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FINAL REPORT

PRESSURIZED STORM SEWER SIMULATION: MODEL ENHANCEMENT

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

A modified Pressurized Flow Simulation Model was developed and attached to the Federal Highway Administration's Pooled Fund PFP-HYDRA program. Four hydrograph options are available for simulating inflow to a sewer system under surcharged or pressurized conditions. Several key parameters, such as time-step and print options, are discussed on a theoretical basis for the development of guidelines for parameter selection. The *User's Manual* was completed, providing detailed instructions on the use of the model.

FINAL REPORT

PRESSURIZED STORM SEWER SIMULATION: MODEL ENHANCEMENT

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INTRODUCTION

A microcomputer program module called the Pressurized Flow Simulation Model (PFSM) was developed by modifying the EXtended TRANsport (EXTRAN) module of the Environmental Protection Agency's Storm Water Management Model (SWMM) as described in an earlier report (Yu & Wu, 1989). PFSM, which computes sewer flow, velocity, gradeline elevation, etc. under either open-channel or surcharged conditions, is being attached to the PFP-HYDRA program of the Federal Highway Administration's (FHWA) Pooled Fund HYDRAIN package. PFSM can also be run as a stand-alone program.

The previous PFSM module generates storm hydrographs by using only the rational formula and assuming a triangular hydrograph. Further improvements on hydrograph options were therefore desirable, for example, a synthetic unit hydrograph method, such as the Clark method, for ungaged watersheds. Another desirable modification was the development of an "advisory module" to help the user select pertinent flow simulation parameters, printout options, etc.

The principal objective of this study was, therefore, to modify and enhance models developed for pressurized flow simulations and open-channel gradeline computations to suit the needs of the Virginia Department of Transportation (VDOT). Such modifications included an enhanced hydrograph procedure and a parameter selection procedure. A user's manual for PFSM was also prepared as part of the final report. The manual provides detailed instructions on the use of the model and illustrates its use with sample runs.

ENHANCED HYDROGRAPH OPTIONS

In order to estimate inflows to the sewer system better, the modified PFSM provides four hydrograph options for computing stormwater runoff. Previously, the

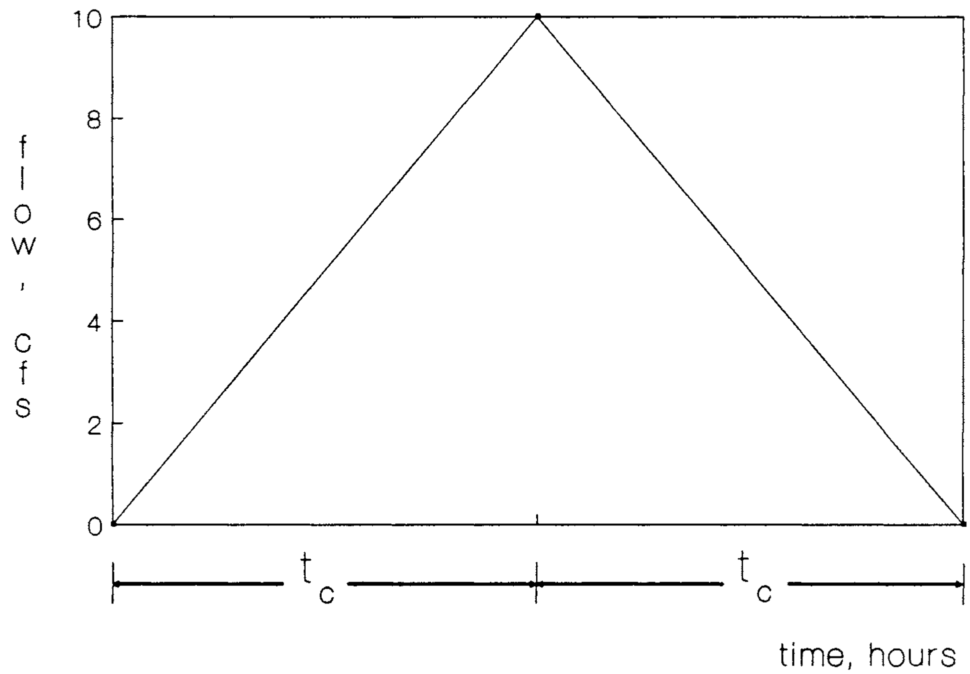

Figure 1. Rational Method Triangular Hydrograph

rational method triangular hydrograph (Figure 1) and user-supplied hydrographs were options available for estimating inflows to the system. Two additional methods, the Soil Conservation Service's (SCS) unit hydrograph method and the Clark method, which are synthetic hydrograph methods, have been incorporated into the PFSM model. These two methods offer the option of generating hydrographs based on land characteristics when storm runoff data are not available for unit hydrograph derivation.

SCS Unit Hydrograph Method

The SCS unit hydrograph method was designed for watersheds up to 1,000 acres (Viessman, Lewis, & Knapp, 1989). The dimensionless unit hydrograph (Figure 2) is the result of an analysis of a large number of natural unit hydrographs from watersheds of a wide range of sizes and geographic locations (Viessman *et al.*, 1989). The method requires only the determination of the time to peak and the peak discharge. Parameters t_p and q_p are computed as follows:

$$t_p = \frac{D}{2} + t_l \qquad \text{(eq. 1)}$$

where
t_p = time to peak (hr)
D = duration of rainfall (hr)
t_l = lag time (hr).

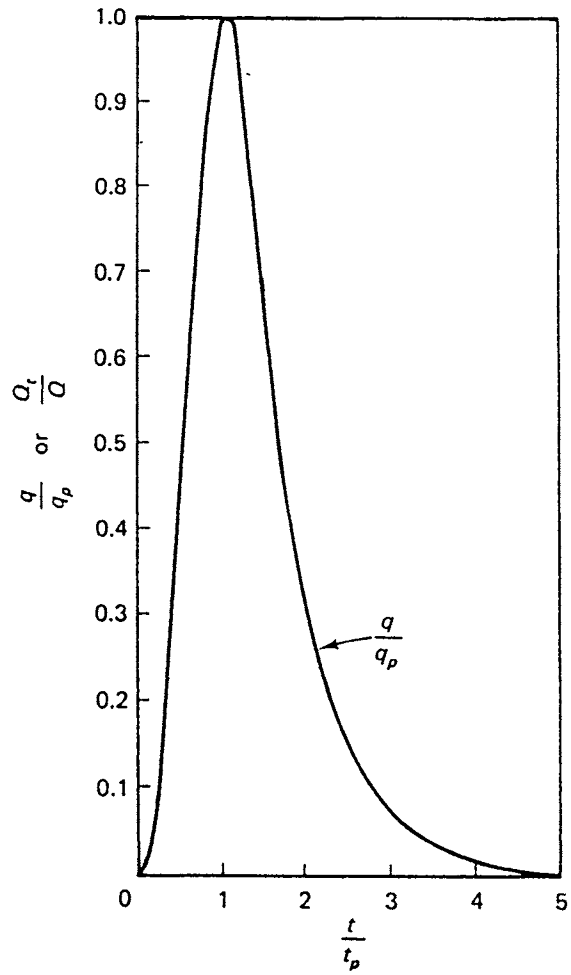

Figure 2. Dimensionless Unit Hydrograph. *Source*: U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

The peak flow for the hydrograph is computed by approximating the unit hydrograph as a triangular shape with a base time of 8/3 t_p and unit area. The peak flow is determined by

$$q_p = \frac{484A}{t_p} \qquad \text{(eq. 2)}$$

where A = watershed area (mi^2)
t_p = time to peak (hr)
q_p = peak flow (ft^3/sec).

Notice that the empirical constant, 484, or K, represents the fraction of the area under the rising limb of the hydrograph. In other words, the constant of 484 represents a hydrograph with 3/8 of its area under the rising limb. The fraction is less for a flat, swampy area (K = 300) and greater for a mountainous area (K = 600).

The unit hydrograph can be obtained using the dimensionless hydrograph of q/q_p vs. t/t_p as shown in Figure 2.

The lag time, t_l, is affected by land characteristics. Watershed area, slope, and a number of other factors have been used in empirical formulas for estimating the lag time, whereas other empirical formulas determine lag time through a relationship with the time of concentration. Equation 3 is a general SCS equation that calculates the lag time based on characteristics of the watershed and is used in the PFP-HYDRA calculations:

$$t_l = \frac{l^{0.8}(S + 1)^{0.7}}{1,900Y^{0.5}} \qquad \text{(eq. 3)}$$

where

t_l = lag time (hr)
l = length to divide (ft)
Y = average watershed slope (%)
S = (1,000/CN) – 10 = potential maximum retention
CN = SCS curve number.

The representative SCS curve number for the watershed area can be determined using values listed in SCS Technical Release No. 55. Soil types for the watershed can be found on SCS county soil maps. In determining the characteristic length, l, one can take l as the distance from the outlet to a point with the longest travel time.

Clark Method

The Clark method relates storage to outflow using the concept of the linear reservoir, i.e., $S = KQ$, where S is the storage of the reservoir, Q the discharge, and K a constant. By continuity, the time rate of change of the storage is equal to the difference between the input and output (Chow, Maidmont, & Mays, 1988). The Clark method uses a time-area histogram to route a hydrograph through the linear reservoir (Figure 3) and a storage coefficient to satisfy the needs of continuity. The continuity equation is expressed as:

Inflow – Outflow = Time rate of change of storage

or

$$I - Q = \frac{dS}{dt} \qquad \text{(eq. 4)}$$

After this equation is discretized, it becomes

$$I - Q = K\frac{Q_{\Delta t} - Q_{\Delta t-1}}{\Delta t} \qquad \text{(eq. 5)}$$

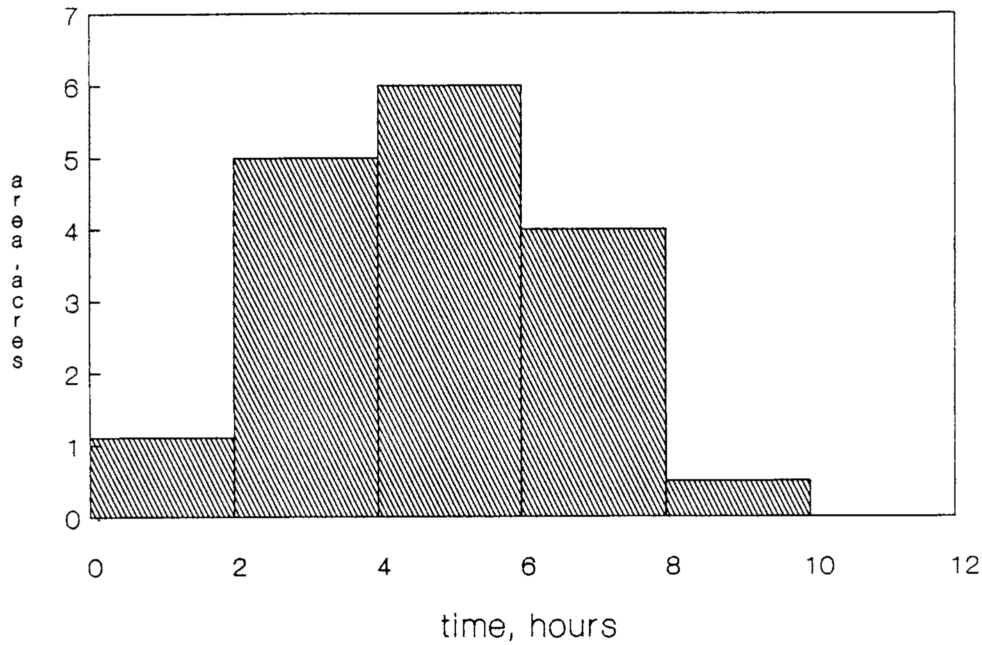

Figure 3. Time-Area Diagram

and

$$Q = C_0 I_{\Delta t} + C_1 Q_{\Delta t-1} \quad \text{(eq. 6)}$$

where

$$C_0 = \frac{2\Delta t}{2K + \Delta t}$$

and

$$C_1 = \frac{2K - \Delta t}{2K + \Delta t}$$

The unit hydrograph is found by solving for Q at the end of each time interval, Δt. Either a Muskingum routing method or the Muskingum-Cunge method (Viessman *et al.,* 1989) can be used to obtain values for K specific to the watershed area. This determination requires actual inflow and outflow hydrographs. A value of K equal to the travel time is often used when a storage coefficient has not been predetermined (Viessman *et al.*, 1989). The PFSM program module assumes a value equal to the time step if no storage coefficient is entered.

Specific-duration unit hydrographs are determined using the S-hydrograph method when the Clark method is used to generate a unit hydrograph. The S-hydrograph results from a continuous rainfall at a constant rate for an indefinite period (Chow *et al.*, 1989). Two such S-hydrographs can then be "lagged" with the appropriate time length to obtain the unit hydrograph with the desired storm duration using principles of superposition.

The time-area histogram used directly determines inflow based on the incremental area and time interval. Outflows are calculated by using equation 6 with known values of C_0 and C_1.

Storm runoff flows calculated with any of the hydrograph options represent inflows, through inlets, into the sewer system (i.e., manholes, drop inlets, etc.). The resulting pipe flow is routed through the sewer system to the outlet.

SELECTION OF KEY PARAMETERS

In running the pressurized flow program, it is necessary for the user to specify several key parameters, such as time step, print options, etc. The following paragraphs provide some discussion on the theoretical basis for the development of guidelines for parameter selection. Procedures for such selection processes and sample cases are described in the attached *User's Manual.*

Time Step

PFSM follows the theoretical background and numerical algorithms of EXTRAN with dynamic wave simulation capability. The program solves the full dynamic equation for gradually varied flow (one-dimensional momentum equation and continuity equation) using an explicit solution technique to step forward in time. The entire sewer length is considered as a single computational reach, and the dynamic wave equation is written in backward time difference between time level $n + 1$ and n for the sewer. It is expressed explicitly as

$$Q_{n+1} = \left(1 + \frac{gn^2\Delta t}{2.21R_n^{4/3}}|V_n|\right)^{-1}\left(Q_n + 2\overline{V}_n\Delta A + \overline{V}_n^2\frac{A_{u,n} - A_{d,n}}{L}\Delta t - g\overline{A}_n\frac{h_{u,n} - h_{d,n}}{L}\Delta t\right) \quad \text{(eq. 7)}$$

where

Q = discharge (ft³/sec)
V = velocity (ft/sec)
A = area (ft²)
L = the entire sewer length (ft)
g = gravitational acceleration (ft/sec²)
Δt = time step (sec)
n = Manning's coefficient
R = hydraulic radius (ft)
h = depth of flow (ft).

The subscript u denotes the upstream end of a sewer (i.e., entrance), and d denotes the downstream end (i.e., exit). The bar indicates the average of values at the entrance and exit locations. Presumably, $\Delta A = A_{n+1} - A_n$ is also the average of the values at the sewer ends. The junction condition used is the continuity equation expressed explicitly in terms of the depth, H, and discharge values at the time $n\Delta t$ as

$$H_{n+1} = H_n + \frac{\Delta t}{A_j}(\Sigma Q_{i,n} + Q_{j,n}) \qquad \text{(eq. 8)}$$

Equations 7 and 8 are solved explicitly by using a modified Euler method and half-step and full-step calculations. Thus, PFSM, being an explicit difference formulation, solves the flows sewer by sewer by using the one-sweep explicit solution method with no need for simultaneous solution of the sewers of the network (Yen, 1986). As a result, the time step, Δt, is most critical to the cost and stability of the PFSM run and must satisfy the following inequalities (Roesner *et al.*, 1981):

- Pipe:

$$\Delta t \le \frac{L}{\sqrt{gD}} \qquad \text{(eq. 9)}$$

- Node:

$$\Delta t \le \frac{C' A_s H_{\max}}{\Sigma Q} \qquad \text{(eq. 10)}$$

where
L = the entire sewer length (ft)
C' = dimensionless constant
D = pipe depth (in)
H_{max} = maximum water-surface rise (ft)
A_s = corresponding surface area (ft^2)
ΣQ = net inflow to the junctions (ft^3/sec).

PFSM checks each pipe for possible violation of the surface wave criteria. If the time step, Δt (the second parameter in the PFA command), provided by the user violates the criteria, the program will select a new Δt for the pressurized flow simulation to replace the value given by the user. Based on past experience with EXTRAN, a time step of 10 sec is nearly always sufficiently small to produce outflow hydrographs and state-time traces. In most applications, 15- to 30-sec time steps are adequate. Occasionally, time steps up to 60 sec can be used.

Printout Option

In PFSM, three options are available to the user for the final printout. These options can be chosen by changing the value of *pr option*, the fourth parameter in the PFA command, to *0*, *1*, or *2*. If *pr option* is equal to 0, the results of PFSM analysis will show only the summary tables for all functions and pipes in the system. If *pr option* is 1, the summary table and the time history of depths and flows for those junctions and pipes given by the user will be included in the output. If *pr option* is 2, the summary and the time history tables in addition to the detailed, cycle-by-cycle printout will appear without normal interruption of normal page breaks. The detailed printout gives the depth at each junction and flow in each pipe in the system at a user-specified time interval (the third parameter in the PFA command). A junction in surcharge is indicated by the printing of an asterisk beside its depth. Also, if surcharge iterations are occurring at the time of the intermediate printout, PFSM will print the flow differential over the iterations required. An asterisk beside a pipe flow indicates that the flow is the normal flow for the pipe. The detailed printout ends with the printing of the continuity balance of water passing through the system during the simulation. Outflows from junctions not designated as outfalls are junctions that have flooded.

MODEL TESTING

Three case examples were used to test the modified PFSM program. The use of different hydrograph options is illustrated. The selection of key parameters and the new commands used for generating hydrographs is also described.

Example 1: Rational Method

The Campostella Road (U.S. Route 460) storm sewer in the city of Norfolk, Virginia, is located off the east end of the Campostella Bridge over the Elizabeth River and discharges into the river. This sewer system contains 16 pipes of different lengths and ground elevations. The layout of this system is shown in Figure 16 in the *User's Manual*. A 10-year intensity-duration-frequency (IDF) curve was used for computing runoff inputs to the system. A tailwater elevation of 103.5 ft (just higher than the crown elevation) is assumed at the outfall. This example is intended for demonstrating the use of the rational method option to generate hydrographs at junctions. This option requires three commands from the original PFP-HYDRA (i.e., SWI, STO, and RAI) and three commands in PFSM (i.e., PFA, PHJ, and PFP). In the PFA command, a time step of 10 sec, a total simulation time of 25 min, a printing interval of 1 min, and a printout option of 1 were selected. Simulation was started at 0.0 hr. The time history of water depths at six junctions and flows for 8 pipes were desired. Since the printout option is equal to 1, the output will show the summary tables of all junctions and pipes for the system and the time history tables.

The entire output is shown as Table 3 of the *User's Manual*. The output is divided into three parts, namely, the output of the original PFP-HYDRA, the open-channel hydraulic gradeline, and the pressurized flow results. The pressurized flow results include the following:

- an echo of input data for simulation and a listing of pipes and junctions
- the time history of depths for six junctions and the time history of flows
- the summary tables of maximum flows and depths for all junctions and pipes.

As indicated in the output, if a 10-sec time step violates the stability criteria, the program computes a new Δt of 2 sec instead.

Example 2: SCS Unit Hydrograph Method

Example 2 demonstrates the use of the SCS unit hydrograph method by giving a new command called SHY for each inflow manhole. As mentioned earlier, the SCS unit hydrograph method is based on land characteristics. There are six parameters required by the SHY command: watershed surface area, average slope, length to divide, land surface characteristics, storm duration, and total storm depth. In the *User's Manual*, Figure 20 shows an eight-line sewer system. The system contains pipes of various lengths, diameters, and roughnesses, as listed in Table 1 below. Initial conditions are specified. The time step given is 10 sec, and the total simulation time is 70 min. The print interval is 2 min.

The program checked the Δt value (10 sec) and found it to be too large. A new Δt of 1 sec was used.

The results for this example are shown in Table 7 of the *User's Manual*.

Table 1. Stadium Road Data Summary

Nodes		Length	Diameter	Manning's	
Upstream	Downstream	(ft)	(in)	n	Angle
7	6	90	48	.022	22
6	5	345	36	.012	40
15	5	75	15	.012	0
5	4	93	36	.012	11
4	3	160	36	.012	0
3	2	95	36	.012	61
2	1	36	36	.012	0

Example 3: Clark Method

This is a hypothetical example to show the use of the Clark method. The hypothetical system has four pipes of varying diameter and slope. A total of 218 acres is the catchment area for this system. The catchment is divided into three areas feeding each inlet. The total simulation time is 2 1/2 hr, and the time step given is 20 sec. Each inflow hydrograph is identical (i.e., time-area diagrams and storage coefficients are identical). Pipe system data are listed in the *User's Manual* (Table 8). The Clark method will usually be used for large areas; therefore, the user should pay close attention to the output. Because the system pipes may be very long, the results may not make sense. Table 10 in the *User's Manual* is the system output.

CONCLUSIONS

1. The modified PFSM provides four hydrograph options for computing stormwater runoff at junctions in the sewer system. The rational method is used with the original PFP-HYDRA, hydraulic gradeline computation, and pressurized flow simulation, whereas the SCS unit hydrograph method, the Clark method, and the user-supplied hydrograph option goes directly into pressurized flow analysis. The rational method is applied for small drainage areas; the SCS unit hydrograph method can be used when land characteristics, such as watershed area and slope, are available; and the Clark method is suitable for ungaged watersheds if one knows the time-area histogram.

2. A time step, Δt, is one critical parameter for pressurized flow simulation. The PFSM checks each pipe for possible violation of the surface wave criteria and selects a new Δt if the user-supplied Δt violates the criteria.

3. Print options make it easier for the user to read the results. The summary table provides maximum flows in pipes and maximum depths at junctions. The time history table of depths prints water depth changes vs. time at a particular junction, and the time history table of flows prints flow and velocity changes vs. time at the desired pipe. The detailed printout gives the depth at each junction and flow in each pipe in the system at a user-specified time interval.

4. With the addition of PFSM, the capability of PFP-HYDRA is significantly enhanced. PFSM can predict the location and duration of surcharge as well as flow rate, velocity, and hydraulic gradeline at selected locations in the sewer system.

RECOMMENDATIONS

1. PFSM, derived from the EXTRAN module of the model SWMM, should be used as a sewer analysis tool when there is a possibility that pipes might be surcharged. PFSM is attached to the FHWA's Pooled Fund PFP-HYDRA program but can also be used as a stand-alone program.

2. In general, the rational method is recommended for use with a smaller drainage area with an upper limit of 600 acres. The SCS unit hydrograph method should be used for midsized areas, up to 1,000 acres. The Clark method may be used for midsized areas but can also be used for larger areas (greater than 1,000 acres). The Clark method has a limitation on travel time; therefore, a watershed with a small time of concentration, 10 to 20 min, should not be modeled with this method. A user hydrograph or a triangular hydrograph generated by using the rational method would be better for this case.

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PRESSURIZED FLOW SIMULATION MODEL

USER'S MANUAL

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Appendix B

INTRODUCTION

The Pressurized Flow Simulation Model (PFSM) was developed in a previous HPR study at the Virginia Transportation Research Council (Yu & Wu, 1989). This module was designed to run in the analysis phase of PFP-HYDRA. The pressurized flow module simply adds new commands to the existing PFP-HYDRA commands to allow the user the option of computing possible surcharging within a storm sewer system. The pressurized flow option will work only as an analysis tool, not as a design tool.

This user documentation takes the user step by step through the use of the pressurized flow commands. (This guide is intended for use in conjunction with the *PFP-HYDRA User's Manual* [GKY & Associates, 1986]). This will include command orders and selection of critical parameters. All pressurized flow commands will be used in conjunction with existing PFP-HYDRA commands.

This manual has four main sections. The first section is an overview of pressurized flow, discussing the main options with this module. The second section is a technical section, discussing the general theoretical basis for the pressurized flow module. The third section is an overview of additional commands, and the fourth section includes several examples of pressurized flow input and output files.

OVERVIEW OF PRESSURIZED FLOW

The pressurized flow module is currently programmed for use with the rational method in hydraulic gradeline system analysis. The PNC command must be used. If the user wants to go directly into pressurized flow analysis, input hydrographs for each junction for inflow must be given. These hydrographs may be entered directly by the user or calculated using the SCS unit hydrograph or Clark method. The SCS and Clark hydrographs will be available only after the "pressurized flow only" option (Figure 1) is selected.

