CECW-EH-Y Engineer Technical Letter 1110-2-367	Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	ETL 1110-2-367 31 March 1995
	Engineering and Design INTERIOR FLOOD HYDROLOGY	
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

CECW-EH-Y

Technical Letter
No. 1110-2-367

31 March 1995

Engineering and Design
INTERIOR FLOOD HYDROLOGY

1. Purpose. This ETL provides guidance for conducting hydrologic engineering flood damage reduction analyses of interior areas. The Hydrologic Engineering Center Interior Flood Hydrology (HEC-IFH) program is the primary tool used to demonstrate the analysis procedures presented.

2. Applicability. This guidance applies to HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities having civil works responsibilities.

3. General. Procedures described herein are considered appropriate and usable for hydrologic engineering planning and design studies involving flood damage reduction measures for interior areas. Specifically, the document is intended to assist with better scoping, planning, and analysis of interior flooding studies using the HEC-IFH program. Hydrologic engineering requirements for existing and future with and without conditions analyses are summarized. The minimum facility concept is presented. Technical analysis procedures for hydrologic analysis using hypothetical events and continuous simulation for various conditions of coincidence between interior and exterior flooding are described. Emphasis is placed on hydrologic analyses of gravity outlets, pumping stations, and detention storage. Appendices provide two example applications.

FOR THE COMMANDER:

R. C. JOHNS
Colonel, Corps of Engineers
Chief of Staff

CECW-EH-Y

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Chapter 1
Introduction

1-1. Purpose

This ETL provides guidance for conducting hydrologic engineering analyses for interior areas. The Hydrologic Engineering Center Interior Flood Hydrology (HEC-IFH) program is used as the primary tool for analyzing interior flooding. This document is intended to assist with better scoping, planning, and analysis of interior flooding studies using the HEC-IFH program. The information and analysis strategies presented are consistent with present guidance, specifically, ER 1105-2-100, EM 1110-2-1413, EC 1105-2-205, and procedures described in the HEC-IFH Package User's Manual (USACE 1992).

1-2. Overview of Interior Flood Hydrology Concepts

a. An interior area is defined as the area protected by a line-of-protection from direct river, lake, or tidal flooding. Interior areas may also include low depressions and natural sinks. Figure 1-1 is a conceptual illustration of an interior area. The following paragraphs describing interior flooding are taken from EM 1110-2-1413.

b. The levee, floodwall, or seawall associated with an interior area is called the line-of-protection. The line-of-protection excludes flood water originating from the exterior source but often aggravates the problem of interior flooding by blocking natural flow paths or outlets. Protected interior areas, formerly flooded from the exterior source by slowly rising flood waters generated from regional storms, may now flood from rainfall events that are more localized, occur more suddenly, and provide less warning. For example, flooding from the Mississippi River can be forecast several days in advance, but flooding from a localized storm on a protected interior area may occur in several hours or less. The flooding may be aggravated by coincident high exterior stages. The interior flooding that results usually may be of the nuisance variety (shallow, temporary flooding), but sometimes it can be more dangerous than the situation without the levee.

c. Interior flood waters are normally passed through the line-of-protection by gravity outlets when the interior water levels are higher than water levels of the exterior. This is called a positive gravity condition. When exterior stages are higher than the interior, flood waters are stored and/or diverted and pumped over or through the line-of-protection. This condition is known as a blocked gravity condition and is illustrated in Figure 1-2.

d. Gravity outlets, pumping stations, interior detention storage basins, diversions, and pressure conduits reduce flood damage within interior areas. Other measures, such as hillside reservoirs, channels, floodproofing, relocations, regulatory policies, and flood warning preparedness actions, may also be integral elements of interior systems.

e. Interior areas are studied to determine the specific nature of flooding and to formulate alternatives that reduce the residual and/or induced flooding. The objectives are the same

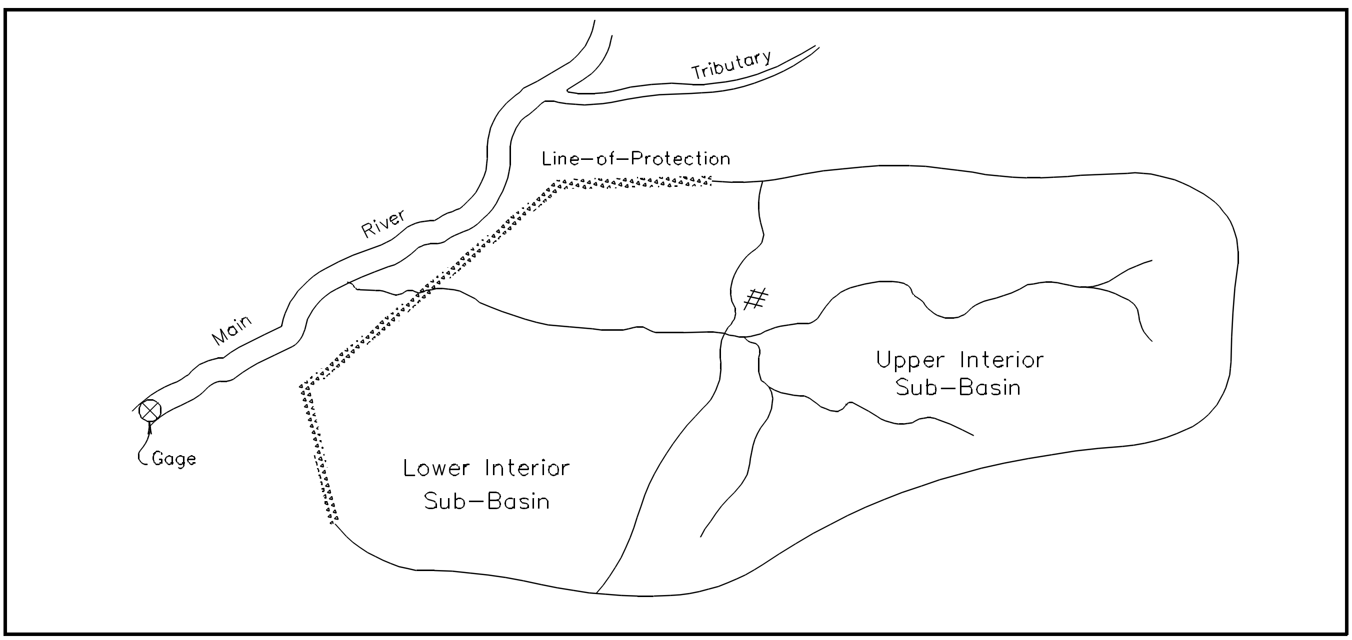


Figure 1-1. Typical interior area

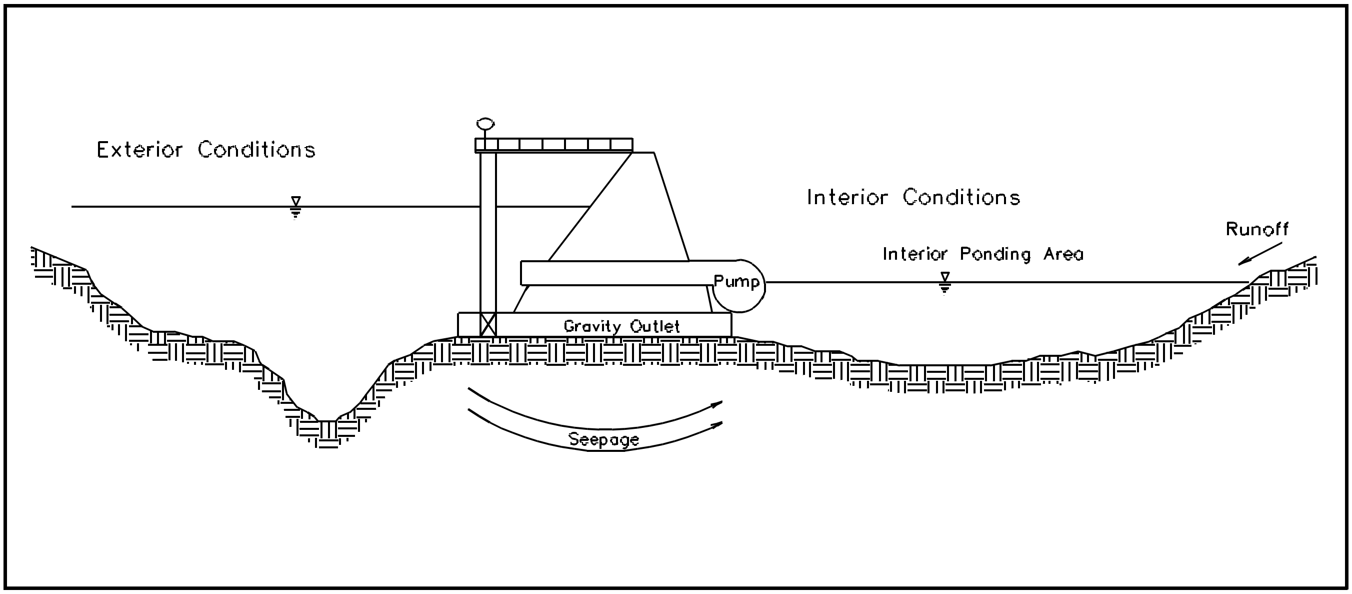


Figure 1-2. Cross section of typical interior system

as any flood reduction measure: to strengthen the national economy, enhance the environment, promote social well-being, and foster regional development. The plan selected for implementation is the one that best meets these objectives.

f. Hydrologic analysis of interior areas is complex and often difficult. Records may be scant or nonexistent, land use (and thus runoff) may have changed and is often continuing to change, natural flow paths are altered, and coincident flooding is the common situation (coincident flooding is discussed in paragraphs 2-6 and 2-7). Interior areas are generally flat and small (less than 2.59 sq km or 10 sq miles) and the measures to be considered are numerous, making the analysis tedious. The HEC-IFH program makes the technically complex problem of interior flooding easier to analyze.

g. Interior area investigations are different from other studies by hydrologic analysis factors and the uniqueness of commonly implemented flood damage reduction measures. But the study process and types of studies conducted to plan and design flood damage reduction actions are identical to those of other Corps investigations. Interior area analysis must follow current federal planning and design policies and regulations. Analysis includes formulation and evaluation procedures, level of protection considerations, and hydrologic, economic, environmental, and social assessment criteria.

h. Interior area planning studies are an essential aspect of feasibility studies. Although facilities and costs may at times be small components of a major line-of-protection project, the elements are often major items in the negotiated local sponsor agreements. They can represent a significant proportion of local costs, especially operation and maintenance costs.

1-3. Organization of Document

a. This document follows the technical steps necessary to successfully conduct a flood damage reduction analysis for interior areas. Hydrologic engineering aspects, data collection requirements, and evaluation of a minimum interior facility for interior areas are discussed. HEC-IFH modular concepts, data input procedures, and evaluation of with- and without-project conditions are also discussed. The main document provides information on:

(1) Study strategy.

(2) General analysis procedures when beginning an interior analysis.

(3) Concepts and applications of the HEC-IFH program.

(4) Preliminary investigations of the study area and data assembly.

(5) Analysis of existing and future without-project conditions for evaluating a minimum facility evaluation.

(6) Analysis of interior flood damage reduction measures to determine the appropriate gravity outlet, pumping and detention storage capacity.

(7) Comparison and evaluation of plans.

b. The HEC-IFH output summaries, data modules, and plotting capabilities of the program satisfy many reporting requirements. Appendices include references, a glossary of terms, a detailed work plan example, and two case studies that exemplify the use of HEC-IFH in a study setting.

1-4. Program Documentation

The primary documentation for the HEC-IFH program is the user's manual: a comprehensive description of the HEC-IFH program capabilities, theoretical basis for computations, and example problems illustrating data input and output. The user's manual should be carefully reviewed before using the computer program.

Chapter 2
Analysis Concepts and Procedures for Interior Areas

2-1. Overview

Study strategy includes procedures, assumptions, and activities associated with the study process. Hydrologic engineering analyses evaluate interior facilities using present planning guidelines. The interior system is analyzed separate from the line-of-protection project analysis. A minimum outlet facility is required to remove water through the levee or floodwall. This "minimum" facility, discussed in later chapters, becomes the starting point from which additional outlet facilities are formulated. Economic and other analyses are performed for several time- and development-related conditions. These are existing conditions and future conditions for with- and without-project features in place (EM 1110-2-1413 and ER 1105-2-100).

2-2. Planning Study Phases

There are two phases of the planning study process (ER 1105-2-100): reconnaissance and feasibility. The preconstruction engineering and design phase follows the planning phases.

a. Reconnaissance phase. The reconnaissance phase is fully funded by the federal government and is normally completed in 12 months. The objectives are to identify the flood problem, determine if there is at least one feasible solution that has a federal interest, identify a local cost-sharing sponsor, and (assuming a possible project) prepare an initial project management plan (IPMP) for the feasibility phase.

b. Feasibility phase. This second phase takes up to 4 years to complete and is cost-shared equally between the federal government and the local sponsor. The objectives of the feasibility phase are to perform detailed investigations and evaluations of a range of alternatives, and recommend a plan to reduce the flood damage potential.

c. Preconstruction engineering and design (PED) phase. The PED phase continues the design efforts of the recommended plan and encompasses the more detailed construction planning and engineering necessary for building the project. Major items are a reevaluation report, design documents, and plans and specifications. For interior area analysis, the key elements of the recommended plan will be reevaluated considering any additional information. If there are no changes, the reevaluation report may be brief. Design documents, usually called design memoranda (DM), are required for key features such as pumping stations and major gravity outlet works. Hydrologic engineering requirements are normally minimal, with emphasis on detailed hydraulic design studies of the major features (USACE 1991).

2-3. Hydrologic Engineering Studies

Hydrologic engineering studies are conducted within the framework of the planning and design processes. The without-project and with-project conditions must be studied and a hydrologic engineering management plan developed.

a. Without-project conditions. The initial step is to develop stage-frequency relationships at key locations for existing without-project conditions. The process is repeated for at least one future time period if conditions affecting hydrology and hydraulics change. The process is critical to establish the magnitude of the flooding problem and to define potential flood damage reduction measures and actions to study. For studies with an existing line-of-protection in place, this hydrologic analysis is for the existing system and facilities. Where a new line-of-protection is to be established, a minimum facility must be evaluated as part of the line-of-protection feature. The hydrologic analysis of the interior area then includes the minimum outlet as the without-project condition.

b. With-project conditions. After the without-project conditions are evaluated, a number of flood damage reduction plans are arrayed and evaluated. Common interior measures include gravity outlets, pumping stations, and detention storage areas. Other measures should also be evaluated, including at least one nonstructural plan (Section 73 of Public Law 93-251), and a flood warning-preparedness program plan that is complete or a component of a comprehensive plan (ER 1105-2-100).

c. Hydrologic engineering management plan (HEMP). The HEMP is a technical outline of the hydrologic/hydraulic studies necessary to successfully formulate a solution to a particular water resource problem. It should be detailed enough to define the study strategy. It is used to establish resource allocations and time and cost estimates. Study resources include personnel, schedules, and funding. Besides being a technical guide, a HEMP is valuable in explaining and justifying to the local sponsor the activities needed for the study and any in-kind service agreements. The HEMP is also used to define the hydrologic engineering requirements for the IPMP. Appendix C provides an example of a HEMP for an interior area.

2-4. Study Setting

Corps studies are normally in urban settings or partially developed areas. For some studies, an analysis of agricultural areas is required. The type and size of the flood damage reduction measures studied and implemented are influenced by the setting.

a. Agricultural areas. Hydrologic engineering analyses for agricultural areas generally involve a single subbasin adjacent to the levee. Volume and duration of flooding are usually more important than peak inflow to the line-of-protection. Seasonal effects are often important due to crop growing patterns and changing damage potential throughout the year. A continuous record analysis is normally used in the analysis.

b. Urban areas. Urban area analyses are usually more complex than agricultural areas. Rainfall-runoff analysis may include multiple subbasins. If natural or detention storage is limited, peak flow may be as important as volume. Layout, design, and operation of existing and potential future storm sewer systems must be considered. Investigations involving trade-offs between pumping capacity and nonstructural measures, such as relocation to gain more ponding area, may be required. The feasibility of flood-warning-preparedness components should be investigated.

2-5. Initial Preparation

Hydrologic engineering requires coordination early on with the study manager and other study team members to clarify the type of study, study objectives, and general scope of the requirements and constraints. Known problems and issues that affect the detail, cost, and conduct of the study should be described. Communication with counterparts are established and maintained. Field reconnaissances are conducted to collect information and insights about the study. The use of previous study data and information should be scrutinized and used to the extent possible.

a. Information needed. The following information typically is needed to develop hydrologic engineering analyses.

(1) Previous study data and reports.

(2) Maps, including USGS quadrangle sheets, topographic maps, aerial photographs, ortho-photographs, zoning plans, storm sewer layouts, etc.

(3) Historic flood events information including storm intensity and distribution patterns, high-water marks, frequency of overtopping, flow patterns, debris and sediment, and response times and actions.

(4) Existing and potential future flood control facilities including design capacities and operation procedures of gravity outlets and pumping stations.

(5) Survey cross-sectional information of major conveyance system.

(6) Future land use projections.

(7) Institutional responsibilities/capabilities.

(8) Regulatory policies affecting development off and on the floodplain.

(9) Identification of environmentally and culturally sensitive areas.

(10) Secondary water effects such as water quality, sediment, debris, and ice, which may affect study procedures and analysis costs.

b. Information sources. The following are common sources of information:

(1) Corps files of previous studies.

(2) Local agencies such as drainage and levee districts, planning commissions, public works departments.

(3) Federal agencies such as USGS, SCS, USBR, FEMA, TVA.

(4) State agencies such as Department of Water Resources, Natural Resources or Conservation.

(5) Railroads, highway departments.

2-6. Relationship Between Interior and Exterior Stage

A detailed description of the relationship between interior and exterior stages is found in EM 1110-2-1413. The following paragraphs summarize that material.

a. Fluctuating water levels both exterior and interior to the line-of-protection make interior area analysis unique. If the exterior and interior occurrences display a consistent relationship with each other, then, to a certain degree, one can be predicted from the other. The interior and exterior events are said to be **correlated**. If the physical and meteorologic processes of the interior and exterior events are related to one another, they are said to be **dependent**. If the interior and exterior events produce stages that coincide, e.g., the interior is high when an exterior event occurs, they are said to be **coincidental**. Coincidence can exist whether or not the interior and exterior occurrences are correlated or dependent.

b. It is possible, though not likely, that there is complete noncoincidence in a study area, e.g., the interior and exterior water levels will never be high or low at the same time. The interior analysis could be performed without consideration of exterior conditions, thus simplifying the analysis. The occurrences could be correlated and either dependent or independent, but it would not affect the analysis.

c. At the other extreme, it is possible that there is complete coincidence, e.g., high exterior levels are always present when an interior event occurs. The occurrences would likely be correlated, although not necessarily dependent, but it would not be important to the analysis approach.

d. The study situation most likely lies between these two extremes. Analyses to determine the degree of correlation may help determine the likelihood of coincidence or independence but are of doubtful value. Correlation studies are most useful for developing a predictive capability. Formal study to determine the degree of independence is not possible now. Lack of correlation can suggest, but not prove, independence. More likely, the degree of dependence is based on inspection of the available record and judgments of the meteorological and physiographic origins of the interior and exterior events. Thus, the critical focus for the analysis must be an assessment of coincidence.

e. Inspection of the historic record is required to determine correlation, independence, and coincidence. Establishing bounds on the consequences of decisions regarding these factors is an important analytical approach. Analysis at the two extremes of assuming complete coincidence and noncoincidence is useful. Also, by determining the relative consequences of independence, judgments regarding its importance to the study can be made. Table 2-1 summarizes hydrologic analysis considerations for various levels of coincidence and dependence of interior and exterior conditions.

2-7. Interior Analysis Computational Methods

Two hydrologic computation methods are normally performed for analyses of interior areas: continuous record simulation, and hypothetical events. Analyses of significant historic events for

Table 2-1
Assessment of Coincidence

COINCIDENCE	DEPENDENCE	EXAMPLE/COMMENTS	ANALYSIS CONSIDERATIONS
(HIGH)	(HIGH)	Hurricanes, large regional events; interior and exterior areas of similar magnitude.	Blocked gravity outlet conditions are common. Conventional hypothetical frequency analyses often appropriate for urban areas.
	(LOW)	Storm season of small interior area coincides with snowmelt runoff of large basins.	Continuous record analysis methods or probabilistic approaches generally required. Gravity outlet is often blocked during interior events.
	(HIGH) (LOW)	This range of coincidence is most common. Relatively high likelihood of interior and exterior events occurring simultaneously.	Continuous record analysis or probabilistic methods generally required. Gravity outlets may be blocked during critical interior events.
	(HIGH)	Timing of interior and exterior events is such that they rarely coincide. May be affected by operation of upstream project.	Considerable study may be required to identify this condition and to assume its existence in the physical process. Coincident hydrology generally appropriate.
(LOW)	(LOW)	Rare condition. Interior flooding rarely if ever coincides with high exterior stages. Studies generally limited to gravity outlet assessments.	Coincident interior analysis is not necessary.

model calibration/validation and system performance are normally required. The methods used depend largely on the study type and setting, resources availability, nature of flooding, available information, and a host of other factors. Most studies require combinations of both approaches.

a. Continuous simulation analysis (CSA) concepts. Continuous simulation methods involve analysis of continuous records of hydrologic events. The procedure consists of performing sequential hydrologic simulation of inflow, outflow, and change in storage to derive interior water surface elevation hydrographs given exterior stages and interior runoff and/or seepage for the entire period-of-record. Figure 2-1 presents a general summary of the concepts involved in the continuous simulation method.

(1) CSA overview. Continuous precipitation data (normally historic rainfall gaged records) are developed for each subbasin. Subbasin loss rates are subtracted and the runoff is transformed to the outlet. Base flow is added to yield continuous runoff hydrographs. Hydrographs are combined and routed through the system to the line-of-protection to yield inflows for the interior ponding area. These data are used with exterior stage data and the characteristics of gravity outlet and pumping stations at the line-of-protection to simulate the operation of the system. The results are continuous stage hydrographs at the interior ponding area. Subsequently, interior stage-frequency relationships can be derived.

(2) CSA applicability and limitations.

(a) Continuous simulation is attractive because it preserves the seasonality, persistence, and coincidence or noncoincidence of exterior river stages and interior flooding. The method enables project performance to be displayed. It is easily understood by the other study participants, the local sponsor, and the general public. Most importantly, the issue of coincidence of flooding is addressed inherently in the analysis. The analysis is particularly relevant for evaluating agricultural damage.

(b) Two major considerations in continuous simulation application are the length-of-record and the amount of data required for the analysis. The record of data may be unrepresentative (records are often too short), resulting in an inappropriate size and mix of measures and operation specifications of the system. Continuous simulation procedures require a significant amount of information and possibly extensive calibration and extrapolation.

b. Hypothetical event analysis (HEA) concepts. HEA uses single historic or synthetic events to develop frequency-based estimates of flow and/or stage.

(1) Hypothetical analysis for dependent events. This procedure is applicable when interior and exterior floods are dependent for the same meteorologic events. A single series of storm events is assumed to occur over both the interior and exterior areas. A constant exterior stage, "blocked" or "unblocked" exterior conditions may be evaluated using a series of hypothetical storm events on the interior area to evaluate the two bounds. These conditions represent total coincidence and noncoincidence, respectively. Figure 2-2 graphically depicts the concepts for dependent events. Event precipitation data, subbasin loss rates, and runoff transforms are used to compute the runoff hydrograph. Base flow is added to yield the total subbasin hydrograph at the outlet. This is called the unit hydrograph procedure and it is described in detail in EM 1110-2-1417. Hydrographs are combined and routed through the system to yield an inflow hydrograph for the interior area. These data are used with exterior stage data for the same flood event to simulate the expected operation of the system. Exterior

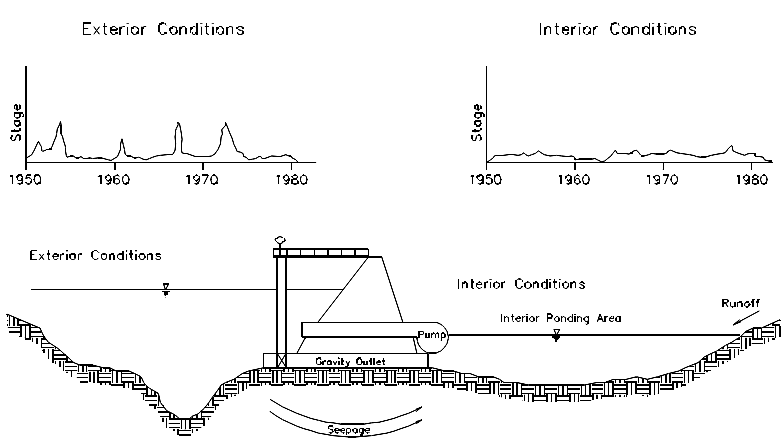


Figure 2-1. Continuous simulation analysis concepts

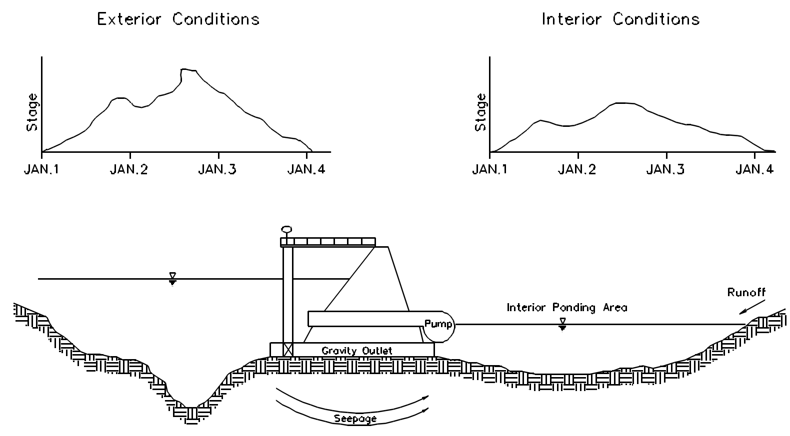


Figure 2-2. HEA concepts for dependent events

discharge hydrographs are computed using the same method described for the interior discharge hydrographs. The exterior stage hydrograph is then defined by applying the exterior discharge hydrograph to a rating curve at the interior ponding area primary outlet.

(2) Hypothetical analysis for independent events. This procedure is applicable when floods affecting the interior area can be independent of floods that affect the exterior stages. These areas are often relatively small interior areas located along large rivers, lakes, or coastlines. One probabilistic procedure applicable to the analysis of independent events using hypothetical rainfall is the coincident frequency method, conceptualized in Figure 2-3. This method applies the total probability theorem to generate stage-frequency functions for interior areas affected by various combinations of interior and exterior flooding. Figure 2-4 defines the steps necessary to perform the coincident frequency procedure.

(3) HEA applicability and limitations. HEA requires less data than the continuous record technique. The analysis generates hypothetical frequency hydrographs in which the peak flow rate, runoff volume, and all durations are assumed to be statistically consistent with the percent chance exceedance assignment of the rainfall events. This method overcomes the potential lack of data problems of CSA. However, for many study settings, interior and exterior flooding are not totally dependent or independent.

c. Using both CSA and HEA. Often continuous record data are available, but the number of years of record is short. Short historic records may be unrepresentative with respect to giving good estimates of more rare events or combinations of events. Thus, 30 to 40 years of record may be inadequate to derive stage-frequency results for rare events (1- to 0.2-percent events). For this situation, the CSA method should be used to define the more frequent events and the HEA method to help determine the rarer events. The resulting frequency relationship may be a product of both approaches.

2-8. Summary

Hydrologic analysis techniques used in planning studies of interior areas vary in analytical concepts and procedures. Unfortunately, the analysis is usually tedious and complex. Selection of techniques should be based on the type and phase of the study; complexity and relative importance of the coincident nature of flooding at the outlet; complexity of the hydrologic system; the nature of the flood damage, environmental, and social factors pertinent to the study area; and the experience of the analyst. The two techniques presented here are the continuous simulation approach and the hypothetical event approach; several variations exist with each. When working on a study, one should try to use everything available from both methods. For example, the CSA may be the best method to use on a particular study; however, the continuous record precipitation is so short that an HEA analysis is needed to include the larger, rarer events. To get the minimum and maximum range of interior stages, an analysis of both totally blocked and unblocked conditions is also recommended.

