed in the same manner but input to the program as a function of depth rather than flow.

The results of the Tennessee model application show that, for the 10-year, 1-hour design storm, the gutter flow spread (2 to 4 feet) is much less than the maximum allowed (8 feet from the curb face) and the depth of flow (maximum approximately 3 inches) is much less than the depth of the circular channels (6 inches). This indicates a possible overly safe design of the present system by the Rational Method. A sample of the program output is shown in Exhibit III-2.

Out of a total of 1.73×10^5 cubic feet of rainfall (approximately 2 inches), 51% entered the inlets. Of the remaining amount, 43% infiltrated and the rest became watershed or channel storage. Modest infiltration parameters were applied in the model and the apparent large loss due to infiltrated water can be attributed to the watershed area being over 60% pervious.

Drainage Design Program

The Drainage Design Program utilized the inlet hydrographs generated by the Surface Runoff Program to size the pipe network. Each pipe in the network was specified according to its upstream and downstream elevation, length, and downstream pipe connectivity as obtained from the Tennessee plans and profiles. The model was run for a two hour time period with a one minute time step. An initial pipe diameter of 0.5 feet was specified for each pipe. The resized pipe diameters were compared to the actual design.

The resized pipe diameters are similar to the actual design. Results for a major trunk line at the site are shown in Table III-11. Apparently, a minimum pipe diameter of 18 inches was utilized at the site. The program found that some smaller pipe diameters would be adequate in upstream sections of the network. Elsewhere, the results indicate differences of up to no more than one pipe size, as can be seen in Table III-11.

FEDERAL HIGHWAY ADMINISTRATION **** URBAN HIGHWAY DRAINAGE MODEL **** WATER RESOURCES DIVISION
DEPARTMENT OF TRANSPORTATION **** **** CAMP DRESSER AND MCKEE
WASHINGTON, D.C. **** SURFACE RUNOFF PROGRAM **** ANNANDALE, VIRGINIA

SUMMARY STATISTICS FOR ABOVE-GROUND GUTTERS/CHANNELS

GUTTER/ CHANNEL NUMBER	DESIGN FLOW (CFS)	DESIGN VELOCITY (FPS)	DESIGN DEPTH (FT)	DESIGN FLOW SPREAD (FT)	MAXIMUM COMPUTED FLOW (CFS)	MAXIMUM COMPUTED VELOCITY (FPS)	MAXIMUM COMPUTED DEPTH (FT)	MAXIMUM COMPUTED SPREAD (FT)	TIME OF OCCURENCE HR.	MIN.
3120	9.08	8.86	.50	-	1.83	5.05	.23	-	12	30
2120	19.42	7.63	.64	8.0	1.31	3.86	.23	2.9	12	29
3121	9.08	8.86	.50	-	2.66	5.83	.28	-	12	32
3200	9.08	8.86	.50	-	1.56	4.86	.21	-	12	30
2200	19.42	7.63	.64	8.0	1.31	3.86	.23	2.9	12	29
3201	9.08	8.86	.50	-	2.45	5.55	.27	-	12	31
3202	11.19	10.92	.50	-	1.67	5.89	.19	-	12	31
2201	23.94	9.41	.64	8.0	1.34	4.57	.22	2.7	12	29
3203	11.19	10.92	.50	-	1.80	6.10	.20	-	12	31
3204	12.84	12.53	.50	-	1.76	6.34	.19	-	12	30
2202	27.46	10.79	.64	8.0	1.35	5.12	.21	2.6	12	29
3206	12.84	12.53	.50	-	1.57	6.16	.18	-	12	30
2203	27.46	10.79	.64	8.0	2.57	5.95	.26	3.3	12	29
2204	27.46	10.79	.64	8.0	.08	2.37	.07	.9	12	28
2210	16.01	6.29	.64	8.0	2.52	3.57	.32	4.0	12	30
2211	21.62	8.50	.64	8.0	1.39	4.45	.22	2.8	12	29
2212	27.46	10.79	.64	8.0	1.36	5.19	.20	2.6	12	29
2213	27.46	10.79	.64	8.0	1.14	4.93	.19	2.4	12	29
3212	10.11	9.86	.50	-	2.49	6.08	.26	-	12	33
3214	12.84	12.53	.50	-	1.63	6.28	.18	-	12	30
3216	12.84	12.53	.50	-	1.57	6.30	.17	-	12	30
3218	12.84	12.53	.50	-	.22	3.10	.06	-	12	28
3211	10.11	9.86	.50	-	1.39	5.24	.18	-	12	31
3213	12.84	12.53	.50	-	2.16	6.91	.21	-	12	31
3215	12.84	12.53	.50	-	1.89	6.63	.19	-	12	31
3217	12.84	12.53	.50	-	1.85	6.72	.19	-	12	31
3100	7.70	7.52	.50	-	2.90	5.21	.32	-	12	31
2100	16.48	6.48	.64	8.0	1.41	3.51	.25	3.2	12	30
3101	7.70	7.52	.50	-	3.04	5.23	.33	-	12	31
2101	18.22	7.16	.64	8.0	1.62	3.88	.26	3.2	12	29
3102	8.52	8.31	.50	-	2.55	5.43	.29	-	12	34
3222	10.74	10.48	.50	-	1.67	5.53	.20	-	12	30
3224	10.74	10.48	.50	-	2.47	6.35	.25	-	12	31
3226	10.74	10.48	.50	-	2.03	5.95	.22	-	12	31
2220	22.98	9.03	.64	8.0	1.56	4.63	.23	2.9	12	29