In general, the rational method is recommended for smaller catchments with an upper limit of 600 acres (Ponce, 1989). The SCS unit hydrograph method should be used for midsized areas, up to 1,000 acres (Viessman *et al.*, 1989). The Clark hydrograph may also be used for midsized areas but can also be used for larger areas (Ponce, 1989). The Clark method has a limitation on travel time; therefore, a watershed with a small time of concentration, 10 to 20 min, should not be modeled with this method. A user hydrograph or a triangular hydrograph generated by using the rational method would be better for this case.

The pressurized flow PFP-HYDRA output is divided into three parts: (1) the output of the original PFP-HYDRA, (2) the open-channel hydraulic gradeline, and (3) the pressurized flow results. The pressurized flow results include the following:

1. an echo of input data for simulation and a listing of pipes and junction
2. a continuity balance of the water passing through the system during the simulation
3. the time history of depths and flows for junctions and pipes specified by the user
4. summary tables of maximum computed water surface elevation for junctions and maximum computed flow for pipes.

Figure 1 shows the organization of the pressurized flow commands. From storm flow analysis, the user may choose to go into pressurized flow by one of two methods: the rational method or pressurized flow directly. Using the rational formula, the main PFP-HYDRA program will do an analysis and a hydraulic gradeline computation and then do a pressurized flow analysis if requested. Using pressurized flow directly, no hydraulic gradeline information is provided. Each string shows the commands required to achieve the user's goal.

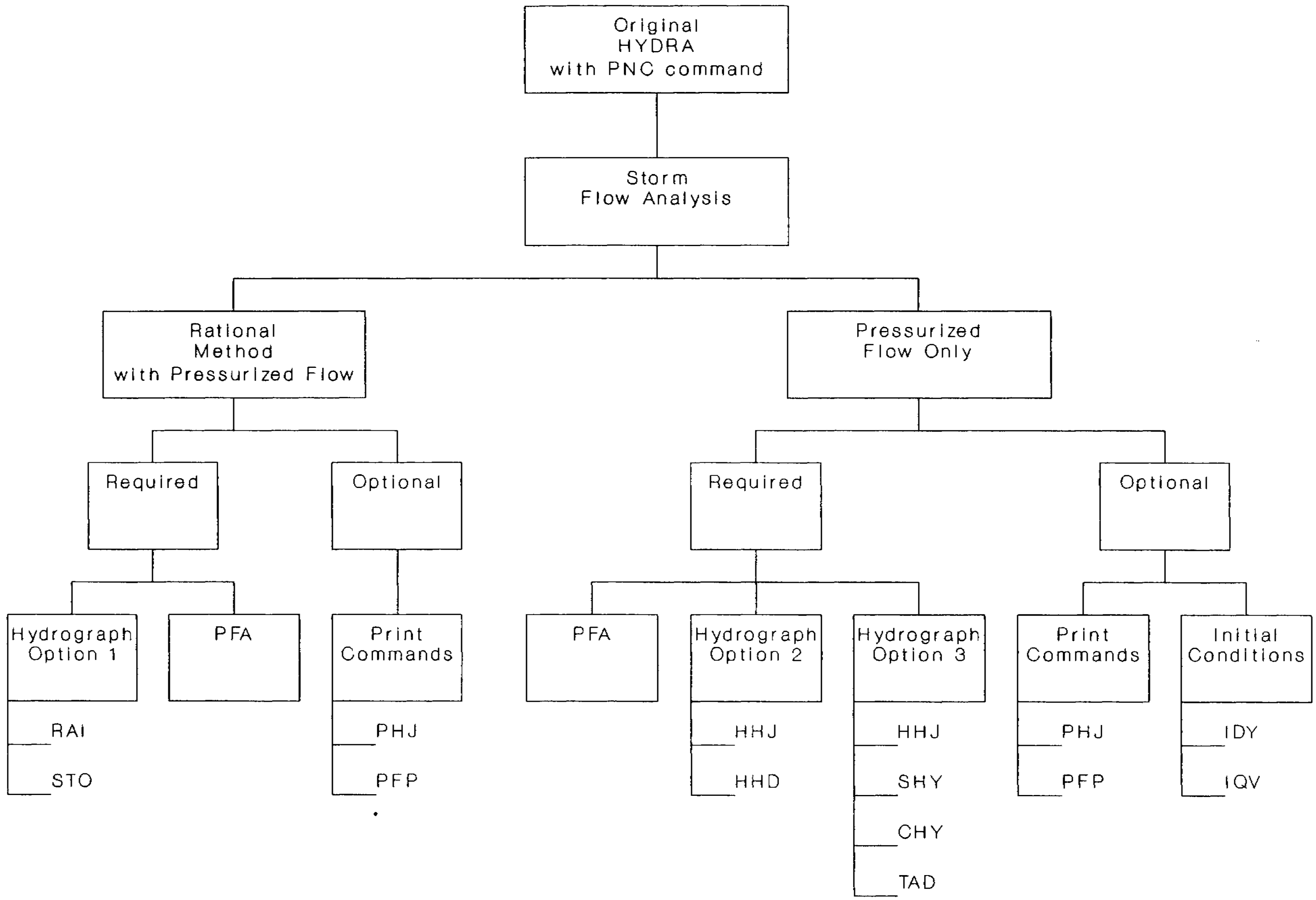

Figure 1. Organization of Pressurized Flow Commands

TECHNICAL INFORMATION

Storm Inflow

Option 1: Rational Method

Given a rainfall of constant intensity, I, uniformly distributed over a drainage area, A, the peak discharge, Q, is given by

$$Q = CIA \qquad \text{(eq. 1)}$$

The runoff coefficient, C, represents the ratio of the runoff volume and the rainfall volume. Common values of C are given in Appendix B, Table B4. An inflow triangular hydrograph (Figure 2) is generated based on the flow obtained from equation 1. The base of the hydrograph equals twice the time of concentration; i.e., the time to peak equals the time of concentration (Yu & Wu, 1989).

No new commands are used to generate this hydrograph. This is automatically done when the hydraulic gradeline computation is run simultaneously.

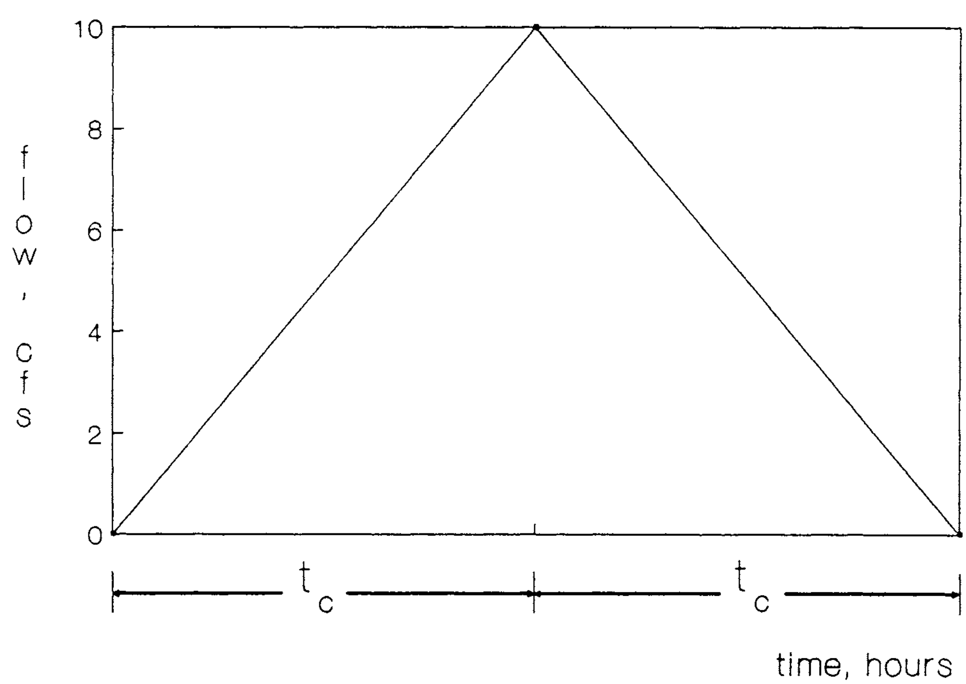

Figure 2. Rational Method Triangular Hydrograph

Option 2: SCS Unit Hydrograph Method

This hydrograph is generated using the SCS unit hydrograph method. The hydrograph determined using this method has a predetermined shape. However, the calculation of the hydrograph will depend heavily on the land characteristics used. Three equations govern the formation of this hydrograph. First, the determination of the lag time is found using the following equation:

$$t_l = \frac{l^{0.8}(S + 1)^{0.7}}{1,900Y^{0.5}} \qquad \text{(eq. 2)}$$

where
t_l = lag time (hr)
l = length to divide (ft)
Y = average water course slope (%)
S = potential maximum retention = (1,000/SCS curve number) − 10.

The SCS curve number may be determined from the SCS tables (Tables B1 through B3, Appendix B). Composite curve numbers for an area with multiple land use characteristics may be calculated accordingly, as described in SCS Technical Release No. 55. The length of divide is the distance from the centroid of the drainage area to the outfall point (or point of entrance into the sewer system).

The lag time is then used to calculate the time to peak and the peak flow. All other points on the hydrograph are functions of the peak flow (SCS Technical Release No. 55). The equations for these calculations are

$$t_p = \frac{D}{2} + t_l \qquad \text{(eq. 3)}$$

where
D = duration of rainfall (hr)
t_p = time to peak (hr)

and

$$q_p = \frac{484A}{t_p} \qquad \text{(eq. 4)}$$

where
A = drainage area (sq mi)
q_p = peak discharge (cfs).

The HHJ and SHY commands are needed to calculate the SCS hydrograph. SHY specifies the SCS curve number, the drainage area (entered in acres; the program makes proper conversions), the duration of rainfall, the depth of rainfall, the land slope, and the length to divide.

Option 3: Clark Method

The calculation of the Clark hydrograph depends on the availability of a time-area diagram. The time-area diagram is a histogram of incremental area vs.

time (Veissman *et al.*, 1989). An area is divided into several subareas, each of which has an equal travel time. The dividing lines are drawn equal time steps apart (see Figure 3). Using a topographical map makes this determination easier. A sample time-area histogram is shown in Figure 4.

After the time-area diagram is obtained, the flow is routed using a form of the continuity equation:

$$I - Q = K\frac{dQ}{dt} \qquad \text{(eq. 5)}$$

and

$$Q_2 = (C_0)(I) + (C_1)(Q_1) \qquad \text{(eq. 6)}$$

where
I = inflow
Q = outflow
K = routing constant (user supplied)
C_0 = $f(K$, time step$)$ = $2\Delta t/(2K + \Delta t)$
C_1 = $1 - C_0$.

If a K is not specified, a default value equal to the watershed travel time is assumed. (It is recommended that the user supply K.)

Three commands are needed to calculate a Clark hydrograph. HHJ specifies the junctions at which hydrographs are to be calculated. TAD supplies the time-

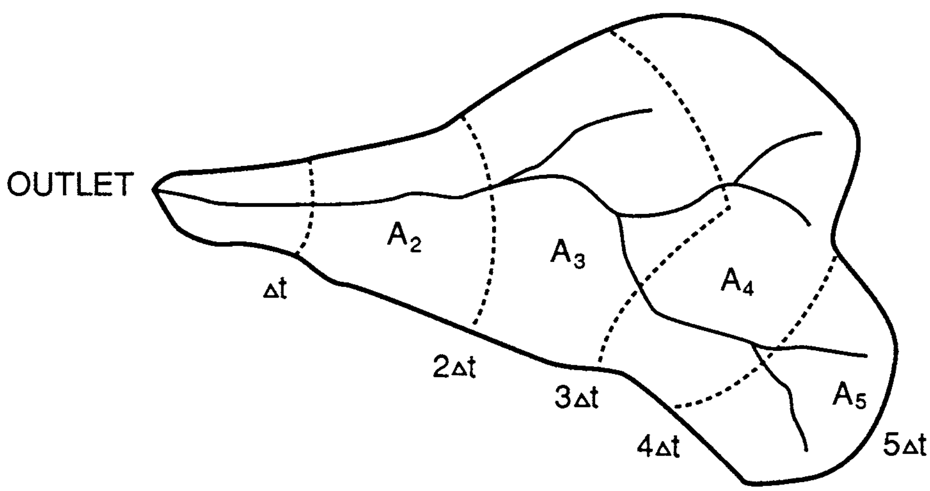

Figure 3. Area with Isochrones

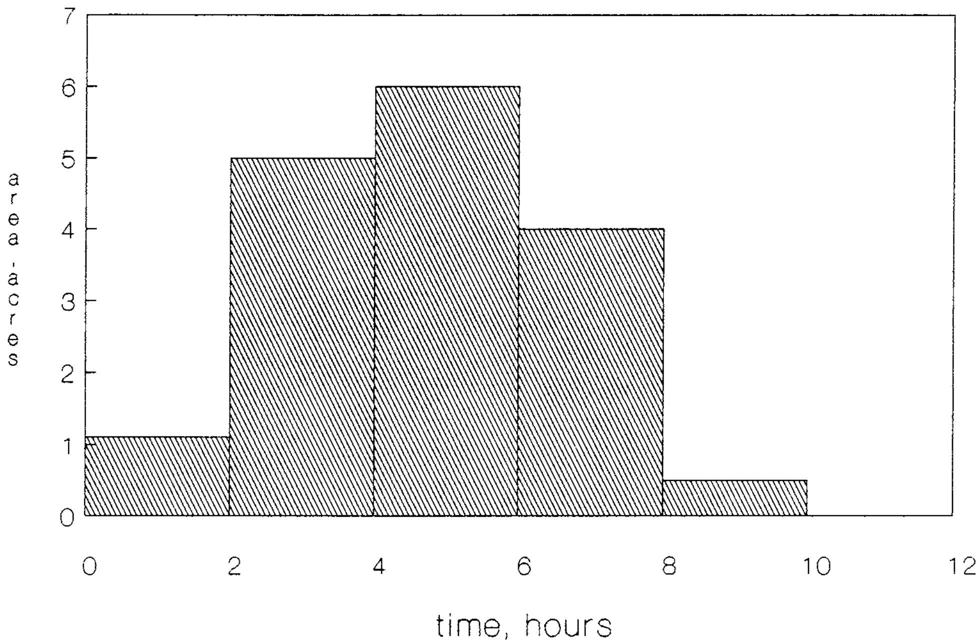

Figure 4. Time-Area Histogram

area diagram. CHY specifies the routing constant and the depth and duration of the storm.

Option 4: User Hydrographs

This option requires the user to input points defining the hydrograph. It is advised that the user choose these points as (1) flow at 0.0 time, (2) flow at peak, (3) inflection point on recession portion, and (4) amount at the end of the storm's influence. This hydrograph may be input using two commands: HHJ and HHD. HHJ specifies the junctions at which hydrographs will be supplied, and HHD actually contains the hydrographs points.

Hydraulics

Saint Venant Equations

The Saint Venant equations for calculating unsteady flow are:

- Continuity:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \qquad \text{(eq. 7)}$$

- Momentum:

$$\frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{1}{gA}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \cos\theta\frac{\partial h}{\partial x} - (S_0 - S_f) = 0 \qquad \text{(eq. 8)}$$

The pressurized flow model uses the kinematic wave approximation of the momentum equation. This assumes that inertia terms are negligible and the friction slope equals the bed slope (Viessman *et al.*, 1989). The basic differential equation becomes (Yu & Wu, 1989)

$$\frac{\partial Q}{\partial t} = -gAS_f + 2V\frac{\partial A}{\partial t} + V^2\frac{\partial A}{\partial x} - gA\frac{\partial H}{\partial x} \qquad \text{(eq. 9)}$$

Manning's equation defines the friction slope as

$$S_f = \frac{k}{gAR^{4/3}}Q|V| \qquad \text{(eq. 10)}$$

where
- Q = flow (ft^3/sec)
- k = $g(n/1.49)^2$ where n = Manning's coefficient
- A = cross-sectional area (ft^2)
- R = hydraulic radius (ft)
- V = velocity (ft/sec)
- S_f = friction slope
- g = 32.2 ft/sec^2.

A finite difference numerical method is employed to calculate the flow at each time step, Δt.

Choosing the Time Step

Since an explicit time-varying numerical scheme is employed, a stability criterion must be established. Stability is accomplished through the use of the time step, Δt, which satisfies the following (Yu & Wu, 1989):

- For a conduit:

$$\Delta t \le \frac{L}{\sqrt{gD}} \qquad \text{(eq. 11)}$$

- For a node:

$$\Delta t \le \frac{C'A_sH_{max}}{\Sigma Q} \qquad \text{(eq. 12)}$$

where

L = pipe length (ft)
C' = 0.1
D = pipe depth (in)
H_{max} = maximum water surface rise (ft)
A_s = corresponding surface area to the junction (ft^2)
ΣQ = net inflow to the junction (cfs).

Normally, the time step will be determined using the shortest, smallest pipe having a high inflow.

GLOSSARY OF ADDITIONAL COMMANDS

BEN	Allows the user to specify the bend angle and radius for a specified pipe system.
CHY	Enters a hydrograph generated by the Clark method.
HHD	Enters inflow hydrographs generated by the user.
HHJ	Allows the user to specify junctions with inflow hydrographs.
IDY	Allows the user to give an initial depth.
IQV	Allows the user to give an initial velocity.
NGL	Controls the hydraulic gradeline computation.
PFA	Defines the parameters for pressurized flow analysis.
PFP	Allows the user to define pipes for a detailed printout.
PHJ	Allows the user to define junctions for a detailed printout.
PNC*	Defines the node-link connections for hydraulic gradeline and pressurized flow computation.
SHY	Enters a hydrograph generated by the SCS unit hydrograph method.
SWI*	Sets the switch for determining the method of storm/sanitary/ pressurized flow analysis.
TAD	Allows the user to define a time-area diagram for flow.

* Commands modified from previous versions of PFP-HYDRA.

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COMMAND: BEN (Pipe Bend Data)

Purpose: To specify the bend angle and radius for the computation of losses due to curved alignment of pipe as shown in Figure 5.

Structure:

BEN radius, angle

1. radius — Bend radius of the link specified by the previous PIP command (ft).
2. angle — Bend angle of the link specified by the previous PIP command (degrees).

Notes:

1. The bend angle is usually between 0 and 120 degrees.
2. This command is usually placed after the PNC command to indicate that a bend occurs at the link specified by the previous PIP command.

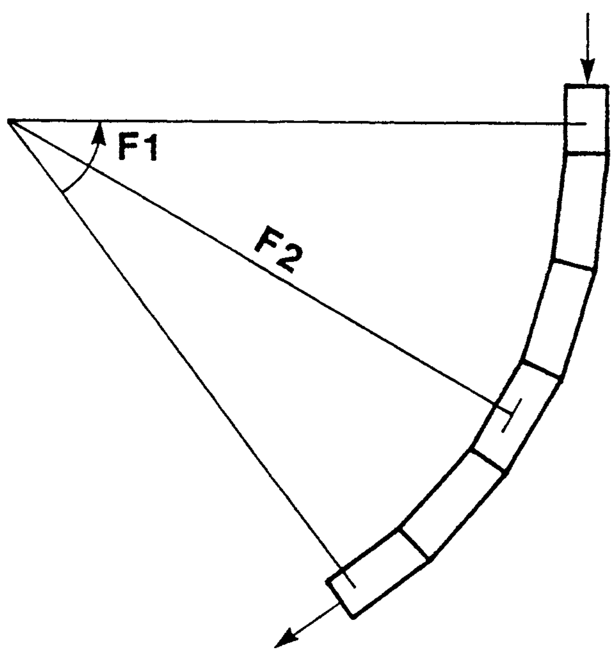

Figure 5. BEN Diagram

COMMAND: CHY (Clark Hydrograph)

Purpose: To calculate an inflow hydrograph using the Clark method.

Structure:

CHY K, duration, depth

1. K — Routing constant or storage constant. Used to determine how much of the runoff is actually discharged versus how much is stored. If no value is entered, the default value is equal to the travel time (hr).
2. duration — Storm duration (hr).
3. depth — Total storm depth (in).

Parameter Selection:

1. *Selection of K.* The best way to select a storage constant is to use a pre-calculated value based on runoff data. The Muskingum/Cunge method can be used for determination of a storage constant. When K is not known, a general guide is to use 1 to 2 times the travel time for the isochronal areas. The default value in the program is 1 × travel time.

2. *Duration and depth selection.* Both categories are based on a uniform rainfall. If a uniform rainfall is assumed, such as shown in Figure 6, the total depth is simply:

   $$0.5 \text{ in/hr} \times 2 \text{ hr} = 1.0 \text{ in.}$$

   If a hyetograph with a nonuniform rainfall is given, as shown in Figure 7, then the total depth is

   $$(1.0 \text{ in/hr} \times 1 \text{ hr}) + (2.0 \text{ in/hr} \times 1 \text{ hr}) + (0.4 \text{ in/hr} \times 1 \text{ hr})$$
   $$+ (0.7 \text{ in/hr} \times 1 \text{ hr}) + (2.2 \text{ in/hr} \times 1 \text{ hr}) + (0.1 \text{ in/hr} \times 1 \text{ hr})$$
   $$= 6.4 \text{ in}$$

COMMAND: CHY (cont.)

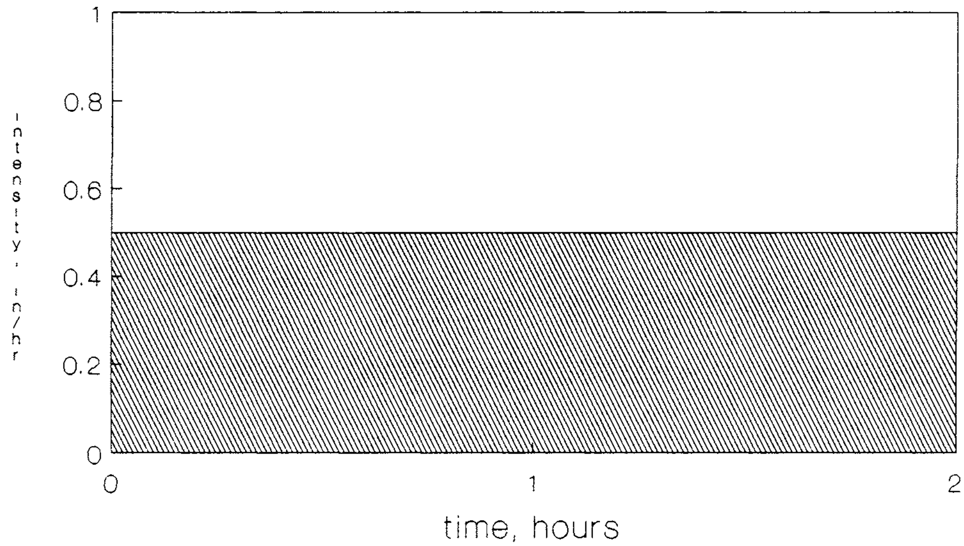

Figure 6. Uniform Rainfall Hyetograph

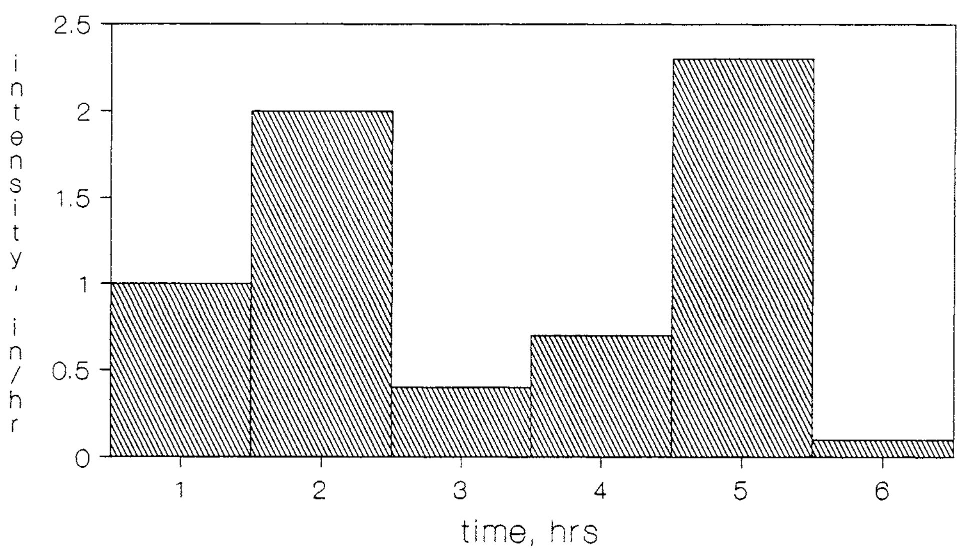

Figure 7. Variable Rainfall Hyetograph

COMMAND: CHY (cont.)