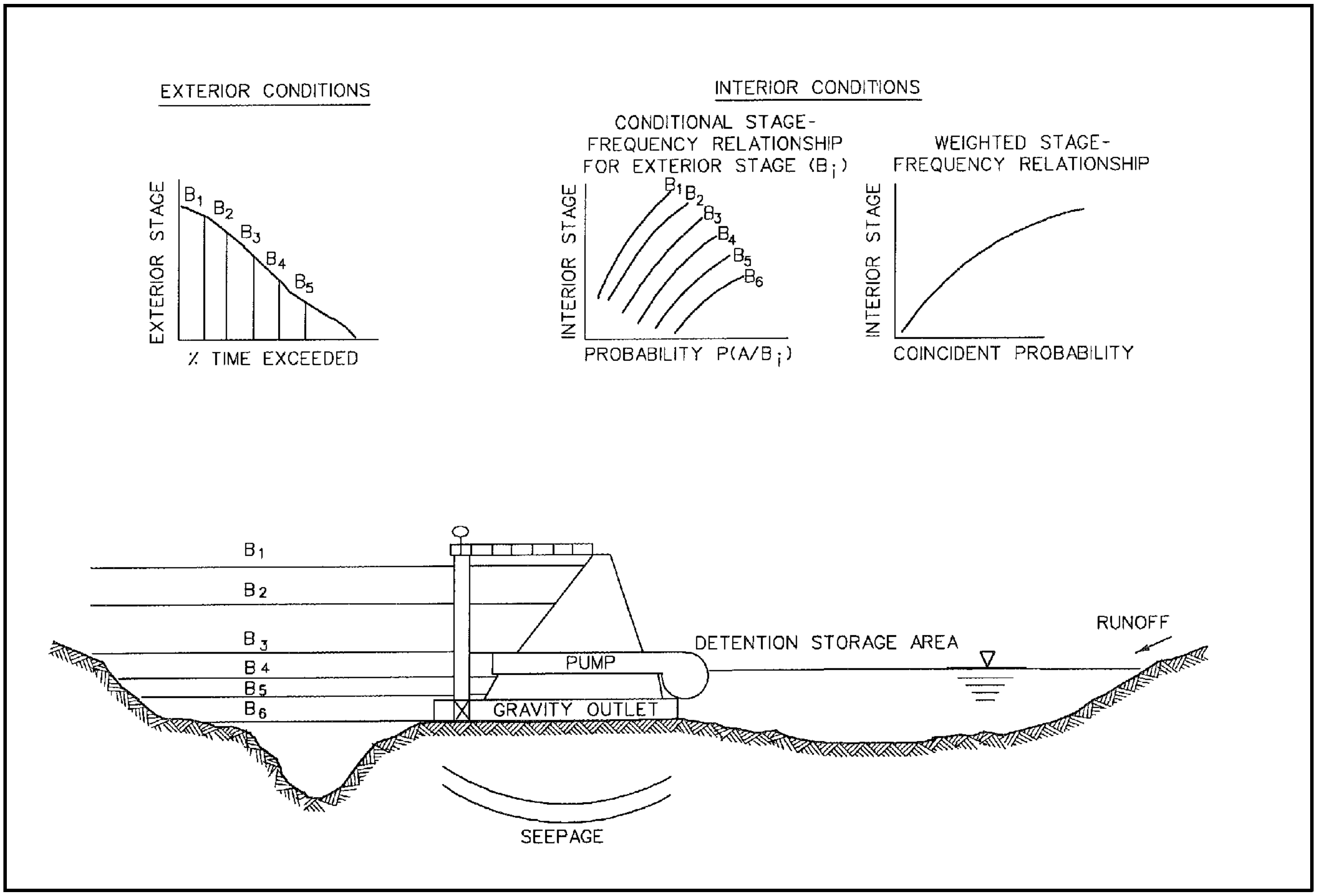


Figure 2-3. Coincident frequency analysis concepts

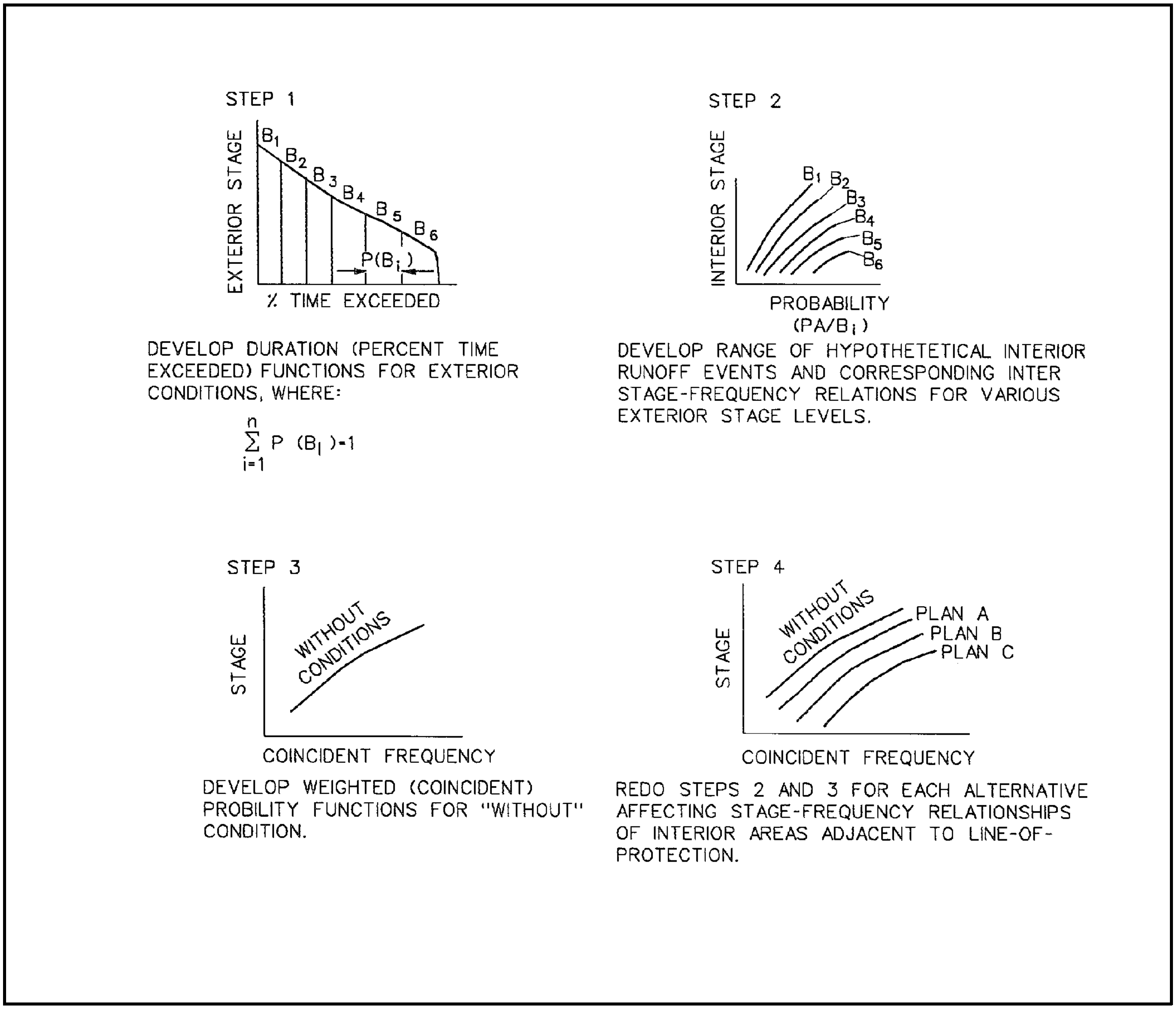


Figure 2-4. Coincident frequency procedures

Chapter 3
HEC-IFH Program Concepts and Applications

3-1. General

a. HEC-IFH is an interactive PC program using the MS-DOS system. The program is used for interior flood analyses based on continuous records or hypothetical and/or historic events. HEC-IFH facilitates technical computations, and helps manage the often complex and tedious task of data processing required for conducting interior studies.

b. HEC-IFH enables full-screen, interactive data entry, with input data verification and plotting prior to running the program. Analysis methods are selected using program menus. The analysis may be performed in steps, with the opportunity to review and assess results after each step. Reports and plots may be generated from input and output data. Additional output may be retrieved later without repeating the program execution. Detailed information about the program is available in the HEC-IFH Package user's manual (USACE 1992).

3-2. Computer System Requirements and Program Structure

a. Computer hardware requirements. HEC-IFH requires an IBM PC-compatible computer based on an 80386 or greater microprocessor. HEC-IFH also requires a math coprocessor for the 80386 or 80386SX computers. The operating system must be MS-DOS or IBM PC-DOS (version 3.0 or higher). The computer must have 4 MB of RAM memory as a minimum, with at least 3 MB configured as extended memory. A hard disk with at least 3.2 MB of storage capacity is required to install the HEC-IFH program and an additional 2.5 MB to copy and use CSA and HEA test data files. Significant storage is required if the CSA method is used, with a plan using 40 years of continuous record data at 1-hr increments requiring 8-10 MB of free space. Appendix B of the HEC-IFH user's manual suggests a minimum of 2 MB of free space for the HEA method.

b. Use of HEC-DSS. A key feature of the HEC-IFH program is the use of the HEC Data Storage System (HEC-DSS, USACE 1992) to store analysis input and output. Data can be imported from HEC-DSS interactively from within the HEC-IFH program. Also, data from other computer applications such as HEC-1 (USACE 1990b) can be imported directly as input to the HEC-IFH program. All HEC-IFH output is written to HEC-DSS and may be used by other programs that access HEC-DSS.

3-3. Program Menu Structure

HEC-IFH uses a menu screen format from a hierarchical (tree-like) structure to select different program options. Figure 3-1 illustrates the program menu structure. An introductory screen is displayed showing the name and version of the program at the beginning of every interactive session. Proceeding to the next screen, the user is asked to create a study ID subdirectory or recall an existing study subdirectory. All data for plans associated with a given study are stored in this subdirectory. An example of an opening menu is shown in Figure 3-2.

3-4. Program Configuration and Data Management Utilities

The main menu screen follows the study ID screen and allows the user to select different options for program use. The Main Menu selections (Figure 3-3) are Program Configuration Options, Data Management Utilities, Continuous Simulation Analysis, and Hypothetical Event Analysis.

- **Program Configuration.** HEC-IFH allows several configuration options to be set. These options control the appearance of program screens, plots, and printed reports. The units of measurement can also be specified.

- **Data Management Utilities.** HEC-IFH uses a Data Management Menu screen to list, archive, retrieve, and delete selected input and output data for a study or plan. Appendix D of the HEC-IFH user's manual describes the use of the menu screen in detail.

3-5. Program Application Structure

a. When either CSA or HEA is selected from the HEC-IFH Main Menu (Figure 3-3), the following choices are presented (see Figure 3-4):

- **Define Interior Analysis Data:** Allows input data to be entered or edited.

- **Perform Interior Analysis:** Allows definition of a plan for analysis.

- **Hydrologic Analysis Summaries:** Allows display of the results of a single interior analysis plan.

- **Comparison of Plans:** Allows display of a comparison of the hydrologic results of up to seven different interior analysis plans.

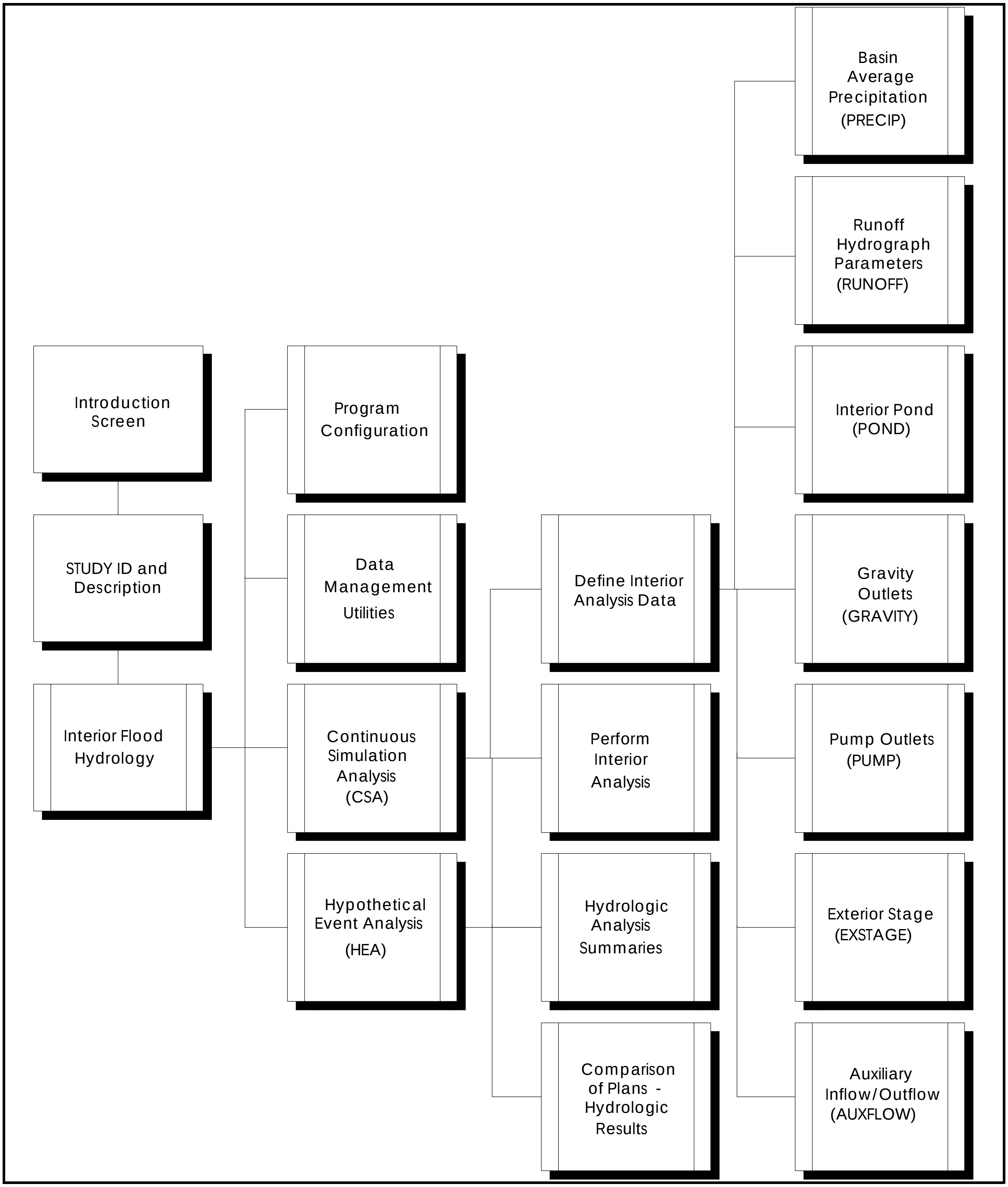


Figure 3-1. HEC-IFH program menu hierarchy

```
IFH 01.04.00

                         H.E.C. INTERIOR FLOOD
                       HYDROLOGY ANALYSIS PROGRAM
                            Version 01.04.00

          Study ID:          RBEND1
          Short Description: Plan 1 results - CSA example, App. C.

          Full Description:  The complete Plan 1 results are provided
                             for the CSA Example described in
                             Appendix C of the HEC-IFH User's Manual.

                             You may wish to view the study results
                             by pressing F10 to continue or work
                             through the example by following the
                             instructions in Appendix C.

          System of Measurement:      [English/Imperial] Metric/S.I

1Help   2PrtScr 3Index  4       5       6DOS    7       8       9       10Exit
           Press <Esc> to Quit program; or <F10> to Proceed to the Menu
```

Figure 3-2. Study ID and descriptions

```
IFH 01.04.00
Study ID  RBEND1          H.E.C. INTERIOR FLOOD HYDROLOGY



                   Select Option:

                     A. Program Configuration Options
                     B. Data Management Utilities
                     C. Continuous Simulation Analysis (CSA)
                     D. Hypothetical Event Analysis (HEA)



1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
               Press Letter; or use Arrow Keys and <Enter> to Select
```

Figure 3-3. HEC-IFH main menu

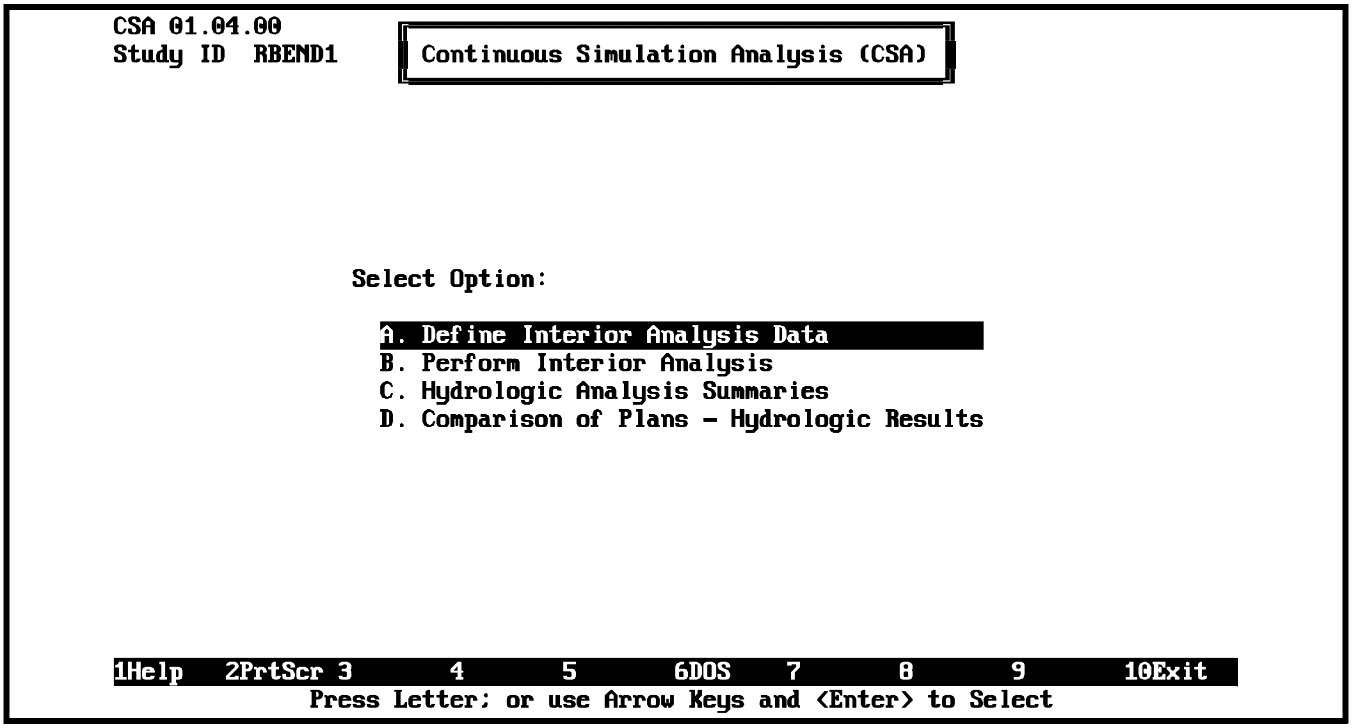


Figure 3-4. HEC-IFH continuous simulation analysis menu

b. The initial step is normally to define the interior analysis data for the study. This chapter emphasizes data entry procedures for accomplishing this task.

3-6. Define Interior Analysis Data

a. Data requirements. Data that define the interior and exterior are required to perform an interior area analysis. The information presented here can be used for any analytical method, but is specifically targeted for HEC-IFH data entry. Analyses are assumed to use both continuous record and hypothetical event approaches. The tasks are:

(1) Define interior areas to be studied. Consider the line-of-protection alignment, minimum facility requirements, runoff topology, topography of local ponding areas, present storm sewer systems, and potential for additional storm water collector/conveyance systems.

(2) Delineate interior subbasins considering locations needed for stage-frequency relationships and storm sewer configuration.

(3) Select computation time interval (Δt) for this and subsequent analyses. Refer to Section 3-7 for more details in determining appropriate computation intervals.

b. HEC-IFH modular concepts. Data entry is performed after the study ID and type of analysis are specified. The HEC-IFH program uses a modular data entry format to store the input data needed to execute a plan. The modules contain all the data needed for a specific category of information. Seven modules are used to represent groups of related data (Figure 3-5). The program provides separate data entry screens and computational procedures to develop the data for each module. Several sets of data may be entered and stored with module identifiers (module ID's) identifying each set. The seven modules are:

- **PRECIP Module:** Basin Average Precipitation.
- **RUNOFF Module:** Runoff Hydrograph Parameters.
- **POND Module:** Interior Pond Data.
- **GRAVITY Module:** Gravity Outlet Data.
- **PUMP Module:** Pump Outlet Data.
- **EXSTAGE Module:** Exterior Stage Data.
- **AUXFLOW Module:** Auxiliary Inflows and Outflows.

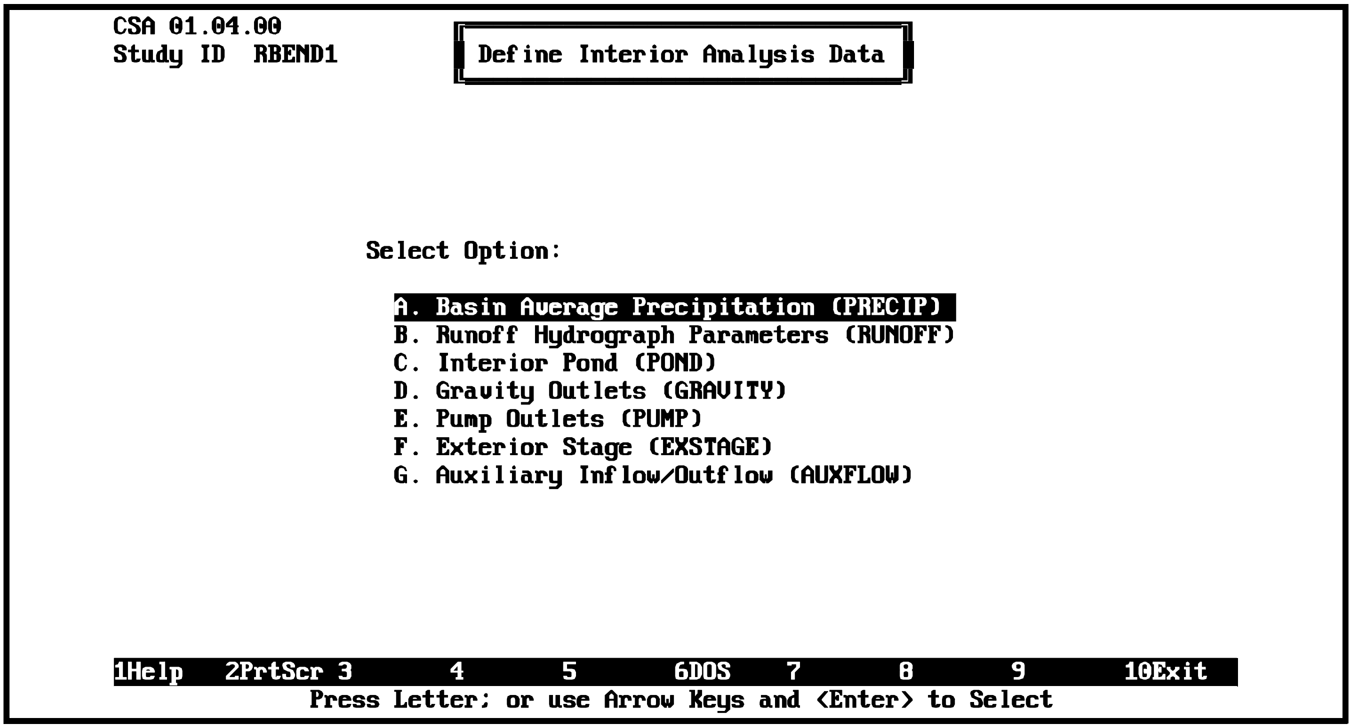


Figure 3-5. HEC-IFH data entry menu

(1) PRECIP module.

(a) This module contains continuous rainfall (normally historic records) and/or historical storm records and hypothetical frequency event data. Runoff computations require subbasin rainfall records.

(b) Rainfall data for recording and nonrecording rain gauges generally can be obtained from the National Weather Service (NWS) publications or CD's. Figure 3-6 shows what data can be obtained from the National Climatic Data Center. Estimates of rainfall data may also be acquired from newspaper articles that describe flooding after a large storm event and from rain gauges placed by local citizens, drainage districts, public works departments, and college or university science departments.

(c) Rainfall data can be entered into HEC-IFH manually, or imported from an existing HEC-DSS database. HEC-IFH checks imported values for missing data and either replaces them with zeros, or terminates the procedure. It is recommended to correct missing values using external utilities before importing them to HEC-IFH. One-year, one-month, or one-day hyetograph plots can be generated from the rainfall data. Figures 3-7 and 3-8 show precipitation data entry screens for CSA and HEA, respectively.

(d) HEC's PRECIP program is a useful tool for developing continuous basin average precipitation records from area recording and non-recording rain gauge data. See the PRECIP user manual (USACE 1989) for more information.

(e) Hypothetical frequency storm depth-frequency-duration relationships are normally developed from standard rainfall depth-frequency-duration information published by the National Weather Service. These data are entered into HEC-IFH as illustrated in Figure 3-8. HEC-IFH uses this information to compute rainfall distributions for up to seven storms ranging from 50 percent to 0.2 percent exceedance frequency. Figure 3-9 illustrates a rainfall hyetograph for a hypothetical storm.

(f) HEC-IFH allows the user to compute a standard project storm (SPS) using the same computation method utilized in the HEC-1 computer program. The SPS is normally used to generate a large event to evaluate how the system would perform if the event occurs. Figure 3-10 illustrates a typical SPS precipitation distribution.

(g) After the rainfall records are adjusted and verified, weightings are assigned to each gauge so that a composite rainfall record is developed for each subbasin. The weightings are based on conventional methods as described in Section 3.2.2 of the HEC-IFH user's manual.

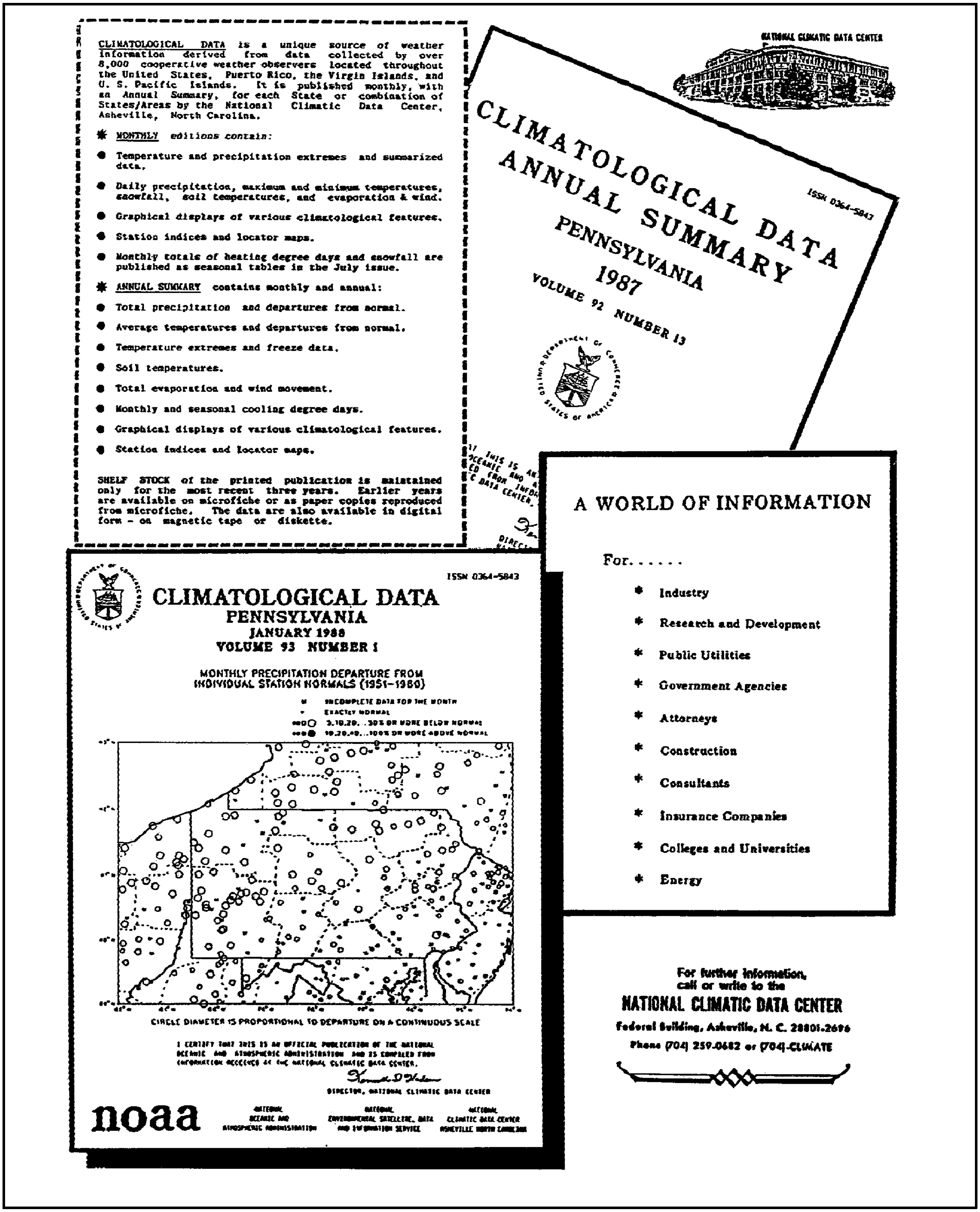


Figure 3-6. Source of climatological data

CSA 01.04.00
Study ID RBEND1

Basin Average Precipitation (PRECIP)

Enter/Import Precipitation Station Data

Precipitation Station ID GAGE1
Description:
Gage 1 recorded precip. WY1950-WY1960

Starting Period 01OCT1950/0100
(e.g. 01JAN1989/1300)

Ending Period 30SEP1960/2400

Time Interval 1HOUR
(e.g. 1HOUR, 1DAY, ...)

Date/Time DaMonYear/HrMn	Precipitation (in)
10OCT1954/0100	0.19
10OCT1954/0200	0.13
10OCT1954/0300	0.13
10OCT1954/0400	0.21
10OCT1954/0500	0.28
10OCT1954/0600	0.21
10OCT1954/0700	0.10
10OCT1954/0800	0.01
10OCT1954/0900	0.03
10OCT1954/1000	0.17
10OCT1954/1100	0.14
10OCT1954/1200	0.03
10OCT1954/1300	0.02
10OCT1954/1400	0.05

1Help 2PrtScr 3Index 4 5 6DOS 7 8 9 10Exit
Press <F10> to Save Data and Return

Figure 3-7. CSA precipitation data entry

HEA 01.04.00
Study ID RBEND1
Module ID STORM1

Basin Average Precipitation (PRECIP)

Enter Partial-Duration Rainfall Depth-Duration-Frequency Data

Duration	Rainfall Depth (in) for each Hypothetical Event						
	50%	20%	10%	4%	2%	1%	0.2%
5 minutes	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15 minutes	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1 hour	1.50	1.65	1.95	2.30	2.50	2.75	3.20
2 hours	1.80	2.00	2.30	2.70	2.90	3.25	3.60
3 hours	2.20	2.40	2.60	2.90	3.25	3.60	4.00
6 hours	2.40	2.60	3.00	3.50	3.80	4.25	4.70
12 hours	2.60	3.00	3.50	4.00	4.50	5.00	5.60
24 hours	2.80	3.50	4.00	4.60	5.20	5.70	6.20
2 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit
Press <F10> to Save Data and Continue

Figure 3-8. HEA precipitation data entry

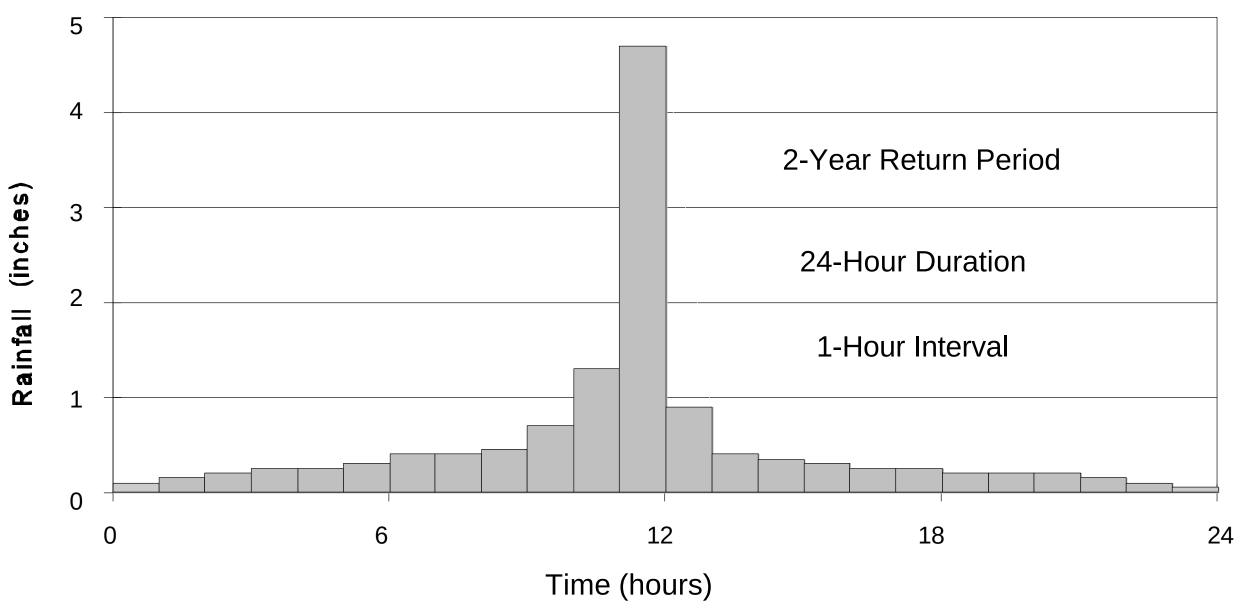


Figure 3-9. Hypothetical frequency storm hyetograph

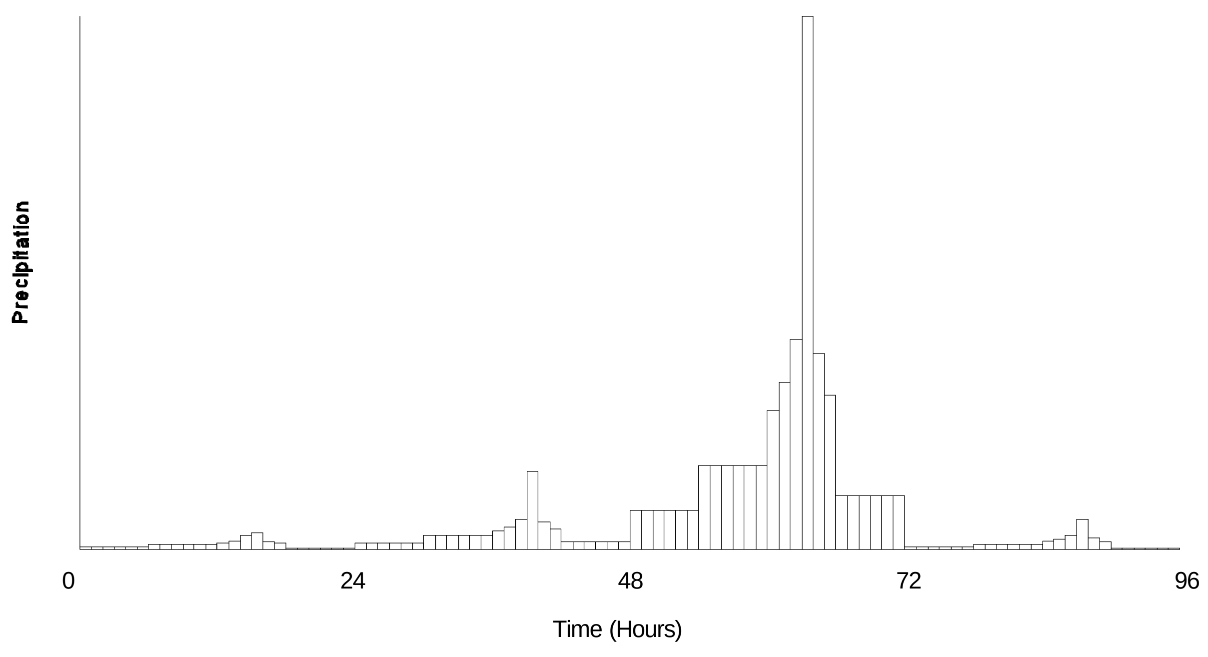


Figure 3-10. Typical SPS precipitation distribution

(2) RUNOFF module. Interior runoff hydrographs may be computed or imported from an external HEC-DSS file. HEC-IFH subbasin runoff parameters include data entry for basin characteristics, unit hydrographs, and loss rates. Data entry for channel routing between the upper and lower subbasins is also included. Figure 3-11 shows a typical subbasin runoff data entry screen. The program is limited to two interior subbasin areas per analysis.