EXHIBIT III-2
SAMPLE OUTPUT, SURFACE RUNOFF PROGRAM
TENNESSEE TEST SITE

FEDERAL HIGHWAY ADMINISTRATION	**** URBAN HIGHWAY DRAINAGE MODEL ****	WATER RESOURCES DIVISION
DEPARTMENT OF TRANSPORTATION	**** ****	CAMP DRESSER AND MCKEE
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SUMMARY STATISTICS FOR ABOVE-GROUND GUTTERS/CHANNELS

GUTTER/ CHANNEL NUMBER	DESIGN FLOW (CFS)	DESIGN VELOCITY (FPS)	DESIGN DEPTH (FT)	DESIGN FLOW SPREAD (FT)	MAXIMUM COMPUTED FLOW (CFS)	MAXIMUM COMPUTED VELOCITY (FPS)	MAXIMUM COMPUTED DEPTH (FT)	MAXIMUM COMPUTED SPREAD (FT)	TIME OF OCCURENCE HR.	MIN.
2221	22.98	9.03	.64	8.0	1.17	4.26	.21	2.6	12	30
2222	22.98	9.03	.64	8.0	1.54	4.57	.23	2.9	12	29
3221	10.74	10.48	.50	-	1.33	5.25	.18	-	12	32
3223	10.74	10.48	.50	-	2.75	6.53	.26	-	12	32
3225	10.74	10.48	.50	-	2.49	6.30	.25	-	12	31
2223	22.98	9.03	.64	8.0	1.44	4.51	.23	2.8	12	29
2310	10.99	4.32	.64	8.0	.65	2.14	.22	2.8	12	31
2312	10.99	4.32	.64	8.0	1.03	2.39	.26	3.3	12	30
2314	10.99	4.32	.64	8.0	1.99	2.82	.34	4.2	12	30
2316	10.99	4.32	.64	8.0	1.05	2.39	.26	3.3	12	29
2317	19.42	7.63	.64	8.0	1.12	3.89	.21	2.7	12	29
2230	24.56	9.65	.64	8.0	1.28	4.82	.21	2.6	12	29
3315	5.14	5.01	.50	-	.69	2.60	.18	-	12	33
3316	9.08	8.66	.50	-	2.62	5.75	.28	-	12	34
3230	11.48	11.20	.50	-	1.83	6.10	.20	-	12	32
3317	9.18	8.86	.50	-	.79	4.02	.14	-	12	31
2231	22.65	8.90	.64	8.0	.63	3.74	.16	2.1	12	29
2232	22.98	9.03	.64	8.0	1.53	4.64	.23	2.9	12	29
2233	22.31	8.77	.64	8.0	1.39	4.35	.23	2.8	12	29
3231	10.59	10.33	.50	-	1.41	5.44	.18	-	12	31
3233	10.74	10.48	.50	-	1.86	5.91	.21	-	12	31
3270	3.63	3.54	.50	-	3.19	3.11	.50	-	12	32
3271	3.63	3.54	.50	-	3.19	3.11	.50	-	12	31
3272	81.20	79.22	.50	-	3.23	35.85	.07	-	12	33
3235	10.43	10.18	.50	-	2.32	6.18	.24	-	12	31