Notes:

1. The TAD command must precede the CHY command.
2. In order to use this method, the time of concentration of the watershed area must be greater than 10 min. If the time of concentration is less than 10 min, a user or triangular hydrograph is suggested.

Example:

```
CHY 1.2 3.0 0.7
```

COMMAND: HHD (Hydrograph Data)

Purpose: To allow the user to input an inflow hydrograph.

Structure:

HHD time, inflow, inflow, inflow, . . .

1. time Time at which the inflow occurs (hr).
2. inflow Flow rate (cfs).

Parameter Selection:

The input for four user hydrographs (Figures 8 through 11) is obtained in the following manner for a 45-min pressurized flow simulation.

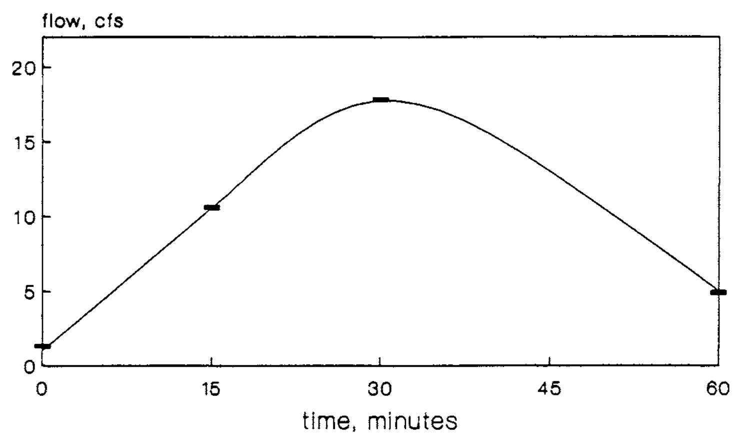

Figure 8. Junction 10 Hydrograph

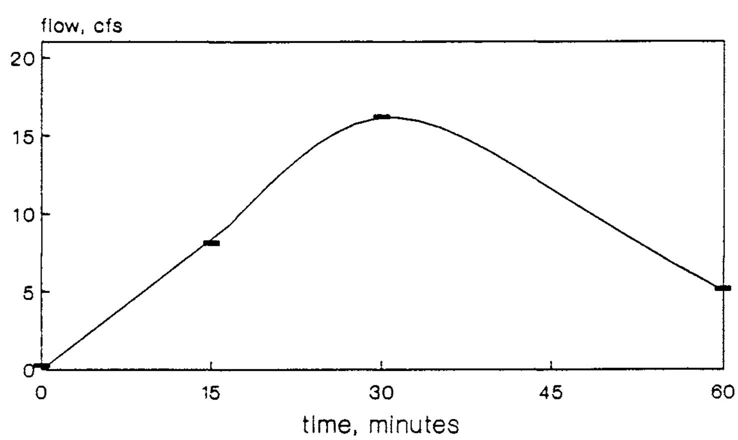

Figure 9. Junction 20 Hydrograph

COMMAND: HHD (cont.)

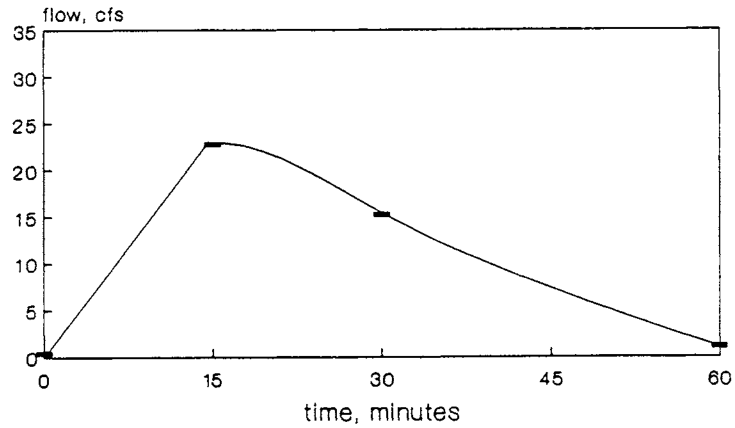

Figure 10. Junction 30 Hydrograph

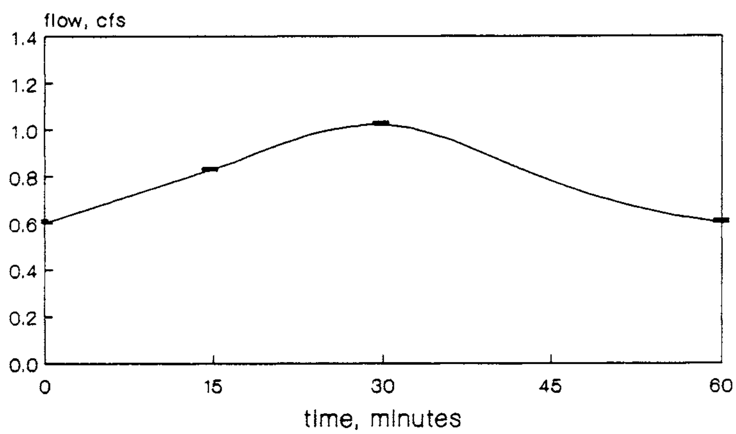

Figure 11. Junction 40 Hydrograph

Time (hr)	Jctn 10 Flow (cfs)	Jctn 20 Flow (cfs)	Jctn 30 Flow (cfs)	Jctn 40 Flow (cfs)
0.0	1	0	0	0.6
0.25	10	7	23	0.8
0.50	18	16	14	1.0
1.0	5	5	1	0.6

COMMAND: HHD (cont.)

Notes:

1. Only four points can be input for time and discharge flows.
2. The first point must be at time 0 hours.
3. The time steps must be the same for each hydrograph.
4. The HHJ command must precede the HHD command.

Examples (hydrograph points for four nodes):

HHD 0.0 1.0 0.0 0.0 0.6

HHD 0.25 10.0 7.0 23.0 0.8

HHD 0.50 18.0 16.0 14.0 1.0

HHD 0.75 13.0 11.0 7.0 0.7

COMMAND: HHJ (Hydrograph Junction Input)

Purpose: To specify which junctions will have inflow hydrographs and in what order.

Structure:

HHJ junction number, junction number, junction number, . . .

Notes:

1. The maximum number of junction hydrographs is defined by field 8 on the PFA command.
2. The PFA command must precede the HHJ command.

Example:

HHJ 10 20 30 40

COMMAND: IDY (Initial Depth)

Purpose: To supply the initial depth in the upstream pipe from the node for pressurized flow evaluation.

Structure:

IDY depth, depth, depth, . . .

1. depth — Initial depth (ft) in pipe as shown in Figure 12.

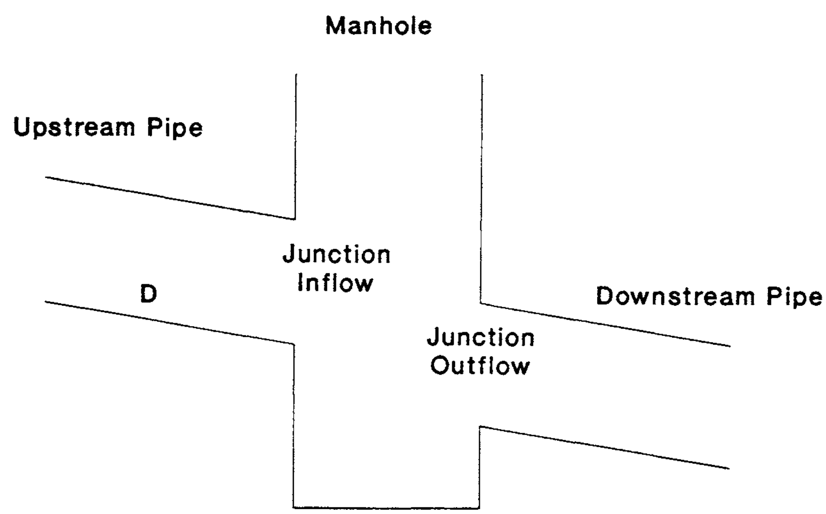

Figure 12. Location of Initial Depth

Notes:

1. The IQV command must precede the IDY command.
2. This command is not used with the rational method.
3. The order of entry should be exactly as junctions appear in the PNC commands preceding the PFA command. *For example:*
   - PNC 111 11 5 1 1 1 30. 0 0.
   - PNC 112 1 1 12 1 1 0. 0 0.
   - PNC 120 12 1 0 4 1 15. 0 0.

   The IDY command would contain depths in the following order: 11 1 12 0. If any depth is zero or unknown, the zero must be entered to "hold the place" occupied by that value. Do not confuse this order with the junction order in the HHJ command.
4. For an example, see the IQV example.

COMMAND: IQV (Initial Discharge and Velocity)

Purpose: Supplies the initial discharge and velocity in the same order as the PNC command specified at upstream nodes and the outfall at downstream nodes.

Structure:

IQV discharge, velocity, discharge, velocity, . . .

1. discharge Initial discharge in most upstream pipe (cfs).
2. velocity Initial velocity in most upstream pipe (fps).
3. discharge

Notes:

1. The values should be placed in the same order as the junctions appear in the PNC commands preceding the PFA command.
2. The location of each data set should be as illustrated in Figure 13.

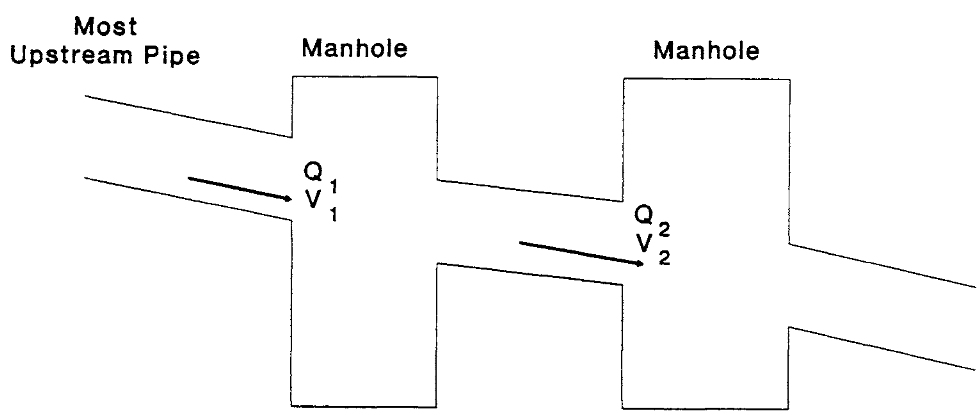

Figure 13. Location of Initial Velocities and Flows

Example:

IQV 5.0 0.785 5.0 3.142 5.0 7.069

IDY 7.0 3.0 1.5

COMMAND: NGL (Hydraulic Gradeline Computation Control)

Purpose: To stop the computation of the hydraulic gradeline in PFP-HYDRA. When PFP-HYDRA reads this command in the input data file, the gradeline will not be computed after the design or analysis of the system is completed. Otherwise, PFP-HYDRA will assume that the user wants to compute the hydraulic gradeline. This command has no parameters following it. NGL can be placed anywhere in the data file.

Structure:

NGL

COMMAND: PFA (Pressurized Flow Data)

Purpose: To define control parameters for running the pressurized flow option.

Structure:

PFA sim time, time step, interval, pr option, start time, junctions, pipes, hydrographs, iterations, tolerance, run options

1. sim time — Total simulation time to run the pressurized flow (min).
2. time step — Defines the incremental time used to calculate flows (sec).
3. interval — Printing interval between points in history table (integer number).
4. pr option — Printout type. Select:

   0 Summary table.

   1 Summary and time history tables.

   2 Summary and time history tables and a detailed printout including each cycle result.
5. start time — Start time of simulation (hr).
6. junctions — Junctions for detailed printing of head output when print option is 1 or 2 (20 max).
7. pipes — Pipes for detailed discharge printing when print option is 1 or 2 (20 max).
8. hydrographs — Number of junctions having input hydrographs.
9. iterations — Maximum number of times to readjust head and flow of surcharged junctions.
10. tolerance — Segment of flow in surcharged area to be used as the tolerance for ending surcharge iterations.
11. run options — Run pressurized flow only combined with selecting the SWI command. Select:

    1 If running pressurized flow only.

    0 With rational method, default value.

Notes:

1. The total simulation time should be equal to or greater than the longest base time of hydrographs in the system plus the travel time for the longest pipe.

COMMAND: PFA (cont.)

2. The time step is critical in terms of computing time and the stability of the program. It must be selected carefully. Equations 11 and 12 can be used to calculate a time step if the user desires. If a time step provided by the user violates the preset stability limit, the program will select an appropriate time step.

3. Iterations and tolerance control the accuracy of the solution in surcharged areas. Flows and heads in these areas are recalculated until the difference between inflow and outflow is less than the tolerance limit the user selects, or until the maximum number of iterations the user specifies has been reached. Acceptable values for iterations and tolerance have been found to be 30 and 0.05, respectively.

4. The combinations of SWI command and run options are as follows:

SWI	Option	Result
6	1	Pressurized flow only
6	0	Error, will not run
Less than 6	1	PFP-HYDRA, pressurized flow only
Less than 6	0	PFP-HYDRA, hydraulic gradeline and pressurized flow if necessary

Examples:

SWI 2 (Rational method with summary printout.)

PFA 20. 10. 0 0 0. 4 4 0 40 0.5

SWI 6 (Pressurized flow only.)

PFA 10. 10. 0 0 0. 4 4 3 40 1

COMMAND: PFP (Printed Flow Pipe)

Purpose: To print a list of pipes for which flows and velocities are to be printed.

Structure:

PFP pipe, pipe, pipe

1. pipe   Pipe number for detail printout.

Note:

1. Prints detailed output for pipes specified in this command. Can specify up to the number of pipes entered in field 7 of the PFA command. A maximum of 20 pipes may be specified.

Example:

PFP 11 12 13

COMMAND: PHJ (Printed Heads Junctions)

Purpose: To print a list of individual junctions for which water depth and water surface elevations are to be printed.

Structure:

PHJ junction, junction, . . .

1. junction Junction number for detailed printout.

Note:

1. Can specify up to the number of junctions entered in field 6 of the PFA command. A maximum of 20 junctions may be specified.

Example:

PHJ 10 20 30

COMMAND: PNC (Pipe Node Connection)

Purpose: To specify the connection of links and nodes for the computation of the hydraulic gradeline. Each PNC command must immediately follow the PIP command.

Structure:

PNC pipe no., us node, us type, ds node, ds type, id main, angle, id side, angle, terminal loss, tail elev, minor loss, us invert, ds invert, shaping

1. pipe no. — Pipe number.
2. us node — Number (label) of node connecting the upstream end of the pipe specified in field 1.
3. us type — Type of node in field 2. Select:
   - 1 Manhole.
   - 2 Pipe junction.
   - 3 Pump.
   - 4 Terminal manhole.
4. ds node — Number (label) of node connecting the downstream end of the pipe specified in field 1.
5. ds type — Type of node in field 4. Select:
   - 1 Manhole.
   - 2 Pipe junction.
   - 3 Pump.
   - 4 Outfall point.
6. id main — Identification of pipe specified by the previous PIP command and field 1 as mainline link. Select:
   - 1 Yes.
   - 0 No.
7. angle — Deflection angle of mainline link. Always less than 90 degrees.
8. id side — Identification of pipe specified by the previous PIP command and field 1 as sideline pipe. Select:

COMMAND: PNC (cont.)

		1	Yes.
		0	No.
9.	angle	Deflection angle of sideline link. Always less than 90 degrees.	
10.	terminal loss	Loss coefficient for terminal nodes. Can be manhole loss coefficient, entrance loss coefficient, etc. The default value used is 1.5 (recommended by VDOT).	
11.	tail elev	Tailwater elevation at the point of the system's outlet. This field is optional.	
12.	minor loss	Minor loss coefficient. Required only when the downstream velocity is less than the velocity within a pipe. This field is optional. Examples are given in Table 1.	
13.	us invert	Distance of pipe invert above junction invert at upstream end (ft). This field is optional.	
14.	ds invert	Distance of pipe invert above junction invert at downstream end (ft). This field is optional.	
15.	shaping	Identification of inlet shaping. User can specify shaping coefficient here. If none is available, leave blank. Program will use a default value of 0.5.	

Table 1. Loss Coefficients for PNC Command

Type of Entrance	K
Square-cornered entrance flush with wall	0.5
Rounded entrance	0.04–0.2
Inward-projecting, square-cornered entrance	0.8–0.9

Source: Brater, E. F., & King, H. W. (1976). *Handbook of hydraulics for the solution of hydraulic engineering problems* (6th ed.). New York: McGraw Hill.

Note:

1. It is suggested that the user describe the system using the technique illustrated in Figure 14. Then, pipes and node locations are easily identified.

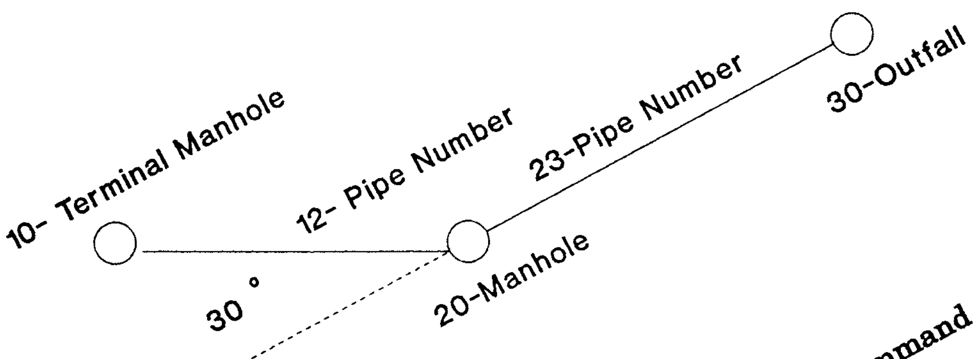

Figure 14. System Labeling for PNC Command

Examples:

PNC 12 10 5 20 1 1 47. 2 0. (Minimum required.)

PNC 12 10 5 20 1 1 47. 2 0. 1.5 0.2 (Specifies loss coefficients.)

PNC 12 10 5 20 1 1 47. 2 0. 1.5 2.0 0.2 3.1 2.1 (Excludes inlet shapin

COMMAND: SHY (SCS Hydrograph)

Purpose: To give PFP-HYDRA the parameters necessary to calculate the inflow hydrograph to a node using the SCS unit hydrograph method.

Structure:

SHY area, slope, length, SCS-CN, duration, depth

1.	area	Watershed area (acres).
2.	slope	Average land slope (%).
3.	length	Length to divide (ft).
4.	SCS-CN	SCS curve number used to describe land surface characteristics (SCS Technical Release No. 55).
5.	duration	Storm duration (hr).
6.	depth	Total storm depth (in).

Parameter Selection:

1. Watershed area is the area of all the land that will contribute to inflow at a particular junction. Choose this area just as in the rational method of choosing an area for the STO command.
2. An average land slope may be obtained by calculating slopes over several different reaches (e.g., the steeper and shallower reaches) and averaging these.
3. The curve number may be selected according to the type of development that occurs in that watershed area. *For example*: Given 1/4-acre residential lots in Albemarle County. SCS soil classification for Albemarle County is Group B. This corresponds to a curve number of 75.
4. Choose the total depth of excess rainfall the storm will produce. This is the same total depth used in the CHY command.

Notes:

1. The distance from the manhole to the catchment centroid can be used for field 3, length.
2. The HHJ command must precede the SHY command.
3. If the watershed area has several different land characteristics, a composite SCS-CN may be entered. (See Appendix B for how to calculate the composite curve number.)

Example:

SHY 5.0 38.1 210.0 67.0 3.0 0.7

COMMAND: SWI (Criteria Switch)

Purpose: To establish the method by which PFP-HYDRA is to analyze storm flows.

Structure:

SWI number

1. number — A number describing the PFP-HYDRA method. Select:

   1 Sanitary analysis only.

   2 Storm analysis—rational method only.

   3 Storm analysis—hydrographic method only.

   4 Sanitary and rational analysis.

   5 Sanitary and hydrographic analysis.

   6 Pressurized flow simulation only. Can be combined with the 11th parameter of the PFA command to control hydraulic gradeline computation.

COMMAND: TAD (Time-Area Diagram)

Purpose: To provide a time-area diagram of the catchment flow processes for the calculation of a hydrograph.

Structure:

TAD time, area, time, area, . . .

1. time — Time at which the subarea contributes to the outflow of the catchment (hr).
2. area — Area that contributes to the outflow of the catchment in the allotted time (acres).

Parameter Selection:

1. Using knowledge of land surface, obtain the slope between the junction and the point of contributing area that takes the longest time to get to the junction.
2. Look up the slope and corresponding land characteristics in Figures B1 and B2 (Appendix B) to obtain a velocity. Divide the distance to the point in the watershed by the velocity to get the travel time.
3. Separate the area into increments based on travel times to the junction. (*Note:* Time increments must be equal.)
4. Plot the time-area histogram. A sample time-area histogram is given in Figure 15.

Notes:

1. The first time-area set must be 0.0, 0.0.
2. The time-area diagram is entered from the point most downstream to the point most upstream.
3. The time must be entered in equal steps. *For example:* 0.0 0.2 0.4 0.6.
4. The HHJ command must precede the TAD command.
5. The CHY command must follow the TAD command.

COMMAND: TAD (cont.)

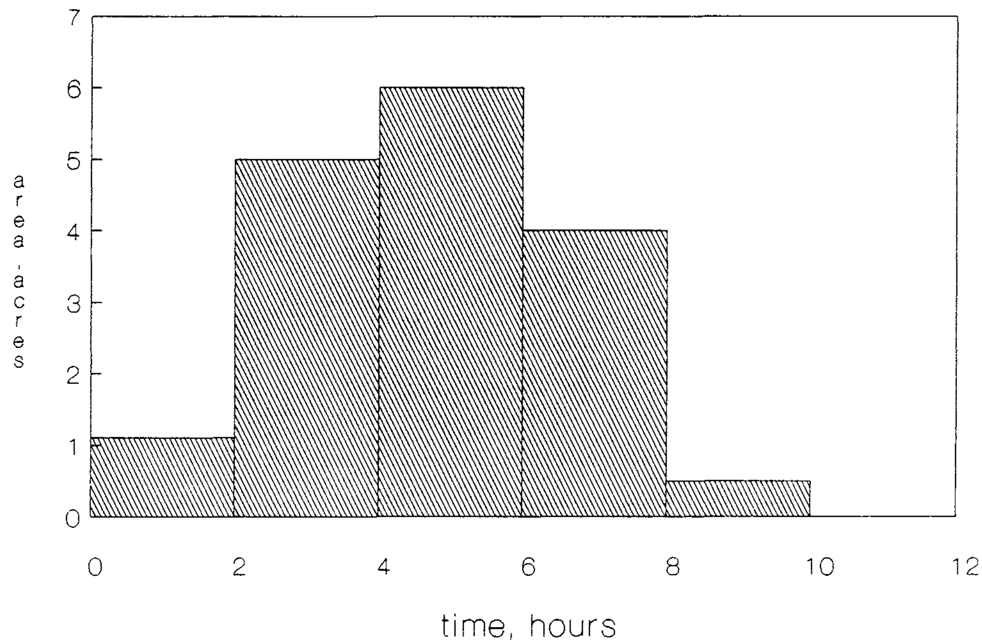

Figure 15. Time-Area Histogram

Example:

TAD 0.0 0.0 0.25 5.2 0.50 3.1 0.75 0.0

EXAMPLES

Example 1: Rational Method

The Campostella Road Sewer project is located in the tidewater region of Virginia. The sewer network contains 16 pipes of different lengths and elevations, with relatively flat slopes. A 10-year intensity-duration-frequency (IDF) curve inputs runoff conditions to the system, as required by the rational method. A tailwater elevation of 103.5 ft is assumed at the outfall point. A 10-sec time step and total simulation time of 25 min are input for pressurized flow control parameters. The resulting input and output files appear in Tables 2 and 3. Figure 16 is a diagram of the sewer system.