(a) Basin characteristics. The subbasin drainage area and percent imperviousness are entered.

(b) Unit hydrograph. The user may select Clark's, Snyder's, or Soil Conservation Service (SCS) unit hydrographs or enter a unit hydrograph directly. A plot of a typical unit hydrograph used by HEC-IFH is shown in Figure 3-12.

(c) Loss rates. Loss rate methods and parameter values include monthly rates for continuous record analysis and event rates for hypothetical event analyses. Often an adequate representation of the flood volumes is more important than peak flows. Because of this, estimates of the loss rate parameters can be more critical than unit hydrograph and stream routing parameters into HEC-IFH, as illustrated in Figure 3-8. HEC-IFH enables users to select several loss rate options. CSA loss options are generalized runoff coefficients, initial-uniform-recovery method, and no losses. The generalized method is a simple percentage of the rainfall. It is normally used in agricultural areas with daily time intervals and where a significant amount of interior ponding exists. The initial-uniform-recovery is used for most continuous analyses performed by HEC-IFH and includes a simplified method of soil moisture accounting.

HEA loss options are the SCS Curve Number, Holtan, Green-Ampt, Initial-Uniform Methods, and no loss. The method used is largely a user preference based on calibration studies and reasonableness of runoff volumes.

(d) Base flow. Continuous simulation analysis can incorporate monthly rates for base flow. Hypothetical event analysis can incorporate an initial base flow rate and recession variables similar to the HEC-1 program.

(e) Streamflow routing. HEC-IFH has four routing techniques: simple lag method with no flow attenuation, modified Puls, Muskingum, and Muskingum-Cunge methods. The simple lag, the modified Puls, and the Muskingum methods can be used in either CSA or HEA. Muskingum-Cunge is only available in HEA. Modified Puls requires a storage versus outflow relationship and the number of routing steps. Figure 3-13 shows the data entry screen for channel routing. An HEC-IFH plot of a modified Puls storage versus outflow relationship is illustrated in Figure 3-14.

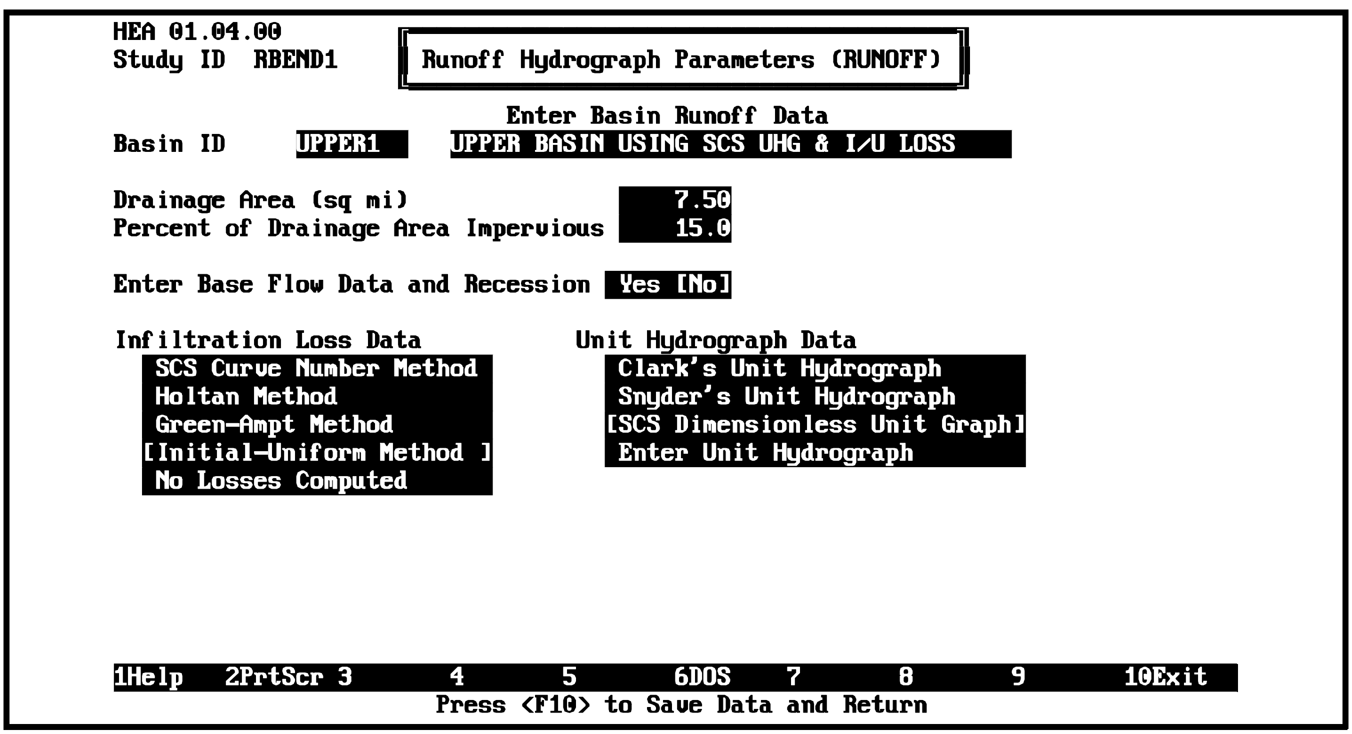


Figure 3-11. Subbasin runoff data entry

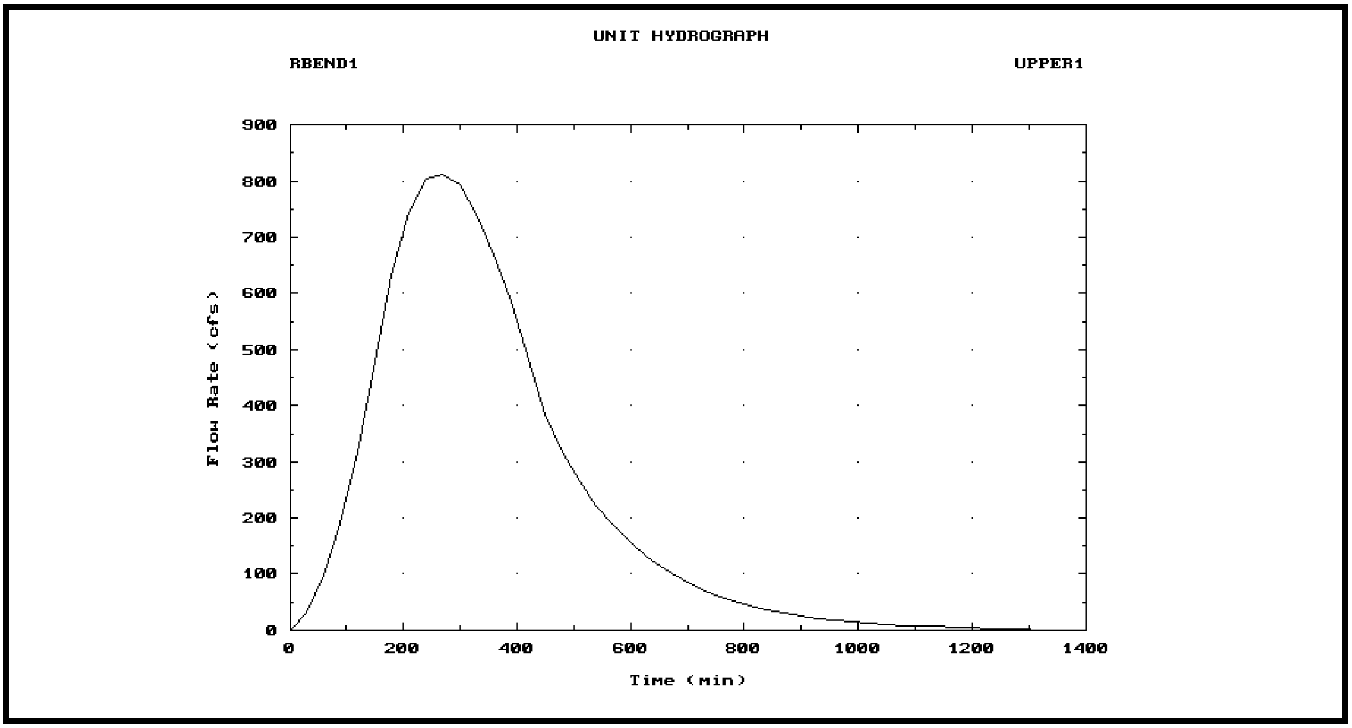


Figure 3-12. Unit hydrograph plot

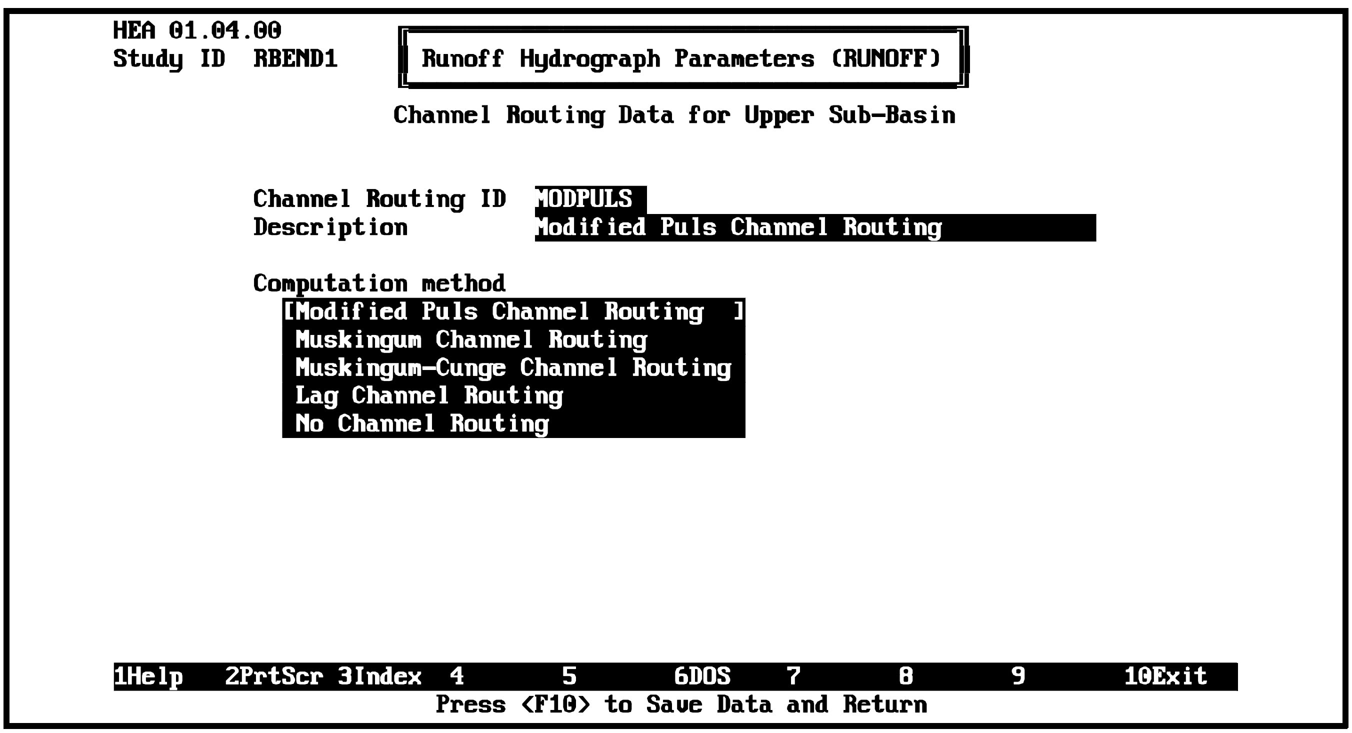


Figure 3-13. Channel routing data entry

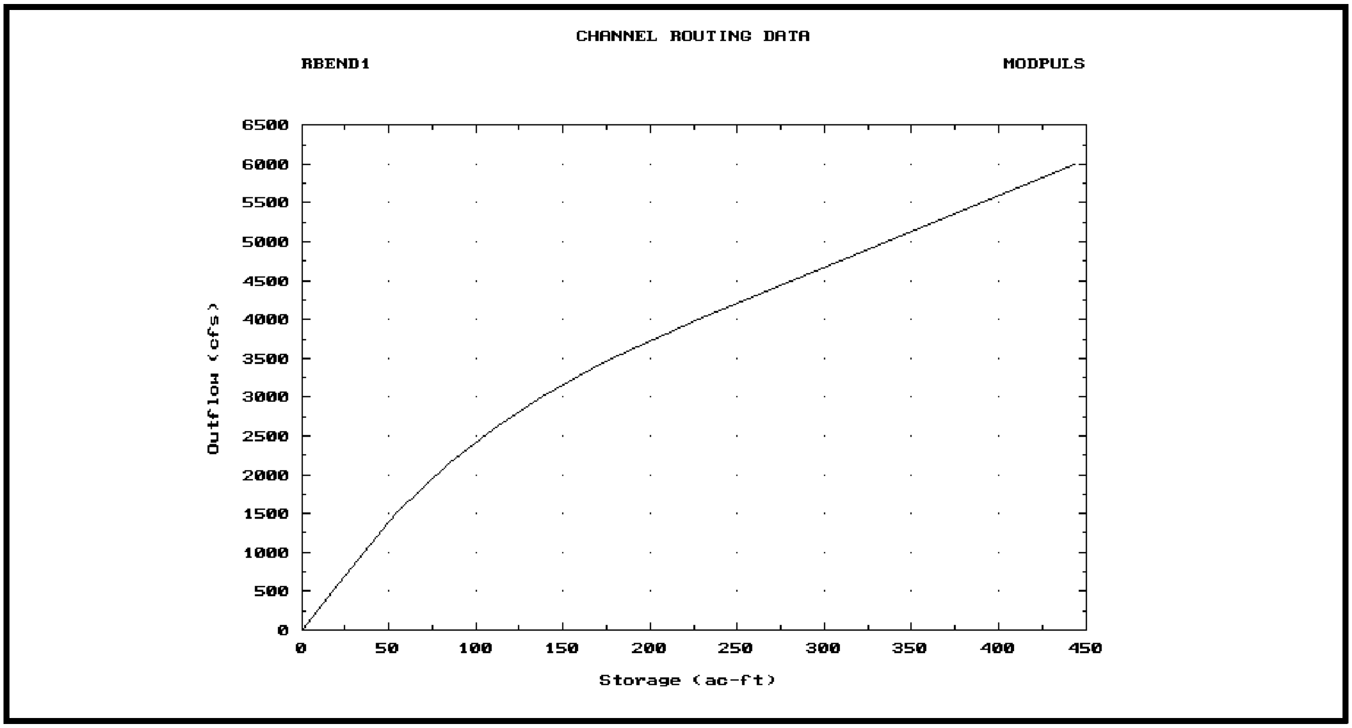


Figure 3-14. Modified Puls storage-outflow plot

For channel routing, the degree of attenuation depends on the number of routing steps used. The number of routing steps is a calibration parameter and represents the number of subreaches into which the total channel reach should be divided. The Muskingum method is defined by three parameters: number of routing steps, Muskingum K coefficient (which is the travel time through the reach), and Muskingum X (which is a weighting factor). The Muskingum-Cunge method is a nonlinear routing technique that is defined by channel length, channel invert slope, channel roughness coefficient, and channel shape. A trapezoid, a circular cross section, or a maximum eight-point cross section are the allowable channel shapes. This method is only available for HEA.

(3) POND module.

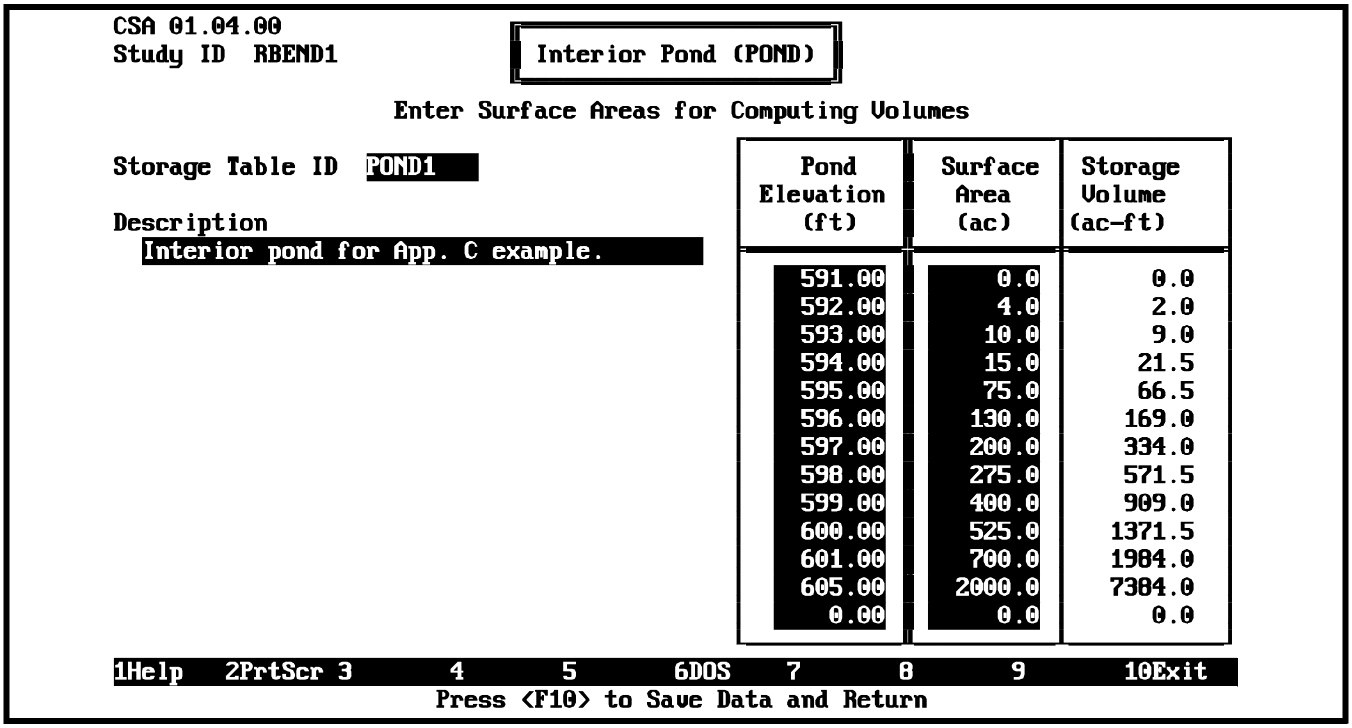
(a) Elevation-area relationships for the ponding area adjacent to line-of-protection should be developed using 15-20 points to define the relationship. HEC-IFH automatically generates the storage values. The minimum value should define the pond bottom (zero storage) and must be at the same elevation or below the lowest outlet invert elevation. The maximum value should exceed the highest stage anticipated in the analysis. No extrapolation is performed above or below these maximum or minimum elevations. Figure 3-15 illustrates the ponding area data entry screen and Figure 3-16 shows typical elevation-area-storage for a ponding area.

(b) A ditch rating or discharge-elevation relationship may be entered for a conveyance channel connecting the ponding area to the gravity outlet and/or pump. It is required if the flow is controlled from the ponding area to the primary outlets.

(4) GRAVITY module.

(a) Gravity outlets through the line-of-protection are normally the most cost-effective means of evacuating interior flood waters when the interior stage is greater than the exteriors. Analysis of culvert hydraulics is complex because inlet or outlet controls may govern. The GRAVITY module produces a family of outlet rating curves based on different exterior stage conditions.

(b) HEC-IFH performs gravity outlet analysis by direct entry of the outlet rating or by enabling the user to define the outlet characteristics and a range of computation elevations and intervals for computing the outlet rating curve. Exterior and interior invert elevations define the lower bound of the rating. No flow can occur until the interior ponding elevation exceeds the invert elevation. The interior water elevation must also be greater than the exterior for flow to occur. Figures 3-17 and 3-18 depict the basic data entry screen for the gravity outlet rating computations and the corresponding computed rating table, respectively. Instead of using only the limited data shown in Figure 3-18, the program uses a computed 50x50 matrix of



CSA 01.04.00
Study ID RBEND1

Interior Pond (POND)

Enter Surface Areas for Computing Volumes

Storage Table ID POND1

Description
Interior pond for App. C example.

Pond Elevation (ft)	Surface Area (ac)	Storage Volume (ac-ft)
591.00	0.0	0.0
592.00	4.0	2.0
593.00	10.0	9.0
594.00	15.0	21.5
595.00	75.0	66.5
596.00	130.0	169.0
597.00	200.0	334.0
598.00	275.0	571.5
599.00	400.0	909.0
600.00	525.0	1371.5
601.00	700.0	1984.0
605.00	2000.0	7384.0
0.00	0.0	0.0

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit
Press <F10> to Save Data and Return

Figure 3-15. Ponding surface area data entry screen

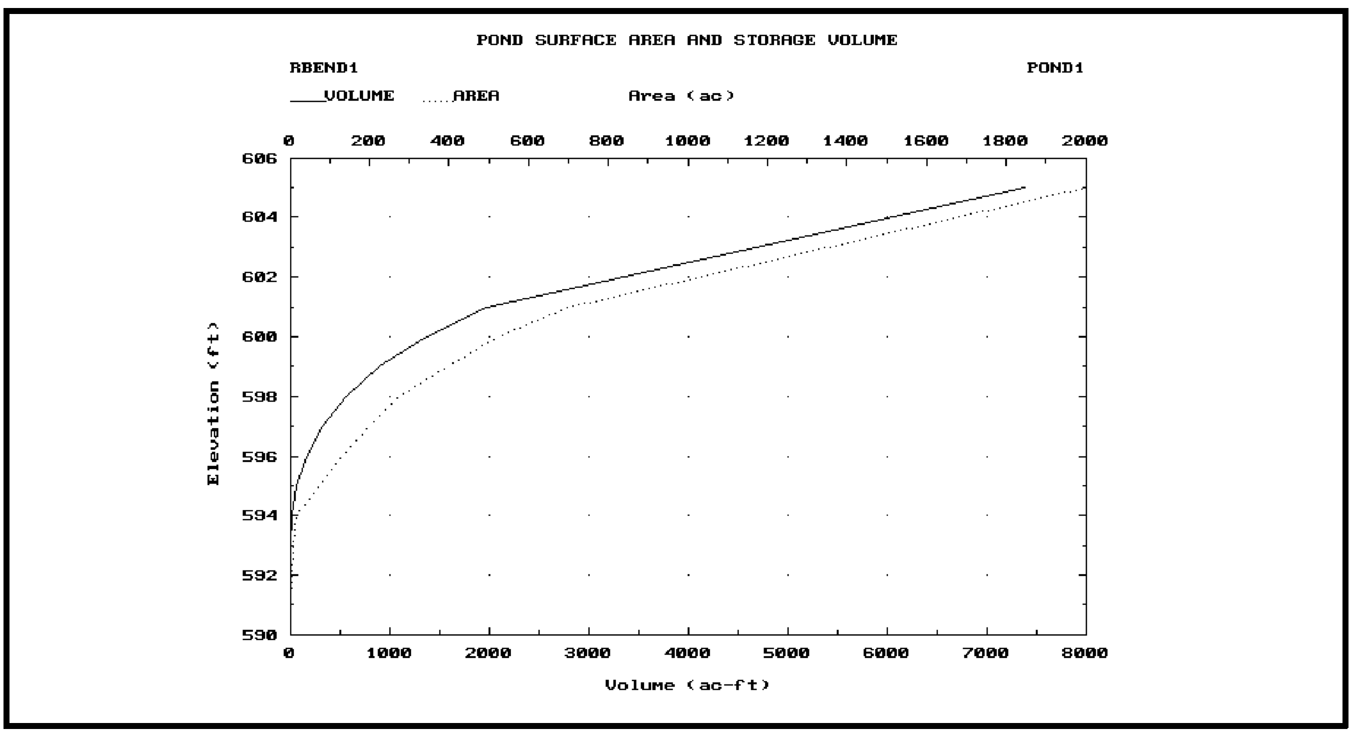


Figure 3-16. Pond surface area and storage volume plot

```
CSA 01.04.00
Study ID  RBEND1                Gravity Outlets (GRAVITY)

              Compute Gravity Outlet Rating Table for Culvert

            Outlet Structure ID  4X4BOX
            Description          Single 4x4 Box culvert.

            Culvert Type:                              [Box] Circular

            Number of Identical Outlets                     1
            Length (ft)                                200.00
            Manning's n                              0.012000
            Entrance Loss Coefficient                0.400000

          * Tailwater Tabulation Interval (ft)           4.00
         ** Flow Capacity Tabulation Interval (cfs)      20.0

            Exterior Outlet Invert Elevation (ft)      589.00
            Interior Outlet Invert Elevation (ft)      591.00
            Exterior Elevation for Gate Closure (ft)   605.00

* 1/7th the expected elevation range       ** 1/20th the expected flow range
1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
                      Press <F10> to Save Data and Return
```

Figure 3-17. Data entry screen for culvert computations

```
CSA 01.04.00
Study ID  RBEND1                Gravity Outlets (GRAVITY)
Struc.ID  4X4BOX
                 View Computed Gravity Outlet Rating Table
```

Flow Capacity (cfs)	Headwater Elevation (ft) No TailWater	TailWater Elev. 1 593.00	TailWater Elev. 2 597.00	TailWater Elev. 3 601.00	TailWater Elev. 4 605.00	TailWater Elev. 5 609.00	TailWater Elev. 6 613.00
0.0	591.00	593.00	597.00	601.00	605.00	609.00	613.00
20.0	* 592.42	593.05	597.05	601.05	605.05	609.05	613.05
40.0	* 593.30	* 593.30	597.22	601.22	605.22	609.22	613.22
60.0	* 594.04	* 594.04	597.49	601.49	605.49	609.49	613.49
80.0	* 594.71	* 594.71	597.87	601.87	605.87	609.87	613.87
100.0	* 595.34	* 595.34	598.36	602.36	606.36	610.36	614.36
120.0	* 596.29	* 596.29	598.96	602.96	606.96	610.96	614.96
140.0	* 597.17	* 597.17	599.66	603.66	607.66	611.66	615.66
160.0	* 598.07	* 598.07	600.48	604.48	608.48	612.48	616.48
180.0	* 599.09	* 599.09	601.40	605.40	609.40	613.40	617.40
200.0	* 600.24	* 600.24	602.44	606.44	610.44	614.44	618.44

```
1Help   2PrtScr 3       4       5       6DOS    7       8       9Plot   10Exit
* Inlet Control            Press <PgDn>, <PgUp> or <F10>
```

Figure 3-18. Computed gravity outlet rating table headwater versus tailwater with discharge as the matrix's internal elements to interpolate outlet discharge.

(c) Gravity outlets are open whenever the interior water elevation exceeds the exterior elevation by a user-specified minimum value (head). The outlet is assumed closed for all other conditions. A different operation is performed if a gate closure value is specified. Gravity flows are then assumed to cease when the exterior stage exceeds the gate closure elevation. Up to five gravity outlets may be entered at the primary location and for each of the four secondary locations. Chapter 6 of the HEC-IFH user's manual provides detailed descriptions of the gravity outlet data entry and analysis options.

(5) PUMP module.

(a) The PUMP module specifies pump characteristics used to determine the amount of water pumped from the interior area during flood events. Up to ten different pumping units may be defined for an interior area. The station is assumed to be located at the primary outlet.

(b) The pumping facilities are defined by a total head-capacity-efficiency relationship, shown in Figure 3-19. It is normally determined from mechanical and/or electrical engineering analyses. For standard type pumps, the information may be obtained from the pump manufacturers. The head loss represents the lump sum of all various losses due to friction, bends, contractions, expansions, entrance, and exit for the pumping unit. The total head represents the operating head at various pumping outflow capacities. It is computed as the sum of the head loss and static head (exterior elevation minus interior elevation). The final value of head is entered in the total head column. It is the maximum head against which the pump can discharge water from the interior. If the maximum head is exceeded, the pump is assumed to shut off.

(c) The user may also specify pump start and stop elevations on a monthly basis as shown in Figure 3-19. This flexibility is useful where seasonal operation requires different pumping and interior ponding operation criteria such as for agricultural or environmentally sensitive areas. On-off elevations are typically constant throughout the year in urban areas. Chapter 7 of the HEC-IFH user's manual provides a detailed description of the PUMP module.

(6) EXSTAGE module.