EXHIBIT III-2
(continued)

TABLE III-11

DRAINAGE DESIGN PROGRAM RESULTS
TENNESSEE TEST SITE

Pipe Number	Upstream Station	Downstream Station	Existing Diameter (inches)	Computed Diameter (inches)
4310	0 + 00	2 + 00	18	9
5310	2 + 00	4 + 50	18	12
5225	4 + 50	7 + 25	18	15
5226	7 + 25	8 + 25	18	21
5227	9 + 25	12 + 50	24	24
5230	12 + 50	14 + 50	24	24
9998	14 + 50	16 + 00	30	36

Discussion of Results

Model application to the Tennessee Interstate-40 test site showed similar results when compared to the actual design. Smaller pipes could be used in upstream sections if allowed. Errors in flow continuity were 5% in the Surface Runoff Program and practically negligible in the Drainage Design Program.

Inlet capacity for inlets in gutters was computed from curves as a function of gutter slope, cross-slope and gutter flow. The capability of using a second set of curves to calculate capacity of inlets in channels as a function of channel slope and flow depth was added.

CHAPTER IV
CONCLUSIONS AND RECOMMENDATIONS

The project described in this Final Report resulted in the successful development and testing of the Urban Highway Storm Drainage Model, a package of six computer programs organized into four Modules. The development of each computer program was accompanied by the preparation of a User's Manual and Documentation Report, giving a detailed description of the program and instructions for its use.

In addition to example problems given in the User's Manual and Documentation Reports, the capabilities of the Model were demonstrated by a series of test applications to actual highway sites, described in this report. Although the test applications proved very useful, the full capabilities and limitations of these programs cannot be identified until they are used by practicing engineers with actual highway drainage design and analysis problems to solve.

All four of the Modules should be immediately useful to practicing engineers, with the numerous capaciblities of this package makes available to them. However, further program refinements will undoubtedly be required as the limitations of the Model are more fully explored. In addition, there are several features of two of the Hydraulics/Quality Module programs that should be considered for further development and testing work in the near future.

The Inlet Design Program of the Hydraulics/Quality Module has several features that could be expanded to be more useful. First, the program presently spaces inlets along a single series of gutters or channels from the top of grade to the sump; this should be expanded to allow inlet speacing from the top of grade on both sides of the sump with a single program run. This would allow simulation of flow into the sump inlet from both sides. Second, further examination of the simulation of sump inlet ponding should be undertaken. At present, a single simplified approach to this problem is built into the program. This approach may be adequate, but further research into alternate approaches is recommended. Third, at present only one of the six possible inlet types in gutters and none of the inlet types in channels have empirical equations for inlet efficiency built into the program. (All inlet types can be simulated with efficiency curves supplied by the user as input.) Other sound inlet efficiency equations will be incorporated in the program.

The Surface Runoff Program of the Hydraulics/Quality Module also should be considered for further development work in the near future, especially with regards to runoff quality computations. The basic approach to computation of pollutant accumulation, washoff and transport used in the program has been developed and applied successfully over a number of years in such programs as the U.S. Environmental Protection Agency's Storm Water Management Model. However, the methodology is dependent on pollutant accumulation rates for different land uses and geographical locations. It is recommended that the collection of the detailed rainfall-runoff quantity and quality data required for calibration of this program to urban highways be undertaken at selected test sites. (It should be noted that the Federal Highway Administration has sponsored the collection of highway runoff quality data, but not the type of data required for a deterministic, single-event model of this type. Past studies have been oriented towards estimating long-term runoff pollutant loads from highways, while this program simulates detailed hydrographs and pollutographs from single storm events.)

Finally, it is recommended that the Federal Highway Administration undertake an effort for training users of these programs and for distribution and continuing support of the programs. Past experience has shown conclusively that the most successful and widely-used computer programs in engineering have been those that have received active and continuing support from the sponsoring agency, such as the U.S Army Corps of Engineers and the U.S.

Environmental Protection Agency. If the Federal Highway Administration undertakes such an effort, we believe that a significant positive impact on the practice of highway drainage design and analysis could result over the next several years.

CHAPTER V

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

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This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.