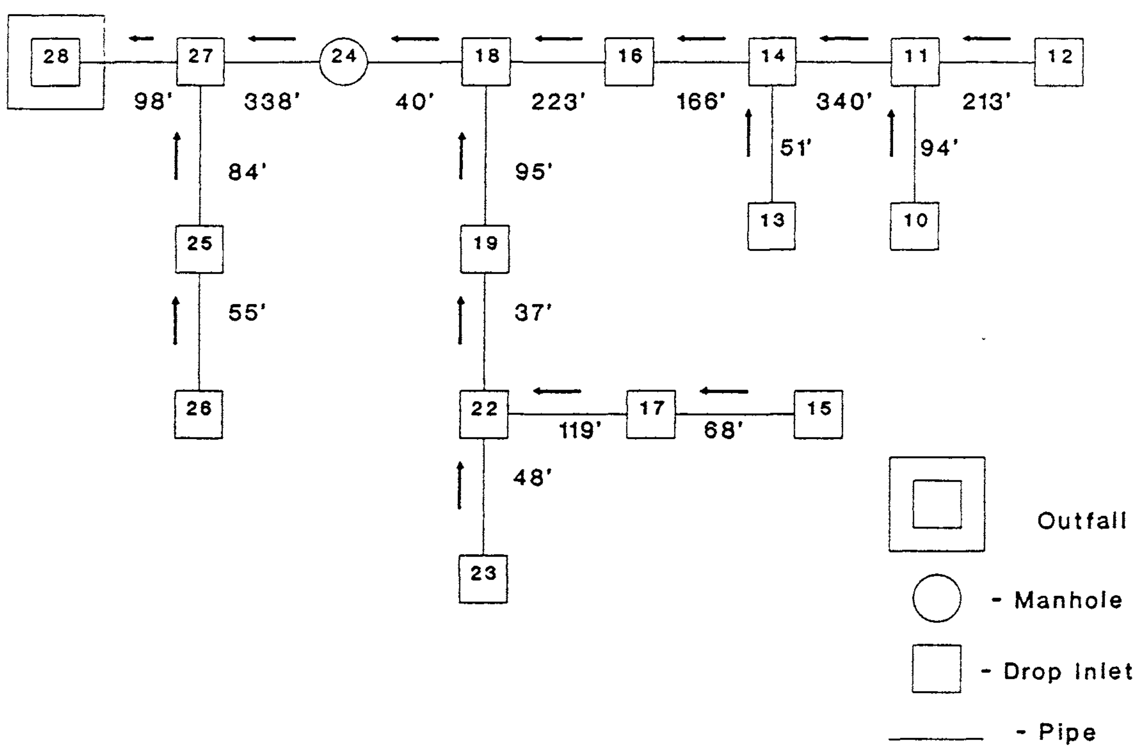

Figure 16. Campostella Road Layout

Table 2. Campostella Road Input File

```
0010 JOB CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA
0020 SWI 2
0030 CRI 0
0040 PDA .013 15 3.92 2.5 2.5 .0025 72
0050 RAI 0 7.1 5 7.1 8 6.4 10 6 15 5.1 20 4.5 30 3.6 40 3 +
0055     50 2.6 60 2.3 120 1.4 300 1.4
0060 NEW LATERAL: 12 TO 11
0070 STO 0.23 .9 10
0080 PIP 213 114.44 113.95 111.42 110.7 -15
0085 PNC 1211 12 5 11 1 2 0 1 0 1.5 0 0.2 0 0 0
0090 HOL 1
0100 NEW LATERAL: 13 TO 14
0110 STO .19 .9 10
0120 PIP  51 114.81 113.65 109 107.63 -15
0125 PNC 1314 13 5 14 1 2 0 1 90 1.5 0 0.2 0 0 0
0130 HOL 2
0140 NEW LATERAL: 15 TO 22
0145 REM LATERAL: 15 TO 17
0150 STO .08 .9 5
0160 PIP 68 116.9 113.66 112.98 109.74 -15
0162 PNC 1517 15 5 17 1 2 0 1 0 1.5 0 0.2 0 0 0
0163 REM LATERAL: 17 TO 22
0164 STO .21 .9 5
0166 PIP 119 113.66 110.5 109.74 108.23 -15
0168 PNC 1722 17 1 22 1 2 0 1 90 0 0 0.2 0 0 0
0170 HOL 3
0180 NEW LATERAL: 23 TO 18
0185 REM LATERAL: 23 TO 22
0190 STO .19 .9 10
0200 PIP 48 112.5 110.5 108.58 108 -15
0210 PNC 2322 23 5 22 1 2 0 1 0 1.5 0 0.2 0 0 0
0220 REM LATERAL: 22 TO 19
0270 STO .15 .9 10
0280 REC 3
0300 PIP 37 110.5 122.25 106.5 106.1 -15
0305 PNC 2219 22 1 19 1 2 0 1 0 0 0 0.2 0 0 0
0307 REM LATERAL: 19 TO 18
0310 STO .63 .9 10
0320 PIP 95 122.25 121.39 106.1 105.5 -15
0325 PNC 1918 19 1 18 1 2 0 1 90 0 0 0.2 0 0 0
0327 HOL 3
0329 NEW LATERAL: 26 TO 27
0330 REM LATERAL: 26 TO 25
0332 STO .44 .9 10
0333 PIP 55 108.09 107.89 104.17 103.97 -15
0334 PNC 2625 26 5 25 1 2 0 1 0 1.5 0 0.2 0 0 0
0335 REM LATERAL: 25 TO 27
0336 STO .27 .9 10
0337 PIP 84 107.89 105.1 103.97 102.83 -15
0338 PNC 2527 25 1 27 1 2 0 1 90 0 0 0.2 0 0 0
0339 HOL 4
0340 NEW TRUNK: 10 TO 14
0345 REM TRUNK: 10 TO 11
0350 STO 1.78 .9 15
0360 PIP 94 113.95 113.95 108.91 108.34 -18
0365 PNC 1011 10 5 11 1 1 90 2 0 1.5 0 0.2 0 0 1
0367 REM TRUNK: 11 TO 14
0370 STO 0.32 .9 15
```

```
0375 REC 1
0380 PIP 340 113.95 113.65 108.34 106.81 -21
0390 PNC 1114 11 1 14 1 1 0 2 0 0 0 0.2 0 0 1
0400 REM TRUNK: 14 TO 16
0410 STO .19 .9 10
0420 REC 2
0440 PIP 166 113.65 114.99 106.81 105.86 -21
0445 PNC 1416 14 1 16 1 1 0 2 0 0 0 0.2 0 0 1
0447 REM TRUNK 16 TO 18
0450 STO .26 .9 10
0460 PIP 223 114.99 121.39 105.86 105.23 -21
0465 PNC 1618 16 1 18 1 1 0 2 0 0 0 0.2 0 0 1
0480 REM TRUNK: 18 TO 24
0490 STO .74 .9 15
0500 REC 3
0520 PIP 40 121.39 117.38 105.23 104.89 -24
0535 PNC 1824 18 1 24 1 1 0 2 0 0 0 0.2 0 0 1
0537 REM TRUNK: 24 TO 27
0538 FLO 0.2
0530 PIP 338 117.38 105.1 104.89 102.02 -24
0540 PNC 2427 24 1 27 1 1 0 2 0 0 0 0.2 0 0 1
0610 REM TRUNK: 27 TO OUT
0620 STO 3.41 .9 15
0630 REC 4
0650 PIP 98 105.1 105.1 101.48 100.7 -30
0655 PNC 2728 27 1 28 4 1 0 2 0 0 103.2 0.2 0 0 1
0660 PFA 25 10 1 1 0 6 8 0 30 0.05
0670 PHJ 19 18 16 14 10 11
0680 PFP 1918 1011 1114 1416 1618 1824 2427 2728
0690 END
```

Table 3. Campostella Road Output File

```
*** PFP-HYDRA (Version of Oct. 2, 1986) ***            DATE 06-04-90
                                                        PAGE NO   1


CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA

Commands Read From File example.hda
   10 JOB
   20 SWI 2
   30 CRI 0
   40 PDA .013 15 3.92 2.5 2.5 .0025 72
   50 RAI 0 7.1 5 7.1 8 6.4 10 6 15 5.1 20 4.5 30 3.6 40 3 +
        50 2.6 60 2.3 120 1.4 300 1.4
```

IDF CURVE

```
.71E+01**.....................................................................
       .                                                                     .
       . *                                                                   .
       . *                                                                   .
.53E+01.                                                                     .
       .   *                                                                 .
       .                                                                     .
       .    *                                                                .
       .                                                                     .
.35E+01.      *                                                              .
       .                                                                     .
       .        *                                                            .
       .           *                                                         .
       .             *                                                       .
.18E+01.                                                                     .
       .                           *                                         *
       .                                                                     .
       .                                                                     .
       .                                                                     .
.00E+00*......................................................................
       .00       .71      1.43      2.14      2.86      3.57      4.29      5.00
```

PLOT-DATA (VALUE Vs.TIME)

.000	7.100	2.000	1.400	.000	.000	.000	.000	.000	.000
.083	7.100	5.000	1.400	.000	.000	.000	.000	.000	.000
.133	6.400	.000	.000	.000	.000	.000	.000	.000	.000
.167	6.000	.000	.000	.000	.000	.000	.000	.000	.000
.250	5.100	.000	.000	.000	.000	.000	.000	.000	.000
.333	4.500	.000	.000	.000	.000	.000	.000	.000	.000
.500	3.600	.000	.000	.000	.000	.000	.000	.000	.000
.667	3.000	.000	.000	.000	.000	.000	.000	.000	.000
.833	2.600	.000	.000	.000	-99.000	.000	.000	.000	.000
1.000	2.300	.000	.000	.000	.000	.000	.000	.000	.000

```
   60 NEW LATERAL: 12 TO 11
   70 STO 0.23 .9 10
   80 PIP 213 114.44 113.95 111.42 110.7 -15
```

Table 3. Campostella Road Output File, cont.

```
*** PFP-HYDRA (Version of Oct. 2, 1986) ***          DATE 06-04-90
                                                     PAGE NO   2

    CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA
 85 PNC 1211 12 5 11 1 2 0 1 0 1.5 0 0.2 0 0 0
 90 HOL 1
100 NEW LATERAL: 13 TO 14
110 STO .19 .9 10
120 PIP  51 114.81 113.65 109 107.63 -15
125 PNC 1314 13 5 14 1 2 0 1 90 1.5 0 0.2 0 0 0
130 HOL 2
140 NEW LATERAL: 15 TO 22
145 REM LATERAL: 15 TO 17
150 STO .08 .9 5
160 PIP 68 116.9 113.66 112.98 109.74 -15
162 PNC 1517 15 5 17 1 2 0 1 0 1.5 0 0.2 0 0 0
163 REM LATERAL: 17 TO 22
164 STO .21 .9 5
166 PIP 119 113.66 110.5 109.74 108.23 -15
168 PNC 1722 17 1 22 1 2 0 1 90 0 0 0.2 0 0 0
170 HOL 3
180 NEW LATERAL: 23 TO 18
185 REM LATERAL: 23 TO 22
190 STO .19 .9 10
200 PIP 48 112.5 110.5 108.58 108 -15
210 PNC 2322 23 5 22 1 2 0 1 0 1.5 0 0.2 0 0 0
220 REM LATERAL: 22 TO 19
270 STO .15 .9 10
280 REC 3
300 PIP 37 110.5 122.25 106.5 106.1 -15
305 PNC 2219 22 1 19 1 2 0 1 0 0 0 0.2 0 0 0
307 REM LATERAL: 19 TO 18
310 STO .63 .9 10
320 PIP 95 122.25 121.39 106.1 105.5 -15
325 PNC 1918 19 1 18 1 2 0 1 90 0 0 0.2 0 0 0
327 HOL 3
329 NEW LATERAL: 26 TO 27
330 REM LATERAL: 26 TO 25
332 STO .44 .9 10
333 PIP 55 108.09 107.89 104.17 103.97 -15
334 PNC 2625 26 5 25 1 2 0 1 0 1.5 0 0.2 0 0 0
335 REM LATERAL: 25 TO 27
336 STO .27 .9 10
337 PIP 84 107.89 105.1 103.97 102.83 -15
338 PNC 2527 25 1 27 1 2 0 1 90 0 0 0.2 0 0 0
339 HOL 4
340 NEW TRUNK: 10 TO 14
345 REM TRUNK: 10 TO 11
350 STO 1.78 .9 15
360 PIP 94 113.95 113.95 108.91 108.34 -18
365 PNC 1011 10 5 11 1 1 90 2 0 1.5 0 0.2 0 0 1
367 REM TRUNK: 11 TO 14
370 STO 0.32 .9 15
```

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Table 3. Campostella Road Output File, cont.

```
     *** PFP-HYDRA (Version of Oct. 2, 1986) ***          DATE 06-04-90
                                                          PAGE NO   3

     CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA
 375 REC 1
 380 PIP 340 113.95 113.65 108.34 106.81 -21
 390 PNC 1114 11 1 14 1 1 0 2 0 0 0 0.2 0 0 1
 400 REM TRUNK: 14 TO 16
 410 STO .19 .9 10
 420 REC 2
 440 PIP 166 113.65 114.99 106.81 105.86 -21
 445 PNC 1416 14 1 16 1 1 0 2 0 0 0 0.2 0 0 1
 447 REM TRUNK 16 TO 18
 450 STO .26 .9 10
 460 PIP 223 114.99 121.39 105.86 105.23 -21
 465 PNC 1618 16 1 18 1 1 0 2 0 0 0 0.2 0 0 1
 480 REM TRUNK: 18 TO 24
 490 STO .74 .9 15
 500 REC 3
 520 PIP 40 121.39 117.38 105.23 104.89 -24
 535 PNC 1824 18 1 24 1 1 0 2 0 0 0 0.2 0 0 1
 537 REM TRUNK: 24 TO 27
 538 FLO 0.2
 530 PIP 338 117.38 105.1 104.89 102.02 -24
 540 PNC 2427 24 1 27 1 1 0 2 0 0 0 0.2 0 0 1
 610 REM TRUNK: 27 TO OUT
 620 STO 3.41 .9 15
 630 REC 4
 650 PIP 98 105.1 105.1 101.48 100.7 -30
 655 PNC 2728 27 1 28 4 1 0 2 0 0 103.2 0.2 0 0 1
 660 PFA 25 10 1 1 0 6 8 0 30 0.05
 670 PHJ 19 18 16 14 10 11
 680 PFP 1918 1011 1114 1416 1618 1824 2427 2728
 690 END
END OF RUN.
```

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct. 2, 1986) *** DATE 06-04-90
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CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA

*** LATERAL: 12 TO 11 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	Diam (in)
1	213	15	111.4	.00338	3.0	1.7	2.8	1.24	33		
			110.7		3.3	1.9	3.1	3.77			

LENGTH = 213. COST = 0.
TOTAL LENGTH = 213. TOTAL COST = 0.

*** LATERAL: 13 TO 14 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	Diam (in)
2	51	15	109.0	.02686	5.8	4.5	5.5	1.03	10		
			107.6		6.0	4.7	8.7	10.62			

LENGTH = 51. COST = 0.
TOTAL LENGTH = 51. TOTAL COST = 0.

*** LATERAL: 15 TO 22 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	Diam (in)
3	68	15	113.0	.04765	3.9	2.6	5.4	.51	4		
			109.7		3.9	2.6	11.5	14.14			
4	119	15	109.7	.01269	3.9	2.6	4.9	1.84	25		
			108.2		2.3	.9	5.9	7.30			

1300	LENGTH	=	187.	COST	=	0.
	TOTAL LENGTH	=	187.	TOTAL COST	=	0.

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct. 2, 1986) *** DATE 06-04-90
PAGE NO 5

CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA

*** LATERAL: 23 TO 18 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	Diam (in)
5	48	15	108.6	.01208	3.9	2.6	4.1	1.03	14		
			108.0		2.5	1.1	5.8	7.12			
6	37	15	106.5	.01081	4.0	2.6	5.5	3.38	50		
			106.1		16.2	14.8	5.5	6.73			
7	95	15	106.1	.00632	16.2	14.8	5.5	6.74	131	1.59	15
			105.5		15.9	14.5	4.2	5.15			

LENGTH = 180. COST = 0.
TOTAL LENGTH = 367. TOTAL COST = 0.

*** LATERAL: 26 TO 27 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	Diam (in)
8	55	15	104.2	.00364	3.9	2.6	3.3	2.38	61		
			104.0		3.9	2.6	3.2	3.91			
9	84	15	104.0	.01357	3.9	2.6	6.1	3.80	50		
			102.8		2.3	.9	6.1	7.55			

LENGTH = 139. COST = 0.
TOTAL LENGTH = 139. TOTAL COST = 0.

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct. 2, 1986) *** DATE 06-04-90
PAGE NO 6

CAMPOSTELLA RD, PRESSURIZED FLOW WITH RATIONAL FORMULA

*** TRUNK: 10 TO 14 Analysis of Existing Pipes

Link	Length (ft)	Diam (in)	Invert Up/Dn (ft)	Slope (ft/ft)	Depth Up/Dn (ft)	Cover Up/Dn (ft)	Velocity Act/Full (ft/sec)	--Flow-- Act/Full (cfs)	Load (%)	-Solutions- Remove (cfs)	-Solutions- Diam (in)
10	94	18	108.9	.00606	5.0	3.4	5.3	8.17	100		
			108.3		5.6	4.0	4.6	8.20			
11	340	21	108.3	.00450	5.6	3.7	5.1	10.62	100		
			106.8		6.8	4.9	4.4	10.66			
12	166	21	106.8	.00572	6.8	4.9	5.0	12.02	100	.00	15
			105.9		9.1	7.2	5.0	12.02			
13	223	21	105.9	.00283	9.1	7.2	5.4	13.00	154	4.56	18
			105.2		16.2	14.3	3.5	8.44			
14	40	24	105.2	.00850	16.2	14.0	6.8	21.39	102	.47	15
			104.9		12.5	10.3	6.7	20.91			
15	338	24	104.9	.00849	12.5	10.3	6.9	21.53	103	.63	15
			102.0		3.1	.9	6.7	20.90			
16	98	30	101.5	.00796	3.6	.9	7.8	38.41	105	1.72	15
			100.7		4.4	1.7	7.5	36.69			

LENGTH = 1299. COST = 0.
TOTAL LENGTH = 2069. TOTAL COST = 0.

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***   DATE 06-04-90
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Link	Node Number U/S	Node Number D/S	Node Type U/S	Node Type D/S	Main Line	Deflected Angle	Side Line	Skew Angle	Bend Radius [Ft]	Bend Angle
1	12	11	5	1	2	.0	1	.0	.00	.0
2	13	14	5	1	2	.0	1	90.0	.00	.0
3	15	17	5	1	2	.0	1	.0	.00	.0
4	17	22	1	1	2	.0	1	90.0	.00	.0
5	23	22	5	1	2	.0	1	.0	.00	.0
6	22	19	1	1	2	.0	1	.0	.00	.0
7	19	18	1	1	2	.0	1	90.0	.00	.0
8	26	25	5	1	2	.0	1	.0	.00	.0
9	25	27	1	1	2	.0	1	90.0	.00	.0
10	10	11	5	1	1	90.0	2	.0	.00	.0
11	11	14	1	1	1	.0	2	.0	.00	.0
12	14	16	1	1	1	.0	2	.0	.00	.0
13	16	18	1	1	1	.0	2	.0	.00	.0
14	18	24	1	1	1	.0	2	.0	.00	.0
15	24	27	1	1	1	.0	2	.0	.00	.0
16	27	28	1	4	1	.0	2	.0	.00	.0

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-04-90
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Node#	Potential Water Level (Ft)	Ground Level (Ft)	Lowest Crown Elevation of Links Connecting Node Link#	Elevation (Ft)	Location	Possible Surcharging to the Link
12	113.0	114.4	1	112.7	Upstream	Yes
11	112.7	114.0	10	109.8	Downstream	Yes
13	111.7	114.8	2	110.3	Upstream	Yes
14	111.0	113.7	11	108.6	Downstream	Yes
15	114.0	116.9	3	114.2	Upstream	No
17	110.7	113.7	3	111.0	Downstream	No
22	108.2	110.5	6	107.8	Upstream	Yes
23	109.6	112.5	5	109.8	Upstream	No
19	109.0	122.3	6	107.3	Downstream	Yes
18	108.4	121.4	7	106.8	Downstream	Yes
26	105.3	108.1	8	105.4	Upstream	No
25	105.0	107.9	8	105.2	Downstream	No
27	104.6	105.1	16	104.0	Upstream	Yes
10	113.9	114.0	10	110.4	Upstream	Yes
16	110.0	115.0	12	107.6	Downstream	Yes
24	107.7	117.4	14	106.9	Downstream	Yes
28	103.2	105.1	16	103.2	Downstream	Yes

Table 3. Campostella Road Output File, cont.

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*** PFP-HYDRA (Version of Oct.2, 1986) ***           DATE 06-04-90
                                                      PAGE NO   9

***** PRESSURIZED FLOW SIMULATIONS  *****

TOTAL SIMULATION TIME IS      25 MIN.
INCREMENTAL TIME IS           1 MIN.
LENGTH OF INTEGRATION STEP IS    2. SECONDS
INITIAL TIME   .00 HOURS
SURCHARGE VARIABLES: ITMAX...    30
                    SURTOL...  .050
PRINTED OUTPUT AT THE FOLLOWING  6 JUNCTIONS

     19     18     16     14     10     11

          AND FOR THE FOLLOWING  8 PIPES

   1918   1011   1114   1416   1618   1824   2427   2728
```

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***

DATE 06-04-90
PAGE NO 10

	PIPE NUMBER	LENGTH (FT)	AREA (SQ FT)	MANNING COEF.	MAX. WIDTH (FT)	DEPTH (FT)	JUNCTIONS AT ENDS		INVERT HEIGHT ABOVE JUNCTIONS	
1	1211	213.	1.23	.013	1.25	1.25	12	11	.00	2.36
2	1314	51.	1.23	.013	1.25	1.25	13	14	.00	.82
3	1517	68.	1.23	.013	1.25	1.25	15	17	.00	.00
4	1722	119.	1.23	.013	1.25	1.25	17	22	.00	1.73
5	2322	48.	1.23	.013	1.25	1.25	23	22	.00	1.50
6	2219	37.	1.23	.013	1.25	1.25	22	19	.00	.00
7	1918	95.	1.23	.013	1.25	1.25	19	18	.00	.27
8	2625	55.	1.23	.013	1.25	1.25	26	25	.00	.00
9	2527	84.	1.23	.013	1.25	1.25	25	27	.00	1.35
10	1011	94.	1.77	.013	1.50	1.50	10	11	.00	.00
11	1114	340.	2.41	.013	1.75	1.75	11	14	.00	.00
12	1416	166.	2.41	.013	1.75	1.75	14	16	.00	.00
13	1618	223.	2.41	.013	1.75	1.75	16	18	.00	.00
14	1824	40.	3.14	.013	2.00	2.00	18	24	.00	.00
15	2427	338.	3.14	.013	2.00	2.00	24	27	.00	.54
16	2728	98.	4.91	.013	2.50	2.50	27	28	.00	.00

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***　　DATE 06-04-90
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	JUNCTION NUMBER	GROUND ELEV.	CROWN ELEV.	INVERT ELEV.	QINST (CFS)	CONNECTING PIPES		
1	12	114.44	112.67	111.42	.00	1211		
2	13	114.81	110.25	109.00	.00	1314		
3	15	116.90	114.23	112.98	.00	1517		
4	17	113.66	110.99	109.74	.00	1517	1722	
5	23	112.50	109.83	108.58	.00	2322		
6	22	110.50	109.48	106.50	.00	1722	2322	2219
7	19	122.25	107.35	106.10	.00	2219	1918	
8	26	108.09	105.42	104.17	.00	2625		
9	25	107.89	105.22	103.97	.00	2625	2527	
10	10	113.95	110.41	108.91	.00	1011		
11	11	113.95	111.95	108.34	.00	1211	1011	1114
12	14	113.65	108.88	106.81	.00	1314	1114	1416
13	16	114.99	107.61	105.86	.00	1416	1618	
14	18	121.39	107.23	105.23	.00	1918	1618	1824
15	24	117.38	106.89	104.89	.00	1824	2427	
16	27	105.10	104.08	101.48	.00	2527	2427	2728
17	28	105.10	103.20	100.70	.00	2728		

Table 3. Campostella Road Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***              DATE 06-04-90
                                                         PAGE NO  12


              * * * *  FREE OUTFALL DATA  * * * *

       FREE OUTFLOW AT JUNCTIONS          28

OUTFLOW CONTROL WATER SURFACE ELEV. IS     103.20 FEET

    * * * *  SUMMARY OF INITIAL HEADS, FLOWS AND VELOCITIES  * * * *


       INITIAL HEADS, FLOWS AND VELOCITIES ARE ZERO
```

Table 3. Campostella Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***   DATE 06-04-90
PAGE NO 13

***** JUNCTION HYDROGRAPHS OBTAINED BY SIMPLIFIED RATIONAL FORMULA *****

JUNCTION NUMBER	TRIANGLE HYDROGRAPH TIME (MIN)/INFLOW (CFS)					
12	.00/	.00	10.00/	1.24	26.70/	.00
13	.00/	.00	10.00/	1.03	26.70/	.00
15	.00/	.00	5.00/	.51	13.35/	.00
17	.00/	.00	5.00/	1.34	13.35/	.00
23	.00/	.00	10.00/	1.03	26.70/	.00
22	.00/	.00	10.00/	.81	26.70/	.00
19	.00/	.00	10.00/	3.40	26.70/	.00
26	.00/	.00	10.00/	2.38	26.70/	.00
25	.00/	.00	10.00/	1.46	26.70/	.00
10	.00/	.00	15.00/	8.17	40.05/	.00
11	.00/	.00	15.00/	1.47	40.05/	.00
14	.00/	.00	10.00/	1.03	26.70/	.00
16	.00/	.00	10.00/	1.40	26.70/	.00
18	.00/	.00	15.00/	3.40	40.05/	.00
24	.00/	.00	.00/	.00	.00/	.00
27	.00/	.00	15.00/	15.65	40.05/	.00

Table 3. Campostella Road Output File, cont.