(a) The exterior stage module defines the stage hydrograph in the channel exterior to the line-of-protection. Exterior stage represents tailwater elevations that effect seepage and outflow of the gravity outlet and pumping stations of the interior area. For CSA, a continuous exterior stage hydrograph is required. For HEA, exterior stage hydrographs are required for each event analyzed. The magnitude of the exterior stages and their coincidence with interior runoff/inflow affect outflow and,

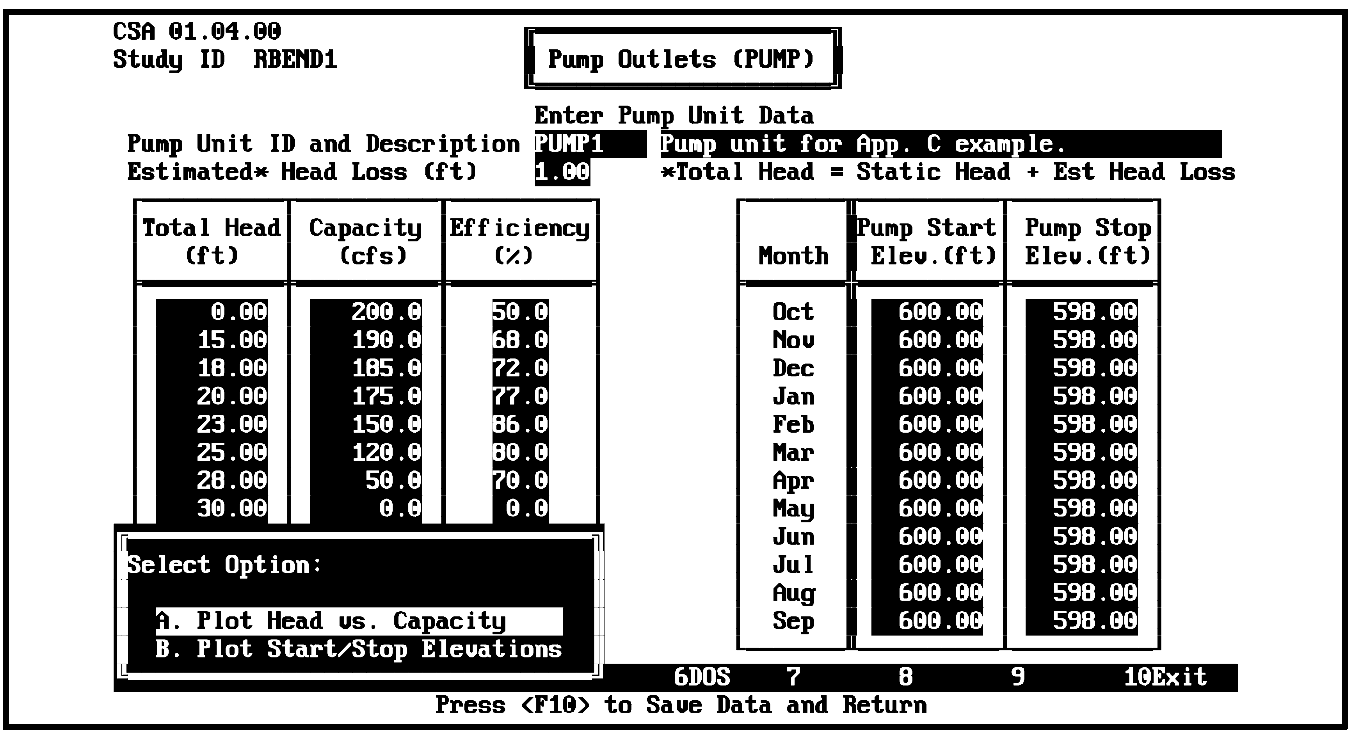


Figure 3-19. Pump unit data entry screen for continuous simulation analyses

therefore, interior ponding elevation.

(b) Exterior stage hydrographs may be entered directly, computed from discharge hydrographs and rating curves, or computed from rainfall-runoff as defined in a PRECIP and RUNOFF module (exterior subbasin) and rating curve. The latter is used where there is a high degree of dependence and coincidence between exterior and interior events.

(c) HEC-IFH can transfer exterior stages (such as from a nearby gauge) to another upstream or downstream location using river transfer relationships. Figure 3-20 illustrates the concept of relating data from the index location to another location based on the slope in the water surface profiles. Evaluation of interior systems with outlets on a tributary to the main stem where the exterior stages at the outlet are affected by the main stem backwater may also be performed. Chapter 8 of the HEC-IFH user's manual describes the EXSTAGE module and data entry options in detail.

(7) AUXFLOW module. The AUXFLOW module defines external flow into the system, overflow and diversion out of the system, and seepage inflow from the exterior river to the interior area. Chapter 9 of the HEC-IFH user's manual describes in detail the AUXFLOW module.

(a) Head-versus-seepage relationships. A secondary inflow into the ponding area is seepage through or under the line-of-protection during high exterior river stages. A relationship of seepage rate versus differential head between the interior pond and the exterior river stage is generally estimated by the geotechnical member of the study team. It is based on soil materials of the levee and pumping tests of interior relief wells for an existing levee project, or estimated from a similar project (preferably in the same river basin). On a potentially large study, money may be available for subsurface investigation early enough to coordinate with the geotechnical engineer to have a pump test at one or more boring locations. Generally seepage is lagged 1 day to simulate the flow rate along the seepage path.

(b) Auxiliary inflow. Auxiliary inflows provide means to enter hydrographs from adjacent areas or to compute them using methods other than in HEC-IFH. For example, a more detailed analysis of a complex system (more than two subbasins) may be performed using HEC-1 or another program and the hydrographs imported into HEC-IFH from HEC-DSS. HEC-1 may be used to compute hypothetical runoff hydrographs using the kinematic wave in an urban area. Similarly, a continuous runoff record generated from a more detailed moisture accounting program could be imported and used in HEC-IFH. Data for the PRECIP and RUNOFF modules would not be required in these cases. Another application of auxiliary inflow is to import overflow from an adjacent interior area into HEC-IFH for the area under study. This would be applicable where adjacent subbasins have a cascading effect and are analyzed as separate interior areas. Appendix D provides a case example application that uses auxiliary inflows.

(c) Diversions. Diversions transfer all or portions of the runoff from one location to another. Diversions may be made to remove flow from an upper subbasin to the exterior river via a pressure conduit. They may be designed to alter all flows or to convey flows above or below some target value.

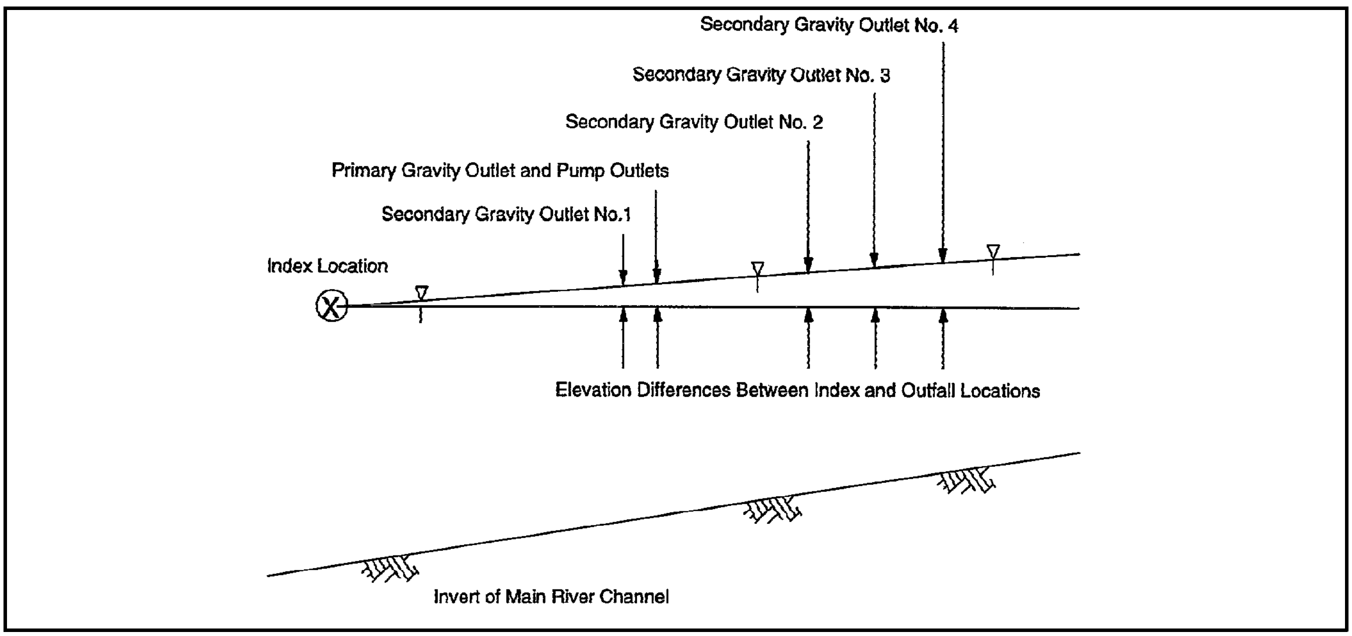


Figure 3-20. Main river transfer concept: slope-profile

(d) Overflow. Overflows occur when an interior ponding area exceeds the available storage, which causes flows to spill into an adjacent interior area. HEC-IFH assumes that the flow leaving the original interior area does not return to that area. The overflow is defined by specifying a pond elevation-overflow discharge relationship.

3-7. Interior Analysis

a. Plan development. The interior analysis may be performed after the input data entry is completed. The analysis defines a plan that consists of a unique combination of modular data for precipitation, runoff, exterior stage, and interior facilities. Figure 3-21 shows the data screen used to specify the various data modules that comprise the plan.

A study typically will have different plans. The first plan may describe a minimum gravity outlet, a second plan may include additional gravity outlet capacity, and a third plan may include a pumping station. Each plan is given a unique plan ID. The plan ID is used to identify the plan results.

b. Analysis time.

(1) The "Beginning Date for Analysis" and "Ending Date for Analysis" are entered as shown in Figure 3-21. The standard HEC-DSS format for time series data is used. The beginning date is the end of the first computation interval, and the ending date is the end of the last computation interval in the analysis. For example, hourly values for the month of October 1990 would have a beginning date of 01OCT1990/0100 and an ending date of 31OCT1990/2400. If the analysis of October 1990 consisted of daily instead of hourly values, the starting date would be 01OCT1990/2400 (the end of the first day), and the ending date is not changed.

(2) The specified beginning and ending date should be consistent with the starting and ending periods of time series used as input for the calculations. After the dates are specified, HEC-IFH checks all precipitation, exterior stage, and auxiliary inflow time series used in the plan. If any of these time series start after the beginning date of the interior analysis, or end before the ending date of the analysis, the interior analysis will proceed using zero (0) for all missing values. If so, a message is written to the error warning message file.

c. Computation time interval.

(1) General. The computation time interval, shown in Figure 3-21, is the time-step for all subbasin runoff, channel routing, and pond routing computations for the interior analysis. This value must be between 5 min and 24 hr. Choosing an appropriate time interval is important. If the primary interior problem is providing facilities to handle the volume of water reaching the line-of-protection (such as a large ponding area in an agricultural area), a long computational time interval of up to

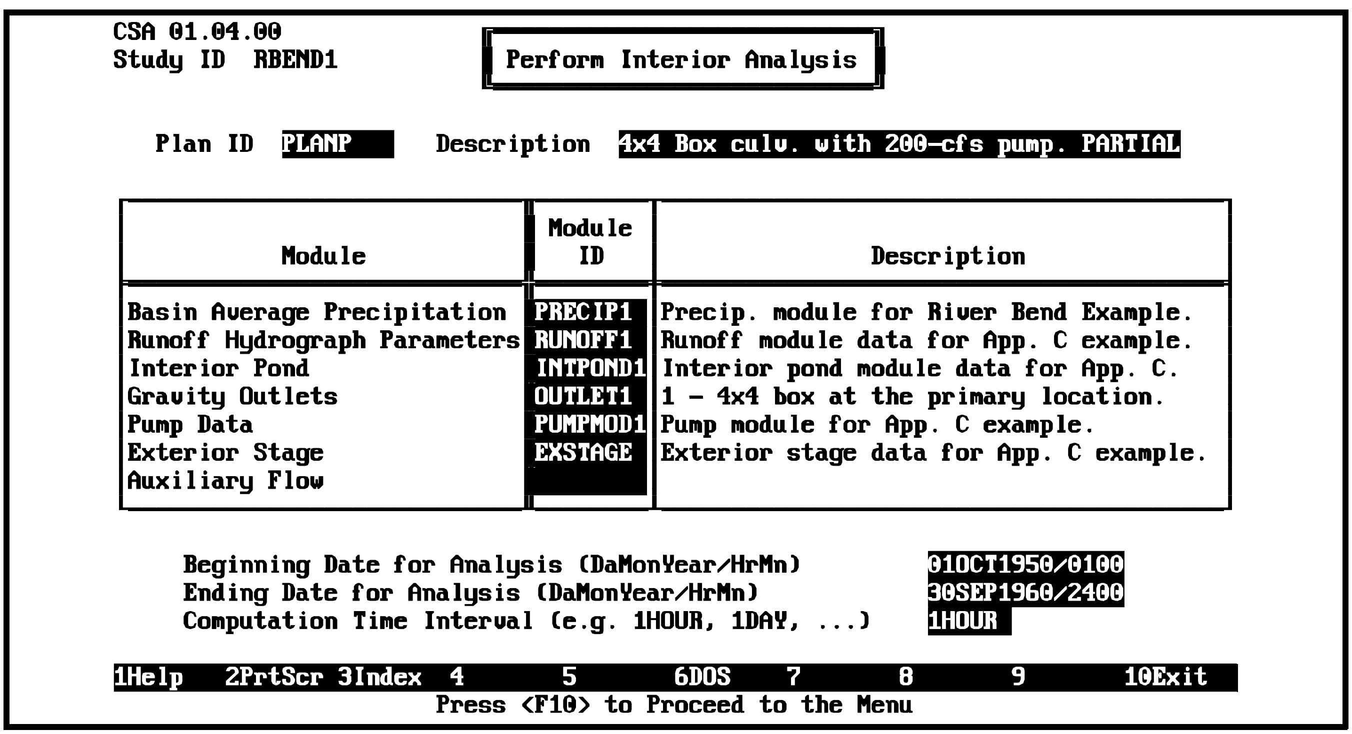


Figure 3-21. Plan specification screen

1 day may be appropriate. If the problem is providing facilities to handle peak flow reaching the line-of-protection (such as for an urban area with little or no ponding volume), then a short time interval is required. A good test is to analyze a plan configuration using several time intervals until the results are consistent, especially the stage-frequency relationship.

(2) Effect of the Computational Time Interval on Other Computations. Selection of a computation time interval can affect the validity and numerical stability of several computations. Shorter time intervals generally provide more stable results. If the output results indicate a significant difference between total inflow and outflow volume, a shorter time interval may be required.

d. Interior analysis computation sequence. After the plan is specified, the screen illustrated in Figure 3-22 is displayed. This menu controls the interior analysis computations performed for a single operation. Five options are available:

- **Perform Upper Sub-Basin Analysis (Option A).** Compute the runoff hydrograph for the upper interior subbasin using the precipitation record from the PRECIP module and the infiltration loss, unit hydrograph, and base flow parameters from the RUNOFF module. Add the auxiliary inflow for the upper subbasin. Subtract the diversion from the upper subbasin. Route the resulting hydrograph downstream to the lower subbasin.

- **Perform Lower Sub-basin Analysis (+ Upper as needed) (Option B).** Execute Option A, if appropriate and if not already executed. Then, compute a runoff hydrograph for the lower interior subbasin using the precipitation record, infiltration loss, base flow, and unit hydrograph parameters. Add the auxiliary inflow for the lower subbasin. Combine the routed hydrograph from the upper subbasin, if present as a result of Option A above.

- **Perform Exterior Basin Analysis (Option C).** Execute Options A and B, if appropriate and if not already executed. Then, compute the exterior stage hydrograph at the primary outlet location using the data specified in the exterior stage module.

- **Perform Pond Routing Analysis (+ Upper, Lower, Exterior as needed) (Option D).** Execute Options A, B, and C, if appropriate and if not already executed. Then, compute the pond stages and outflows for each time period throughout the analysis using the data for the interior pond, gravity outlets, pumps, seepage, overflow, exterior stage, and combined inflow hydrograph.

- **Perform Frequency Analysis (+ Upper, Lower, Exterior, Pond as needed) (Option E).** Execute Options A, B, C and D, if appropriate and if not already executed. Then, compute a graphical annual or partial duration series interior

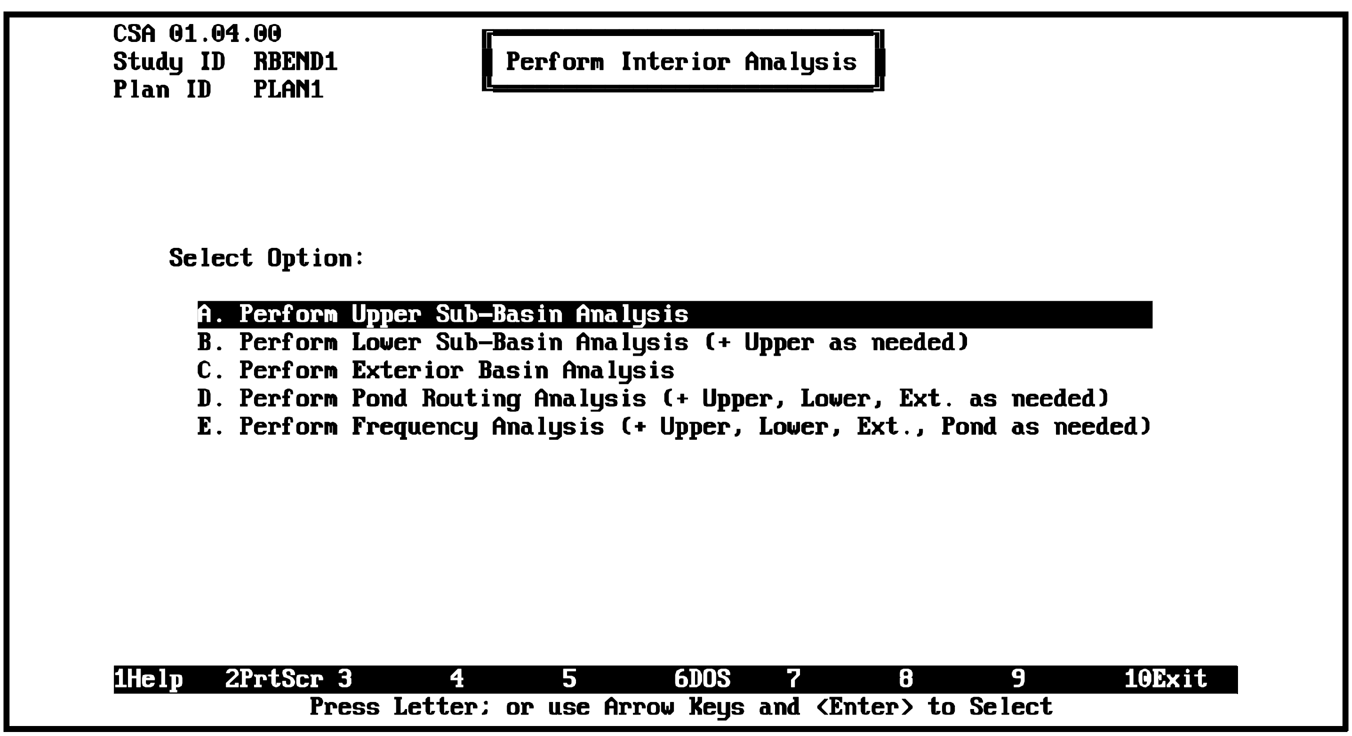


Figure 3-22. Interior analysis menu

area elevation-frequency and duration relationship using the computed interior stage hydrograph.

e. Interior pond routing parameters.

(1) The "Starting Pond Elevation" of Figure 3-23 is the interior storage pond elevation at the beginning of the analysis. The starting pond elevation must be within the range of elevations specified in the pond elevation-surface area table. If the starting pond elevation is below the minimum elevation, or above the maximum elevation, HEC-IFH adjusts the starting elevation to the minimum or maximum value as appropriate. It also writes a warning message to the plan message file.

(2) The "Minimum Head of Gravity Outlet Operation" specifies the minimum positive differential head (interior minus exterior water surface elevation) necessary before the gravity outlets will operate. Some levee systems close the gravity outlets when the exterior water surface elevation rises to a level close to the interior water surface elevation. The user may specify gates on gravity outlets that require a small head differential before the outlet will open. Any value greater than or equal to zero may be entered.

(3) The "Operate Pumps, Gravity Outlets Simultaneously?" option requires a "yes or no" response. If "Yes" is selected, then the pumps and gravity outlets operate independently. They may operate simultaneously at times during the analysis. If "No" is selected, then pumps and gravity outlets do not operate simultaneously. In this case, the pumps are assumed to stop when the gravity outlets are discharging.

3-8. Analytical Procedures

An overview of procedures used to perform the CSA and HEA analyses are described in the following subsections.

a. Analytical procedures for CSA. HEC-IFH continuous simulation analyses are performed in the following sequence:

(1) Rainfall. Enter continuous record rainfall data for a single gauge or several gauges. If appropriate, compute the composite basin average precipitation for a subbasin as the weighted average of measurements for up to five individual rain gauges. Chapter 3 of the HEC-IFH user's manual describes rainfall data entry.

(2) Rainfall excess. Compute subbasin rainfall excess values using either the generalized runoff coefficients or the initial-uniform recovery method. Chapter 4 of the HEC-IFH user's manual describes these methods.

(3) Runoff. Transform rainfall excess into a runoff hydrograph for each interior subbasin using user-defined unit hydrograph methods. Add base flows to the computed runoff hydrographs. Chapter 4 of the HEC-IFH user's manual describes these methods.

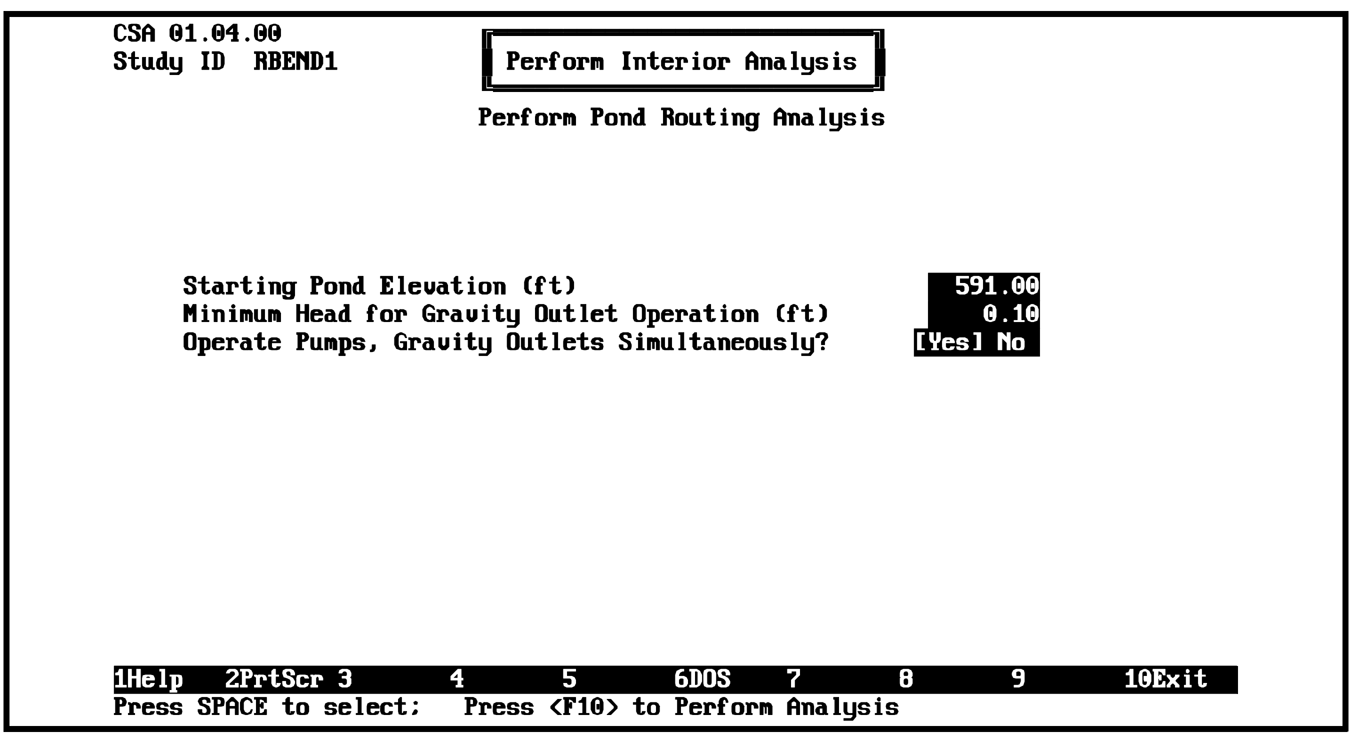


Figure 3-23. Pond starting conditions screen

(4) Auxiliary flows. Determine auxiliary flows such as diversions from the upper interior drainage area, overflow from an adjacent lower area, or seepage through the levee. Chapter 9 of the HEC-IFH user's manual discusses auxiliary flows.

(5) Channel routing. Route the total discharge hydrograph from the upper portion of the interior area to the interior ponding area using the modified Puls, Muskingum, or Lag methods. Chapter 4 of the HEC-IFH user's manual discusses channel routing.

(6) Exterior stages. Define exterior stage data using an exterior stage hydrograph or an exterior discharge hydrograph and channel rating curve. Exterior discharge hydrographs may also be computed using the same rainfall-runoff methods described for interior discharge hydrographs. Chapter 8 of the HEC-IFH user's manual describes exterior stage data.

(7) Pond routing. Route interior inflow through the ponding area and discharge it through the line-of-protection via the gravity outlets and/or pumping stations. Seepage and auxiliary flows into or out of the ponding area are included in the pond analysis. Chapter 5 of the HEC-IFH user's manual describes the interior pond module, while Chapter 10 describes the interior pond routing computations. The gravity outlet rating curve, the pump outlet capacity, and seepage and overflows are described in Chapters 6, 7, and 9, respectively, in the user's manual.

(8) Results analysis. Develop elevation-frequency relationships, duration of flooding, and other pertinent hydrologic information from the analysis results. Chapter 11 of the HEC-IFH user's manual documents the program results, output tables, and plots.

b. Analytical procedures for HEA. HEC-IFH program procedures for hypothetical event analysis are performed in the following sequence:

(1) Rainfall. Enter hypothetical storm depth-duration-frequency data for individual or multiple hypothetical events historic storms and/or for the SPS. Hypothetical frequency storms are balanced storm distributions with total rainfall amounts consistent with specific exceedance frequencies or recurrence intervals. The program can consider the 0.2-percent (500-year), 1-percent (100-year), 2-percent (50-year), 4-percent (25-year), 10-percent (10-year), 20-percent (5-year), and 50-percent (2-year) frequency storms. The SPS is determined according to the criteria discussed in EM 1110-2-1411. Chapter 3 of the HEC-IFH user's manual describes rainfall data entry.

(2) Rainfall excess. Compute rainfall excess for each interior subbasin using SCS curve number, Holtan, Green-Ampt, or the Initial-Uniform methods. Chapter 4 of the HEC-IFH user's manual describes these methods.

(3) Runoff. Transform rainfall excess into a runoff hydrograph for each interior subbasin. Unit hydrographs may be entered directly, or computed using the Clark, Snyder, or SCS Dimensionless unit hydrograph methods. Compute base flow and base flow recession. Chapter 4 of the HEC-IFH user's manual discusses the available unit hydrograph methods.

(4) Auxiliary flows. Determine auxiliary flows such as diversions from the upper interior area, overflow from an adjacent lower area, and levee seepage. Chapter 9 of the HEC-IFH user's manual describes auxiliary inflows and diversions.

(5) Channel routing. Route the total discharge hydrograph from the upper portion of the interior area to the interior ponding area. The modified Puls, Muskingum, Muskingum-Cunge, or Lag methods are available. Streamflow routing is discussed in Chapter 4 of the HEC-IFH user's manual.

(6) Exterior stages. Define exterior stage data using an exterior stage hydrograph or an exterior discharge hydrograph and channel routing curve. Exterior discharge hydrographs may be computed using the same methods described for interior discharge hydrographs. Chapter 8 in the HEC-IFH user's manual describes exterior stage data.

(7) Pond routing. Route interior inflow through the ponding area and discharge it through the line-of-protection via the gravity outlets and/or pumping stations. Include seepage flows through the line-of-protection, as well as overflows from the ponding area. Gravity outlet rating curves, pump station capacity, seepage/diversions, and interior pond routing computations are described in Chapters 6, 7, 9, and 10, respectively, in the HEC-IFH user's manual.

(8) Analysis results. Determine the interior elevation-frequency relationships and other results from the computation outputs of the HEC-IFH program.

3-9. Analysis Summaries

HEC-IFH has extensive reporting capabilities. Table 3-1 provides an overview of the output capabilities for both the CSA and HEA options. Figures 3-24 and 3-25 show the hydrologic analysis summary screens, from which the user may view the output and print results. Chapter 12 of the HEC-IFH user's manual provides a detailed description of the output summary capabilities of HEC-IFH.

3-10. Plan Comparison

The HEC-IFH program enables users to compare the performance of various plans in tables and graphically. Figures 3-26 and 3-27 show users options for plan comparison for the CSA and HEA. Chapter 13 of the HEC-IFH user's manual provides details on the plan comparison capabilities.

Table 3-1
Overview of HEC-IFH Hydrologic Analysis Summaries

Type of Output	Continuous Simulation Analysis	Hypothetical Event Analysis
Input data	Analysis input summaries	Analysis input summaries
Detailed output	Calculation period summaries	Analysis by events
Monthly totals/averages	Monthly summaries	-
Annual totals/averages	Water year annual summaries	-
Summary of all results	Analysis record summaries	Event comparisons
Error messages	Analysis, warning/error messages	Analysis, warning/error messages

```
CSA 01.04.00
Study ID  RBEND1       Hydrologic Analysis Summaries        Begin 01OCT1950/0100
Plan ID   PLANP                                             End   30SEP1960/2400

Analysis Input Summaries                    Water Year Annual Summaries
   A. Data Management Summary                  N. Rainfall-Runoff Data
   B. Rainfall-Runoff Summary                  O. Interior/Exterior/Pump Data
   C. Gravity Outlet Data                      P. Maximum Area Flooded
   D. Pump Station Data

Calculation Period Summaries                Analysis Record Summaries
   E. Rainfall-Runoff Data                     Q. Maximum Values
   F. Interior/Exterior Data                   R. Inflows and Outflows
   G. Detailed Inflow Data                     S. Exceedance Duration Table
   H. Detailed Outflow Data                    T. Plotting Position Table
   I. Detailed Grav. Outflow Data              U. Stage-Frequency Table
   J. Area Flooded Data                        V. Pump Operation

Monthly Summaries                           Analysis Error Messages
   K. Average Monthly Rainfall                 W. List Warning/Error Messages
   L. Interior/Exterior Data
   M. Pump Operation

1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
              Press Letter; or use Arrow Keys and <Enter> to Select
```

Figure 3-24. Menu of continuous simulation hydrologic analysis summaries

3-11. Summary

Feasibility studies are conducted within the framework of ER 1105-2-100, with specific hydrologic engineering guidance found in EM 1110-2-1413. If HEC-IFH is to be applied, the hydrologic engineer should review and understand the concepts and application capabilities of the program as described in the HEC-IFH user's manual (USACE 1992). Once the program is installed and running, and the test problems yield correct results, the study is ready to be conducted.

```
HEA 01.04.00
Study ID  RBEND1          Hydrologic Analysis Summaries
Plan ID   PLANP

 Analysis Input Summaries                 Event Comparisons
    A. Data Management Summary               M. Rainfall-Runoff Data
    B. Rainfall-Runoff Summary               N. Maximum Flows
    C. Gravity Outlet Data                   O. Flood Volumes
    D. Pump Station Data                     P. Gravity Outlet Analysis
                                             Q. Pump Analysis
                                             R. Frequency Analysis
 Analysis by Events
    E. Rainfall-Runoff Data               Analysis Error Messages
    F. Interior/Exterior Data                S. List Warning/Error Messages
    G. Detailed Inflow Data
    H. Detailed Outflow Data
    I. Detailed Grav. Outflow Data
    J. Area Flooded Data
    K. Maximum Values
    L. Inflows and Outflows

1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
              Press Letter; or use Arrow Keys and <Enter> to Select
```

Figure 3-25. Menu of hypothetical event hydrologic analysis summaries

```
CSA 01.04.00
Study ID  RBEND1               Comparison of Plans

                    Analysis Summaries
                      A. Maximum Values
                      B. Flood Volume Data

                    Gravity Outlet Analysis
                      C. Outflow Volumes
                      D. Days Blocked

                    Pump Analysis
                      E. Capacity Summary and Days Pumped

                    Interior Analysis
                      F. Maximum Interior Elevations
                      G. Duration of Interior Flooding
                      H. Maximum Interior Area Flooded

1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
              Press Letter; or use Arrow Keys and <Enter> to Select
```

Figure 3-26. Continuous simulation plan comparison summary menu

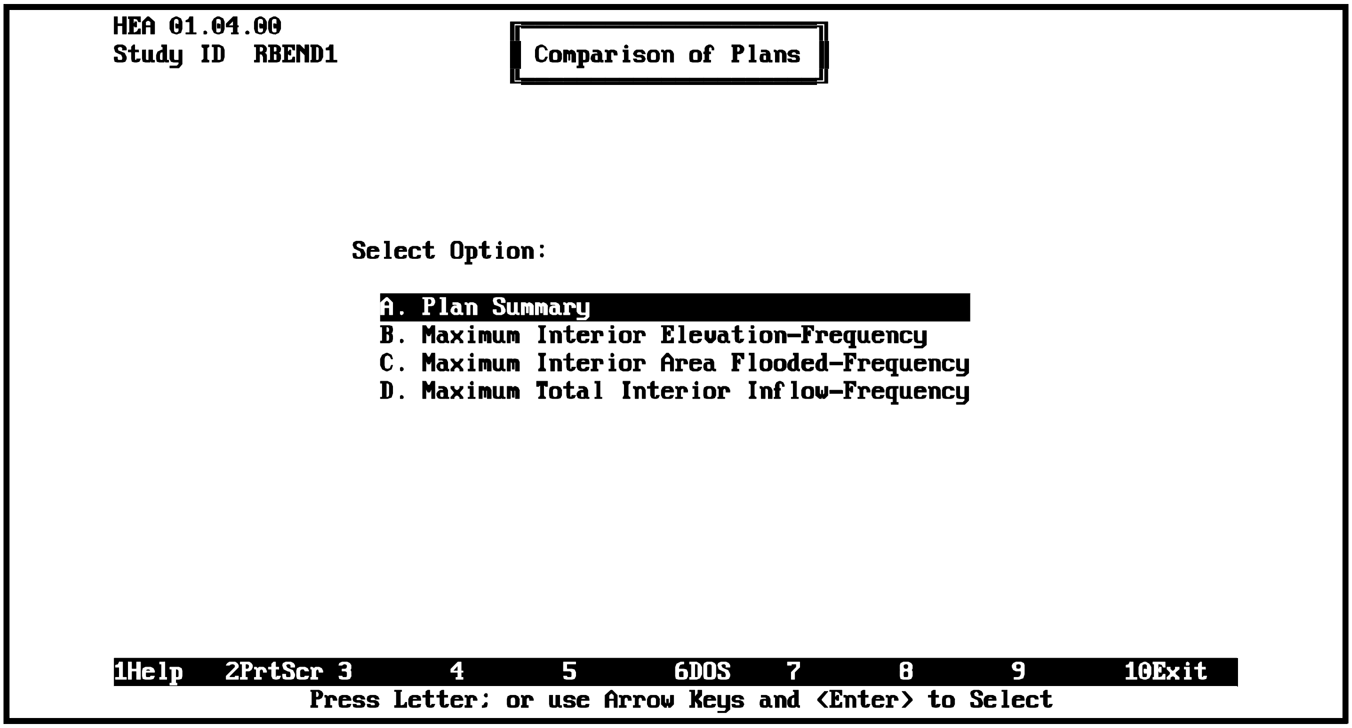


Figure 3-27. Hypothetical event plan comparison summary menu

Chapter 4
Line-of-Protection and Minimum Facility Analysis Concepts

4-1. Overview

a. This chapter discusses the hydrologic engineering analysis for studies where the line-of-protection is analyzed as part of the study prior to analysis of the interior system. It focuses on hydrologic engineering study requirements and associated HEC-IFH analysis capabilities for implementing a minimum interior facility as part of a line-of-protection project.

b. The study strategy assumes that the interior facilities (which will become part of the recommended plan) are planned and evaluated separately and incrementally from the line-of-protection project. The major project (levee/floodwall) is conceptually divided from the planned interior facilities by initially evaluating a minimum facility considered integral to the line-of-protection. If a levee/floodwall exists, the minimum interior facility is that which is presently in place. If the levee/floodwall is being planned, the minimum facility must be formulated and the evaluation of the line-of-protection benefits performed with the facility in place. The residual interior flooding is the target of the interior planning efforts; benefits attributed to the increased interior facilities will be the reduction in the residual damage.

c. The following sections assume that the line-of-protection does not exist and is being planned as the initial part of the investigation. The minimum facility analysis is therefore part of the study.

4-2. Without Line-of-Protection Condition Analysis

a. Overview. The without line-of-protection condition assumes no protection is in place. HEC-IFH cannot directly analyze the without-project condition. Traditional analytical procedures and programs, beyond the scope of this document, are used. It is briefly discussed here because the hydrologic runoff analyses of the main stem (exterior) and local stream (interior) and their coincidence and dependence may be applicable in subsequent interior analyses involving HEC-IFH analysis.

b. Hydrologic engineering analysis concepts.

(1) The without line-of-protection analysis is often complicated by the coincident and dependent nature of flooding from the main stem and local stream. The nature of flooding between the main stem and local stream is critical to the type of hydrologic engineering approach used and the corresponding flood damage computations. Is the flooding between the two systems coincident? Are the events dependent? The assessment of the study area to determine the coincidence and dependence of flooding from the main stem and local stream is often a complex but necessary step in flood damage analyses. Section 2-3 and Table 2-1 describe coincidence and dependence for interior studies, and are relevant for line-of-protection feasibility studies. Figure 4-1 illustrates how a damage center can be flooded by both the main stem and the local stream runoff.

(2) The dependence of events causing the flooding of the two systems can influence the type of hydrologic analysis. Analysis of observed or historical events should always be used for validation and calibration of the assumptions and results. If the main stem and local stream are highly dependent, such as for a main stem drainage area that is relatively small (e.g., 259 sq km or 100 sq miles) in comparison to the local stream (e.g., 25.9 sq km or 10 sq miles), the same storm events would likely affect each system. Analyses would normally include evaluation of balanced hypothetical storms over both systems. For thunderstorms, the evaluation may also include storms centering over the interior area. Continuous record analysis could also be used, if sufficient data are available.

(3) For studies with no or little dependence, such as a 25.9-sq-km (10-sq-mile) local stream flowing into the Mississippi River main stem, a different approach is normally required. The events causing flooding are likely independent and may be highly noncoincident. Again, assessment of historic data and other information is required to assure this assumption is valid. Assuming it is, the two systems could be analyzed using the coincident frequency method or continuous record analyses described in Chapter 2.

(4) For most studies, the degree of dependence and coincidence will not be at the two extremes. The hydrologic engineering analysis may include continuous records, hypothetical event type studies, or combinations of both. As applicable, all other information and analyses should be used to provide data and insights as to the reasonableness of the results.

4-3. With Line-of-Protection and No Interior Facilities

a. General. The formulation and evaluation of the size and configuration of the line-of-protection are separate problems beyond the focus of this document. Required analysis procedures are described in the following documents:

- Guidance for Conducting Civil Works Planning Studies, ER 1105-2-100.

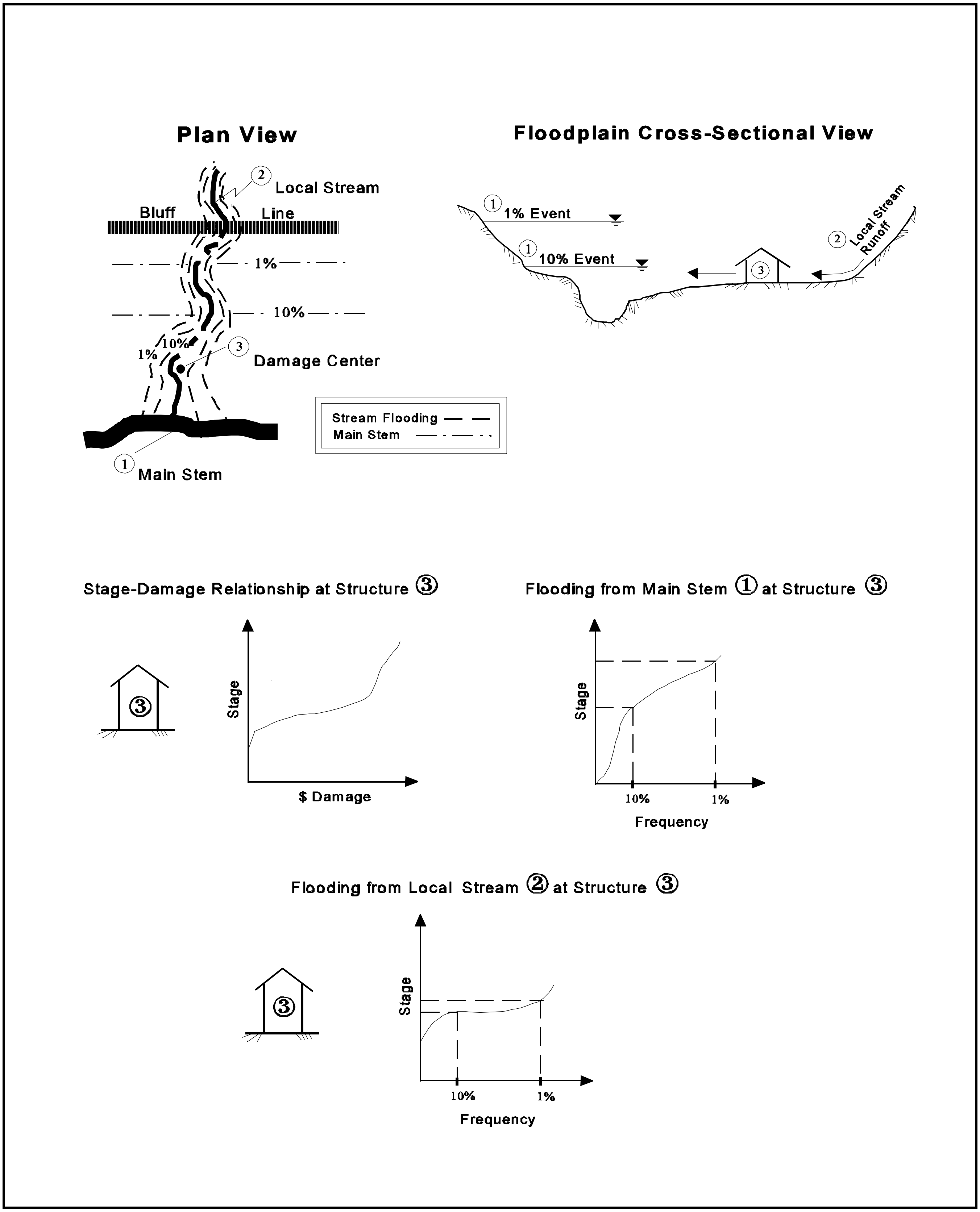


Figure 4-1. Without line-of-protection flooding

- Risk-Based Analysis for Evaluation of Hydrology/ Hydraulics and Economics in Flood Damage Reduction Studies, EC 1105-2-205.

- Hydrologic Analysis of Interior Areas, EM 1110-2-1413.

- Hydraulic Design for Local Flood Protection Projects, ER 1110-2-1405, and other documents.

For the interior area analysis, the line-of-protection is assumed in place and local stream conveyance to the main stem or exterior is cut off by the line-of-protection as shown in Figure 4-2. The runoff and contributing area of the existing and potential storm sewer system must be considered. Flooding from the exterior is blocked by the line-of-protection up to the overtopping event. This is the without-project condition for the minimum facility analysis and represents an upper bound for the stage-frequency relationship with the minimum facility in place. The goal is to subsequently reduce the stage-frequency relationship for the local stream without the line-of-protection in place by implementing the minimum facility discussed in the following section.

b. HEC-IFH analysis. HEC-IFH may be used to determine the stage-frequency relationship for the ponding area associated with the line-of-protection in place and no interior facilities. The runoff procedures and hydrographs generated for the local stream are often event-based since this condition only represents an upper limit for the minimum facility analysis and has no outlets to enable evacuation of water from the interior area. The analysis will normally be HEA but could be discrete observed events using HEC-IFH analysis that includes a plan consisting of the PRECIP, RUNOFF, POND, EXSTAGE, and perhaps AUXFLOW modules. Gravity outlets and pumps are not analyzed. Stage-frequency relationships may be developed for each interior ponding area using HEC-IFH. The local stream runoff analysis may be the same as described for the without line-of-protection condition including, if applicable, future without-project conditions. The difference, however, is that local stream runoff will pond behind the line-of-protection and main stem (exterior) flooding will be blocked to the top of the line-of-protection.

4-4. Minimum Facility Analysis

a. General. The minimum facility of the interior area is justified as an integral part of the line-of-protection as shown in Figure 4-3. The minimum facility should provide interior flood protection during gravity (unblocked or low exterior) conditions such that the local storm sewer system functions essentially the same as it did without a levee in place for floods up to the storm sewer design. The stage-frequency relationship for the with-minimum-facility-in-place condition becomes the without-project condition for evaluating additional interior flood damage reduction measures. The residual damage with the minimum facility in place is thus the target for damage reduction of additional flood reduction measures.

b. Storm sewer design and configuration.

(1) The layout, planned changes, design discharges, and invert elevations of existing and potential future storm sewer systems must be considered as part of the minimum facility analysis. These data are used to define contributing drainage areas, invert elevations of major conveyance channels, gravity outlet inverts, pump on-off elevations, and local design criteria for inlet and outlet works. Data collection and analysis of storm sewer systems, which include the existing and future system layout, design, and operation information, are generally provided by the local public works department or city engineer. The proper delineation of drainage areas that contribute to the interior ponding adjacent to the line-of-protection is important to the interior analysis. The natural topography should be used for initial boundaries. The storm sewer layout often crosses topographic boundaries and thus may affect the amount of runoff into or out of the system.

(2) The location of flow concentration at the line-of-protection often affects where gravity outlets or pumps may be located and the layout of the collector/conveyance system adjacent to the line-of-protection. The potential of combining flows into a collector system should be evaluated. Finally, if a storm sewer system does not exist, one may need to be designed to assure the interior system is compatible with contributing flow areas and invert elevations of any planned interior flood damage reduction system.

(3) The effect of storm sewers may be analyzed using HEC-IFH by modifying the unit hydrograph for events affected by storm sewers in the RUNOFF module of HEC-IFH. The contributing drainage areas may also be adjusted in the RUNOFF module or the AUXFLOW diversion option can be used to adjust storm sewer flows into or out of the subbasin. The time series of runoff hydrographs, including storm sewer flows, may be imported into HEC-IFH (AUXFLOW module) instead of directly calculating the runoff. This is appropriate for complex systems and those requiring more sophisticated runoff computations such as for situations when pressure storm sewer flows are a significant issue.

c. Evaluate range of minimum facilities. The minimum facility will almost always consist of gravity outlets, but may include pumps if the coincidence of flooding between the interior and exterior is high for very prolonged periods such as for lakes or new upstream storage projects. The physical characteristics of the minimum facility gravity outlets should be established prior to the analysis and refined as the analysis proceeds. The analysis should be performed for the range of hypothetical frequency events. The analysis is performed

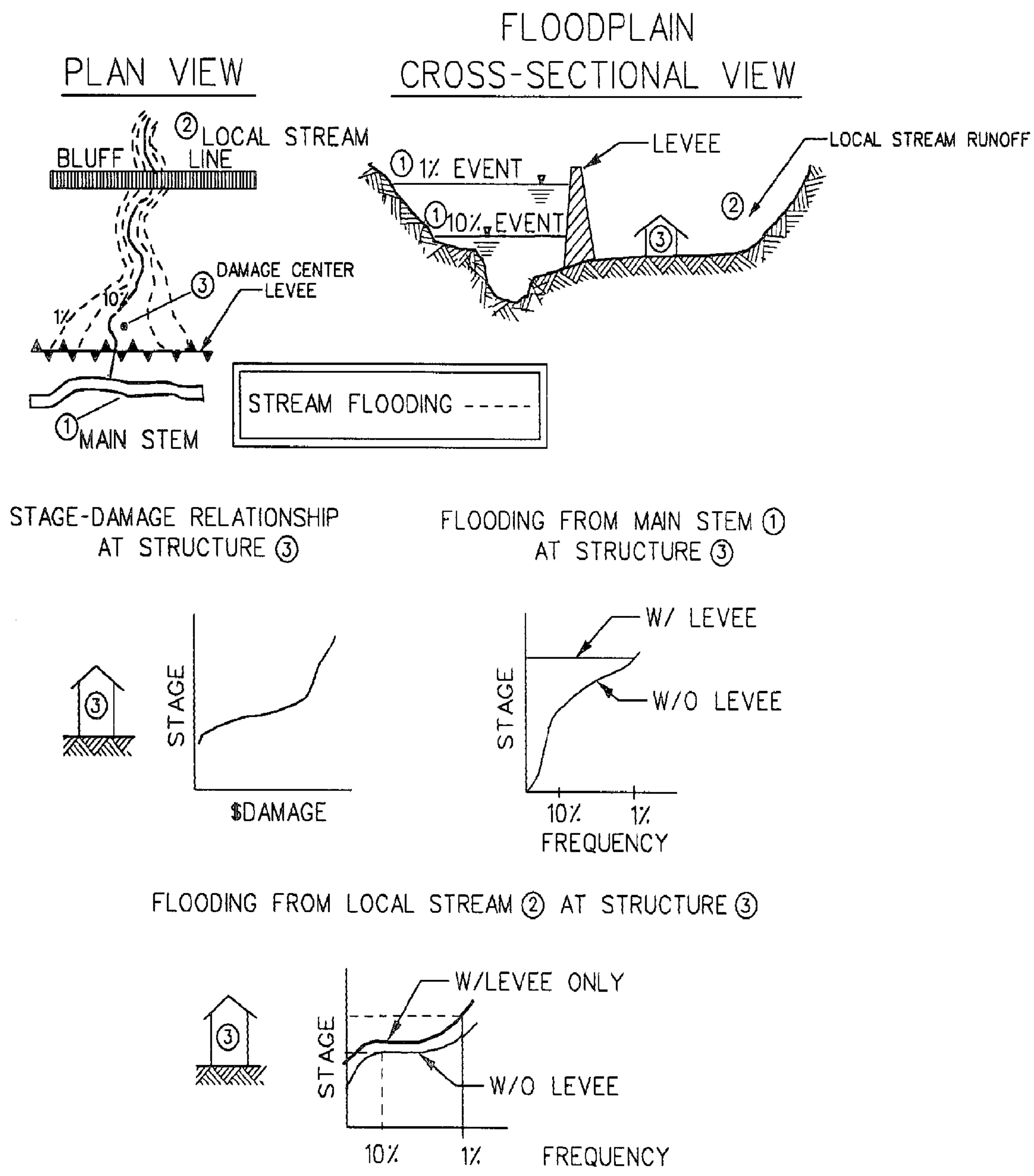


Figure 4-2. Line-of-protection without minimum facility

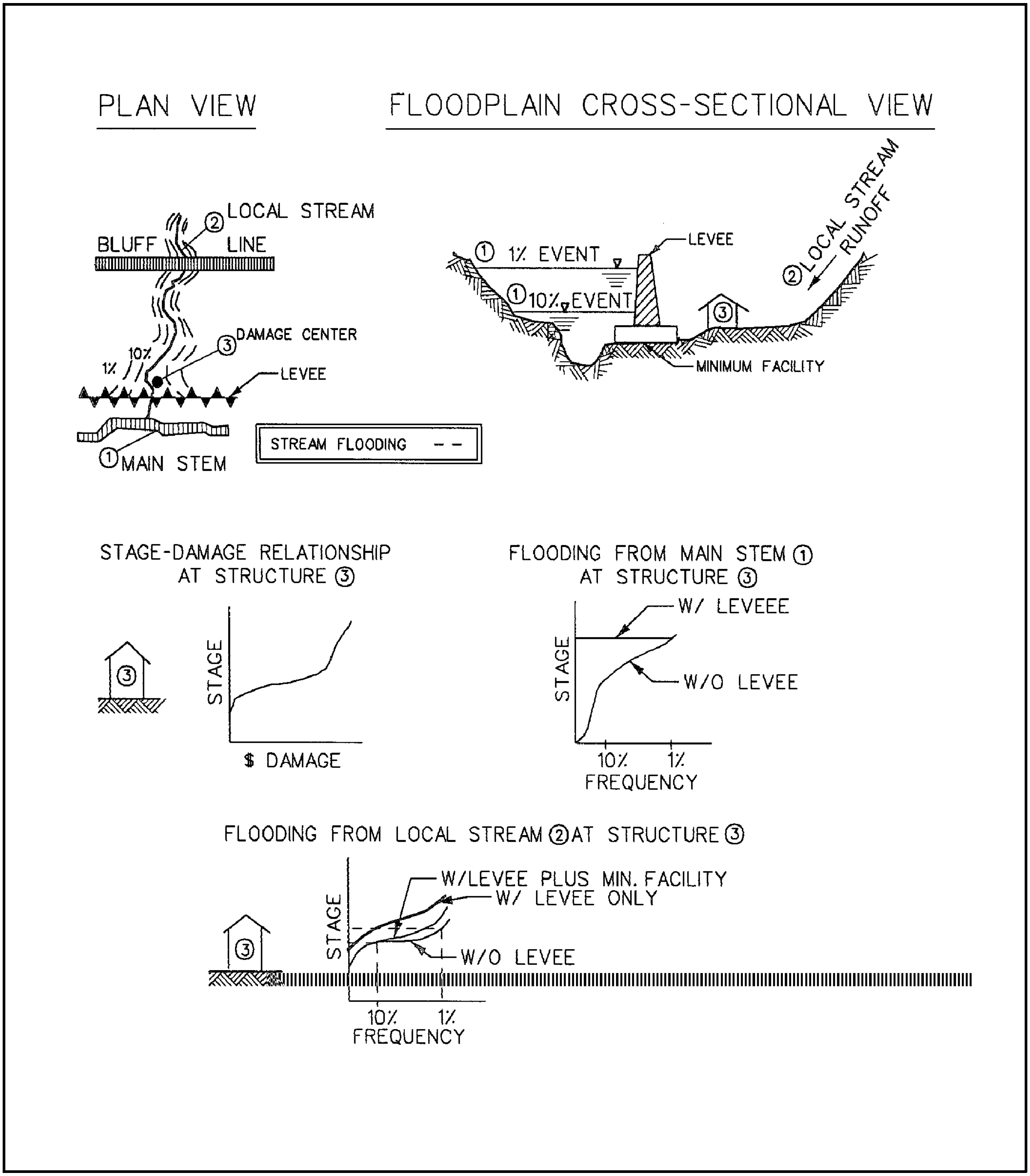


Figure 4-3. Line-of-protection with minimum facility

assuming unblocked gravity outlet conditions. Each plan evaluated would include the same data or PRECIP, RUNOFF, POND, EXSTAGE, and AUXFLOW modules as the without line-of-protection condition plus the GRAVITY module.

d. Minimum facility sizing analyses. The following paragraphs describe the strategy for sizing the minimum gravity outlet facility using HEC-IFH.

(1) Define three or four gravity outlet configurations (different GRAVITY modules) of increasing capacity. Outlet sizes should envelop the largest storm sewer size or ditch capacity at the line-of-protection.

(2) Enter the gravity outlet data requirements into HEC-IFH. Both the CSA and HEA methods have the same data requirements. For interior analyses, the outlet headwater is the interior ponding elevation and the tailwater is the exterior stage. The following two items of information are required for each gravity outlet:

(a) A gravity outlet rating table that lists the headwater depth required for a range of outlet flow rates and tailwater depths. This table may be entered by the user or computed by HEC-IFH for circular or box culverts. Generally, the user will choose the option that allows the program to compute the outlet rating tables.

(b) HEC-IFH allows the user to adjust the exterior stage or tailwater condition to match the actual location of each gravity outlet.

(3) Define a new plan for each gravity outlet capacity to be evaluated. All HEC-IFH data entry modules will be the same except the GRAVITY module will change for each plan. Using local storm HEA, compare the results of each plan using the program's plan comparison capability. The plan comparison assessment should be for the with line-of-protection and no outlets (Section 4-3) condition and each gravity outlet plan analyzed by HEC-IFH. They should then be compared to the targeted local stream frequency that is not computed in HEC-IFH.

(4) Select the minimum facility which is the gravity outlet capacity or plan that essentially makes the stage-frequency and associated flood damage to the interior area no worse than flooding to the area from the local stream without the line-of-protection in place. Rarer events, which exceed the local storm sewer design, may be greater with the minimum facility in place. See Figure 4-3.

4-5. Summary

The minimum facility is justified as part of the line-of-protection. It is almost always gravity outlets. Minimum facility analysis involves both the base year conditions and at least one future condition analysis, if it is likely to change and impact the analysis. Interior stage-frequency relationships for these conditions may be needed to select a minimum facility. The minimum facility provides interior flood protection during unblocked or low exterior conditions such that the local storm sewer system functions essentially the same as without the levee in place for floods up to the storm system design. The subsequent without-project condition is used to formulate and evaluate interior flood damage reduction measures assuming the minimum facility in place.

Chapter 5
Analysis of Interior System Flood Damage Reduction Measures

5-1. Overview

a. This chapter describes the formulation and evaluation of a set of flood damage reduction plans for interior areas. The condition with the line-of-protection and the selected minimum facility becomes the without-project condition for evaluating additional features. If the line-of-protection is in place, the existing system is the without condition for analysis of enhanced interior facilities. The enhanced facilities may include additional gravity outlet capacity, pumping stations, ponding area storage, and nonstructural measures. Figure 5-1 conceptually shows an interior system with gravity outlets and pumps.

b. The criteria specified in the "Planning Guidance Notebook" (ER 1105-2-100) and EM 1110-2-1413, are principal references for analysis of interior systems. The application of continuous record and hypothetical event analytical procedures using HEC-IFH is detailed in this chapter. More detailed examples of its application are provided in the case example studies described in Appendices D and E.

5-2. Without-project Conditions

a. General. Existing and future without-project conditions analyses are required to determine the value of implementing flood damage reduction measures. The initial hydrologic engineering goal is to define the flood hazard, performance, and operation procedures of the existing without-project condition. Observed event information is important to define these characteristics and validate the analysis results. The continuous simulation and/or hypothetical event options of HEC-IFH may be used in the analyses depending on the information available and the nature and complexity of the interior and exterior system.

b. Storm sewer design and configuration. If the levee and minimum facilities are in place, the layout, planned changes, design discharges, and invert elevations of existing and potential future storm sewer systems must be considered as part of the with- and without-project conditions for the interior analysis. See section 4-4*b*.

c. Existing without-project conditions.

(1) The existing without-project condition used in the evaluation of interior flood damage reduction measures is the initial focus. The line-of-protection and minimum facilities are assumed in place, as described in Chapter 4 and EM 1110-2-1413. The analysis is the same as that for the minimum facility except now the dependence and coincidence of interior and exterior flooding must be considered. This is instead of just the unblocked outlet condition used to size the minimum facility for most studies. Input data and analysis would essentially be the same as described in Chapter 3. The existing without-project conditions plan is described in HEC-IFH by the PRECIP, RUNOFF, POND, EXSTAGE, GRAVITY (minimum facility) modules, and perhaps the AUXFLOW and the PUMP modules.

(2) The HEC-IFH analysis results should be validated from several perspectives. Historic events (stage-frequency, durations, coincidences, etc.) may be analyzed and the model calibrated to observed and reasonable results. The percent run-off for historic and hypothetical frequency events and monthly recovery rates for continuous record analysis must be reasonable, as should other factors such as gravity flow, seepage and general operation and performance. The results should be carefully inspected and the flood hazard (stage-frequency, depth and extent of flooding, duration, warning time, etc.), performance, and operation of the system clearly defined. Performance includes how the interior system responds for a range of events and conditions. Operation should closely approximate that presently used in a physical and institutional sense. This normally is the gravity outlet but includes pumps if they presently exist.

d. Future without-project conditions.

(1) Hydrologic engineering analysis of future without-project conditions typically involves urbanization effects on watershed runoff. The process includes identification of areas for the most likely future urbanization or intensification of existing urbanization from future land use planning information obtained during the preliminary investigation phase. This includes types of land use and conveyance system changes. Conveyance system changes refer to the storm drainage and authorized flood control projects likely to be implemented by locals. Other future alternate land use conditions may be assessed if necessary. The future years in which to determine project hydrology are normally specified by the study manager. Generally, the start of project operation or base year (existing conditions may be appropriate), and some year during the project life (often the year when land use planning information is available) are selected.

(2) The HEC-IFH plan for future without-project conditions normally consists of the existing conditions plan with changes only to the runoff and perhaps routing characteristics defined in the RUNOFF module. Runoff would relate to urbanization effects on the unit hydrograph and loss rates. Routing changes might be related to alterations in the conveyance channel prior to entering the lower ponding area or encroachment into the natural storage remote from the line-of-protection. Other changes could also occur depending on the study area and any projected flood damage reduction measure enhancements.

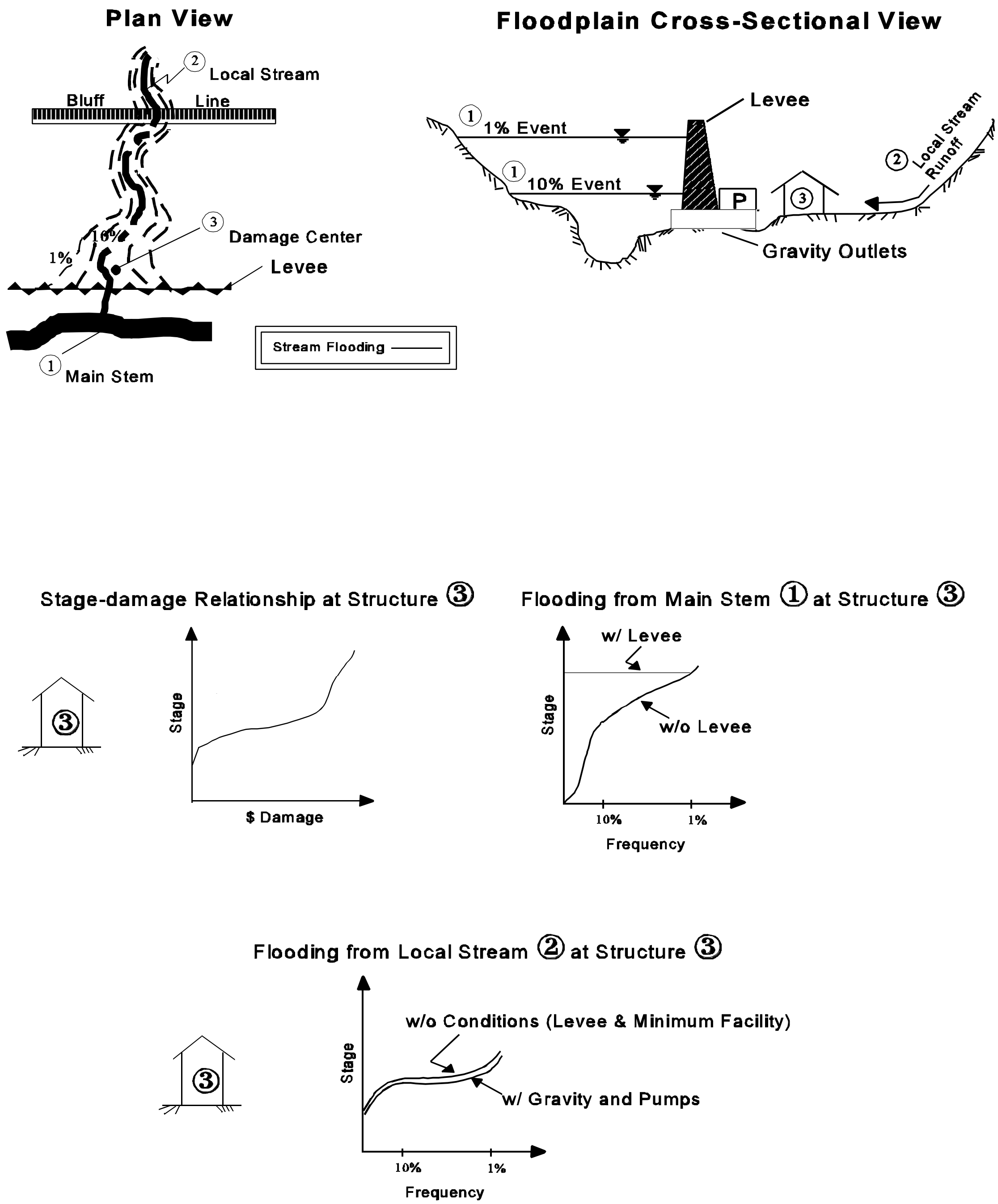


Figure 5-1. Interior system with gravity outlets and pumps

5-3. Flood Damage Reduction Measures

a. General. A range of potential flood damage reduction measures and performance standards should be addressed in the study of interior areas. These measures may be structural or nonstructural in nature. Emphasis here is on gravity outlets, detention or ponding at or near the line-of-protection, and pumping stations since they represent primary flood damage reduction measures for interior areas. A comprehensive array of other measures combined into plans should also be investigated.

b. Gravity outlets.