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* * * * TIME HISTORY OF HYDRAULIC GRADELINE * * * *
(VALUES IN FEET)

	JUNCTION 19		JUNCTION 18		JUNCTION 16		JUNCTION 14	
TIME	GRND	122.25	GRND	121.39	GRND	114.99	GRND	113.65
HR.MIN	ELEV	DEPTH	ELEV	DEPTH	ELEV	DEPTH	ELEV	DEPTH
0. 1	106.32	.22	105.35	.12	105.89	.03	106.84	.03
0. 2	106.54	.44	105.70	.47	105.98	.12	106.95	.14
0. 3	106.69	.59	105.96	.73	106.11	.25	107.13	.32
0. 4	106.82	.72	106.09	.86	106.34	.48	107.31	.50
0. 5	106.95	.85	106.26	1.03	106.58	.72	107.45	.64
0. 6	107.06	.96	106.41	1.18	106.77	.91	107.56	.75
0. 7	107.10	1.00	106.50	1.27	106.92	1.06	107.65	.84
0. 8	107.17	1.07	106.57	1.34	107.07	1.21	107.73	.92
0. 9	107.25	1.15	106.65	1.42	107.22	1.36	107.82	1.01
0.10	107.57	1.25	106.73	1.50	107.41	1.55	107.90	1.09
0.11	107.47	1.25	106.77	1.54	107.63	1.75	107.99	1.18
0.12	107.27	1.17	106.73	1.50	107.69	1.75	108.13	1.32
0.13	107.11	1.01	106.72	1.49	107.78	1.75	108.29	1.48
0.14	106.99	.89	106.70	1.47	107.86	1.75	108.51	1.70
0.15	106.92	.82	106.74	1.51	108.03	1.75	108.81	2.00
0.16	106.89	.79	106.70	1.47	107.73	1.75	108.30	1.49
0.17	106.80	.70	106.54	1.31	107.46	1.60	107.91	1.10
0.18	106.76	.66	106.56	1.33	107.66	1.75	108.09	1.28
0.19	106.71	.61	106.56	1.33	107.67	1.75	108.18	1.37
0.20	106.67	.57	106.52	1.29	107.65	1.75	108.16	1.35
0.21	106.62	.52	106.47	1.24	107.60	1.74	108.07	1.26
0.22	106.57	.47	106.43	1.20	107.53	1.67	107.95	1.14
0.23	106.52	.42	106.36	1.13	107.41	1.55	107.86	1.05
0.24	106.46	.36	106.29	1.06	107.31	1.45	107.81	1.00
0.25	106.40	.30	106.22	.99	107.22	1.36	107.76	.95

	JUNCTION 10		JUNCTION 11	
TIME	GRND	113.95	GRND	113.95
HR.MIN	ELEV	DEPTH	ELEV	DEPTH
0. 1	109.22	.31	108.39	.05
0. 2	109.37	.46	108.61	.27
0. 3	109.36	.45	108.82	.48
0. 4	109.43	.52	108.94	.60
0. 5	109.50	.59	109.02	.68
0. 6	109.56	.65	109.08	.74
0. 7	109.62	.71	109.16	.82
0. 8	109.68	.77	109.24	.90
0. 9	109.74	.83	109.31	.97
0.10	109.80	.89	109.39	1.05
0.11	109.86	.95	109.46	1.12
0.12	109.92	1.01	109.52	1.18

0.13	109.98	1.07	109.58	1.24
0.14	110.05	1.14	109.64	1.30
0.15	110.14	1.23	109.80	1.46
0.16	111.30	1.50	108.81	.47
0.17	110.05	1.14	109.73	1.39
0.18	110.05	1.14	109.67	1.33
0.19	109.97	1.06	109.59	1.25
0.20	109.93	1.02	109.53	1.19
0.21	109.89	.98	109.48	1.14
0.22	109.86	.95	109.44	1.10
0.23	109.82	.91	109.40	1.06
0.24	109.79	.88	109.37	1.03
0.25	109.75	.84	109.33	.99

Table 3. Campostella Road Output File, cont.

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* * * * SUMMARY STATISTICS FOR JUNCTIONS * * * *

JUNCTION NUMBER	GROUND /INVERT ELEV. (FT)	UPPERMOST PIPE CROWN ELEV. (FT)	FEET MAX. COMPUTED WATER SURFACE ELEV	TIME OF OCCURRENC HR.	MIN.	FEET OF SURCHARGE AT MAX. DEPTH	LENGTH OF SURCHARGE (MIN)
12	114.44 111.42	112.67	111.95	0	11	.00	.00
13	114.81 109.00	110.25	109.26	0	10	.00	.00
15	116.90 112.98	114.23	113.14	0	5	.00	.00
17	113.66 109.74	110.99	110.16	0	5	.00	.00
23	112.50 108.58	109.83	108.90	0	10	.00	.00
22	110.50 106.50	109.48	107.63	0	10	.00	.00
19	122.25 106.10	107.35	107.58	0	10	.23	2.10
26	108.09 104.17	105.42	104.89	0	10	.00	.00
25	107.89 103.97	105.22	104.60	0	10	.00	.00
10	113.95 108.91	110.41	113.95	0	16	3.54	.93
11	113.95 108.34	111.95	110.09	0	16	.00	.00
14	113.65 106.81	108.88	108.89	0	16	.01	.03
16	114.99 105.86	107.61	108.06	0	16	.45	8.57

Table 3. Campostella Road Output File, cont.

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**** SUMMARY STATISTICS FOR JUNCTIONS ****

JUNCTION NUMBER	GROUND /INVERT ELEV. (FT)	UPPERMOST PIPE CROWN ELEV. (FT)	FEET MAX. COMPUTED WATER SURFACE ELEV	TIME OF OCCURRENCE HR.	MIN.	FEET OF SURCHARGE AT MAX. DEPTH	LENGTH OF SURCHARGE (MIN)
18	121.39 105.23	107.23	106.78	0	11	.00	.00
24	117.38 104.89	106.89	106.38	0	15	.00	.00
27	105.10 101.48	104.08	104.00	0	15	.00	.00
28	105.10 100.70	103.20	103.20	0	0	.00	.00

Table 3. Campostella Road Output File, cont.

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* * * * TIME HISTORY OF FLOW AND VELOCITY * * * *
FLOW(CFS),VEL(FPS)

TIME	PIPE 1918		PIPE 1011		PIPE 1114		PIPE 1416	
HR.MIN	FLOW	VEL	FLOW	VEL	FLOW	VEL	FLOW	VEL
0. 1	.35	2.3	.29	2.1	.01	.7	.01	.6
0. 2	1.40	3.5	1.07	3.2	.34	2.1	.14	1.7
0. 3	2.36	4.1	1.57	3.4	1.29	3.1	.73	2.8
0. 4	3.28	4.4	2.10	3.5	2.38	3.6	2.16	3.9
0. 5	4.15	4.7	2.65	3.7	3.29	4.0	3.42	4.0
0. 6	4.78	4.9	3.20	4.0	3.98	4.1	4.54	4.1
0. 7	5.07	4.8	3.74	4.1	4.75	4.2	5.54	4.2
0. 8	5.35	4.8	4.29	4.2	5.53	4.4	6.54	4.3
0. 9	5.60	4.7	4.84	4.4	6.32	4.5	7.54	4.4
0.10	5.95	4.8	5.38	4.5	7.09	4.6	8.54	4.4
0.11	5.57	4.5	5.93	4.6	7.81	4.7	8.81	4.2
0.12	5.23	4.3	6.47	4.7	8.44	4.6	9.29	4.2
0.13	4.67	4.1	7.01	4.8	9.02	4.5	9.70	4.2
0.14	4.19	3.9	7.56	4.9	9.60	4.4	10.07	4.2
0.15	3.70	3.5	8.00	4.8	9.24	4.0	10.89	4.5
0.16	3.46	3.4	7.93	5.1	.11	.0	10.07	4.4
0.17	3.13	3.5	7.59	4.8	8.97	4.8	8.64	4.4
0.18	2.80	3.2	7.26	4.7	9.82	5.1	9.78	4.5
0.19	2.49	2.9	6.91	4.8	9.13	4.7	9.92	4.4
0.20	2.18	2.7	6.58	4.7	8.58	4.6	9.83	4.4
0.21	1.87	2.5	6.25	4.7	8.10	4.6	9.54	4.4
0.22	1.56	2.2	5.93	4.6	7.63	4.7	9.13	4.5
0.23	1.25	2.0	5.60	4.5	7.13	4.7	8.08	4.3
0.24	.94	1.7	5.27	4.5	6.69	4.6	7.41	4.2
0.25	.64	1.4	4.95	4.4	6.24	4.6	6.83	4.1

TIME	PIPE 1618		PIPE 1824		PIPE 2427		PIPE 2728	
HR.MIN	FLOW	VEL	FLOW	VEL	FLOW	VEL	FLOW	VEL
0. 1	.01	.2	.05	1.2	.00	.0	-1.91	-.9
0. 2	.08	.3	.83	2.9	.07	.1	2.57	1.0
0. 3	.38	.6	2.77	4.0	1.28	.8	7.84	1.4
0. 4	1.35	1.5	4.98	4.8	3.78	3.2	7.40	1.9
0. 5	2.93	2.4	7.54	5.5	6.45	3.6	15.10	3.2
0. 6	4.44	3.0	10.11	6.0	9.18	5.3	16.88	3.9
0. 7	5.71	3.4	12.05	6.4	11.40	5.8	21.15	4.7
0. 8	6.88	3.7	13.70	6.6	13.13	6.3	24.16	5.3
0. 9	7.99	3.9	15.34	6.9	14.76	6.6	26.93	5.9
0.10	9.17	4.1	17.00	7.1	16.39	6.8	29.86	6.4
0.11	10.17	4.4	18.42	7.3	18.04	7.0	32.44	6.8
0.12	10.46	4.5	18.42	7.4	18.35	6.9	33.98	7.1
0.13	10.85	4.6	18.51	7.4	18.50	6.8	34.93	7.2

0.14	11.13	4.7	18.49	7.5	18.48	6.7	35.65	7.3
0.15	11.87	5.0	18.90	7.5	18.72	6.6	36.41	7.4
0.16	11.23	4.9	18.51	7.5	18.71	6.6	36.57	7.5
0.17	9.41	4.4	15.90	7.2	16.48	6.4	34.79	7.3
0.18	10.56	4.7	16.14	7.3	15.98	6.6	32.15	6.9
0.19	10.59	4.7	16.04	7.2	16.09	6.7	31.33	6.7
0.20	10.43	4.8	15.54	7.2	15.75	6.7	30.33	6.6
0.21	10.11	4.7	14.75	7.1	15.01	6.7	28.80	6.3
0.22	9.74	4.7	13.96	7.1	14.24	6.7	27.08	6.0
0.23	8.90	4.5	12.80	6.9	13.23	6.5	25.23	5.7
0.24	8.07	4.4	11.51	6.7	11.94	6.3	22.99	5.2
0.25	7.37	4.3	10.35	6.5	10.75	5.9	20.77	4.8

Table 3. Campostella Road Output File, cont.

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**** SUMMARY STATISTICS FOR PIPES ****

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	TIME OF OCCURRENCE MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	MAX. DEPTH ABOVE INVERT PIPE ENDS DS (FT)
1211	3.8 3.1	15.0	1.2 2.8	0	10	.3	.53	-.61
1314	10.6 8.6	15.0	1.0 5.4	0	10	.1	.26	1.26
1517	14.1 11.5	15.0	.5 2.3	0	5	.0	.16	.42
1722	7.3 5.9	15.0	1.8 4.9	0	5	.2	.42	-.60
2322	7.1 5.8	15.0	1.0 4.1	0	10	.1	.32	-.37
2219	6.7 5.5	15.0	2.8 3.8	0	6	.4	1.13	1.48
1918	5.1 4.2	15.0	6.0 4.9	0	10	1.2	1.48	1.28
2625	3.9 3.2	15.0	2.4 3.5	0	10	.6	.72	.63
2527	7.5 6.1	15.0	3.8 5.8	0	10	.5	.63	1.17
1011	8.2 4.6	18.0	8.5 8.2	0	17	1.0	5.04	1.75
1114	10.6 4.4	21.0	9.8 7.2	0	18	.9	1.75	2.08
1416	12.0 5.0	21.0	10.9 4.7	0	16	.9	2.08	2.20
1618	8.4 3.5	21.0	11.9 5.1	0	16	1.4	2.20	1.55

Table 3. Campostella Road Output File, cont.

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* * * * SUMMARY STATISTICS FOR PIPES * * * *

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	TIME OF OCCURRENCE MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	MAX. DEPTH ABOVE INVERT PIPE ENDS DS (FT)
1824	20.9	24.0	18.9	0	15	.9	1.55	1.49
	6.6		7.5					
2427	20.8	24.0	18.8	0	15	.9	1.49	1.98
	6.6		7.0					
2728	36.6	30.0	36.9	0	16	1.0	2.52	2.50
	7.5		7.5					

* * * * * PRESSURIZED FLOW SIMULATION ENDED * * * * *

Evaluation of Results

Case 1 was run using a 10-year IDF curve to provide inflow. Notice that the 10-sec time step entered in the PFA command changes during the course of the program to 2 sec. When pressurized flow checked the time step entered and found it to be too large, the program calculated a new value.

Analyzing the various aspects of the output list (analysis, hydraulic gradeline, pressurized flow), we find a number of junctions at risk for surcharging. Only four junctions actually surcharge in the pressurized flow analysis. A plot of the hydraulic gradeline versus time, with a value of zero at the lowest pipe invert elevation, shows where, when, and how much surcharging will occur (Figure 17). Similar plots can be constructed for other junctions to illustrate the action of the water level in the various junctions.

Figure 18 is an illustration of the water surface elevation for Junction 19. The maximum water surface elevation is higher than the crown elevation of the uppermost link. This causes the surcharge situation. A continued evaluation of the hydraulic gradeline results shows us that the elevations from the hydraulic gradeline portion of PFP-HYDRA are consistently higher than those of the pressurized flow portion of PFP-HYDRA. This occurs because the hydraulic gradeline routine performs a conservative estimate of maximum water depth. Most of the time, the hydraulic gradeline results for the mainline will follow the same trend.

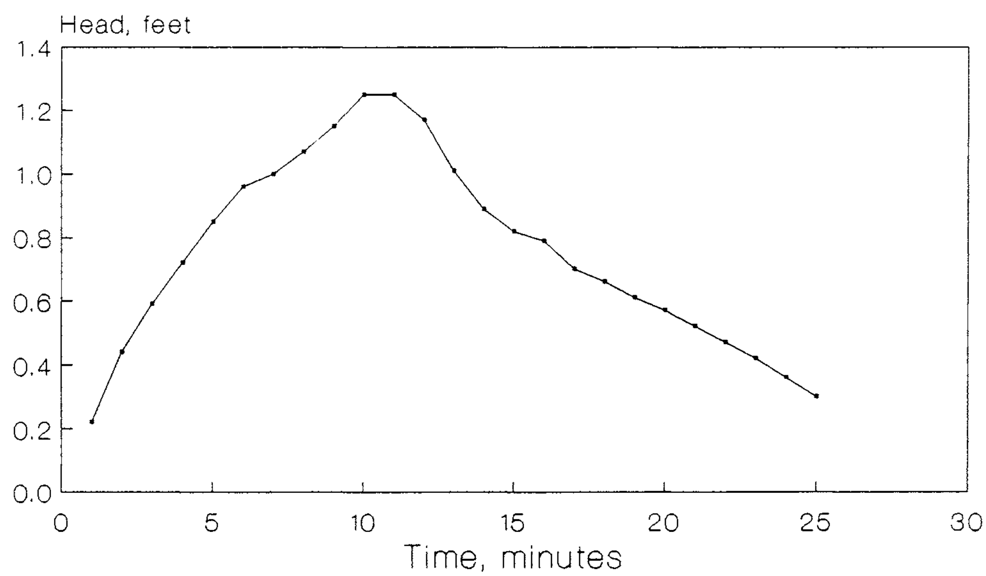

Figure 17. Hydraulic Gradeline (Head) Computation at Junction 19

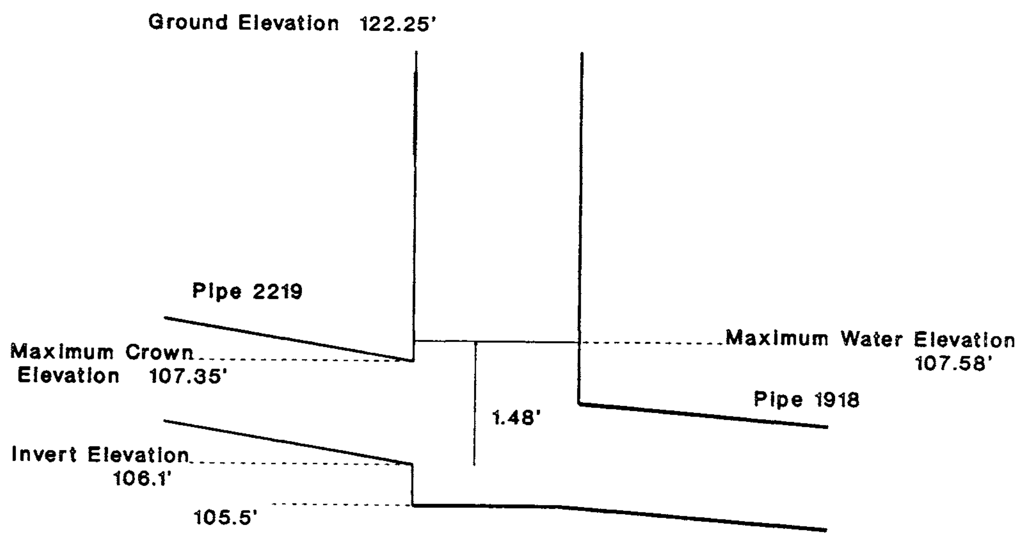

Figure 18. Maximum Water Depth at Junction 19

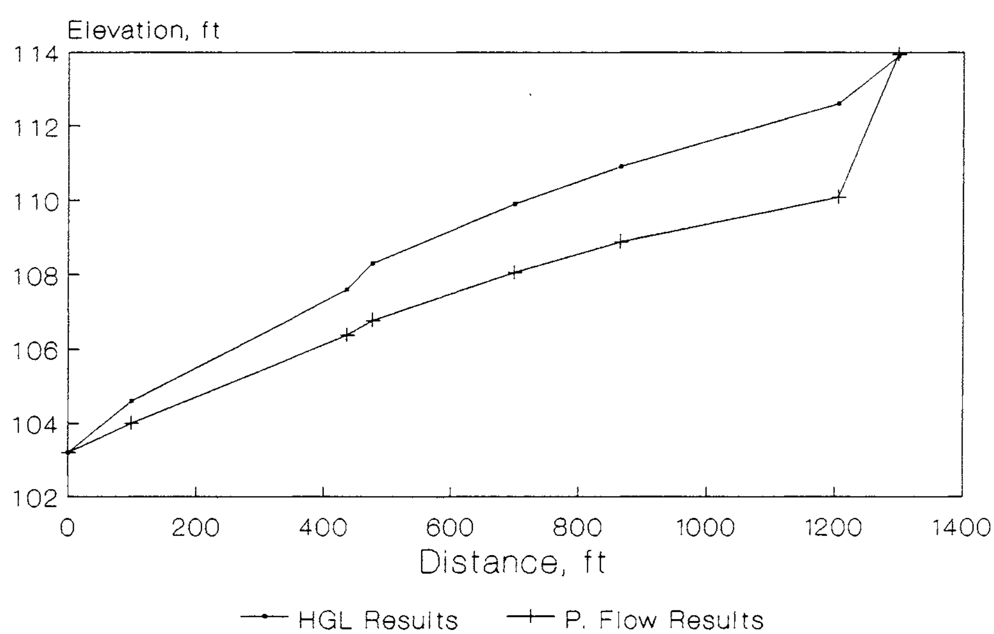

Figure 19. Mainline Hydraulic Gradeline Results

The links in Table 4 labeled "Surcharge" are in greatest need to be sized. Other links listed are shown to be very close to the critical level. A larger storm would cause those links to surcharge as well. (PFP-HYDRA can be used to determine the effect of placing larger diameter pipe.)

Table 4. Possible Surcharging Links in PFP-HYDRA Main Program

Line	Junction Upstream	Junction Downstream	Pressurized Flow Results Ratio of Max to Design Flow
7	19	18	1.2 Surcharge
10	10	11	1.0 Surcharge
11	11	14	0.9
12	14	16	0.9
13	16	18	1.4 Surcharge
14	18	24	0.9
15	24	27	0.9
16	27	28	1.0 Surcharge

Example 2: SCS Unit Hydrograph Method

The Stadium Road sewer network contains eight sewers of different length, ground elevation, roughness, and diameter (see Table 5). It gives runoff parameters as required by the SCS method for each inflow manhole. Initial conditions are specified. The time step given is 2 sec, and the total simulation time is 65 min. The print interval is 2 min. The resulting input and output files are given in Tables 6 and 7. A diagram of the pipe system appears in Figure 20.