(1) Gravity outlets are defined as culverts, conduits, or other openings that permit discharge of interior waters through the line-of-protection. The size of the gravity outlet is based on the economic, environmental, and social aspects associated with the outfall ditch, gravity conduit, and ponding area analyzed as a collective system. The size selection must be based on the functional operation of the outlet for a range of expected events and not on a single design event. Where possible, gravity outlets should be located at or near where the line-of-protection intersects the natural or existing conveyance system or detention area, called the primary location. It is normally more feasible to provide one large gravity outlet than several smaller ones. This may require an interceptor system along the line-of-protection.

(2) Most gravity outlets are corrugated metal or reinforced concrete pipes, or reinforced concrete box culverts. Guidance in EM 1110-2-3104 states that reinforced concrete pipe should be used exclusively for urban levees and agricultural levees where substantial loss of life and/or property can occur due to embankment failure at the outlet location. For agricultural levees where no substantial loss of life and/or property can occur, corrugated pipe with a protective coating may be used. In those cases, fill heights of levee embankment must be less than or equal to 3.66 m (12 ft) above the pipe invert, and pipe diameters cannot exceed 0.914 m (36 in.). Corrugated pipe between 0.914 and 1.52 m (36 and 60 in.) may be used if service conditions are investigated in detail and safety requirements are satisfied. Corrugated pipe with a diameter greater than 1.52 m (60 in.) should never be used. Some new gravity outlet pipes are made of reinforced fiberglass and polyethylene that do not rust and have very low flow resistance.

(3) Gravity outlets should have a sufficient invert elevation and slope to minimize siltation in the outlet. An exterior stage-exceedance duration table or plot can help pick an invert in which the exterior stage is below the invert most of the time. HEC-IFH can determine and plot a stage-exceedance duration table, if continuous simulation data are available. Likewise, the invert must be low enough to flow full before interior depth reaches damage elevation.

(4) The type of inlet chosen defines the entrance loss coefficient, which affects the design headwater elevation. Chapter 6 of the HEC-IFH user's manual lists these coefficients for both corrugated metal pipes and concrete pipes and box culverts. Inlet designs using a headwall and wingwall or a precast concrete or corrugated end section give lower loss coefficients and therefore greater flow capacity. Sometimes, in locations where large debris can reach the inlet, a debris retarder or trashrack is needed.

(5) The gatewell for the gravity outlet is normally located on the riverside of the line-of-protection (see Figure 5-2). This is done so that if problems in the gravity outlet under the line-of-protection occur, the gate can be closed and exterior water cannot enter the protected area. Hydrostatic pressure through a break or separation in the outlet will not jeopardize the stability of the earth levee or floodwall above it. Many Districts also provide flap gates at the discharge end of the gravity outlet to prevent backflow into the interior area when the outlet is open. Interior water could still flow into the exterior any time the interior ponding elevation exceeded the exterior.

(6) Gravity outflow rating curves are normally required to assess the outflow conditions of the major outlets. Rating curves should be developed for primary gravity outlets but may be combined for secondary outlets. Interior area discharge rating curves for gravity outlets are determined for a range of low to high tailwater conditions. Chapter 3 overviews the gravity outlet input data for HEC-IFH and Chapter 6 of the HEC-IFH user's manual describes the GRAVITY module concepts in detail.

(7) Existing gravity outlet operation criteria should be obtained from the agency responsible for operating the interior system. Analysis of modified operation procedures is part of the plan formulation process. The normal operational procedure is to release water in an attempt to follow the lowering of the interior stages while maintaining a small positive head. The lag time between interior and exterior peak stages may be a critical factor in the operation specification. Detention storage near the line-of-protection can reduce the capacity needed for outlets. Conveyance channels must be sized to assure that flows are conveyed to gravity outlets. The ditch rating curve option of the POND module may be used to approximate controlled inflow to the gravity outlet at the primary location.

Staff gauges are usually placed on both sides of the line-of-protection to effectively operate the gravity outlets. These gauges show the water surface elevation on each side of the line-of-protection and thus give the differential head between the inlet and outfall sides of the gravity outlet. When the exterior stage reaches a specified staff gauge stage or elevation, the gravity outlet gates are closed to prevent backwater flowing into the interior and to maintain the necessary storage in the ponding area. This elevation is called the gate closing elevation.

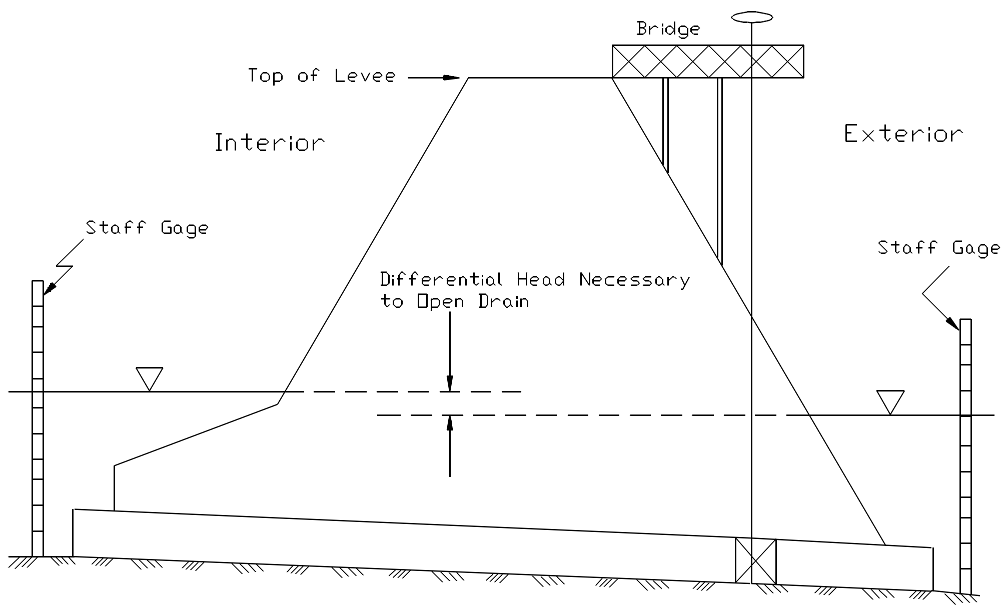


Figure 5-2. Gravity outlet concepts

Anytime the interior elevation is higher than the exterior, the gate could be opened to allow flow out of the interior until the differential becomes zero.

c. Pump stations.

(1) Pumps are designed to lift storm water and other interior flows over or through the line-of-protection to the exterior river, lake, or coastal areas as shown in Figure 5-3. Pump stations operate to reduce peak stages and duration of ponding when flow through gravity outlets is precluded or impeded by high exterior stages. Consideration should be given to setting these elevations so that the pumps may be operated at least once or twice annually for maintenance and testing purposes. Pumps may be used for storm runoff, groundwater and seepage, water accumulated from overtopping waves, and mixed flows with sanitary sewage.

(2) Pump stations are generally considered after analysis of gravity outlets and detention storage, since the initial and continuous operations, maintenance, and power costs of the stations are commonly significantly greater than other measures. For areas where interior and exterior flooding are highly dependent (high likelihood of blocked gravity outlets coincident with interior flooding), pumping may be the only means to significantly reduce interior flood stages. For areas with independent interior and exterior flood conditions, where coincident flooding is not likely, pumping facilities may not be required.

(3) Pump stations are typically located adjacent to the line-of-protection. Normally a larger capacity station is more desirable than several smaller ones. Gravity outlets may be offset if located near pump stations where significant direct flow access to both the pump and gravity outlets is unavailable.

(4) As with gravity outlets, pump stations should have staff gauges on both sides of the line-of-protection, unless the gravity outlet already has staff gauges. Pump start elevation should be set such that all pumps are in operation before the start of interior damage. The sequencing of the pumps is dependent on the approach channel's ability to deliver adequate water; therefore, an approach channel rating curve is required. The pump stop elevation is set below the damage elevation and although not necessarily tied to the channel rating curve, pumping should not continue if the capacity is not delivered by the channel. If the pump stop elevation is set too low, the sump would have to be lowered to maintain sufficient water depth over the impeller. A significant cost increase would occur in this situation.

(5) The pumping station should be aligned to allow direct flow patterns into the forebay from the conveyance channel or detention areas. The key, therefore, is to design the station with an evenly balanced flow distribution in the approach channel or pipe. A long straight approach of about 100 m (several hundred feet) is recommended as well as a straight approach through the station inlet into the sump area. A trashrack is located at the

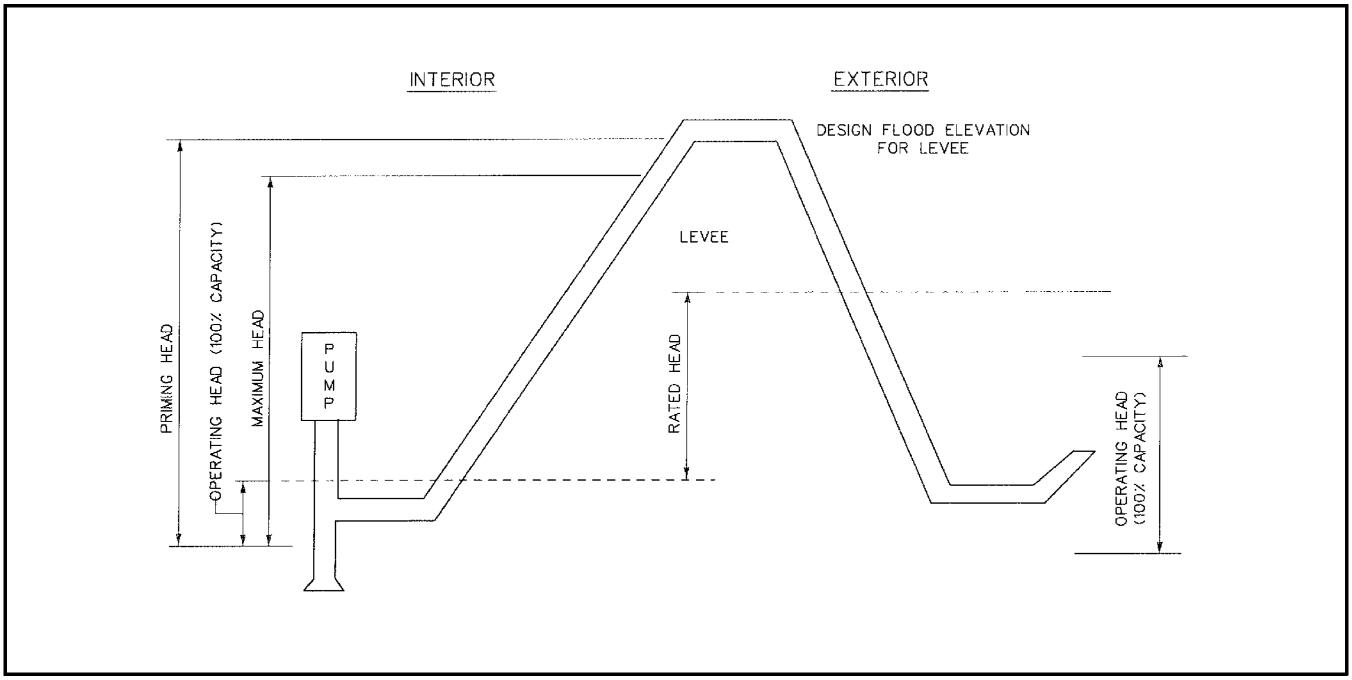


Figure 5-3. Pump station concepts

inlet to the station and should be designed to pass flow into the sump with a minimum of head loss and flow disturbance. For open channel approaches, reversing the invert slope away from the station, if practical, is done to minimize siltation and pumping station dewatering problems. The ability to maintain an even flow distribution minimizes vortex formation. If an unacceptable vortex forms during pump operation, it could eventually damage the impeller and pump bearings.

(6) The pumping station selection is part of the planning process. The feasibility of pumping stations is based on economics and other considerations. In general, the without-pump condition (with gravity outlets and detention storage implemented) must show adverse effects under present and the most likely future condition. Implementation of a pumping station must reduce the adverse effects sufficiently to justify the construction and operation of the facility. Finally, it must be demonstrated that the implementation of a pumping station is the most effective means of reducing the adverse effects.

(7) The feasibility study should investigate the general characteristics of the pumping station that might include number and type of pumps, and on-off elevations to the detail necessary for plan evaluation and selection. These and other features are finalized and detailed in the design phase. The number and types of pumps are determined to provide the total capacity developed in the planning study. Pump on-off elevations are specified. Pumping heads for efficiency and starting assumptions are specified for various combinations of interior and exterior stage conditions. Figure 5-3 shows key pump characteristics. The operating head, 100 percent efficiency, and maximum head are used to define the pump characteristics and efficiency used in planning and design studies.

(8) Additional hydraulic information besides the pump capacity is required. Various pumping heads needed for mechanical design are shown in Figure 5-3 and are described below.

(a) The priming head is the difference between the lowest pump start elevation and the center line of the discharge pipe at its highest point.

(b) The operating head considers the full range of interior and exterior elevations for pump operation. The operating head, also called the total head, is the sum of the estimated head losses and the static head. The estimated head loss is the summation of all the head losses for the pump discharge system, including friction loss, pipe bend loss, etc. The static head is the exterior river elevation minus the interior elevation at the pumping station. The data input to HEC-IFH for each pump unit analyzed gives the operating head information for a pumping unit at various flow capacities.

(c) The high head condition is the difference between the lowest stop elevation and the highest exterior elevation.

(9) First or operation floor elevations of pumping stations should be, as a minimum, at or above ground level to provide convenient access to equipment, to eliminate need for protection

against groundwater, and to simplify the ventilation of the operation areas. The consequence of exceeding pump design stage must be evaluated. Pumping and gravity outlet effects on exterior stages and operation of other downstream gravity outlets should be considered in locating, sizing, and designing the pumping station.

(10) The pumping station capacity in urban areas is generally determined by the physical performance of the facility and its effect on flood damage reduction, costs, and environmental and social factors. Station capacities in rural (agricultural type damage) areas are selected based on economic optimization.

d. Detention areas adjacent to line-of-protection.

(1) The use of detention areas can significantly reduce gravity outlet and pumping station size and costs. A detention basin may also increase the reliability of the system by providing additional time for appropriate operation before damaging water levels occur. A detention area may be natural or excavated sumps, or induced temporary ponding on vacant areas, streets, and parks. Only a few areas are typically available or selected. An interceptor system to collect and convey runoff along the line-of-protection is generally required.

(2) Topography, existing conveyance patterns, and land use usually govern the approximate locations of detention areas. Detention areas are normally located adjacent to the gravity outlet or pumping station, but may be remote from these facilities, connected by appropriately sized channels.

(3) In urban settings, application of nonstructural measures to surrounding structures may be warranted. This is done to gain incremental storage versus increased capacity of gravity outlet or pumping facilities. Detention basins can be designed to be environmentally attractive and contribute to community social goals in urban areas when used as parks and open spaces during periods not needed for runoff storage. Management of the functional integrity of the detention basin by preventing development encroachment and subsequent loss of storage capacity is critically important. Local agency agreements should specify requirements for maintenance of detention basin functional integrity throughout the project life.

e. Intercepting sewers and pressure conduits.

(1) These conveyance systems interconnect two or more existing sewers or channels within the line-of-protection for conveying their flows to gravity outlets, pumping stations, or pressure conduits, for combined discharge through the line-of-protection. Interceptor systems are designed to minimize the number of gravity outlets, pumping stations, and pressure conduits.

(2) Pressure conduits are pipes or closed conduits designed to convey interior flood waters through the line-of-protection under internal pressure. The inlet to the pressure conduit must be at a higher elevation than the river stage against which it functions. Some pressure conduits may serve as discharge lines for pumping facilities. The use of pressure conduits reduces the contributing interior runoff area and the magnitude and volume of flood waters that must be handled by other flood damage reduction measures.

(3) Detention storage adjacent to the line-of-protection is defined in the POND module of HEC-IFH. The elevation-area relationship is entered and the corresponding storage values calculated by the program. A ditch rating curve may be used to represent a channel link between the detention storage and primary outlet at the line-of-protection and thus govern the discharge to the outlet. Future conditions where the detention storage is encroached and thus reduced are modeled by adjusting the elevation-storage relationship appropriately. Sensitivity analysis of potential future development effects could be performed in this manner. Similarly, enhanced flood protection involving several excavation plans for the detention storage area may be readily evaluated.

f. Physical measures remote from line-of-protection. These measures are traditional structures such as channels, diversions, interior levees, and storage reservoirs remote from the line-of-protection. Their functional capability is therefore the same as with any other planning or design investigations involving flood loss reduction measures. Consequently, only the interrelationship with other specific interior measures will be emphasized. For the most part, the evaluation of these measures is performed outside HEC-IFH with the resulting time series hydrographs imported into HEC-IFH using the AUXFLOW module. Conversely, the HEC-IFH ponding area stages may be used as starting water surface profile elevations in the sizing studies of measures remote from the line-of-protection.

(1) Conveyance channels reduce flood losses for damage centers remote from the line-of-protection and collect and transport runoff and other interior waters to gravity outlets, pumping stations, and pressure conduits. Where possible, channels should follow natural drainage and conveyance routes. When this is not possible, consideration should be given to locating channels near and parallel to the line-of-protection. Channels may be required in combinations with detention basins to connect with gravity outlets or pumping stations. Channels may also be needed as exterior connections from the outlet works of gravity or pressure conduits or pumping stations to the river, lake, or ocean. The planning task is to approximately size and locate the channel system. The design task is to perform design in terms of size, location, gradient, and auxiliary control features of erosion protection and grade control.

(2) Diversions are used to transfer all or portions of the runoff from one location to another. They may collect flow for pressure conduits, transfer flow out of the basin (reduce the contributing area), and collect flow from areas to gravity outlets and pumping stations, thereby requiring fewer facilities. They may be designed to permanently alter conveyance systems or to operate only for discharges above (and below) certain values. Diversions may be operated as part of a coordinated system. They may also be used to bypass flow around damage centers.

(3) Remote detention basins (reservoirs) have characteristics similar to those described for detention basins adjacent to the line-of-protection. Bottomland detention basins may be natural sinks, oxbow lakes, or excavated sumps, or may be formed by levees. Hillside or bluff basins are really conventional reservoirs. Implementation of the remote basins may regulate flow to reduce the size of downstream interior flood loss reduction measures. Damage reductions at several downstream locations may be achieved, in contrast to local protection works that are effective only at their individual damage center. Detention basins may also retain sediment from the hillside or bluff areas and thus eliminate it as an interior area problem.

(4) Interior levees and walls along conveyance channels may be implemented as local interior protection features. These barriers are normally lower in height than the conventional main levees and thus failure is less likely to result in catastrophic loss. If the barriers are of sufficient height, and damage potential from failure is great, they are considered the same as the main line levees or walls. The interior levees may create secondary interior flooding problems that must be considered, though the magnitude would likely be minor. Implementation of these measures must meet criteria defined by "Flood Plain Management" (ER 1105-2-100) and other existing federal policy. Flood forecasting emergency-preparedness plans should be an integral part of implementation of interior levees and walls to reduce the potential for loss of life and property when the situation warrants.

g. Measures that permanently modify damage susceptibility of existing structures.

(1) Several types of nonstructural measures are designed to permanently modify damage potential of existing structures. They include: flood proofing (seals, earthen dikes, and walls), raising existing structures, and relocating of occupants and/or structures (damage potential) from the specified threatened area. The measures are designed to modify the damage potential of an area. They are typically implemented on a localized scale (such as a neighborhood) as opposed to structural and other types of nonstructural measures that often are designed to function for larger areas.

(2) Flood proofing and raising of structures to target elevations protect structures and their contents until the design limits are exceeded. These measures, applied to individual or small groups of structures, are generally less environmentally disruptive than structural alternatives. The measures do not reduce damage to vital services (i.e., water, gas, power), streets, bridges, and landscaping, and only slightly reduce the social impact and disruption associated with flood events. Seals, walls, and dikes are often significantly less reliable than other permanent measures.

h. Measures that manage future development.

(1) Management of future development reduces losses by requiring floodplain development and activities to be operated or located in a specific manner commensurate with the flood hazard. Land use development can be controlled by regulations such as zoning ordinances, building codes and restrictions, taxation, or the purchase of land in fee or by the purchase of a flood easement. Structures not precluded from floodplain locations by these measures may locate on the floodplain if constructed and maintained to be compatible with the recognized flood hazard.

(2) Regulatory actions and land acquisition can also cause new use of the floodplain. The measures are attractive from the perspective of managing development to reduce the future damage potential of the area and use of the floodplain for compatible purposes.

(3) Measures that manage future development are generally compatible with implementation of other structural and nonstructural measures. Regulatory actions may be incorporated as part of the agreements with local agencies or the local sponsor. For example, implementation of regulatory policies to preserve the storage and functional integrity of detention basins over the life of the project may be employed.

(4) The HEC-IFH analysis of the impact of implementing these measures and actions is performed similar to that for other alternatives. An exception is the most likely future condition development assumptions, which may be adjusted to reflect the management policies.

i. Flood forecasting-emergency preparedness plans.

(1) Flood emergency preparedness plans are flood emergency management actions and activities that reduce flood losses, minimize social disruption, and assist in recovery and reoccupation of flooded areas. The measures should not be considered instead of other feasible permanent structural or nonstructural alternatives due to their temporary nature and uncertain reliability during flood episodes. Preparedness plans, however, should be considered as interim measures until other flood loss reduction measures are implemented; as companions to, or enhancements of, such other measures; and as a means of

minimizing the risk of loss of life, flood damage, and social disruption if other methods are not feasible.

(2) Flood forecasting-emergency preparedness plans are generally compatible with other structural and nonstructural flood reduction measures. Implementation is more frequent in urban interior areas than in agricultural interior areas. Flood forecasting-emergency preparedness actions are usually feasible even if other structural and nonstructural measures are not.

(3) The HEC-IFH analysis results provide information on the flood hazard (frequency, stage, duration, and extent of flooding) that may be used directly in evaluation of flood warning-preparedness systems or in conjunction with other programs such as those used to compute water surface profiles. The implementation of flood warning-preparedness programs for interior systems may enhance the operation for large and complex systems, but will primarily improve the response so that more damage reduction may occur. The potential for loss of life is normally not a factor for interior systems due to typically shallow flooding, but would be for design exceedances for the line-of-protection.

5-4. Interior Analysis Using HEC-IFH

a. General.

(1) The formulation and evaluation process of interior flood damage reduction measures must be conducted within the framework of Corps guidance and regulations. The details of the hydrologic engineering and other analyses are study dependent. There is, however, an analysis progression that is applicable for most interior studies.

(2) The initial step is to determine the existing and future without-project conditions. The second step is to determine the configuration and feasibility for additional gravity outlet capacity assuming the minimum facility is in place. The third step determines the design and configuration of additional pump capacity, assuming that the minimum facility and the gravity outlets are in place. The next step explores tradeoffs of pumping capacity versus ponding area storage and includes evaluation of nonstructural measures to increase nondamaging ponding area storage. For studies with large and complex systems, such as many urban settings, traditional evaluation of flood damage reduction measures remote from the line-of-protection is often necessary. Finally, the feasibility of other flood damage reduction actions such as flood warning-preparedness and institutional arrangements would be evaluated. The following paragraphs describe the procedures and how both the continuous simulation and the hypothetical event analyses capabilities of HEC-IFH can be applied. Chapter 3 overviews the data entry and the general procedures for HEC-IFH applications. Appendices C, D, and E present a detailed strategy, and two case examples detailing the HEC-IFH analysis procedures, respectively.

b. Without-project conditions. Analyses of the existing and future without-project conditions are performed as previously described in Section 5-2.

c. HEC-IFH gravity outlet analysis. The following is a series of steps that may be used as a guide to tailor the gravity outlet analysis to a specific study. The goal is to determine the appropriate size and configuration of gravity outlets.

(1) Define new plans for evaluating gravity outlets using modules for CSA or HEA with the minimum facility in place. Existing condition rainfall (PRECIP module), runoff and routing parameters (RUNOFF module), ponding area characteristics (POND module), minimum facility (GRAVITY module), and seepage (AUXFLOW module) are from the CSA analysis of the selected minimum facility.

(2) Assemble outlet characteristics for several standard size outlets and develop composite rating curves for each using HEC-IFH. Alinement, invert elevations, number and size of outlets, and entrance and exit configurations are important considerations.

(3) Develop three to six gravity outlet configurations (plans with different GRAVITY modules) with one or more gravity outlets in addition to the minimum facility outlet, with each module representing an incremental increase in total outlet capacity.

(4) Run HEC-IFH using the CSA option and develop several plans that incorporate the gravity outlet modules and determine interior stage-frequency relationship for each plan. A maximum annual interior elevation versus frequency plot comparing plans is illustrated in Figure 5-4.

(5) Test the additional capacity with the HEA-generated balanced storms over the interior and exterior basins for selected frequencies and determine the interior stage-frequency relationship for each plan if interior and exterior flooding can be highly coincident. The relationships help determine if rare combinations of events are being captured in the CSA. These relationships will also help establish the upper end of the graphical stage-frequency relationship.

(6) If the interior and exterior flooding can be independent and noncoincident, define additional plans using HEA and local storm depth-duration-frequency data for a range of exceedance frequency events occurring over the interior area for unblocked gravity outlet conditions. Determine the corresponding stage-frequency relationships for each plan. This relationship helps determine if rare local events are being captured by the CSA and helps define the frequency relationships.

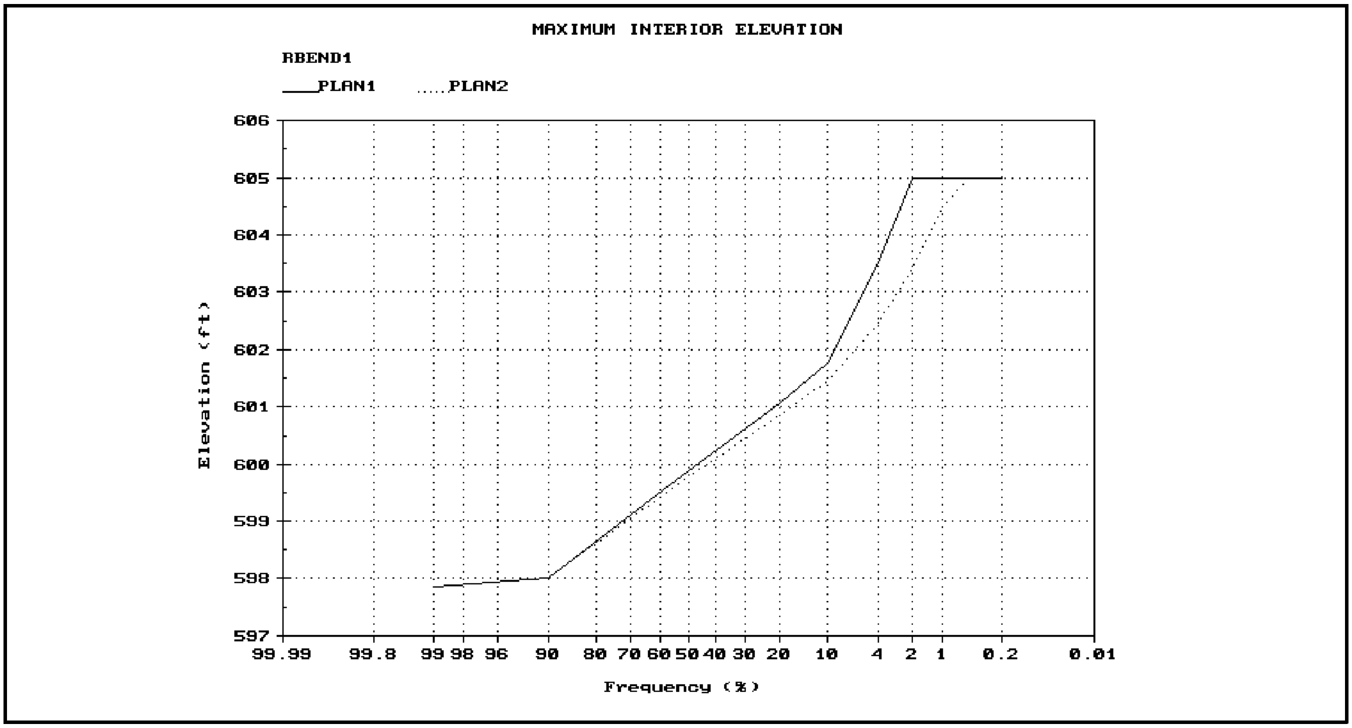


Figure 5-4. Plan comparison of stage-frequency relationships

(7) After examining the results of the CSA and HEA analyses, adopt a final stage-frequency relationship for each gravity outlet plan.

(8) If appropriate, develop future condition stage-frequency relationships by repeating the above process using the most likely and other (if required) future hydrologic conditions.

d. Selection of gravity outlets. The following are steps that may be used to determine the gravity outlet capacity at the primary location. Secondary outlet locations may use a less rigorous procedure if the locations are not critical.

(1) The HEC-IFH results should be reviewed for reasonableness. The gravity outlet should be sized such that the interior stage essentially follows the receding limb of the exterior stage hydrograph with consideration of the operating head differential. HEC-IFH's output results can show this graphically.

(2) An economic analysis is normally required for primary outlet locations to determine the NED (USACE 1990a) gravity outlet size. The cost engineering team member provides cost estimates of each gravity outlet HEC-IFH plan and the economist will provide stage-damage relationships by damage category for existing and potential future conditions. The expected annual damage for each plan is determined by the study economist using the developed stage-frequency relationships and the stage-damage relationships.

(3) A plan comparison array including residual equivalent expected annual damage (EAD), expected annual inundation reduction benefits, average annual costs, and net benefits is developed to identify the economically optimal plan. A similar table is shown for pumping station sizing in the next section. Other information on the flood hazard reduction, operation requirements, performance for a range of events and conditions, environmental and other factors should be considered in determining the recommended gravity outlet plan. This plan should be the base plan for evaluating additional measures. Normally the economically optimum plan is chosen.

e. Pumping station analysis overview. Pumping stations may not be attractive if the gravity outlets are effective in reducing the flood damage and if there is little coincidence between interior runoff and high exterior stages. Often, however, additional gravity outlets are not justified and significant residual damage exists. If most of the damage is from blocked conditions, pumps may be the only effective means of evaluating interior flood waters. The same general application steps for HEC-IFH used for additional gravity outlet capacity are appropriate for determining the economic optimal pumping capacity. Some differences and pumping station analysis considerations are described in the following paragraphs.

(1) The base condition for evaluating pumping capacity is with the selected gravity outlet configuration in place. Several pumping station plans are evaluated against the base plan, each with an incremental increase in pumping capacity.

(2) The pump operation criteria must be defined. Pump-on and pump-off elevations must be determined so that the pumps operate prior to the start of damages. Pump-on elevations are usually set below flood stage with pump-off elevations usually set at 0.3 to 0.6 m (1 to 2 ft) below pump-on elevations. If a levee stability problem exists when the exterior river reaches a certain stage, the pump-off elevation must be set for a higher stage. Two or more pump units generally make up total pumping capacity. Several units that can be operated in phases to step up to the total capacity may be more effective than one or two large-capacity pumps. Pump cycling can become a problem with a few large pumps and limited conveyance capability to the pumping station. Limited flow delivery capacity to the station or flow surges in sewer systems or at locations close to an upper basin with a very short time of concentration can cause cycling problems. Varying the capacity of the pump units and the on-off elevations minimizes pump cycling times.

(3) HEC-IFH can use up to ten pumping units for each interior pumping plan specified by the PUMP module. All pumping units are assumed to be located at the primary outlet location. The PUMP module input is summarized in Chapter 3 for CSA, and in Chapter 7 of the HEC-IFH user's manual. The operating data entered for the CSA and HEA is slightly different. For CSA, different values of pump start and stop may be defined for each calendar month of the year. For HEA, a single pump start and stop elevation is defined for use during the entire analysis.

(4) The CSA and HEA may both be used to evaluate the pumping station design and to derive the existing and future with-project conditions stage-frequency relationships for the pumping plans.

f. Economic analysis of pumping station plans. The following paragraphs describe the procedures for performing the economic analysis of pumping stations.

(1) The cost engineering team member provides cost estimates of several pumping station plans or sizes as were specified and evaluated. The stage-damage relationships previously provided by the economist are still applicable.

(2) An economic analysis is required for all pumping stations to determine the NED (USACE 1990a) pump capacity. The cost engineering team member provides cost estimates of each pumping station analyzed using HEC-IFH and the economist provides stage-damage relationships by damage category for existing and potential future with-project conditions. The expected annual damage for each plan or pumping station capacity is determined by the study economist using the computed stage-frequency relationships and the stage-damage relationships.

(3) The operation and maintenance costs of pumping stations are significant and an important factor, especially from the local sponsor's standpoint. HEC-IFH provides data such as the maximum pump head and the average annual days pumped. These data are evaluated by the electrical/mechanical engineer to determine electrical or fuel costs, and to assist in pump selection.

(4) A plan comparison array as shown in Table 5-1 is developed to aid in identifying the economically optimal or NED plan. The data for benefits and annual costs for each plan versus pump station capacity are then plotted to pick the economically optimal plan as illustrated in Figure 5-5. Other environmental, social impacts, performance, operation, and safety information

Table 5-1
Economic Evaluation of Pumping Station Capacity

Plan	Expected Annual Damage ($1000)	Average Annual Benefits ($1000)	Average Annual Cost ($1000)	Average Net Benefits ($1000)	B/C Ratio
Levee + Minimum Facility	952	-	-	-	-
Plus 80 m^3/s (100 cfs) pump	632	320	400	-80	0.80
Plus 155 m^3/s (200 cfs) pump	328	624	510	+114	1.22
Plus 230 m^3/s (300 cfs) pump	185	767	650	+117	1.18
Plus 385 m^3/s (500 cfs) pump	46	906	980	-74	0.90

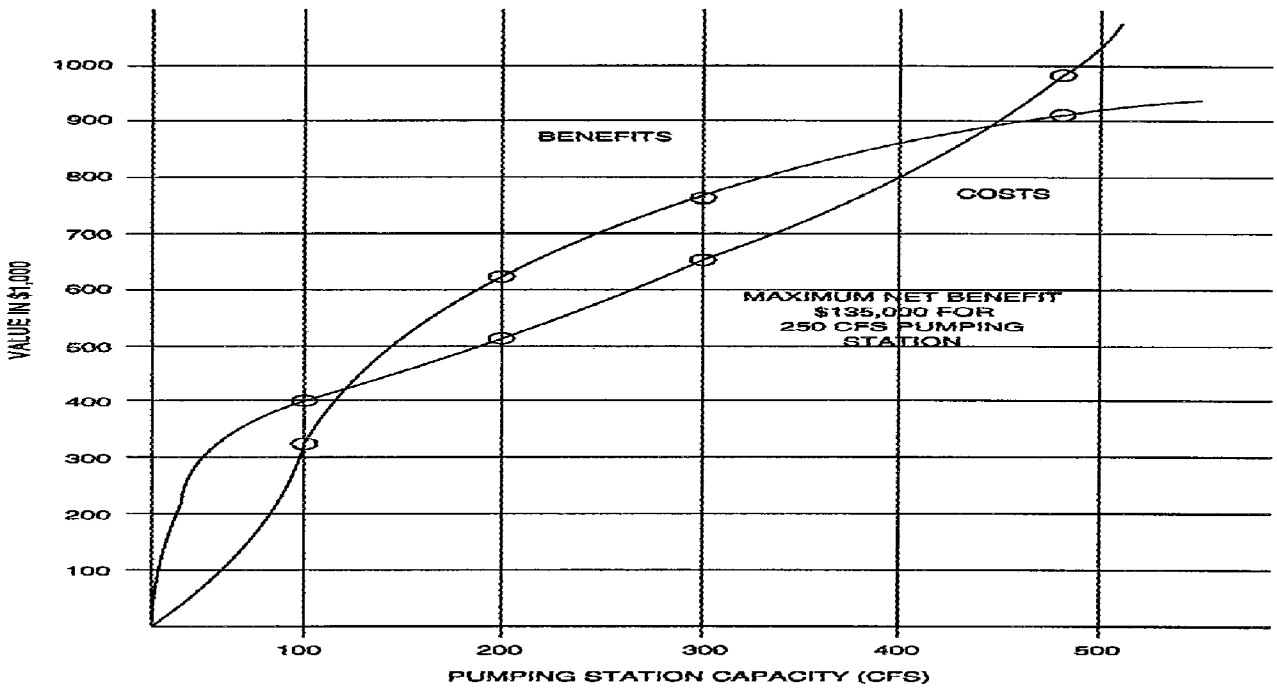


Figure 5-5. Pump station benefit-cost curve

should be developed and used to assist in determination of the appropriate pumping station capacity. The economically optimal plan is the recommended plan in agricultural areas and for most urban areas.

g. Evaluation of increased detention storage capacity.

(1) It is prudent to investigate the tradeoffs between pumping capacity and ponding area storage. Pumps are expensive and an increase in storage capacity will typically allow reduction in required pumping capacity. Several measures can be evaluated, including increasing the physical size of the ponding area and nonstructural actions that will reduce the damage for a given ponding stage.

(2) The sensitivity of ponding area size versus pumping capacity can be readily determined using HEC-IFH. The plan with the identified economically optimal gravity outlet and pumping station would be the base plan for determining if excavation is feasible.

(3) Temporary evacuation, raising existing structures, permanent relocation of structures and/or occupants, floodproofing, and other nonstructural measures that reduce susceptibility to damage (and increase available storage) should be evaluated. Floodproofing, raising, and relocation measures are generally more economically justified than structural measures when only a few structures are involved. Similarly, implementing nonstructural measures to a few structures to permit increasing the size of a detention basin may be more attractive than increasing the size of gravity outlets or pumping stations. Residual damages for evaluated plans would be revised based on new stage-damage relationships resulting from implementing the nonstructural measures.

(4) Other social, institutional, and environmental issues, including the management of future development, and flood warning and preparedness programs, would also be evaluated in the final plan selection.

5-5. Comparison of Plans

One important aspect of HEC-IFH is the ability to generate results from different plans and to compare them directly. The effects of different conditions or assumptions can be quickly evaluated. Up to seven different plans may be selected for comparison using HEC-IFH. Each plan is produced by performing the interior analysis using various combinations of the modular input data. HEC-IFH allows the user to display the results of the specified plans side-by-side in a report called Plan Comparison Summaries. For Continuous Simulation Analyses, eight summaries arranged into four categories are available. Figure 5-6 illustrates the plan comparison summary menu and the eight summaries that are available. For hypothetical event analyses, four plan summaries are available as shown in Figure 5-7. Chapter 13 of the HEC-IFH user's manual lists all the data values that can be specified for both types of analyses. The most important comparison is generally the peak elevation versus the percent chance exceedance frequency event. The minimum facilities plan can easily be compared with another plan having additional gravity capacity or with several plans having various pumping capacities. A tabular comparison of maximum interior elevation versus frequency is illustrated in Figure 5-8 and a screen plot of that same data is shown in Figure 5-9. By looking at the comparisons, a perspective is gained on the effectiveness of additional gravity drains or pumping capacity. This comparison data can then be given to the economist for an economic assessment of the flood damage reduction benefits produced by the various plans to determine which plans are viable features.

5-6. Plan Performance

After the selection of the NED plan, the HEC-IFH program should be operated for both CSA and HEA events using the selected components to verify the desired functional results. By comparing the NED plan results with other plans, the residual impacts of floods with volumes larger than the NED plan can handle can be determined. Also, if a specific ponding area size is required, the impacts of encroachments can be analyzed and the local sponsor can be made aware of the consequences of not maintaining this feature. The consequences of a pump unit failing during an event should also be evaluated.

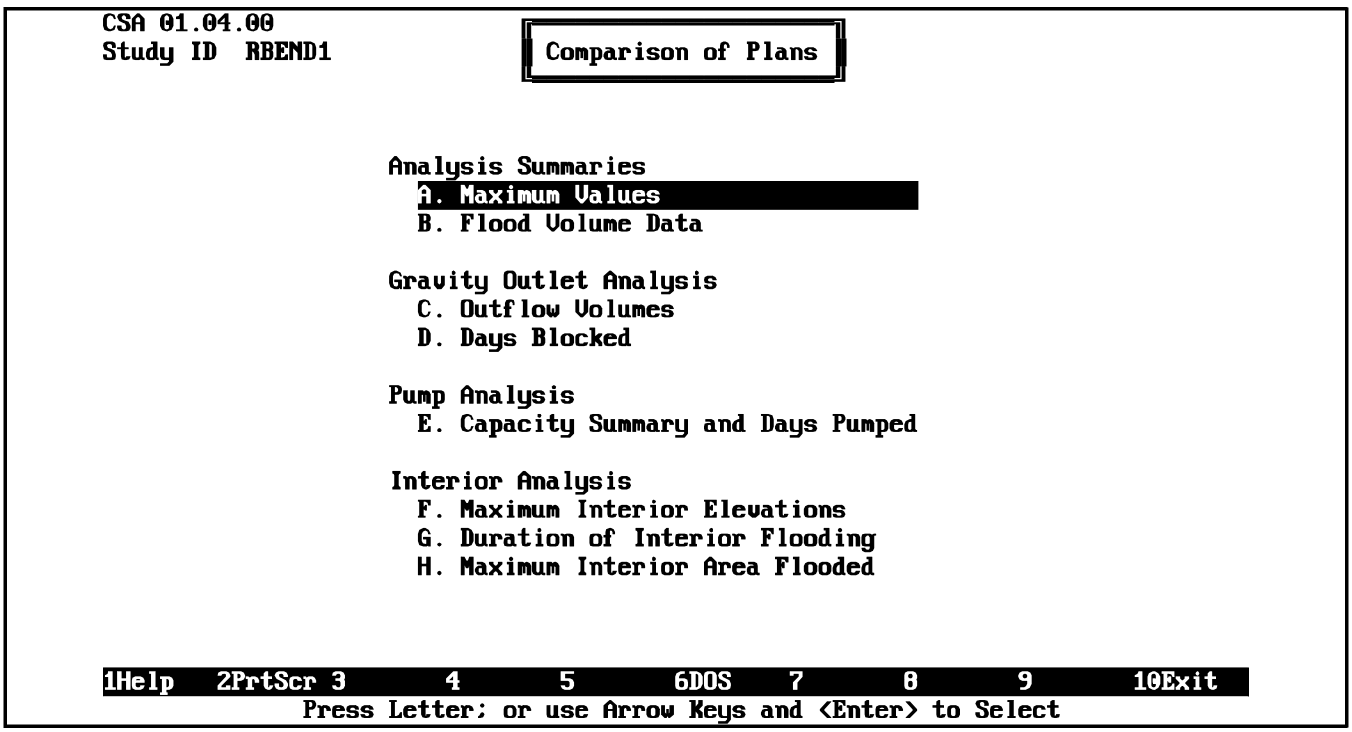


Figure 5-6. Continuous simulation plan comparison summary menu

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HEA 01.04.00
Study ID  RBEND1                    Comparison of Plans



                  Select Option:

                    A. Plan Summary
                    B. Maximum Interior Elevation-Frequency
                    C. Maximum Interior Area Flooded-Frequency
                    D. Maximum Total Interior Inflow-Frequency



              Press Letter; or use Arrow Keys and <Enter> to Select
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Figure 5-7. Hypothetical event plan comparison summary menu

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CSA 01.04.00
Study ID  RBEND1                    Comparison of Plans

              F. Interior Analysis - Maximum Interior Elevations
```

Plan ID	Area Prim. Grav. (sqft)	Total Pump Cap. (cfs)	Peak Elevation (ft) vs. Percent Chance Exceedence Frequency Event 50%	20%	10%	4%	2%	1%	0.2%
PLAN1	16.0	0.0	599.88	601.06	601.75	603.50	605.00	605.00	605.00
PLAN2	16.0	200.0	599.79	600.85	601.46	602.47	603.40	604.49	605.00