Table 5. Stadium Road Data Summary

Node		Length	Diameter	Mannings	
Upstream	Downstream	(ft)	(in)	*n*	Angle
7	6	90	48	.022	22
6	5	345	36	.012	40
15	5	75	15	.012	0
5	4	93	36	.012	11
4	3	160	36	.012	0
3	2	95	36	.012	61
2	1	36	36	.012	0

Table 6. Stadium Road Input File

```
0010 JOB Stadium Road Example with SCS Hydrographs
0015 SWI 6
0035 NEW LINK 7 TO 5
0037 REM LINE 7-6
0036 FLO 5.0
0040 PDA .022 12 4 3 2 .001
0060 PIP 90 546 525 541.9 520.9 -12
0070 PNC 76 7 5 6 1 1 22.0 2 0.0 1.5 0 0 0 0.1 0
0075 REM LINE 6-5
0080 PDA .014 12 4 3 2 .001
0100 PIP 345 525 505 520.3 500.4 -18
0110 PNC 65 6 1 5 1 2 0. 1 40. 0 0 0 0 0.1 0
0115 NEW LINK  15 TO 1
0017 REM LINE 15-5
0130 PIP 75 510 505 505.9 500.9 -12
0140 PNC 155 15 5 5 1 1 0. 2 0. 0 0 0 0 0.1 0
0145 REM LINE 5-4
0160 PIP 93 505 504 500.3 499.4 -18
0170 PNC 54 5 1 4 1 1 11. 2 0. 0 0 0 0 0.1 0
0175 REM LINE 4-3
0190 PIP 160 504.8 504.5 498.4 498.2 -30
0210 PNC 43 4 1 3 2 1 0. 2 0. 0 0 0 0 0.1 0
0220 REM LINE 3-13
0230 PIP 10 504.5 504 498.2 498.1 -30
0240 PNC 313 3 2 13 1 1 61. 2 0. 0 0 0 0 0.1 0
0250 REM LINE 13-2
0260 PIP 85 504 502 496.5 496.3 -30
0270 PNC 132 13 1 2 1 2 0. 1 48. 0 0 0 0 0.1 0
0280 REM LINE 2-1
0290 PIP 25 502 500 495.1 494.8 -24
0300 PNC 21 2 1 1 4 1 0. 2 0. 0 0 0 0 0.1 0
0310 PFA 65 2. 2 1 0. 3 3 7 30 .05 1
0312 PHJ 5 4 2
0317 PFP 132 54 43
0320 HHJ 7 15 6 5 4 13 2
0330 REM FLOW INTO JCTN 7
0340 SHY 0.6 10.6 105.0 83.0 1.0 2.5
0350 REM FLOW INTO JCTN 15
0360 SHY 0.8 6.0 185.0 79.0 1.0 2.5
0370 REM FLOW INTO JCTN 6
0380 SHY 1.0 18.2 182.0 91.2 1.0 2.5
0390 REM FLOW INTO JCTN 5
0400 SHY 3.0 14.6 457.0 90.6 1.0 2.5
0410 REM FLOW INTO JCTN 4
0420 SHY 0.9 9.4 95.0 88.0 1.0 2.8
0430 REM FLOW INTO JCTN 13
0440 SHY 1.2 10.1 245.0 83.0 1.0 2.8
0450 REM FLOW INTO JCTN 2
0460 SHY 0.1 4.1 95.0 90.0 1.0 2.8
0750 END
```

1322 Table 7. Stadium Road Output File

```
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Stadium Road Example with SCS Hydrographs

Commands Read From File example.hda
   10 JOB
   15 SWI 6
   35 NEW LINK 7 TO 5
   37 REM LINE 7-6
   36 FLO 5.0
   40 PDA .022 12 4 3 2 .001
   60 PIP 90 546 525 541.9 520.9 -12
   70 PNC 76 7 5 6 1 1 22.0 2 0.0 1.5 0 0 0 0.1 0
   75 REM LINE 6-5
   80 PDA .014 12 4 3 2 .001
  100 PIP 345 525 505 520.3 500.4 -18
  110 PNC 65 6 1 5 1 2 0. 1 40. 0 0 0 0 0.1 0
  115 NEW LINK  15 TO 1
   17 REM LINE 15-5
  130 PIP 75 510 505 505.9 500.9 -12
  140 PNC 155 15 5 5 1 1 0. 2 0. 0 0 0 0 0.1 0
  145 REM LINE 5-4
  160 PIP 93 505 504 500.3 499.4 -18
  170 PNC 54 5 1 4 1 1 11. 2 0. 0 0 0 0 0.1 0
  175 REM LINE 4-3
  190 PIP 160 504.8 504.5 498.4 498.2 -30
  210 PNC 43 4 1 3 2 1 0. 2 0. 0 0 0 0 0.1 0
  220 REM LINE 3-13
  230 PIP 10 504.5 504 498.2 498.1 -30
  240 PNC 313 3 2 13 1 1 61. 2 0. 0 0 0 0 0.1 0
  250 REM LINE 13-2
  260 PIP 85 504 502 496.5 496.3 -30
  270 PNC 132 13 1 2 1 2 0. 1 48. 0 0 0 0 0.1 0
  280 REM LINE 2-1
  290 PIP 25 502 500 495.1 494.8 -24
  300 PNC 21 2 1 1 4 1 0. 2 0. 0 0 0 0 0.1 0
  310 PFA 65 2. 2 1 0. 3 3 7 30 .05 1
  312 PHJ 5 4 2
  317 PFP 132 54 43
  320 HHJ 7 15 6 5 4 13 2
  330 REM FLOW INTO JCTN 7
  340 SHY 0.6 10.6 105.0 83.0 1.0 2.5
  350 REM FLOW INTO JCTN 15
  360 SHY 0.8 6.0 185.0 79.0 1.0 2.5
  370 REM FLOW INTO JCTN 6
  380 SHY 1.0 18.2 182.0 91.2 1.0 2.5
  390 REM FLOW INTO JCTN 5
  400 SHY 3.0 14.6 457.0 90.6 1.0 2.5
  410 REM FLOW INTO JCTN 4
  420 SHY 0.9 9.4 95.0 88.0 1.0 2.8
  430 REM FLOW INTO JCTN 13
  440 SHY 1.2 10.1 245.0 83.0 1.0 2.8
```

Table 7. Stadium Road Output File, cont.

```
      *** PFP-HYDRA (Version of Oct. 2, 1986) ***          DATE 06-12-90
                                                           PAGE NO   2

      Stadium Road Example with SCS Hydrographs
 450 REM FLOW INTO JCTN 2
 460 SHY 0.1 4.1 95.0 90.0 1.0 2.8
 750 END
END OF RUN.
```

Table 7. Stadium Road Output File, cont.

```
    *** PFP-HYDRA (Version of Oct.2, 1986) ***          DATE 06-12-90
                                                         PAGE NO   3


    *****  PRESSURIZED FLOW SIMULATIONS  *****


TOTAL SIMULATION TIME IS        65 MIN.
INCREMENTAL TIME IS             2 MIN.
LENGTH OF INTEGRATION STEP IS     1. SECONDS
INITIAL TIME    .00 HOURS
SURCHARGE VARIABLES: ITMAX...     30
                     SURTOL...  .050
PRINTED OUTPUT AT THE FOLLOWING  3 JUNCTIONS

      5      4      2

         AND FOR THE FOLLOWING  3 PIPES

    132     54     43
```

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-12-90
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	PIPE NUMBER	LENGTH (FT)	AREA (SQ FT)	MANNING COEF.	MAX. WIDTH (FT)	DEPTH (FT)	JUNCTIONS AT ENDS		INVERT HEIGHT ABOVE JUNCTIONS	
1	76	90.	.79	.022	1.00	1.00	7	6	.00	.60
2	65	345.	1.77	.014	1.50	1.50	6	5	.00	.10
3	155	75.	.79	.014	1.00	1.00	15	5	.00	.60
4	54	93.	1.77	.014	1.50	1.50	5	4	.00	1.00
5	43	160.	4.91	.014	2.50	2.50	4	3	.00	.00
6	313	10.	4.91	.014	2.50	2.50	3	13	.00	1.60
7	132	85.	4.91	.014	2.50	2.50	13	2	.00	1.20
8	21	25.	3.14	.014	2.00	2.00	2	1	.00	.00

132c

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-12-90

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	JUNCTION NUMBER	GROUND ELEV.	CROWN ELEV.	INVERT ELEV.	QINST (CFS)	CONNECTING PIPES		
1	7	546.00	542.90	541.90	.00	76		
2	6	525.00	521.90	520.30	.00	76	65	
3	15	510.00	506.90	505.90	.00	155		
4	5	505.00	501.90	500.30	.00	65	155	54
5	4	504.80	500.90	498.40	.00	54	43	
6	3	504.50	500.70	498.20	.00	43	313	
7	13	504.00	500.60	496.50	.00	313	132	
8	2	502.00	498.80	495.10	.00	132	21	
9	1	500.00	496.80	494.80	.00	21		

Table 7. Stadium Road Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***          DATE 06-12-90
                                                     PAGE NO   6


          * * * *  FREE OUTFALL DATA  * * * *

FREE OUTFLOW AT JUNCTIONS           1

* * * *  SUMMARY OF INITIAL HEADS, FLOWS AND VELOCITIES  * * * *


INITIAL HEADS, FLOWS AND VELOCITIES ARE ZERO
```

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-12-90
PAGE NO 7

* * * *JUNCTION HYDROGRAPHS OBTAINED BY SCS OR CLARK METHOD* * * *

JUNCTION 7		JUNCTION 15		JUNCTION 6		JUNCTION 5	
TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS
0. 0	.00	0. 0	.00	0. 0	.00	0. 0	.00
0. 3	.03	0. 3	.04	0. 3	.06	0. 3	.16
0. 6	.17	0. 6	.21	0. 6	.28	0. 6	.80
0. 9	.35	0.10	.45	0. 9	.59	0.10	1.71
0.12	.62	0.13	.79	0.12	1.03	0.13	2.99
0.15	.95	0.16	1.22	0.15	1.59	0.16	4.60
0.19	1.32	0.19	1.70	0.18	2.21	0.19	6.41
0.22	1.70	0.22	2.18	0.22	2.84	0.22	8.23
0.25	1.96	0.26	2.52	0.25	3.28	0.25	9.51
0.28	2.14	0.29	2.74	0.28	3.58	0.29	10.37
0.31	2.20	0.32	2.83	0.31	3.69	0.32	10.69
0.34	2.16	0.35	2.77	0.34	3.61	0.35	10.48
0.37	2.03	0.38	2.60	0.37	3.39	0.38	9.83
0.40	1.85	0.42	2.38	0.40	3.10	0.41	8.98
0.43	1.65	0.45	2.12	0.43	2.76	0.45	8.02
0.46	1.45	0.48	1.87	0.46	2.43	0.48	7.06
0.49	1.23	0.51	1.58	0.49	2.06	0.51	5.99
0.56	.93	0.58	1.19	0.55	1.55	0.57	4.49
1. 2	.71	1. 4	.90	1. 2	1.18	1. 4	3.42
1. 8	.53	1.11	.68	1. 8	.88	1.10	2.57
1.14	.40	1.17	.51	1.14	.66	1.16	1.92
1.20	.29	1.23	.37	1.20	.48	1.23	1.39
1.26	.22	1.30	.28	1.26	.36	1.29	1.05
1.33	.17	1.36	.21	1.32	.28	1.35	.80
1.48	.08	1.52	.10	1.48	.13	1.51	.38
2. 4	.04	2. 8	.05	2. 3	.07	2. 7	.19
2.19	.02	2.24	.03	2.18	.03	2.23	.10
2.34	.01	2.40	.01	2.34	.01	2.39	.04
2.37	.00	2.44	.00	2.37	.00	2.42	.00

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***

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PAGE NO 8

* * * *JUNCTION HYDROGRAPHS OBTAINED BY SCS OR CLARK METHOD* * * *

JUNCTION 4		JUNCTION 13		JUNCTION 2	
TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS
0. 0	.00	0. 0	.00	0. 0	.00
0. 3	.06	0. 3	.07	0. 3	.01
0. 6	.28	0. 6	.36	0. 6	.03
0. 9	.60	0.10	.77	0. 9	.07
0.12	1.04	0.13	1.34	0.12	.11
0.15	1.60	0.16	2.06	0.16	.18
0.18	2.23	0.19	2.88	0.19	.25
0.22	2.87	0.22	3.69	0.22	.32
0.25	3.31	0.25	4.27	0.25	.36
0.28	3.61	0.29	4.65	0.28	.40
0.31	3.72	0.32	4.80	0.31	.41
0.34	3.65	0.35	4.70	0.34	.40
0.37	3.42	0.38	4.41	0.37	.38
0.40	3.13	0.41	4.03	0.40	.34
0.43	2.79	0.44	3.60	0.43	.31
0.46	2.46	0.48	3.17	0.47	.27
0.49	2.08	0.51	2.69	0.50	.23
0.55	1.56	0.57	2.02	0.56	.17
1. 1	1.19	1. 4	1.54	1. 2	.13
1. 8	.89	1.10	1.15	1. 8	.10
1.14	.67	1.16	.86	1.14	.07
1.20	.48	1.23	.62	1.21	.05
1.26	.36	1.29	.47	1.27	.04
1.32	.28	1.35	.36	1.33	.03
1.48	.13	1.51	.17	1.49	.01
2. 3	.07	2. 7	.09	2. 4	.01
2.18	.03	2.23	.04	2.20	.00
2.34	.01	2.39	.02	2.35	.00
2.37	.00	2.42	.00	2.38	.00

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-12-90
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* * * * TIME HISTORY OF HYDRAULIC GRADELINE * * * *
(VALUES IN FEET)

TIME	JUNCTION 5 GRND ELEV	505.00 DEPTH	JUNCTION 4 GRND ELEV	504.80 DEPTH	JUNCTION 2 GRND ELEV	502.00 DEPTH
HR.MIN						
0. 1	500.35	.05	498.41	.01	495.11	.01
0. 3	500.45	.15	498.59	.19	495.17	.07
0. 5	500.57	.27	498.83	.43	495.31	.21
0. 7	500.70	.40	499.04	.64	495.47	.37
0. 9	500.82	.52	499.21	.81	495.60	.50
0.11	500.95	.65	499.37	.97	495.73	.63
0.13	501.10	.80	499.54	1.14	495.87	.77
0.15	501.26	.96	499.72	1.32	496.02	.92
0.17	501.44	1.14	499.90	1.50	496.16	1.06
0.19	501.76	1.46	500.06	1.66	496.30	1.20
0.21	502.65	1.60	500.31	1.91	496.52	1.42
0.23	503.18	1.60	500.48	2.08	496.70	1.60
0.25	503.63	1.60	500.60	2.20	496.90	1.80
0.27	504.12	1.60	500.69	2.29	497.05	1.95
0.29	504.41	1.60	500.77	2.37	497.12	2.02
0.31	504.54	1.60	500.80	2.40	497.15	2.05
0.33	504.51	1.60	500.79	2.39	497.15	2.05
0.35	504.39	1.60	500.76	2.36	497.12	2.02
0.37	504.12	1.60	500.70	2.30	497.08	1.98
0.39	503.80	1.60	500.63	2.23	496.98	1.88
0.41	503.37	1.60	500.55	2.15	496.85	1.75
0.43	503.04	1.60	500.46	2.06	496.79	1.69
0.45	502.72	1.60	500.37	1.97	496.75	1.65
0.47	502.43	1.60	500.27	1.87	496.71	1.61
0.49	502.14	1.60	500.18	1.78	496.65	1.55
0.51	501.86	1.56	500.10	1.70	496.58	1.48
0.53	501.70	1.40	500.03	1.63	496.53	1.43
0.55	501.53	1.23	499.96	1.56	496.47	1.37
0.57	501.40	1.10	499.87	1.47	496.39	1.29
0.59	501.33	1.03	499.80	1.40	496.33	1.23
1. 1	501.26	.96	499.74	1.34	496.27	1.17
1. 3	501.21	.91	499.68	1.28	496.21	1.11
1. 5	501.16	.86	499.63	1.23	496.15	1.05

Table 7. Stadium Road Output File, cont.

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* * * * SUMMARY STATISTICS FOR JUNCTIONS * * * *

JUNCTION NUMBER	GROUND /INVERT ELEV. (FT)	UPPERMOST PIPE CROWN ELEV. (FT)	FEET MAX. COMPUTED WATER SURFACE ELEV	TIME OF OCCURENCE HR.	MIN.	FEET OF SURCHARGE AT MAX. DEPTH	LENGTH OF SURCHARGE (MIN)
7	546.00 541.90	542.90	542.22	0	31	.00	.00
6	525.00 520.30	521.90	520.81	0	31	.00	.00
15	510.00 505.90	506.90	506.30	0	32	.00	.00
5	505.00 500.30	501.90	504.57	0	32	2.67	31.38
4	504.80 498.40	500.90	500.80	0	32	.00	.00
3	504.50 498.20	500.70	500.00	0	32	.00	.00
13	504.00 496.50	500.60	498.86	0	32	.00	.00
2	502.00 495.10	498.80	497.15	0	32	.00	.00
1	500.00 494.80	496.80	496.63	0	32	.00	.00

1332 Table 7. Stadium Road Output File, cont.

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* * * * TIME HISTORY OF FLOW AND VELOCITY * * * *
FLOW(CFS),VEL(FPS)

TIME	PIPE	132	PIPE	54	PIPE	43
HR.MIN	FLOW	VEL	FLOW	VEL	FLOW	VEL
0. 1	.00	.3	.02	1.0	.00	.2
0. 3	.04	.8	.20	2.2	.07	.8
0. 5	.53	1.8	.70	3.2	.62	1.7
0. 7	1.68	2.6	1.45	3.9	1.54	2.3
0. 9	3.14	3.1	2.52	4.6	2.85	2.7
0.11	4.95	3.5	3.79	5.1	4.35	3.0
0.13	7.15	4.0	5.30	5.6	6.17	3.4
0.15	9.71	4.4	7.06	5.9	8.30	3.7
0.17	12.47	4.7	8.91	6.2	10.55	3.9
0.19	15.20	5.0	10.57	6.3	12.69	4.2
0.21	19.23	5.5	13.74	7.8	16.23	4.6
0.23	22.10	5.8	15.59	8.9	18.50	4.8
0.25	24.27	6.0	17.05	9.7	20.26	5.0
0.27	25.91	6.2	18.12	10.2	21.57	5.1
0.29	27.17	6.4	18.93	10.7	22.55	5.2
0.31	27.72	6.4	19.29	10.9	22.99	5.3
0.33	27.71	6.4	19.23	10.9	22.92	5.3
0.35	27.25	6.4	18.91	10.7	22.51	5.2
0.37	26.27	6.3	18.19	10.3	21.67	5.1
0.39	25.06	6.1	17.31	9.8	20.63	5.0
0.41	23.64	6.0	16.31	9.3	19.43	4.9
0.43	22.10	5.8	15.22	8.7	18.14	4.7
0.45	20.53	5.6	14.13	8.1	16.83	4.6
0.47	18.95	5.5	13.02	7.5	15.50	4.4
0.49	17.28	5.3	11.85	6.8	14.11	4.3
0.51	15.82	5.1	10.93	6.4	13.00	4.2
0.53	14.71	5.0	10.26	6.3	12.13	4.1
0.55	13.54	4.8	9.40	6.2	11.11	3.9
0.57	12.24	4.7	8.43	6.1	10.02	3.8
0.59	11.17	4.5	7.70	6.0	9.14	3.7
1. 1	10.25	4.4	7.06	5.9	8.37	3.6
1. 3	9.37	4.3	6.45	5.8	7.66	3.5
1. 5	8.58	4.2	5.90	5.7	7.00	3.4

Table 7. Stadium Road Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-12-90
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* * * * SUMMARY STATISTICS FOR PIPES * * * *

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	DS (FT)
76	10.2	12.0	2.2	0	31	.2	.32	-.09
	12.9		10.3					
65	23.4	18.0	5.9	0	31	.3	.51	4.17
	13.3		4.0					
155	8.5	12.0	2.8	0	32	.3	.40	3.67
	10.9		6.9					
54	9.6	18.0	19.4	0	32	2.0	4.27	1.40
	5.4		11.0					
43	13.5	30.0	23.1	0	32	1.7	2.40	1.80
	2.7		5.3					
313	38.1	30.0	23.1	0	32	.6	1.80	.76
	7.8		7.0					
132	18.5	30.0	27.8	0	32	1.5	2.36	.85
	3.8		6.4					
21	23.0	24.0	28.2	0	32	1.2	2.05	1.83
	7.3		9.1					

* * * * * PRESSURIZED FLOW SIMULATION ENDED * * * * *

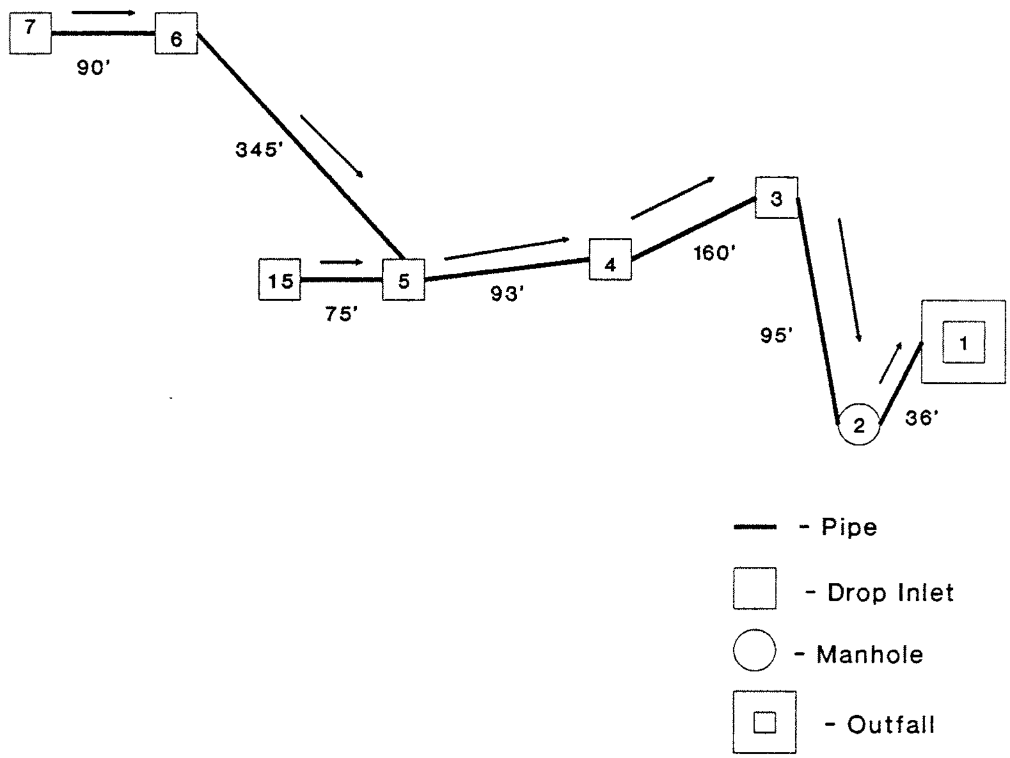

Figure 20. Stadium Road Layout

Evaluation of Results

Case 2, Stadium Road, was run using the SCS hydrograph option. A reference hydrograph was "calibrated" using input data for the SCS unit hydrograph method and adjusting the storm duration and depth accordingly. The storm depth and duration were increased to 1.0 hr and 2.5 to 2.8 in to provide an analysis in unusually high flow conditions. The input time step changed during the running of the program because mathematical conditions were not met.

Analysis of the pressurized flow output shows only one junction surcharging: Junction 5. Figure 21 shows the hydraulic gradeline for Junction 5 and allows a graphic determination of when the surcharge condition began and when it will end. The depth reaches a maximum of 1.6 ft and stays there. This occurs because the depth is calculated to a surcharge condition for the junction as a whole. The depth remains constant until the surcharging ceases in the pipe with the uppermost crown elevation.

A sketch of the depth versus other elevations within the junction (Figure 22) shows the maximum water surface elevation to be 0.5 ft from flooding (i.e., the maximum water surface elevation is 0.5 ft from the ground level). From this plot, we would expect pipe 54 to experience pressurized flow, and it does. Plotting the flow in pipe 54 (Figure 23), a graphic determination provides the beginning and ending of pressurized flow and the maximum flow compared to the pipe design flow.

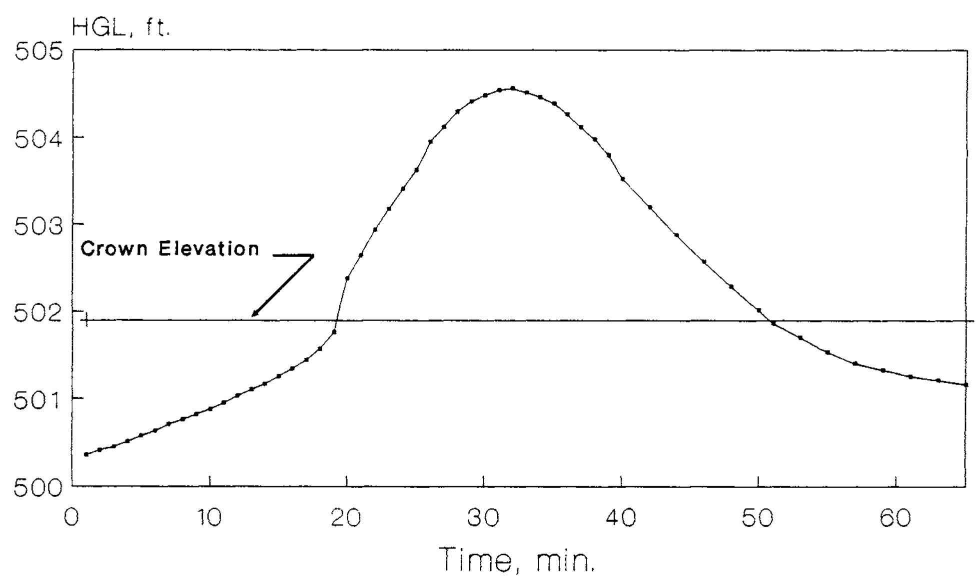

Figure 21. Water Surface Level for Junction 5

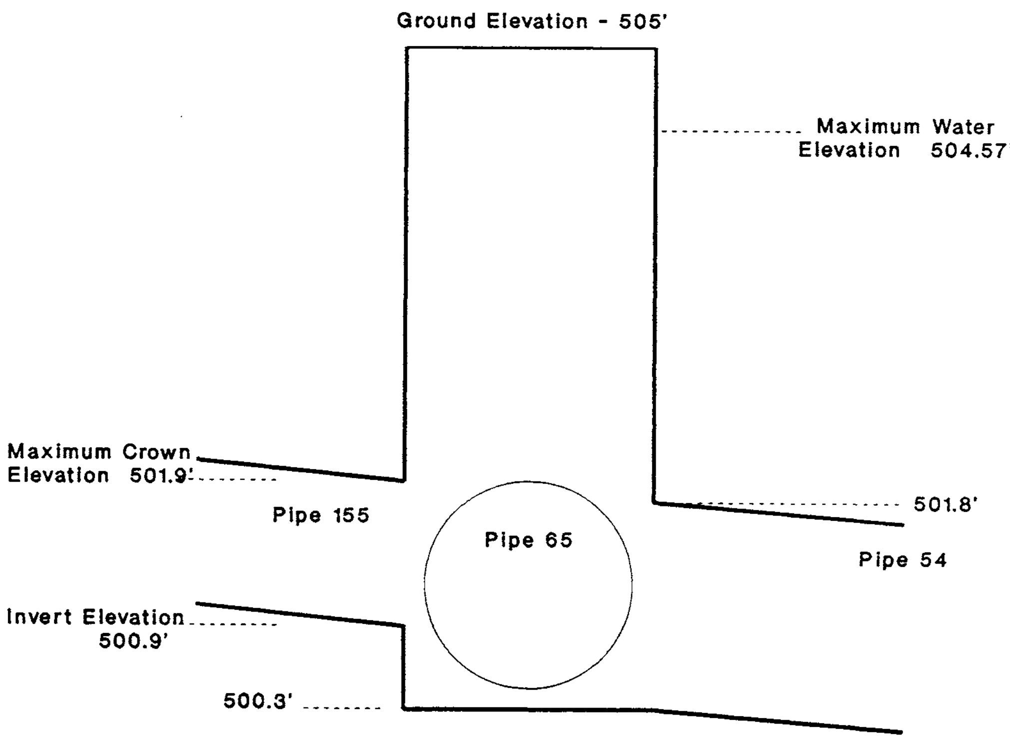

Figure 22. Maximum Water Elevation for Junction 5

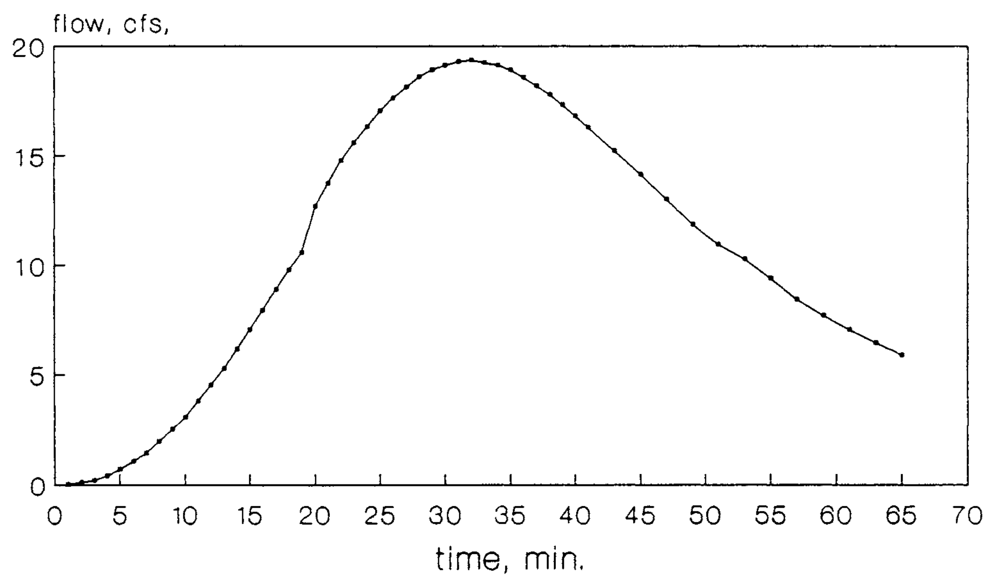

Figure 23. Flow for Pipe 54

Example 3: Clark Method

The sample sewer network contains three sewers of different length, elevation, and diameter. Pipes have a Manning's n of 0.013. Inflow is provided to the system using the Clark method. All subareas are 60 acres and have identical time-area diagrams and storage coefficients. A tailwater elevation of 1098.5 ft is given at the outfall. Pressurized flow run data in the PFA command include

1. 150-min simulation
2. 20-sec time step
3. 10-min print interval.

Pipe system data are listed in Table 8. The resulting input and output files appear in Tables 9 and 10.

Table 8. Clark Method Example Data

Nodes Upstream	Nodes Downstream	Length (ft)	Diameter (in)	Angle
4	3	340	48	41
3	2	630	48	0
2	1	412	60	0

1338

Table 9. Clark Method Input File

```
0010 JOB PRESSURIZED FLOW USING CLARK METHOD
0020 SWI 6
0030 PDA 0.013 24 3.9 2.5 2 .01
0040 NEW KAIGHN MOUNTAIN ROAD
0050 PIP 340 1128 1122 1119.2 1113.2 -48
0060 PNC 43 4 5 3 1 1 0. 0 0.
0070 REM TRUNK 3 TO 2
0080 PIP 630 1122 1108 1112.2 1101.2 -48
0090 PNC 32 3 1 2 1 1 30. 0 0.
0100 REM TRUNK 2 TO 1
0110 PIP 412 1108 1099 1100.2 1093.1 -60
0120 PNC 21 2 1 1 4 1 0. 0 0. 1.5 1098.5
0130 PFA 150. 20. 10 0 0 0 0 3 35 0.05 1
0140 HHJ 4 3 2
0150 REM INFLOW HYDROGRAPHS TO JUNCTIONS
0160 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
0170     1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
0180 CHY 0. 1.0 1.0
0190 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
0200     1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
0210 CHY 0. 1.0 1.0
0220 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
0230     1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
0240 CHY 0. 1.0 1.0
0280 END
```

Table 10. Clark Method Output File

```
*** PFP-HYDRA (Version of Oct. 2, 1986) ***          DATE 06-21-90
                                                     PAGE NO    1


    PRESSURIZED FLOW USING CLARK METHOD

Commands Read From File example.hda
   10 JOB
   20 SWI 6
   30 PDA 0.013 24 3.9 2.5 2 .01
   40 NEW KAIGHN MOUNTAIN ROAD
   50 PIP 340 1128 1122 1119.2 1113.2 -48
   60 PNC 43 4 5 3 1 1 0. 0 0.
   70 REM TRUNK 3 TO 2
   80 PIP 630 1122 1108 1112.2 1101.2 -48
   90 PNC 32 3 1 2 1 1 30. 0 0.
  100 REM TRUNK 2 TO 1
  110 PIP 412 1108 1099 1100.2 1093.1 -60
  120 PNC 21 2 1 1 4 1 0. 0 0. 1.5 1098.5
  130 PFA 150. 20. 10 0 0 0 0 3 35 0.05 1
  140 HHJ 4 3 2
  150 REM INFLOW HYDROGRAPHS TO JUNCTIONS
  160 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
        1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
  180 CHY 0. 1.0 1.0
  190 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
        1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
  210 CHY 0. 1.0 1.0
  220 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
        1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
  240 CHY 0. 1.0 1.0
  280 END
 END OF RUN.
```

Table 10. Clark Method Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***           DATE 06-21-90
                                                      PAGE NO   2


***** PRESSURIZED FLOW SIMULATIONS *****


TOTAL SIMULATION TIME IS      150 MIN.
INCREMENTAL TIME IS           10 MIN.
LENGTH OF INTEGRATION STEP IS   20. SECONDS
INITIAL TIME    .00 HOURS
SURCHARGE VARIABLES: ITMAX...    35
                     SURTOL...  .050
PRINTED OUTPUT AT THE FOLLOWING  0 JUNCTIONS



          AND FOR THE FOLLOWING  0 PIPES
```

Table 10. Clark Method Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***   DATE 06-21-90
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	PIPE NUMBER	LENGTH (FT)	AREA (SQ FT)	MANNING COEF.	MAX. WIDTH (FT)	DEPTH (FT)	JUNCTIONS AT ENDS		INVERT HEIGHT ABOVE JUNCTIONS	
1	43	340.	12.57	.013	4.00	4.00	4	3	.00	1.00
2	32	630.	12.57	.013	4.00	4.00	3	2	.00	1.00
3	21	412.	19.63	.013	5.00	5.00	2	1	.00	.00

Table 10. Clark Method Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
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	JUNCTION NUMBER	GROUND ELEV.	CROWN ELEV.	INVERT ELEV.	QINST (CFS)	CONNECTING PIPES	
1	4	1128.00	1123.20	1119.20	.00	43	
2	3	1122.00	1117.20	1112.20	.00	43	32
3	2	1108.00	1105.20	1100.20	.00	32	21
4	1	1099.00	1098.10	1093.10	.00	21	

Table 10. Clark Method Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***           DATE 06-21-90
                                                      PAGE NO   5


           * * * *  FREE OUTFALL DATA  * * * *

      FREE OUTFLOW AT JUNCTIONS           1

OUTFLOW CONTROL WATER SURFACE ELEV. IS    1098.50 FEET

  * * * *  SUMMARY OF INITIAL HEADS, FLOWS AND VELOCITIES  * * * *


      INITIAL HEADS, FLOWS AND VELOCITIES ARE ZERO
```

Table 10. Clark Method Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
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* * * *JUNCTION HYDROGRAPHS OBTAINED BY SCS OR CLARK METHOD* * * *

JUNCTION 4		JUNCTION 3		JUNCTION 2	
TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS	TIME HR.MIN	FLOW CFS
0. 0	.00	0. 0	.00	0. 0	.00
0.22	6.36	0.22	6.36	0.22	6.36
0.45	33.24	0.45	33.24	0.45	33.24
1. 7	77.93	1. 7	77.93	1. 7	77.93
1.29	115.15	1.29	115.15	1.29	115.15
1.52	121.80	1.52	121.80	1.52	121.80
2.14	104.33	2.14	104.33	2.14	104.33
2.36	80.81	2.36	80.81	2.36	80.81
2.59	61.95	2.59	61.95	2.59	61.95
3.21	47.50	3.21	47.50	3.21	47.50
3.43	36.41	3.43	36.41	3.43	36.41
4. 6	27.90	4. 6	27.90	4. 6	27.90
4.28	21.36	4.28	21.36	4.28	21.36
4.50	16.36	4.50	16.36	4.50	16.36
5.13	12.52	5.13	12.52	5.13	12.52
5.35	9.59	5.35	9.59	5.35	9.59
5.58	7.35	5.58	7.35	5.58	7.35
6.20	5.64	6.20	5.64	6.20	5.64
6.42	4.32	6.42	4.32	6.42	4.32
7. 5	3.31	7. 5	3.31	7. 5	3.31
7.27	2.53	7.27	2.53	7.27	2.53
7.49	1.94	7.49	1.94	7.49	1.94
8.12	1.48	8.12	1.48	8.12	1.48
8.34	1.14	8.34	1.14	8.34	1.14
8.56	.87	8.56	.87	8.56	.87
9.19	.67	9.19	.67	9.19	.67
9.41	.51	9.41	.51	9.41	.51
10. 3	.32	10. 3	.32	10. 3	.32
10.26	.14	10.26	.14	10.26	.14
10.48	.00	10.48	.00	10.48	.00

Table 10. Clark Method Output File, cont.

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PAGE NO 7

* * * * SUMMARY STATISTICS FOR JUNCTIONS * * * *

JUNCTION NUMBER	GROUND /INVERT ELEV. (FT)	UPPERMOST PIPE CROWN ELEV. (FT)	FEET MAX. COMPUTED WATER SURFACE ELEV	TIME OF OCCURRENCE HR.	TIME OF OCCURRENCE MIN.	FEET OF SURCHARGE AT MAX. DEPTH	LENGTH OF SURCHARGE (MIN)
4	1128.00 1119.20	1123.20	1124.45	1	52	1.25	32.00
3	1122.00 1112.20	1117.20	1124.36	1	29	7.16	54.33
2	1108.00 1100.20	1105.20	1105.98	1	52	.78	25.67
1	1099.00 1093.10	1098.10	1098.50	0	0	.40	150.00

Table 10. Clark Method Output File, cont.

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* * * * SUMMARY STATISTICS FOR PIPES * * * *

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	DS (FT)
43	190.8 15.2	48.0	178.6 19.0	1	29	.9	5.25	11.16
32	189.8 15.1	48.0	234.6 18.7	1	41	1.2	12.16	4.78
21	341.9 17.4	60.0	355.0 18.8	1	31	1.0	5.78	5.40

* * * * * PRESSURIZED FLOW SIMULATION ENDED * * * * *

Evaluation of Results

This example was generated using PFP-HYDRA's design capability. The rational method triangular hydrograph provided inflow to the system for design purposes. Using identical Clark hydrographs, with a peak flow of 121.80 cfs, the system analysis was performed. All junctions surcharged.

Junction 3 has a maximum water surface elevation of 1098.5 ft, which is above ground level. The maximum water surface elevation can be used to determine the volume of water that surcharges to the street. Table 11 shows the maximum water elevation compared to ground and crown elevations.

Table 11. Maximum Water and Crown Elevations—Clark Method Example

Junction	Ground Level (ft)	Water Level (ft)	Crown Level (ft) Upstream	Crown Level (ft) Downstream
4	1128	1124.45	—	1123.2
3	1122	1124.36	1117.2	1116.2
2	1108	1105.98	1105.2	1105.2
1	1099	1098.5	1098.1	—

Example 4: User Hydrographs

The North Magazine Avenue network contains six sewers with different characteristics. User-generated hydrographs provide inflow to the system. A tailwater elevation of 1240.1 ft is assumed at the outfall point. Pressurized flow data input includes a 2-sec time step, a total simulation time of 35 min, and six junction hydrographs for inflow. The resulting input and output files appear in Tables 12 and 13.

1348

Table 12. North Magazine Avenue Input File

```
0010 JOB North Magazine Ave.- Pressurized Flow w/ User Hydrographs
0020 SWI 6
0030 PDA .013 12 3.9 2.5 2 .002
0040 NEW TRUNK LINE 511-59
0050 PIP 32 1253.6 1253.4 1249.4 1249.2 -18
0060 PNC 51159 511 5 59 1 1 90 2 0 1.5 0 0 0 0.1 0.5
0070 REM TRUNK LINE 59-57
0080 PIP 48 1253.5 1255.3 1249.1 1248.8 -18
0090 PNC 5957 59 1 57 1 1 50 2 0 0 0 0 0 0.1 0.5
0100 REM TRUNK LINE 57-55
0110 PIP 29 1255.3 1254.2 1248.7 1248.5 -18
0120 PNC 5755 57 1 55 1 1 20 2 0 0 0 0 0 0.1 0.5
0130 REM TRUNK LINE 55-53
0140 PIP 30 1254.2 1254.5 1248.4 1248.0 -18
0150 PNC 5553 55 1 53 1 1 70 2 0 0 0 0 0 0.1 0.5
0160 REM TRUNK LINE 53-51
0170 PIP 39 1254.5 1253.7 1247.9 1247.2 -18
0180 PNC 5351 53 1 51 1 1 45 2 0 0 0 0 0 0.1 0.5
0190 REM TRUNK LINE 51-512
0300 PIP 138 1253.7 1248.6 1247.1 1244.5 -18
0310 PNC 51512 51 1 512 4 1 0 2 0 0 1245.7 0 0 0 0.5
0320 PFA 12. 2. 2 0 0. 0 0 6 30 0.05 1
0330 HHJ 511 59 57 55 53 51
0340 HHD 0.00 1.0 0.0 0.0 0.6 0.0 0.1
0350 HHD 0.18 4.9 2.5 0.8 4.6 4.3 0.7
0360 HHD 0.36 2.5 1.3 0.4 1.2 1.4 0.5
0370 HHD 0.54 1.0 0.5 0.2 0.7 0.0 0.1
0400 END
```

Table 13. North Magazine Avenue Output File

```
*** PFP-HYDRA (Version of Oct. 2, 1986) ***          DATE 06-21-90
                                                     PAGE NO   1

North Magazine Ave.- Pressurized Flow w/ User Hydrographs

Commands Read From File example.hda
   10 JOB
   20 SWI 6
   30 PDA .013 12 3.9 2.5 2 .002
   40 NEW TRUNK LINE 511-59
   50 PIP 32 1253.6 1253.4 1249.4 1249.2 -18
   60 PNC 51159 511 5 59 1 1 90 2 0 1.5 0 0 0 0.1 0.5
   70 REM TRUNK LINE 59-57
   80 PIP 48 1253.5 1255.3 1249.1 1248.8 -18
   90 PNC 5957 59 1 57 1 1 50 2 0 0 0 0 0 0.1 0.5
  100 REM TRUNK LINE 57-55
  110 PIP 29 1255.3 1254.2 1248.7 1248.5 -18
  120 PNC 5755 57 1 55 1 1 20 2 0 0 0 0 0 0.1 0.5
  130 REM TRUNK LINE 55-53
  140 PIP 30 1254.2 1254.5 1248.4 1248.0 -18
  150 PNC 5553 55 1 53 1 1 70 2 0 0 0 0 0 0.1 0.5
  160 REM TRUNK LINE 53-51
  170 PIP 39 1254.5 1253.7 1247.9 1247.2 -18
  180 PNC 5351 53 1 51 1 1 45 2 0 0 0 0 0 0.1 0.5
  190 REM TRUNK LINE 51-512
  300 PIP 138 1253.7 1248.6 1247.1 1244.5 -18
  310 PNC 51512 51 1 512 4 1 0 2 0 0 1245.7 0 0 0 0.5
  320 PFA 12. 2. 2 0 0. 0 0 6 30 0.05 1
  330 HHJ 511 59 57 55 53 51
  340 HHD 0.00 1.0 0.0 0.0 0.6 0.0 0.1
  350 HHD 0.18 4.9 2.5 0.8 4.6 4.3 0.7
  360 HHD 0.36 2.5 1.3 0.4 1.2 1.4 0.5
  370 HHD 0.54 1.0 0.5 0.2 0.7 0.0 0.1
  400 END
 END OF RUN.
```

Table 13. North Magazine Avenue Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***          DATE 06-21-90
                                                     PAGE NO   2

***** PRESSURIZED FLOW SIMULATIONS *****

TOTAL SIMULATION TIME IS      12 MIN.
INCREMENTAL TIME IS           2 MIN.
LENGTH OF INTEGRATION STEP IS    2. SECONDS
INITIAL TIME    .00 HOURS
SURCHARGE VARIABLES: ITMAX...    30
                    SURTOL...  .050
PRINTED OUTPUT AT THE FOLLOWING  0 JUNCTIONS


         AND FOR THE FOLLOWING  0 PIPES
```

Table 13. North Magazine Avenue Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) ***

DATE 06-21-90
PAGE NO 3

	PIPE NUMBER	LENGTH (FT)	AREA (SQ FT)	MANNING COEF.	MAX. WIDTH (FT)	DEPTH (FT)	JUNCTIONS AT ENDS		INVERT HEIGHT ABOVE JUNCTIONS	
1	51159	32.	1.77	.013	1.50	1.50	511	59	.00	.10
2	5957	48.	1.77	.013	1.50	1.50	59	57	.00	.10
3	5755	29.	1.77	.013	1.50	1.50	57	55	.00	.10
4	5553	30.	1.77	.013	1.50	1.50	55	53	.00	.10
5	5351	39.	1.77	.013	1.50	1.50	53	51	.00	.10
6	51512	138.	1.77	.013	1.50	1.50	51	512	.00	.00

Table 13. North Magazine Avenue Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
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	JUNCTION NUMBER	GROUND ELEV.	CROWN ELEV.	INVERT ELEV.	QINST (CFS)	CONNECTING PIPES	
1	511	1253.60	1250.90	1249.40	.00	51159	
2	59	1253.50	1250.70	1249.10	.00	51159	5957
3	57	1255.30	1250.30	1248.70	.00	5957	5755
4	55	1254.20	1250.00	1248.40	.00	5755	5553
5	53	1254.50	1249.50	1247.90	.00	5553	5351
6	51	1253.70	1248.70	1247.10	.00	5351	51512
7	512	1248.60	1246.00	1244.50	.00	51512	

Table 13. North Magazine Avenue Output File, cont.

```
*** PFP-HYDRA (Version of Oct.2, 1986) ***            DATE 06-21-90
                                                        PAGE NO   5


             * * * *  FREE OUTFALL DATA  * * * *


   FREE OUTFLOW AT JUNCTIONS          512

OUTFLOW CONTROL WATER SURFACE ELEV. IS     1245.70 FEET

  * * * *  SUMMARY OF INITIAL HEADS, FLOWS AND VELOCITIES  * * * *


   INITIAL HEADS, FLOWS AND VELOCITIES ARE ZERO
```

Table 13. North Magazine Avenue Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
PAGE NO 6

***** JUNCTION HYDROGRAPHS GIVEN BY USERS *****

JUNCTION NUMBER	TRIANGLE HYDROGRAPH TIME (MIN)/INFLOW (CFS)			
511	.00/ 1.00	10.80/ 4.90	21.60/ 2.50	32.40/ 1.00
59	.00/ .00	10.80/ 2.50	21.60/ 1.30	32.40/ .50
57	.00/ .00	10.80/ .80	21.60/ .40	32.40/ .20
55	.00/ .60	10.80/ 4.60	21.60/ 1.20	32.40/ .70
53	.00/ .00	10.80/ 4.30	21.60/ 1.40	32.40/ .00
51	.00/ .10	10.80/ .70	21.60/ .50	32.40/ .10

Table 13. North Magazine Avenue Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
PAGE NO 7

**** SUMMARY STATISTICS FOR JUNCTIONS ****

JUNCTION NUMBER	GROUND /INVERT ELEV. (FT)	UPPERMOST PIPE CROWN ELEV. (FT)	FEET MAX. COMPUTED WATER SURFACE ELEV	TIME OF OCCURRENCE HR.	MIN.	FEET OF SURCHARGE AT MAX. DEPTH	LENGTH OF SURCHARGE (MIN)
511	1253.60 1249.40	1250.90	1252.49	0	11	1.59	1.30
59	1253.50 1249.10	1250.70	1252.39	0	11	1.69	1.33
57	1255.30 1248.70	1250.30	1252.07	0	11	1.77	1.60
55	1254.20 1248.40	1250.00	1251.84	0	11	1.84	1.90
53	1254.50 1247.90	1249.50	1251.36	0	11	1.86	2.23
51	1253.70 1247.10	1248.70	1250.25	0	11	1.55	2.33
512	1248.60 1244.50	1246.00	1246.00	0	11	.00	.00

Table 13. North Magazine Avenue Output File, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 06-21-90
PAGE NO 8

* * * * SUMMARY STATISTICS FOR PIPES * * * *

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	DS (FT)
51159	8.3 4.7	18.0	5.1 4.3	0	11	.6	3.09	3.19
5957	8.3 4.7	18.0	7.7 5.3	0	11	.9	3.29	3.27
5755	8.7 4.9	18.0	8.5 5.5	0	11	1.0	3.37	3.34
5553	12.1 6.9	18.0	13.2 7.5	0	11	1.1	3.44	3.36
5351	14.1 8.0	18.0	17.5 9.9	0	11	1.2	3.46	3.05
51512	14.4 8.2	18.0	18.2 10.3	0	11	1.3	3.15	1.50

* * * * * PRESSURIZED FLOW SIMULATION ENDED * * * * *

Evaluation of Results

The summary printout of pressurized flow shows all junctions except Junction 512 (outfall) surcharging. Pipes 5755, 5553, 5351, and 51512 experience pressurized flow conditions. A comparison of maximum water elevation and crown elevation for each junction shows which pipe entry and exits are surcharged (see Table 14). This method helps to determine the accuracy of the surcharge and pressurized flow conditions.

Table 14. Maximum Water and Crown Elevations—North Magazine Avenue Example

Junction	Maximum Water Elevation (ft)	Crown Elevation (ft)	
		Upstream	Downstream
511	1252.49	—	1250.9
59	1252.39	1250.9	1250.6
57	1252.07	1250.3	1250.2
55	1251.84	1250.0	1249.9
53	1251.36	1249.5	1249.4
51	1250.25	1248.7	1248.6
512	1246.00	1246.0	—

REFERENCES

Brater, E. F., & King, H. W. (1976). *Handbook of hydraulics for the solution of hydraulic engineering problems* (6th ed.). New York: McGraw-Hill.

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U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

Viessman, W., Jr.; Lewis, G. L.; & Knapp, J. W. (1989). *Introduction to hydrology* (3rd ed.). New York: Harper & Row.

Yu, S. L., & Wu, Y. (1989). *A microcomputer model for simulating pressurized flow in a storm sewer system* (VTRC Report No. 89-R21). Charlottesville: Virginia Transportation Research Council.

APPENDIX A

Calculations and Troubleshooting

CALCULATIONS

Determination of Time Step

Using the following equation

$$\Delta t \le \frac{L}{\sqrt{gD}}$$

find the shortest pipe with the largest diameter and plug the values in. For example, you have a 50-ft pipe of diameter 36 in (3 ft). The acceleration due to gravity is 32.2 ft/sec^2. The allowable time-step calculation would be

$$\Delta t = \frac{50 \text{ ft}}{\sqrt{32.2 \text{ ft/sec}^2 \times 3 \text{ ft}}} = 5.0872 \text{ sec.}$$

You would enter the value 5.0 sec into the program through the PFA command. If more detailed calculations are desired, then a smaller number may be input. If a number larger than 5 sec is input, the program will calculate a new time step because the stability criteria will have been violated.

Determination of Parameters for SCS Unit Hydrograph Method

1. *Finding the SCS curve number.*

The area to be designed for is mostly paved parking lot, with some trees and grass. The two categories for curve numbers might be:

- open space, poor condition, curve number = 79
- paved parking lot, curve number = 98.

The design area is in Charlottesville, Albemarle County, Virginia. Using SCS Technical Release No. 55, we find the soil type to be Cecil Loam, which is hydrologic condition B (Table B2, Appendix B).

This allows the user of the charts in Appendix B to determine the curve numbers.

The curve number for use is, then, a composite of the previous two numbers. The composite number is calculated as follows:

Curve Number (CN)	% Area	Curve Number × % Area
79	60	47.4
98	40	+ 39.2
	New curve number =	86.6

2. *Choosing a rainfall.*

Use a developed IDF curve to determine storm duration and depth, or use your own knowledge to force the conditions you desire.

3. *Choosing a length to divide.*

You may use

1. distance to point within area with longest travel time
2. distance to centroid of area.

It is recommended that the larger of these two values be used.

Determination of Time-Area Diagram

Using a topographical map of the area, calculate travel times from various points within the watercourse area to the outfall point. For example, with an area of 600 acres in the Virginia mountains:

Point 1. Distance to outfall = 729 ft

Average watercourse slope = 80 ft/729 ft = 0.109, or 11%

Using Figure B1 in Appendix B, for forest with sheet flow, the velocity is graphically determined to be 0.7 ft/sec. Multiply the velocity by the distance, and the travel time is 529 sec, or 8.5 min.

Continue this for several points to define the area and then separate the area into equal times as in Figure 3. After a maximum of 300 ft, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from Figure B2 in Appendix B.

The lines separating the area are called isochrones. Find the area within the isochrones and construct a time-area histogram.

TROUBLESHOOTING

Example 1: Design Flow Equal to Zero

If you get a design flow equal to zero (see Table A1), check your invert height! The invert must be input in such a way that this will not happen (see Table A2).

Table A1. Incorrect Output Using North Magazine Avenue Example

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 11-15-90
PAGE NO 8

* * * * SUMMARY STATISTICS FOR PIPES * * * *

PIPE NUMBER	DESIGN FLO/VEL CFS/FPS	PIPE VERTICAL DEPTH (IN)	MAXIMUM COMPUTED FLO/VEL CFS/FPS	TIME OF OCCURRENCE HR.	MIN.	RATIO OF MAX. TO DESIGN FLOW	MAX. DEPTH ABOVE INVERT PIPE ENDS UP (FT)	DS (FT)
51159	8.3 4.7	18.0	1.3 3.4	0	1	.2	.41	.34
5957	8.3 4.7	18.0	1.5 3.3	0	1	.2	.44	.51
5755	.0 .0	18.0	1.5 2.6	0	1	.0	.61	.15
5553	12.1 6.9	18.0	2.4 5.3	0	1	.2	.45	.35
5351	14.1 8.0	18.0	2.7 6.2	0	1	.2	.45	.34
51512	14.4 8.2	18.0	2.6 2.6	0	1	.2	.44	1.20

* * * * * PRESSURIZED FLOW SIMULATION ENDED * * * * *

Table A2. Incorrect Input Using North Magazine Avenue Example

```
0010 JOB North Magazine Ave.- Pressurized Flow w/ User Hydrographs
0020 SWI 6
0030 PDA .013 12 3.9 2.5 2 .002
0040 NEW TRUNK LINE 511-59
0050 PIP 32 1253.6 1253.4 1249.4 1249.2 -18
0060 PNC 51159 511 5 59 1 1 90 2 0 1.5 0 0 0 0.1 0.5
0070 REM TRUNK LINE 59-57
0080 PIP 48 1253.5 1255.3 1249.1 1248.8 -18
0090 PNC 5957 59 1 57 1 1 50 2 0 0 0 0 0 0.1 0.5
0100 REM TRUNK LINE 57-55
0110 PIP 29 1255.3 1254.2 |1248.7 1248.7| -18
0120 PNC 5755 57 1 55 1 1 20 2 0 0 0 0 0 0.1 0.5
0130 REM TRUNK LINE 55-53
0140 PIP 30 1254.2 1254.5 1248.4 1248.0 -18
0150 PNC 5553 55 1 53 1 1 70 2 0 0 0 0 0 0.1 0.5
0160 REM TRUNK LINE 53-51
0170 PIP 39 1254.5 1253.7 1247.9 1247.2 -18
0180 PNC 5351 53 1 51 1 1 45 2 0 0 0 0 0 0.1 0.5
0190 REM TRUNK LINE 51-512
0300 PIP 138 1253.7 1248.6 1247.1 1244.5 -18
0310 PNC 51512 51 1 512 4 1 0 2 0 0 1245.7 0 0 0 0.5
0320 PFA 1. 2. 2 0 0. 0 0 6 30 0.05 1
0330 HHJ 511 59 57 55 53 51
0340 HHD 0.00 1.0 0.0 0.0 0.6 0.0 0.1
0350 HHD 0.18 4.9 2.5 0.8 4.6 4.3 0.7
0360 HHD 0.36 2.5 1.3 0.4 1.2 1.4 0.5
0370 HHD 0.54 1.0 0.5 0.2 0.7 0.0 0.1
0400 END
```

Example 2: Warning in the Output and Hydraulic Gradeline Equal to Zero

If there is a warning in the output that reads:

**** WARNING **** icyc = 306 ZERO SURFACE AREA

(see Table A3), then check the difference between the crown elevation of incoming pipe and the invert elevation of outgoing pipe at a particular junction (i.e., difference = crown elevation – invert elevation). Adjust and make the difference greater than or equal to zero.

If the hydraulic gradeline goes to zero and jumps back up 5 ft (see Table A3), then check the input file (see Table A4) for the tailwater elevation. Add or adjust the tailwater elevation, and check the invert and crown levels to obtain reasonable results.

Table A3. Incorrect Output Using Clark Method Example

```
      *** PFP-HYDRA (Version of Oct.2, 1986) ***          DATE 11-14-90
                                                           PAGE NO   9

CYCLE   270    TIME    1 HRS - 30.00 MIN

JUNCTIONS / DEPTHS

     4/   5.70*      3/   8.70*      2/   8.35*      1/   5.00

CONDUITS / FLOWS

    43/  88.60      32/ 232.16      21/ 394.21   90004/ 394.21
***** WARNING ***** ICYC=  300  ZERO SURFACE AREA
 COMPUTED AT JUNCTION      2
 CHECK INPUT DATA FOR HIGH PIPE

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

CYCLE   300    TIME    1 HRS - 40.00 MIN

JUNCTIONS / DEPTHS

     4/   5.70*      3/   8.70*      2/  18.99       1/    .00

CONDUITS / FLOWS

    43/  88.60      32/ 234.53      21/    .00   90004/    .00
***** WARNING ***** ICYC=  306  ZERO SURFACE AREA
 COMPUTED AT JUNCTION      2
 CHECK INPUT DATA FOR HIGH PIPE
***** WARNING ***** ICYC=  311  ZERO SURFACE AREA
 COMPUTED AT JUNCTION      2
 CHECK INPUT DATA FOR HIGH PIPE
***** WARNING ***** ICYC=  316  ZERO SURFACE AREA
 COMPUTED AT JUNCTION      2
 CHECK INPUT DATA FOR HIGH PIPE

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

CYCLE   330    TIME    1 HRS - 50.00 MIN  FLOW DIFF. IN SURCHARGED AREA= -3.55
                                          ITERATIONS REQUIRED=  1

JUNCTIONS / DEPTHS

     4/   5.70*      3/   8.24*      2/   8.67*      1/   5.00

CONDUITS / FLOWS

    43/  91.52      32/ 233.01      21/ 376.16   90004/ 376.16

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
```

Table A3. Incorrect Output Using Clark Method Example, cont.

*** PFP-HYDRA (Version of Oct.2, 1986) *** DATE 11-14-90
PAGE NO 11

* * * * TIME HISTORY OF HYDRAULIC GRADELINE * * * *
(VALUES IN FEET)

	JUNCTION 4		JUNCTION 3		JUNCTION 2	
TIME	GRND 1128.00		GRND 1122.00		GRND 1108.00	
HR.MIN	ELEV	DEPTH	ELEV	DEPTH	ELEV	DEPTH
0.10	1122.66	.36	1113.87	.57	1097.96	.76
0.20	1122.81	.51	1114.11	.81	1098.28	1.08
0.30	1123.14	.84	1114.47	1.17	1098.74	1.54
0.40	1123.45	1.15	1114.98	1.68	1099.41	2.21
0.50	1123.78	1.48	1115.45	2.15	1100.02	2.82
1. 0	1124.18	1.88	1115.96	2.66	1100.65	3.45
1.10	1124.59	2.29	1116.54	3.24	1101.42	4.22
1.20	1128.00	3.00	1121.08	6.00	1108.00	8.00
1.30	1128.00	3.00	1122.00	6.00	1105.55	8.00
1.40	1128.00	3.00	1122.00	6.00	1116.19	8.00
1.50	1128.00	3.00	1121.54	6.00	1105.87	8.00
2. 0	1128.00	3.00	1120.13	6.00	1097.20	.00
2.10	1128.00	3.00	1119.66	6.00	1097.20	.00
2.20	1127.70	3.00	1122.00	6.00	1097.20	.00
2.30	1125.18	2.88	1119.18	5.88	1102.82	5.62

Table A4. Incorrect Input Using Clark Method Example

```
0010 JOB PRESSURIZED FLOW USING CLARK METHOD
0020 SWI 6
0030 PDA 0.013 24 3.9 2.5 2 .01
0040 NEW KAIGHN MOUNTAIN ROAD
0050 PIP 340 1128 1122 1122.3 1116.3 -36
0060 PNC 43 4 5 3 1 1 0. 0 0.
0070 REM TRUNK 3 TO 2
0080 PIP 630 1122 1108 1113.3 1101.2 -48
0090 PNC 32 3 1 2 1 1 30. 0 0.
0100 REM TRUNK 2 TO 1
0110 PIP 412 1108 1099 1097.2 1091.1 -60
0120 PNC 21 2 1 1 4 1 0. 0 0.
0130 PFA 150. 20. 10 2 0 3 3 3 30 0.05 1
0131 PFP 43 32 21
0132 PHJ 4 3 2
0140 HHJ 4 3 2
0150 REM INFLOW HYDROGRAPHS TO JUNCTIONS
0160 TAD 0.0 0.0 0.2 5.0 0.4 7.0 0.6 15.0 0.8 12.0+
0170     1.0 11.0 1.2 6.0 1.4 4.0 1.6 0.0
0180 CHY 0. 1.0 1.0
0190 TAD 0.0 0.0 0.25 10.0 0.5 26.0 0.75 29.0+
0200     1.0 14.0 1.25 3.0 1.5 0.0
0210 CHY 0. 1.0 1.0
0220 TAD 0.0 0.0 0.25 10.0 0.5 26.0 0.75 27.5+
0230     1.0 12.0 1.25 0.0
0240 CHY 0. 1.0 1.0
0280 END
```

APPENDIX B

SCS Curve Number and Overland Velocity Charts

Table B1. Runoff Curve Numbers for Urban Areas[1]

Cover description: Cover type and hydrologic condition	Average percent impervious area[2]	Curve numbers for hydrologic soil group— A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only).[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation).[5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2a).					

[1] Average runoff condition, $I_a = 0.2S$.
[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition.
[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
[4] Composite CN's for natural desert landscaping should be computed based on the impervious area (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Source: U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

Table B2. Runoff Curve Numbers for Cultivated Agricultural Lands[1]

Cover description			Curve numbers for hydrologic soil group—			
Cover type	Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row + CR	Poor	64	75	83	86
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured + CR	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured & terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured & terraced + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition.
[2] *Crop residue cover (CR)* applies only if residue is on at least 5% of the surface throughout the year.
[3] Hydrologic condition is based on combination of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes in rotations, (d) percent of residue cover on the land surface (good ⩾ 20%), and (e) degree of surface roughness.
Poor: Factors impair infiltration and tend to increase runoff.
Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Source: U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

Table B3. Runoff Curve Numbers for Other Agricultural Lands[1]

Cover description		Curve numbers for hydrologic soil group—			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing.[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element.[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods-grass combination (orchard or tree farm).[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

[1] Average runoff condition.

[2] *Poor:* <50% ground cover or heavily grazed with no mulch.
Fair: 50% to 75% ground cover and not heavily grazed.
Good: >75% ground cover and lightly or only occasionally grazed.

[3] *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

[5] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

[6] *Poor:* Forest, litter, small trees, and brush have been destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Source: U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

Table B4. Runoff Coefficients for Rational Method

Description of Area	Runoff Coefficients
Business	
Downtown areas	0.70–0.95
Neighborhood areas	0.50–0.70
Residential	
Single-family areas	0.30–0.50
Multiunits, detached	0.40–0.60
Multiunits, attached	0.60–0.75
Residential (suburban)	0.25–0.40
Apartment dwelling areas	0.50–0.70
Industrial	
Light areas	0.50–0.80
Heavy areas	0.60–0.90
Parks, cemeteries	0.10–0.25
Playgrounds	0.20–0.35
Railroad yard areas	0.20–0.40
Unimproved areas	0.10–0.30
Streets	
Asphaltic	0.70–0.95
Concrete	0.80–0.95
Brick	0.70–0.85
Drives and walks	0.75–0.85
Roofs	0.75–0.95
Lawns; Sandy Soil:	
Flat, 2%	0.05–0.10
Average, 2–7%	0.10–0.15
Steep, 7%	0.15–0.20
Lawns; Heavy Soil:	
Flat, 2%	0.13–0.17
Average, 2–7%	0.18–0.22
Steep, 7%	0.25–0.35

Source: U.S. Department of Agriculture. Soil Conservation Service. (1986). *Urban hydrology for small watersheds* (Technical Release No. 55). Washington, DC: Author.

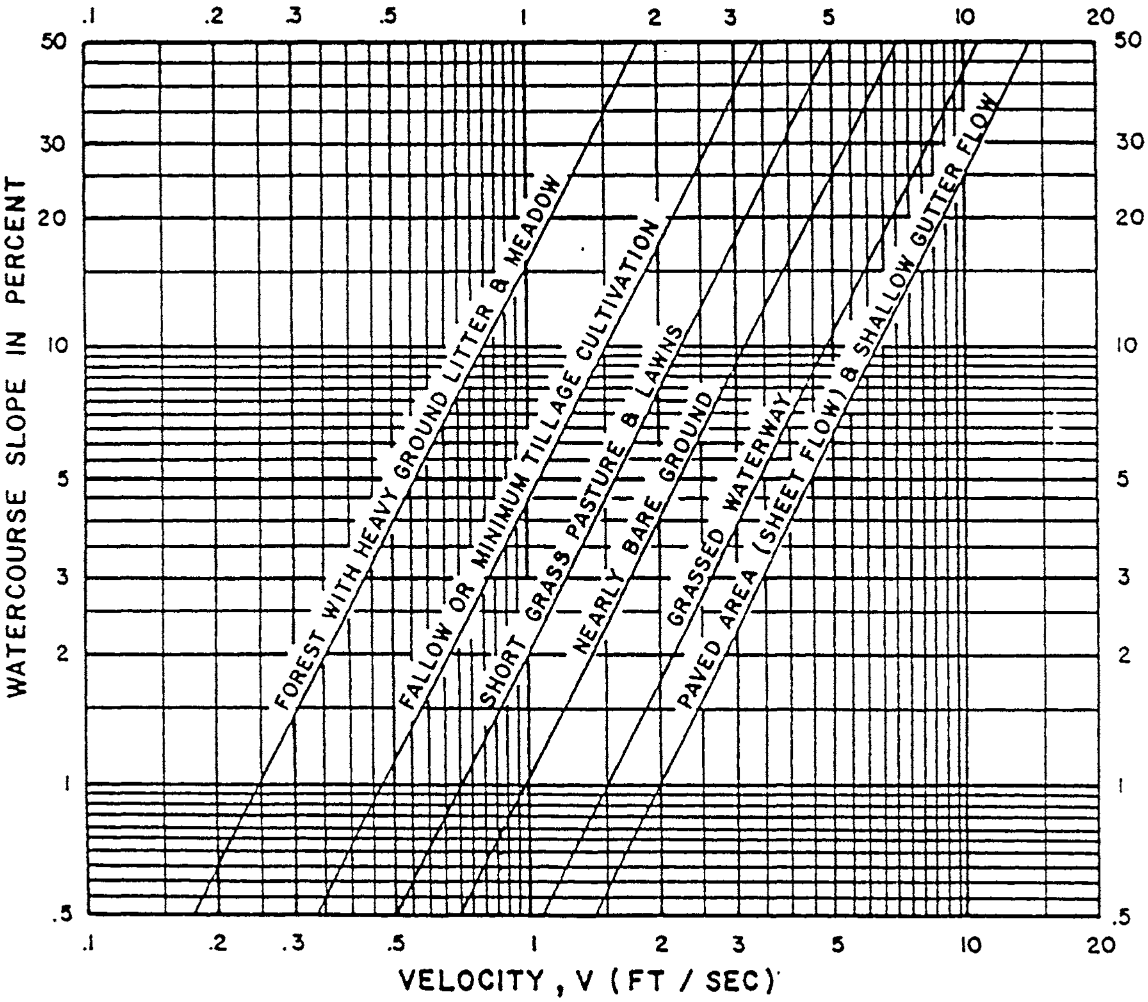

Figure B1. Average Velocities for Estimating Travel Time. *Source:* Federal Highway Administration. (1984). *Hydrology* (FHWA Report No. IP-84-15). Springfield, VA: National Technical Information Service.

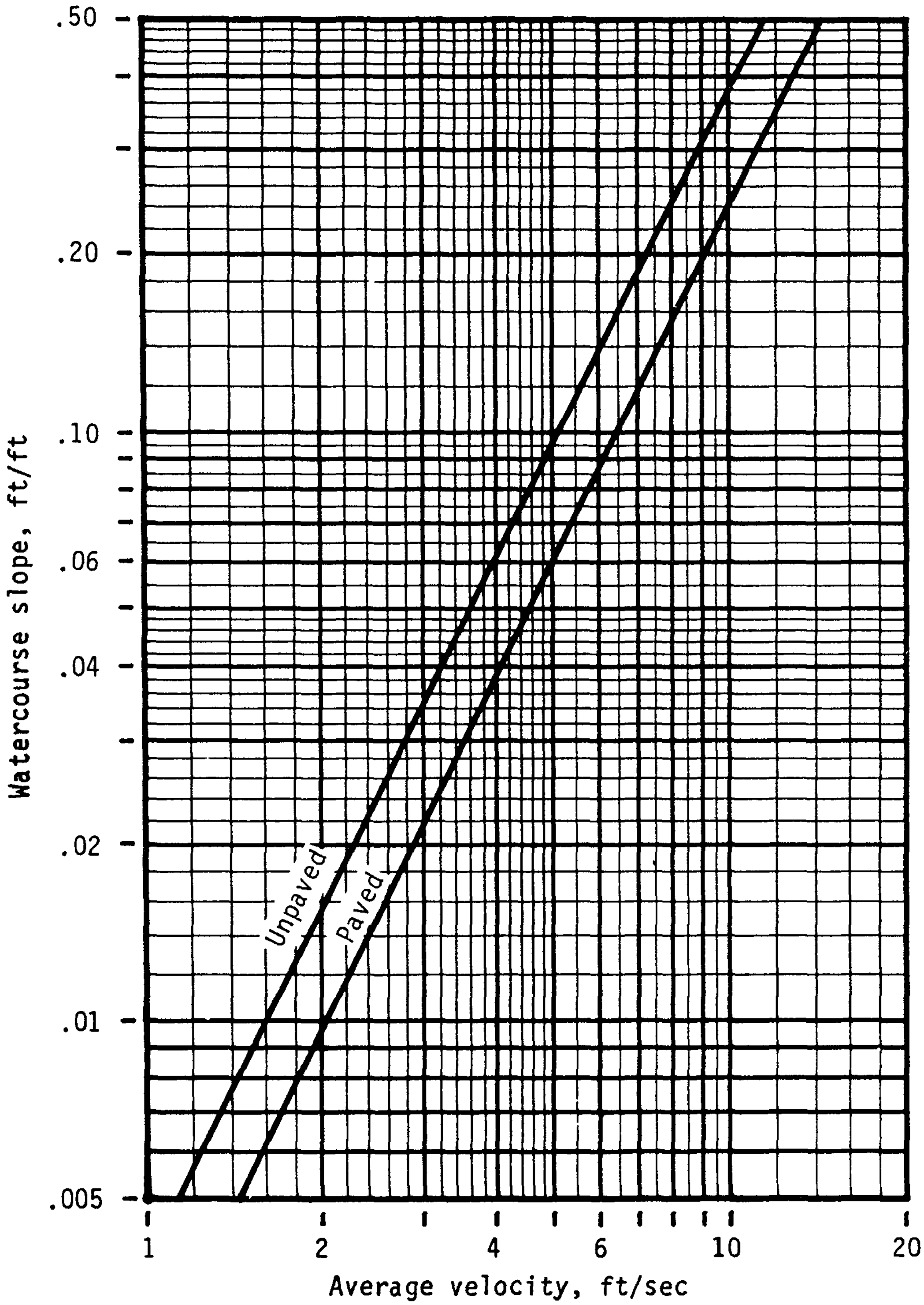

Figure B2. Average Velocities for Estimating Travel Time for Shallow Concentrated Flow. *Source:* Federal Highway Administration. (1984). *Hydrology* (FHWA Report No. IP-84-15). Springfield, VA: National Technical Information Service.