```
1Help   2PrtScr 3      4      5      6DOS    7      8      9Plot   10Exit
                         Press <F10> to Return
```

Figure 5-8. Maximum interior elevation-frequency summary

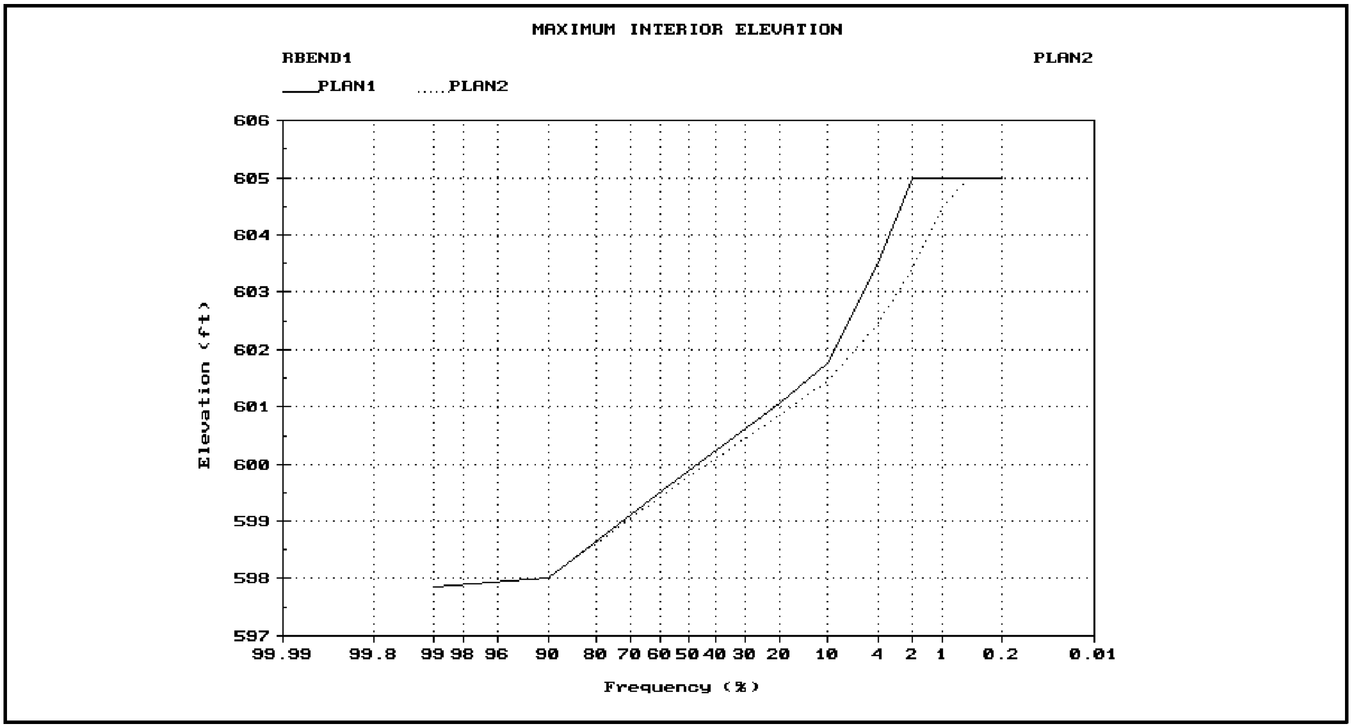


Figure 5-9. Maximum interior elevation-frequency plot

Chapter 6
Study Documentation

6-1. General Requirements

This chapter emphasizes the role of HEC-IFH in study documentation as related to final technical studies reports. Comprehensive, but concise, documentation of the hydrologic engineering analysis is a key aspect of any study. It should be performed continuously throughout the study period. Required hydrologic engineering information ranges from extensive (for feasibility reports) to relatively little (for most Design Memoranda (DM) where more emphasis is placed on hydraulic design). Reporting requirements for different types of studies are described in applicable Engineer Regulations (ER's). In addition, hydrologic and hydraulic Engineer Technical Letters (ETL's) summarize the array of hydrologic engineering data that must be presented for planning reports and suggest display formats. The goal of study documentation should be to describe (in a basic and orderly sequence) the nature of the flood problem, the status and configuration of the existing system, the proposed system and alternatives, the performance characteristics of the proposed system, and operation plans.

6-2. Content Related to Planning Considerations

Hydrologic reporting requirements should include a description of the without-project conditions, alternate flood loss reduction plans analyzed, analytical procedures and assumptions used, and system implementation and operation factors influencing the hydrologic aspects of the study. Basic hydrologic reporting requirements are specified in ER 1105-2-100 and EM 1110-2-1413.

6-3. Content Related to Design Considerations

Hydrologic engineering material presented in the design documents describes in detail the hydrologic system, and any refinements of sizes, performance standards, and operation criteria from the feasibility study. The hydrologic engineering requirements for the DM are specified in ER 1110-2-1150.

6-4. Reporting Capabilities of HEC-IFH

HEC-IFH has extensive reporting and plotting capabilities that document the results of an interior analysis. The data stored in each data module, as well as hydrologic analysis summaries and plan comparison results, can be printed or plotted to provide report documentation. The following outline, which follows the requirements of EM 1110-2-1413, also indicates technical study areas in which tables and plots from the HEC-IFH program may be used for documentation.

• Existing system layout: schematics, aerials, tables, plates, maps.

- Existing facilities on aerials
- Important environmental aspects
- Damage locations
- Cultural features

• Description of physical features of existing (without) conditions.

- Watershed/subbasin boundaries on map
- Dimensions of any existing gravity outlets, channels, storm sewers, etc. **(HEC-IFH)**
- Area capacity data of detention areas **(HEC-IFH)**

• Description of basic hydrologic approach/ assumptions.

- Historic/hypothetical storms **(HEC-IFH)**
- Loss rates **(HEC-IFH)**
- Runoff transforms **(HEC-IFH)**
- Routing **(HEC-IFH)**
- Base flow **(HEC-IFH)**

• Presentation of hydrologic flow characteristics.

- Peak discharge **(HEC-IFH)**
- Duration **(HEC-IFH)**
- Frequency **(HEC-IFH)**
- Velocity

• Impact of future without-project conditions.

- Description of runoff and operation changes similar to existing conditions
- Description of adopted procedures for parameter estimation

• Hydrologic analysis of alternatives.

- Location, dimensions, and operation criteria of alternate plans
- Display of final array of plans on aerials - compare with existing
- Impacts of measures and plans on peak discharges, durations, velocities, etc. **(HEC-IFH)**
- Display of residual effects of large SPF/PMF in urban areas, and 100-year in rural **(HEC-IFH)**
- Hydrologic description of alternate plans shall include description of required local agreements/ maintenance requirements
- Description of consequences if agreements are not met **(HEC-IFH)**

• Design information.

Appendix A
References

A-1. Required Publications

Public Law 93-251
Public Law 93-251, Section 73

ER 1105-2-100
Guidance for Conducting Civil Works Planning Studies

ER 1110-2-1150
Engineering and Design for Civil Works Projects

ER 1110-2-1405
Hydraulic Design For Local Flood Protection Projects

EM 1110-2-1411
Standard Project Flood Determinations (ENG BUL 52-8)

EM 1110-2-1413
Hydrologic Analysis of Interior Areas

EM 1110-2-1417
Flood-Runoff Analysis

EM 1110-2-3104
Structural and Architectural Design of Pumping Stations

EC 1105-2-205
Risk-Based Analysis for Evaluation of Hydrology/Hydraulics and Economics in Flood Damage Reduction Studies

USACE 1988a
USACE (1988a). "Proceedings of a Seminar on Flood Damage Reduction Reconnaissance-Phase Studies," Hydrologic Engineering Center, Davis, California.

USACE 1988b
USACE (1988b). "Pumping Station Inflow-Discharge Hydraulics, Generalized Pump Sump Research Study," WES Technical Report HL-88-2, NTIS, 5285 Port Royal Road, Springfield, Virginia 22161.

USACE 1989
USACE (1989). "Water Control Software, Forecast and Operations," Hydrologic Engineering Center, Davis, California.

USACE 1990a
USACE (1990a). "HEC-1, Flood Hydrograph Package, User's Manual," Hydrologic Engineering Center, Davis, California.

USACE 1990b
USACE (1990b). "HEC-2, Water Surface Profiles, User's Manual," Hydrologic Engineering Center, Davis, California.

USACE 1990c
USACE (1990c). "HEC-DSS, User's Guide & Utility Program Manuals," Hydrologic Engineering Center, Davis, California.

USACE 1992
USACE (1992). "HEC-IFH, Interior Flood Hydrology Package, User's Manual," Hydrologic Engineering Center, Davis, California.

A-2. Other Publications

ER 1110-2-109
Hydroelectric Design Center

EP 1110-2-9
Hydrologic Engineering Studies Design

EM 1110-2-3101
Pumping Stations - Local Cooperation and General Considerations

EM 1110-2-3105
Mechanical and Electrical Design of Pumping Stations

ETL 1110-2-313
Hydraulic Design Guidance for Rectangular Sumps of Small Pumping Stations with Vertical Pumps and Ponded Approaches

USACE 1982
USACE (1982). "Hydrologic Analysis of Ungaged Watersheds Using HEC-1," Hydrologic Engineering Center, Davis, California.

Federal Highway Administration 1985
Federal Highway Administration (1985). "Hydraulic Design of Highway Culverts," Hydraulic Design Series No. 5, Report No. FHWA-IP-85-15.

NOAA 1977
National Oceanic and Atmospheric Administration (NOAA) (1977). Frederick, R. H., et. al., "Five to Sixty Minute Precipitation Frequency for the Eastern and Central U.S.," NOAA Technical Memorandum NWS Hydro-35, Silver Springs, MD.

U.S. Department of Commerce 1961
U.S. Department of Commerce (1961). Hershfield, D. M., "Rainfall Frequency Atlas of the U.S." Technical Paper No. 40, Weather Bureau, Washington, D.C.

WRDA 1986
WRDA (1986). Water Resources Development Act of 1986.

Appendix B
Glossary of Terms

Agricultural areas
Lands intended primarily for crop production, pastures, and other similar uses, including the closely associated facilities of on-farm roads, fences, etc.

Base conditions
The land use and related conditions expected to exist at the beginning of the first year of project operation.

Blocked gravity conditions
Conditions that exist when exterior stages are higher than interior stages, thus preventing flow of interior flood waters through the gravity outlets.

Coincident probability (Frequency)
Probability of flooding to exceed a given elevation based on the joint probability of flooding from each source.

Conditional probability P(a/b)
The probability of flooding from one source given the stage or discharge from another source exceeds a stated level.

Correlated
The degree to which flooding from one source occurs or can be predicted from flooding from another source; a mutual relationship but not necessarily cause and effect.

Culvert
A relatively short length of closed conduit that connects two open channel segments or bodies of water. Culverts are the most common types of gravity outlets for interior areas.

Dependence
The degree to which flooding of an area from one source is physically and meteorologically related to flooding from another source.

Detention storage areas
Any low area, often near the inlets to gravity outlets, pumping stations, or pressure conduits, used to temporarily store interior flood waters in excess of the rate at which these flows can be passed through the line-of-protection.

Discrete events
Flood events in a series that may be considered individually since they are independent of other flood events in the series.

Diversions
Ditches or conduits designed to bypass flood waters around or away from a specific area.

Existing conditions
The present land use and related conditions occurring under existing and authorized improvements, laws, and policies.

Exterior stage
Water surface level on the unprotected (exterior) side of the line-of-protection.

Feasibility investigations
Planning studies performed in response to specific Congressional authorization to determine the feasibility of adopting Federal projects or modifying existing projects. The report is a decision document used to determine the desirability of authorizing a Federal commitment to a project.

Future conditions
The most likely land use and related conditions expected in the future. Conditions other than those deemed the most likely may also be considered future conditions.

Gravity outlet rating table
This table lists the headwater depth required for a range of outlet flow rates and tailwater depths.

Gravity outlets
Culverts, conduits, or other similar conveyance openings through the line-of-protection that permit discharge of interior floodwaters through the line-of-protection by gravity when the exterior stages are lower than interior stages. Gravity outlets are equipped with gates to prevent river flows from entering the protected area during time of high exterior stages.

Headwater
The depth of water at a culvert on the entrance or upstream side, as measured from the upstream invert of the culvert.

Hypothetical frequency storms
Balanced storm distributions with total rainfall amounts consistent with specific exceedance frequencies or recurrence intervals for each time duration.

Independence
Situation in which flooding of an area from one source is unrelated to flooding from another source.

Index location
A point along the main exterior river where recorded or computed stage hydrograph data are available.

Inlet control
A condition where flow capacity of the culvert entrance is less than the flow capacity of the culvert barrel, typically resulting in supercritical flow.

Interception systems
Sewers or ditches provided to connect existing sewers or channels which discharge through the line-of-protection by means of gravity outlets, pumping stations, or pressure conduits.

Interior stage
Water level on the protected side of the line-of-protection.

Interior system
Structural and nonstructural flood loss reduction measures located behind the line-of-protection. These measures may consist of (a) water management measures of gravity outlets, pumping stations, interior detention storage, diversions, pressure conduits, and hillside reservoirs; (2) facility protection measures of flood proofing and structure relocation; and (c) development management measures of floodplain regulations and flood emergency warning-preparedness plans.

Line-of-protection
Location of levee or wall that prevents flood waters from entering an area.

Lower interior subbasin
An interior subbasin that directly contributes to flow behind the line-of-protection, normally considered the floodplain portion of the contributing area.

National economic development (NED) plan
The plan that maximizes net national economic development benefits.

Nonstructural measures
Measures designed to reduce flood losses by implementation of facility flood proofing, raising, or relocation; and development regulations and flood warning-emergency preparedness planning actions.

Outlet control
A condition where culvert capacity is limited by downstream conditions or by the flow capacity of the barrel, typically resulting in subcritical flow.

Overflows
Situation in which the water surface elevation in the interior ponding area rises to a level that causes flows to naturally spill from one interior area into an adjacent interior area.

Pressure conduits
Closed conduits designed to convey interior flows through the line-of-protection under internal pressure. The inlet to a pressure conduit that discharges interior flows by force of gravity must be at a higher elevation than the river stage against which it functions. Some pressure conduits may serve as discharge conduits from pumping stations.

Pump efficiency
The percentage of rated pump capacity actually obtained during pump operations (100 percent at average river stages, less than 100 percent at higher river stages).

Pumping station
Pumps located at or near the line-of-protection to discharge interior flows over or through the levees or flood walls (or through pressure lines) when free outflow through gravity outlets is prevented by exterior stages.

Residual damage
Flood damage remaining after implementation of the flood loss reduction measures.

Seepage
Water that passes through or beneath the line-of-protection when the exterior water surface elevation is higher than the interior water surface elevation.

Standard project storm
Hypothetical storm distribution applicable to basin areas 26 to 2,590 sq km (10 to 1,000 sq miles) located east of 105 deg longitude. Determined according to the criteria discussed in EM 1110-2-1411.

Structural measures
Measures designed to reduce flood losses by construction of levees, gravity outlets, pumping stations, detention storage, reservoirs, and diversions.

Tailwater
The depth of water at a culvert on the downstream side, as measured from the downstream invert of the culvert.

Tieback levee (Flank levee)
Levee that extends from the river, lake, or coast to a bluff line. Part of the line-of-protection.

Total pumping head
This value represents the operating head of a pumping unit at various flow capacities. The total pumping head is the sum of the estimated head loss and the static head.

Transfer relation
Adjustment of the main river stage hydrograph from the index location to a primary or secondary gravity outlet location.

Upper interior subbasin
An interior subbasin, generally a hillside area, producing runoff that is normally routed through a channel segment to the line-of-protection.

Urban areas
Areas presently or expected to be developed for residential, commercial, or industrial purposes within the period considered in project formulation.

Appendix C
Hydrologic Engineering Management Plans for Analysis of Interior Flood Damage Reduction Measures, Napa, California

C-1. Background

a. The Hydrologic Engineering Center (HEC) is performing an interior flood hydrology study of the City of Napa, CA, for the U.S. Army Engineer District, Sacramento. The district is considering a series of levees to reduce the flood damage potential to the city caused by flooding of the Napa River, which flows through the center of the town. Interior flooding that would result because of the levees must be addressed as part of the plan. The study is a preconstruction engineering and design reaffirmation study.

b. The initial task was for HEC to develop a Hydrologic Engineering Management Plan (HEMP) to be used in performing an interior flood hydrologic engineering analysis for the study area. The plan, or HEC's proposal, was to be the basis for deciding if HEC would proceed with the technical study. The district funded HEC $5,000 to develop the HEMP. The final HEMP that was agreed upon is attached as Exhibit C-1.

C-2. Hydrologic Engineering Management Plan Development

a. The development of the HEMP for the Napa study was based on several discussions and reviews. These included discussions with the district's technical and project management staff, review of available information including that from previous studies, review of engineer manuals and other guidance (USACE 1988a, 1990, and 1992), and a field reconnaissance of the study area.

b. The study and project managers, engineers, and economists made presentations and met with the HEC staff to review the Napa study. Two subsequent meetings between HEC and the district's hydraulics staff were held to scope the interior study and to determine the information the district would provide. Maps and previous reports were provided to HEC. A detailed field reconnaissance was conducted by HEC and a meeting was held to review the study with a representative of the Napa City Engineering staff.

c. Key issues identified were the potential effect of San Pablo Bay tidal fluctuations on the exterior stages of the lower study area reaches, tieback levees and associated closure of openings in the highly urban area of Napa Creek, definition of the flow patterns for the interior areas, and analysis of the minimum facilities for the interior areas. The limited rainfall and stream gauge records for the study area also present problems. The district is to provide significant guidance, and where possible, data to address these issues. HEC has retained (under contract) the recently retired city engineer of the City of Napa to assist with specific aspects of the existing flow patterns and storm sewer system.

d. Hydrologic engineering analysis of the interior areas is to be performed using the HEC-Interior Flood Hydrology (HEC-IFH) program (USACE 1992). HEC will establish the with- and without-project conditions for the interior areas. Several size gravity outlets and pumping station capacities will be investigated.

e. HEMP strategy and procedures were defined using an annotated outline format. Study cost estimates are based on the tasks and the assumption that a junior engineer will perform the analyses under the direction of a senior engineer. Cost estimates include actual engineers' salaries times a factor of 2.8 to account for overhead. Overhead charges include secretarial and reproduction expenses. The total HEC cost to perform the study is $65,000. This is based on the district providing HEC a substantial amount of precipitation, runoff, exterior stage, and storm sewer alignment data. The cost is estimated to be more than $150,000 if performed entirely by HEC. A Gant style schedule was subsequently developed based on study milestones defined by the district and the major study tasks to be performed.

Exhibit C-1

C-1-1. Introduction

a. This Hydrologic Engineering Management Plan (HEMP) is developed for the Sacramento District to be used in hydrologic engineering analysis of interior flood damage reduction measures for the City of Napa, CA. Objectives of the hydrologic engineering analysis are to determine (a) the minimum outlet facility associated with the line-of-protection, (b) existing and future stage-frequency relationships for without-project conditions, (c) stage-frequency relationships for a range of gravity outlet and pumping station sizes and configurations for the interior areas, and (d) a formulated set of viable flood damage reduction plans for each interior area (with the assistance of the district staff).

b. The HEMP includes a proposed schedule, person-day, and cost estimate for the hydrologic engineering tasks that HEC would be responsible for completing. These tasks include those described in Sections C-1-5, C-1-6, and C-1-7, "Minimum Facilities Analysis," "Formulation and Comparison of Interior Flood Damage Reduction Measures," and "Technology Transfer." HEC will also be responsible for the portions of Section C-1-4 which deal with the assessment of local flooding when the Napa River is below flood stage. A major HEC goal is to provide the district with the capability of applying HEC's Interior Flood Hydrology (HEC-IFH) program. The degree to which HEC is involved in the formulation process is negotiable. The district will provide stage-damage relationships and other data required to perform the expected annual damage computations for each plan. Cost estimates of the flood damage reduction measures and plans are also to be provided by the district. The district will be responsible for those tasks described in Sections C-1-2, C-1-3, and C-1-4, including preliminary investigations, data development and assembly, and evaluation of without-project conditions for the Napa River. Some of the tasks described in this plan are required for the general hydrologic engineering investigations for the levee, floodwall, and channel improvement features of the Napa River Project. Accordingly, several of the tasks may have already been accomplished. Design requirements for conveyance systems, inlet and outlet works, and cost estimates for project components are not included in the Hydrologic Engineering Management Plan.

C-1-2. Preliminary Investigations

This initial phase includes conducting a literature review of previous reports, obtaining the available data, and requesting additional information needed to perform the investigation.

a. Initial preparation.

(1) Confer with other disciplines involved in the study to determine the objectives, the hydrologic engineering information requirements of the study for other disciplines, study constraints, etc.

(2) Discuss study type, scope, and objectives.

(3) Review available documents.

(a) USGS reports.

(b) Previous Corps work.

(c) Local studies.

(d) Other.

(4) Obtain historic and design discharges, discharge-frequency relationships, high-water marks, bridge designs, cross sections, and other data.

(a) Local agencies.

(b) State.

(c) Federal (USGS, SCS, USBR, etc.).

(d) Railroads.

(e) Industries.

(f) Other.

(5) Scope major hydrologic engineering analysis activities.

(6) Prepare Hydrologic Engineering Management Plan.

b. Obtain study area maps.

(1) County highway maps.

(2) USGS quads.

(3) Aerial photographs.

c. Existing storm sewer design and configuration. The existing and any proposed storm sewer layout, discharge design capacities, and elevation of the inverts of the conveyance network are important for defining drainage areas, minimum facilities, and invert elevations of major conveyance to outlets, gravity outlet inverts, pumping station on-off elevations, and design criteria for inlet and outlet works.

(1) Determine layout and design of existing systems (usually obtained from local public works department or City Engineer).

(2) Determine layout and design of potential future systems. Local drainage system enhancements that have been planned and designed by local interests should be accommodated.

(3) Determine location of flow concentration at the line-of-protection where gravity outlets or pumps may be located and the layout of collector/conveyance systems adjacent to line-of-protection to concentrate flows at these locations where required.

d. Estimate location of cross sections on maps. (Floodplain contractions, expansions, bridges, etc). Determine mapping requirements (orthophoto) in conjunction with other disciplines.

(1) Napa River from downstream of the project through the upper end of project.

(2) Major ditches, channels, in the interior areas that will convey flood waters to the interior area outlets.

e. Field reconnaissance. It is important to establish a relationship with Napa area field office counterparts such as Director of Public Works, City Engineer, and other local, state, and federal agency staff people. These people can be key contacts throughout the study. Other field activities are described below.

(1) Interview local agencies, and residents along the stream, review newspaper files, etc., for historic flood data (high water marks, frequency of road overtopping, direction of flow, land use changes, stream changes, etc.). Document names, locations, and other data for future reference.

(2) Finalize cross-section locations/mapping requirements.

(3) Determine initial estimate of Manning's "n" values for later use in water surface profile computations.

(4) Take photographs or slides of outlet inverts and ditches that will be cut off by the line-of-protection, bridges, construction, hydraulic structures, and floodplain channels and overbank areas at cross-section locations.

f. Survey request. Write survey request for mapping requirements and/or cross sections and high water marks for Napa River and interior area conveyance systems.

C-1-3. Data/Information Assembly

a. General. Data/information assembly is required for the analysis of the interior area. It includes data for both the interior and exterior (Napa River) areas. The information is applicable for any analytical method, but is specifically targeted for application of the HEC-IFH computer program, and assumes that the analyses will be conducted using both a continuous record and hypothetical event approach. An assessment of HEC-IFH as an appropriate model should be made as early as possible.

The continuous record analysis is the most straightforward approach because of the tidal effects on Napa River stages at interior outlet locations and the need to investigate the coincidence of exterior stages on gravity outlet flows and pumping discharges. Potential problems with the continuous analysis approach are lack of data and poor definition of the interior runoff system. The hypothetical event analysis would enable some refinement of the interior runoff system, but presents problems with the tidal effects and coincident interior and exterior storm analyses.

(1) Define interior areas to be studied. Consideration must be given to alignment of the line-of-protection, minimum facility requirements, runoff topology, topography of local ponding areas, present storm sewer systems and potential for additional storm water collector/conveyance systems.

(2) Delineate interior subbasins for each area considering locations needed for stage-frequency relationships and effects of the storm sewer system.

(3) Select computation time interval (Δt) for this and subsequent analyses. The peak discharge of hydrographs at gauges, normally three to four points on the rising limb of the unit hydrograph, must be defined adequately. Routing reach travel times should also be considered, as should the location and types of flood damage reduction measures to be analyzed. The importance of using a small time interval is dependent on the size of the available ponding area and the associated flow attenuation at the outlets.

b. Rainfall data. This activity includes the assembly of historical storm records and hypothetical frequency event data.

(1) Obtain and verify historic rainfall records of nearby recording and nonrecording rain gauges. Determine weighting of gauges for each interior subbasin.

(2) Develop hypothetical frequency storm depth-frequency-duration relationships for general rain and local storms.

(3) Determine the characteristics of the SPS.

c. Runoff and channel routing data. Interior runoff hydrographs may be computed using HEC-IFH or imported from an external HEC-DSS file generated by a different program. For example, the HEC-1 program may be used to perform the runoff and channel routing of a complex system (more than two subbasins). Externally determined hypothetical or period-of-record runoff hydrographs may be imported into HEC-IFH and used in the computations.

(1) Determine interior subbasin drainage areas, unit hydrograph methods, and variables.

> **NOTE**: HEC-IFH does not use kinematic waves, but HEC-1 can be used to compute hypothetical runoff hydrographs using kinematic waves and imported into HEC-IFH. The use of the kinematic wave approach is not possible for the continuous record analysis unless the runoff sequences are generated by another program (other than HEC-1) and imported to HEC-IFH. An alternative would be to use a HEC-1 model with kinematic wave and 1-in. of runoff to generate unit hydrographs for each interior area. These unit hydrographs could be entered into HEC-IFH and used for hypothetical event and/or continuous simulation analysis.

(2) Determine loss rate methods and values. These include monthly rates for continuous record analysis and event variables for hypothetical event analyses.

(3) Determine base flow. Continuous simulation analysis can incorporate monthly rates, and hypothetical event analysis can incorporate an initial rate and recession variables.

(4) Determine streamflow routing method and parameters.

d. Interior ponding area data.

(1) Develop elevation-area relationships for each ponding area adjacent to line-of-protection. (User should specify 15-20 points to define the relationship.) HEC-IFH will automatically generate the storage values. The minimum value should be at or below the lowest invert elevation to be analyzed for that ponding area. The maximum value should be above the highest stage anticipated in the analysis. (The program will not extrapolate above or below these maximum or minimum elevations.)

(2) If applicable, develop the discharge-elevation relationship for the ditch that connects the ponding area to the gravity outlet and/or pump. (Required only if the ponding area is not adjacent to the outlets at the line-of-protection.)

e. Exterior stage data. These data must include continuous stage hydrographs considering the historic patterns of Napa River discharge values coincident with any tidal effects on the exterior stages at the outlet locations of each interior area to be studied. The hypothetical storm analysis would likely involve analysis assuming storms centered over both the interior area and Napa River drainage basin. There is no apparent straightforward manner to account for tidal effects with the hypothetical approach, although a coincidence weighting method, based on percent time (probability) of the stages of the San Pablo Bay associated with a series of hypothetical flood events occurring for each stage, may be appropriate.

(1) Obtain the period of record for elevations of the San Pablo Bay at the mouth of the Napa River. The time interval must be sufficiently small to capture tidal effects (6-hr stages.)

(2) Obtain the period of record of the discharge values of the Napa River at appropriate gauge locations. Determine if adjustments to the discharge values are required for the outlet locations of each interior area to be analyzed.

(3) Develop a family of rating curves at the outlet locations based on various San Pablo Bay elevations and Napa River discharges. The analysis requires running a series of water surface profiles for various bay elevations.

f. Gravity outlets. Determine typical gravity outlet information and operation criteria.

(1) Determine appropriate gravity outlet locations based on local conveyance systems, storm sewer system layouts and invert elevations, and ponding area locations.

(2) Define typical gravity outlet data: lengths from levee or floodwall dimensions, etc.; inverts/slope from storm sewer and ponding area elevations; box or circular; concrete or MP, etc.; entrance and exit configurations.

(3) Define gravity outlet operation criteria: head differential for closing, any gate closure requirements.

(4) Develop cost estimates for various gravity outlet types and sizes.

g. Pumping stations. Determine typical pumping station data and operation criteria.

(1) Define criteria for number of pumps including base flow pump, back-up units, etc.

(2) Define pump characteristics: requirements for on/off elevation determination (may vary monthly in HEC-IFH); head-capacity-efficiency relationships.

(3) Develop cost estimates for various pumping capacities.

h. Auxiliary flow data. Auxiliary flow includes auxiliary inflow to the interior subbasin, diversions out of the system, seepage inflow from the exterior (Napa River) to the interior area, and overflow out of the interior area.

(1) Determine head-versus-seepage relationships for each interior area.

(2) Determine diversions and diversion rates out of the system, and auxiliary inflow hydrographs, if appropriate.

(3) Determine overflow potential and, if required, the pond elevation-overflow discharge relationship.

i. Water surface profile data. Water surface profile analyses are used to determine water surface elevations and rating relationships for the Napa River (and perhaps major conveyance channels to the interior outlets), flood damage reaches, and modified Puls channel routing criteria.

(1) Cross sections (tabulate data from each section). Make cross sections perpendicular to flow. Sections should be typical of reaches upstream and downstream of cross section. Develop effective flow areas.

(2) If modified Puls routing criteria are to be determined from water surface profile analyses, the entire section must be used (for storage) with high "n" values in the noneffective flow areas. Refine "n" values from field reconnaissance and from analytical calculation and/or comparison with "n" values determined analytically from other similar streams.

(3) Bridge and culvert computations. Estimate where floods evaluated will reach on each bridge and select either: (a) normal routine, or (b) special routine.

j. Stage-damage relationships. Representative stage-damage relationships for the interior areas at runoff concentration points (proposed outlet locations) are required for identification of interior plans which maximize net flood damage reduction benefits.

C-1-4. Without-project Conditions Analysis for Minimum Facility Evaluation

a. General. The without-project analysis involves determination of conditions both without the line-of-protection and with the line-of-protection in place. Stage-frequency relationships for these conditions are needed to select a minimum facility. The without-project condition used to formulate and evaluate the interior flood damage reduction measures will assume the minimum facility is in place and is therefore described in Section C-1-5, "Minimum Facility Analysis." The procedures described assume that HEC-IFH will be used to determine interior area local hypothetical storm event runoff hydrographs.

b. Napa River flooding without line-of-protection. This information should be available from the line-of-protection design analysis. It is used to determine Napa River flood elevations over the interior areas and to compare the elevations with those caused by local flooding when the Napa River is below flood stage (see paragraph C-1-4*c*). A series of stage-frequency relationships for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance events should be developed and provided for each interior area.

c. Local runoff flooding without line-of-protection. This analysis is for local flooding without the line-of-protection in place, assuming the present storm sewer system is in place and the Napa River is at or below flood stage. It is the target condition for the minimum outlet facility analysis. Stage-frequency relationships including the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance events are developed for each interior area as described below.

(1) Define precipitation and runoff data sets for computing hypothetical storm runoff hydrographs.

(a) Enter local hypothetical storm depth-duration-frequency data for defining the PRECIP module for hypothetical event analysis (HEA).

(b) Enter appropriate rainfall-runoff and routing parameters, if any, to define RUNOFF module.

(2) Develop normal depth rating for the interior runoff approach to the Napa River. Napa River is assumed to be low and, therefore, there will be no backwater effect.

(3) Define a plan using the precipitation and runoff data and exercise HEC-IFH to compute interior runoff hydrographs. The program computes the interior area runoff and routes the runoff to the area outlet for each hypothetical event. Peak flow is displayed for each hypothetical storm frequency.

(4) Determine interior stage-frequency relationship. The peak flow for each hypothetical storm runoff event will be used with the normal depth rating to determine the maximum interior elevation for each event. The stage-frequency curve will be derived graphically.

d. Local runoff flooding, with line-of-protection and no outlets. This analysis assumes the line-of-protection is in place and the local conveyance systems to the Napa River are blocked by the line-of-protection. It becomes the without line-of-protection condition for the minimum facility analysis and represents an upper bound for the stage-frequency relationship with the minimum facility in place. Stage-frequency relationships including the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance interior runoff events are developed for each interior area. The analysis is the same as described for the without line-of-protection condition, except the runoff will now pond behind the line-of-protection.

(1) Enter appropriate elevation-area relationship and interior ditch rating, if required, to define the ponding area adjacent to the line-of-protection POND module.

(2) Define a new plan using HEA and exercise HEC-IFH to compute interior stage-frequency relationship. The program computes the interior area runoff and routes the runoff to the ponding area where it is stored assuming no outlet to the Napa River. The program displays the maximum interior elevation for each hypothetical event and a graphical fit stage-frequency curve.

e. Assess future without-project conditions impacts. Assess future conditions effects on Napa River interior area local runoff flooding. The effect may well be minimal. Where hydrologic and/or hydraulic conditions are expected to significantly change over the project life, these changes must be incorporated into the H&H analysis. Urbanization effects on watershed runoff are the usual future conditions analyzed. The analysis will derive a set of future condition stage-frequency relationships for the conditions described in paragraphs C-1-4*b*, C-1-4*c*, and C-1-4*d*.

(1) Identify future development. From future land use planning information obtained during the preliminary investigation phase, identify areas of future urbanization or intensification of existing urbanization.

(a) Types of land use (residential, commercial, industrial, etc.)

(b) Storm drainage requirements of the community (storm sewer design frequency, onsite detention, etc.)

(c) Other considerations and information.

(2) Select future years in which to determine project hydrology.

(a) At start of project operation (existing conditions may be appropriate).

(b) At some year during the project life (often the same year as whatever land use planning information is available).

(3) Adjust model hydrology parameters for all areas affected by future land use changes.

(a) Unit hydrograph coefficients reflecting decreased time-to-peak and decreased storage.

(b) Loss rate coefficients reflecting increased imperviousness and soil characteristics changes.

(c) Routing coefficients reflecting decreased travel times through the watershed's hydraulic system.

(4) Operate hydrologic models, including HEC-IFH using local storm HEA, and determine revised discharge-frequency and/or stage-frequency relationships throughout the watershed for future without-project conditions.

C-1-5. Minimum Facility Analysis - Without-project Conditions for Evaluating Interior Measures

a. General. The minimum facility of the individual interior areas will be justified as part of the line-of-protection. The stage-frequency relationships for the with-minimum-facility-in-place condition becomes the without condition for evaluating potential interior flood damage reduction measures. The residual damage with the minimum facility in place is thus the target for damage reduction of implemented interior flood damage reduction measures. The minimum facility should provide interior flood relief such that during low exterior stages (gravity conditions) the local interior area runoff will pass the design storm sewer outflow without an increase in elevation over natural or without line-of-protection conditions. Flood stages with the minimum facility in place should not be significantly higher than stages for less frequent flood events assuming it can be established that these less frequent flood events have and will occur when the Napa River is below pre-project flood stage.

b. Evaluate range of minimum facilities. The minimum facility will normally include gravity outlets but may include pumps if the coincidence of flooding between the interior and exterior is high. For example, the Napa River is high enough to block gravity outlets, but is below pre-project flood stage and flooding occurs in the interior from local runoff. The sequence will be to evaluate a series of gravity outlets; then pumps, if required. The physical characteristics of the gravity outlets should be established prior to the analysis and refined as the analysis proceeds. The analysis should be performed for the range of hypothetical frequency events.

(1) Analyze series of gravity outlet capacities and configurations using local storm hypothetical event analysis and assuming unblocked conditions. The analysis is the same as that for the local flooding with the line-of-protection in place (Section C-1-4), except gravity outlets through the line-of-protection are incorporated.

(a) Define 3 or 4 gravity outlet configurations (modules) of increasing capacity. Outlet sizes should encompass the largest storm sewer size or ditch capacity at the line-of-protection.

(b) Define a new plan for each gravity outlet capacity to be evaluated and, using local storm HEA, exercise HEC-IFH and determine the interior stage-frequency for each outlet.

(2) Compare stage-frequency relationships of gravity outlets with the storm sewer design event and with the local area flooding stage-frequency relationships both with (no outlet) and without the line-of-protection in place.

(3) Select minimum facility. The minimum facility is selected to assure that expected flooding and associated damages from the local, interior area with the line-of-protection in place are no worse than flooding from the local area (not including the Napa River) and associated damages were before the line-of-protection was in place.

(4) Perform analysis for all interior areas and for expected future conditions. The expected future condition hydrologic parameters are incorporated and the analysis is repeated using the selected minimum facility. If the selected facility is not efficient to assure that local flooding with the

line-of-protection and the minimum facility in place will not be worse than what would be expected in the future without the project, upgrade the selected minimum facility accordingly.

c. Develop without-project condition stage-frequency relationship with the minimum facility in place. After the minimum facility is selected, it is evaluated using continuous simulation analysis and general rain hypothetical event analysis. The results of the analysis can be used to test the effectiveness of the minimum facility gravity outlet by assessing local runoff flooding that occurs during blocked conditions. Results of the analysis establish the base plan or without-project condition stage-frequency relationships for evaluating additional interior flood damage reduction measures as described in Section C-1-6.

(1) Define Continuous Simulation Analysis (CSA) plan using HEC-IFH that incorporates period-of-record interior area rainfall, existing condition runoff characteristics, existing interior ponding area, and the selected minimum facility, seepage, and period-of-record exterior stages at the interior area outlet.

(a) Define PRECIP module for CSA. Historical, period-of-record rainfall data for representative recording and non-recording gauges are used. The data are generally retrieved from NWS magnetic tapes or from available CD ROM and stored in an HEC-DSS file where they can be imported directly into HEC-IFH. Gauge weightings are specified for determining basin average precipitation.

(b) Define rainfall, runoff, pond, and outlet parameters. Existing condition rainfall-runoff and routing (RUNOFF module) parameters, ponding area characteristics (POND module), and the minimum facility are defined for CSA in the same manner as previously described for HEA.

(c) Define exterior stage (EXSTAGE module) data for CSA. Historical, period-of-record discharge, or stage hydrographs for main river gauges are obtained from available electronic media and stored in an HEC-DSS file for direct importing to HEC-IFH. Napa River period-of-record stage hydrographs at each interior outlet location are determined by one of the following methods, each of which can be accomplished using HEC-IFH.

- Exterior stage from historical, period-of-record stage hydrographs. Typically, the gauge data (index location) will need to be transferred to interior area outlets (primary and secondary) locations by incorporating transfer functions that relate index stage to primary and secondary outlet locations. These transfer relationships are developed from water surface profiles and are used by HEC-IFH to determine the exterior stage at the outlets for each time period during pond routing computations.

- Exterior stage from historical period-of-record discharge hydrographs. Typically, discharge hydrographs are more readily available than stage hydrographs. If discharge hydrographs are employed, a rating curve is incorporated which is used to convert flow to stage at the index locations. The stages are transferred to primary and secondary outlet location as described above, if required.

- Exterior stage from computed period-of-record discharge. If recorded stages or flow are not available, discharge hydrographs can be computed from rainfall-runoff analysis. Flow is converted to stage and stage transferred to the outlet locations as described above, if required.

- San Pablo Bay impact on exterior stage for CSA. If it is determined that tidal fluctuations in the San Pablo Bay influence the stages at the interior area outlet locations, a family of rating curves for each interior outlet that gives Napa River stage based on Napa River flow and stage in San Pablo Bay is required. These relationships are developed by determining water surface profiles for various stages in the bay. Analysis period San Pablo Bay stages are also required and could be obtained from historical data or generated based on known tidal cycles. These data are used by HEC-IFH to determine the appropriate exterior stage at the gravity outlet for each time period in the analysis.

(d) Define seepage (AUXFLOW module) data for seepage inflow from the Napa River to the interior ponding area, if appropriate. A relationship between differential head (the exterior stage minus the interior stage) and seepage inflow is defined and incorporated. No seepage occurs when the interior stage is equal to or greater than the exterior stage. Data are developed based on field measurements or empirical information.

(2) Exercise HEC-IFH using the developed CSA data modules and specify either a partial duration or annual series frequency analysis. Results will include a graphical fit interior stage-frequency relationship.

(3) Examine the periods of local flooding (Napa River below pre-project flood level) and determine the extent of local flooding caused by blocked gravity outlet conditions. If flooding resulting from this condition is considered worse than pre-project local flooding, the minimum facility may require the addition of a pump to alleviate induced flooding. In this case, pumping capacity would need to be evaluated using the CSA plan data. See Section C-1-6 for evaluating pumping capacity.)

(4) Define a new general rain HEA plan using HEC-IFH that incorporates precipitation depth-duration-frequency data for

general rain events occurring over the Napa River watershed as well as the interior area. Exterior stages will be computed from rainfall-runoff analysis and an appropriate stage-discharge rating for the Napa River at the interior area outlet. San Pablo Bay tidal effects on hypothetical exterior stages will be incorporated using coincident frequency analysis, if required.

(a) Define a new precipitation data set (PRECIP module) using HEA by assembling general rain depth-duration-frequency storm data for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance events occurring over the local interior areas as well as over the Napa River watershed.

(b) Define rainfall, runoff, pond, outlet, and seepage parameters. Existing condition rainfall-runoff and routing (RUNOFF module) parameters, ponding area characteristics (POND module), the minimum facility, and seepage are defined in the same manner as previously described.

(c) Exterior stages for each hypothetical event are computed discharge hydrographs and a specified rating. The discharge hydrographs are computed from rainfall-runoff analysis as described above.

(d) San Pablo Bay impact on exterior stage for general rain HEA. If it is determined that tidal fluctuations in the San Pablo Bay influence the stages at the interior area outlet locations, it may be appropriate to develop a bay elevation-duration relationship and use coincident frequency analysis to account for the bay effect on the stage-frequency curve.

(5) Exercise HEC-IFH using the developed HEA data modules. Results will include a graphical fit interior stage-frequency relationship. This curve will help to determine if rare combinations of events are being captured in the continuous simulation analysis and will help shape the final without-project condition stage-frequency relationship.

(6) Final stage-frequency relationships. Make appropriate adjustments to the CSA stage-frequency relationship based on the results of the without line-of-protection and with line-of-protection and no outlet plans developed from local storm HEA and the results from the general rain HEA.

(7) Future without-project condition stage-frequency relationships with the minimum facility in place. Repeat above CSA and HEA incorporating expected future condition hydrologic parameters and develop future condition stage-frequency relationships.

C-1-6. Formulation and Comparison of Interior Flood Damage Reduction Plans

a. General. The objective of this task is to formulate a set of flood damage reduction plans for each interior area. The condition with the line-of-protection and the selected minimum gravity outlet in place becomes the without-project condition for evaluating additional features such as additional gravity outlets, pumping stations, additional ponding area storage, and nonstructural measures. The first step is to find the economic optimal size and configuration for additional gravity outlet capacity with the minimum facility in place. The second step is to identify the economic optimal pump capacity, assuming that the minimum facility and the optimal gravity outlets are in place. The third step is to explore trade-offs of pumping capacity versus ponding area storage and would include evaluation of nonstructural measures to increase nondamaging ponding area storage. Finally, the conceptual feasibility of other flood damage reduction actions such as flood warning-preparedness and institutional arrangements would be evaluated. The district and HEC will work closely together in the plan formulation and comparison process. The following paragraphs describe the procedures in more detail and show how both continuous simulation and hypothetical event analyses can be applied.

b. Determine economic optimal gravity outlet capacity.

(1) Stage-frequency relationships.

(a) Define new plans for evaluating gravity outlets using data previously defined for the CSA with the minimum facility in place. Existing condition rainfall (PRECIP module), runoff and routing (RUNOFF module) parameters, ponding area characteristics (POND module), minimum facility (GRAVITY module), and seepage (AUXFLOW module) are the same as used for the CSA analysis of the selected minimum facility.

(b) Assemble outlet characteristics for several standard size outlets and develop composite rating curves for each using HEC-IFH.

(c) Develop five or six gravity outlet configurations (modules) with one or more gravity outlets in addition to the minimum facility outlet, each module representing an incremental increase in total outlet capacity.

(d) Exercise HEC-IFH, and using CSA, develop several plans which incorporate the gravity outlet modules, described above, and determine interior stage-frequency relationships for each plan.

(e) Define new plans, and using HEA, assemble general rain depth-duration-frequency storm data for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance events occurring over the local interior areas as well as over the Napa River watershed, and determine the interior stage-frequency relationships for each plan. The analysis is similar to that described for the general rain HEA of the minimum facility but will include analysis of several plans incorporating the additional gravity outlet capacities defined in (c) above. The relationships will help determine if rare combinations of events are being captured in the continuous simulation analysis. These relationships will also help establish the upper end of the graphical curve determined in (d) above.

(f) Define additional plans using HEA and local storm depth-duration-frequency data for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedance events occurring over the interior area with unblocked conditions on the Napa River. Determine the interior stage-frequency relationships for each plan. This relationship will help to determine if rare combinations of events are being captured in the continuous simulation analysis and may help to shape the final stage-frequency relationships.

(g) After examining the results of the continuous and hypothetical event analyses, adopt a final stage-frequency relationship for each gravity outlet plan.

(h) Develop future condition stage-frequency relationships by repeating the described steps using expected future hydrologic condition data, if appropriate.

(2) Determine equivalent expected annual damages (EAD) for each gravity outlet plan.

(a) The district will provide cost estimates of various sized gravity outlets and stage-damage relationships by damage category for existing and potential future conditions.

(b) EAD for each plan will be determined using the developed stage-frequency relationships, the stage-damage relationships, and HEC's EAD program.

(c) A plan comparison array including residual equivalent EAD, expected annual inundation reduction benefits, average annual costs, and net benefits will be developed identifying the economic optimal plan. This plan will most likely become the base plan for evaluating additional measures.

c. Determine economic optimal pumping capacity.

(1) General. If the analysis for determining the economic optimal gravity outlet indicates that gravity outlets are very effective (considerable peak runoff attenuation from ponding and little coincidence between interior runoff and high exterior stages), there would be little residual flood damages with the selected outlet in place. If gravity outlets are shown to be ineffective and residual damages are significant, pumps may be justified. The same steps described for evaluating additional gravity outlet capacity are appropriate for identifying the economic optimal pumping capacity. Some differences in the analysis are described below.

(2) Base condition. The base condition for evaluating pumping capacity is with the minimum facility and, most likely, the economic optimal gravity outlet configuration in place. Several plans are evaluated against the base plan, each with an incremental increase in pumping capacity.

(3) Pump operation criteria. Pump on and off elevations must be determined so that the pumps come on to effectively reduce damaging stages and turn off when stages drop below damaging levels. However, pumps should not cycle on and off over very short periods of time. Therefore, "on" elevations are usually set below flood stage and "off" elevations are usually set 1 to 2 ft below "on" elevations. "On" and "off" elevations can also vary by season (monthly) if appropriate. Two or more pump units make up a pumping plant or station. Several units that can be used for backup and which can be operated in phases to step up total capacity usually prove to be more effective than a few large-capacity pumps.

(4) Type of events and analyses. CSA, general storm HEA, and local storm HEA with blocked gravity conditions would be performed to derive final existing and future condition stage-frequency relationships, as described above, for the gravity outlet plans.

d. Evaluation of increased storage capacity. It is prudent to investigate the trade-offs between pumping capacity and ponding area storage capacity. Pumps are expensive and an increase in storage capacity will typically allow reduction in required pumping capacity. There are several measures that can be evaluated, including increasing the physical size of the ponding area and implementing nonstructural actions that will reduce the damage for a given ponding stage.

(1) Increasing the size of ponding areas. The potential for excavating larger ponding areas should be explored, if physically possible. The sensitivity of ponding area size versus pumping capacity can be readily determined using HEC-IFH. The plan with the identified economic optimal gravity outlet and pumping station would be the base plan for determining if excavation is feasible.

(2) Nonstructural measures. Temporary evacuation, relocation, flood proofing, and other nonstructural measures

that reduce susceptibility to damage (and increase available storage) should be evaluated. Residual damages for evaluated plans would be revised based on new stage-damage relationships resulting from implementing the nonstructural measures.

e. Final plan selection. Other social, institutional, and environmental issues, including the management of future development, and flood warning and preparedness programs, would also need to be evaluated in the final plan selection for each interior area. HEC will assist the district in this evaluation, if desired.

C-1-7. Technology Transfer

a. Study report. A study report that documents the Napa River interior flood analysis will be prepared. The text of the report will generally follow the topics in Sections C-1-4, C-1-5, and C-1-6 of this plan, and a discussion of the results, including tables and figures.

b. HEC workshop. A 1 or 2 day workshop will be conducted at HEC for district staff covering the Napa River interior flood analysis using the HEC-IFH, and EAD programs. It is intended that materials developed for this workshop will be used in future HEC PROSPECT courses on interior flood hydrology.

PROPOSAL FOR HEC ASSISTANCE TO THE SACRAMENTO DISTRICT FOR ANALYSIS OF INTERIOR FLOOD DAMAGE REDUCTION MEASURES, NAPA RIVER, CA

A. Resource Requirements.

Task Description	Person-Days
1. Preliminary Investigation Assistance	2
2. Data Assembly Assistance	5
3. Without-Project Analysis	10
4. Minimum Facility Analysis	15
5. Analysis of Flood Damage Reduction Measures	
a. Stage-frequency for gravity outlets	10
b. Stage-frequency for pumping station(s)	10
c. Formulation of alternative plans	20
d. Plan comparison and evaluation	5
6. Study Documentation and Technology Transfer	20
7. Coordination/Meetings with District Office	10
TOTAL	107

Estimated total cost at $600.00/day = $64,200.00

Use $65,000.00

(Note: Cost includes secretary, reproduction, etc.)

B. Schedule of Work. (See attached schedule)

Figure C-1. HEMP for Napa, CA (Continued)

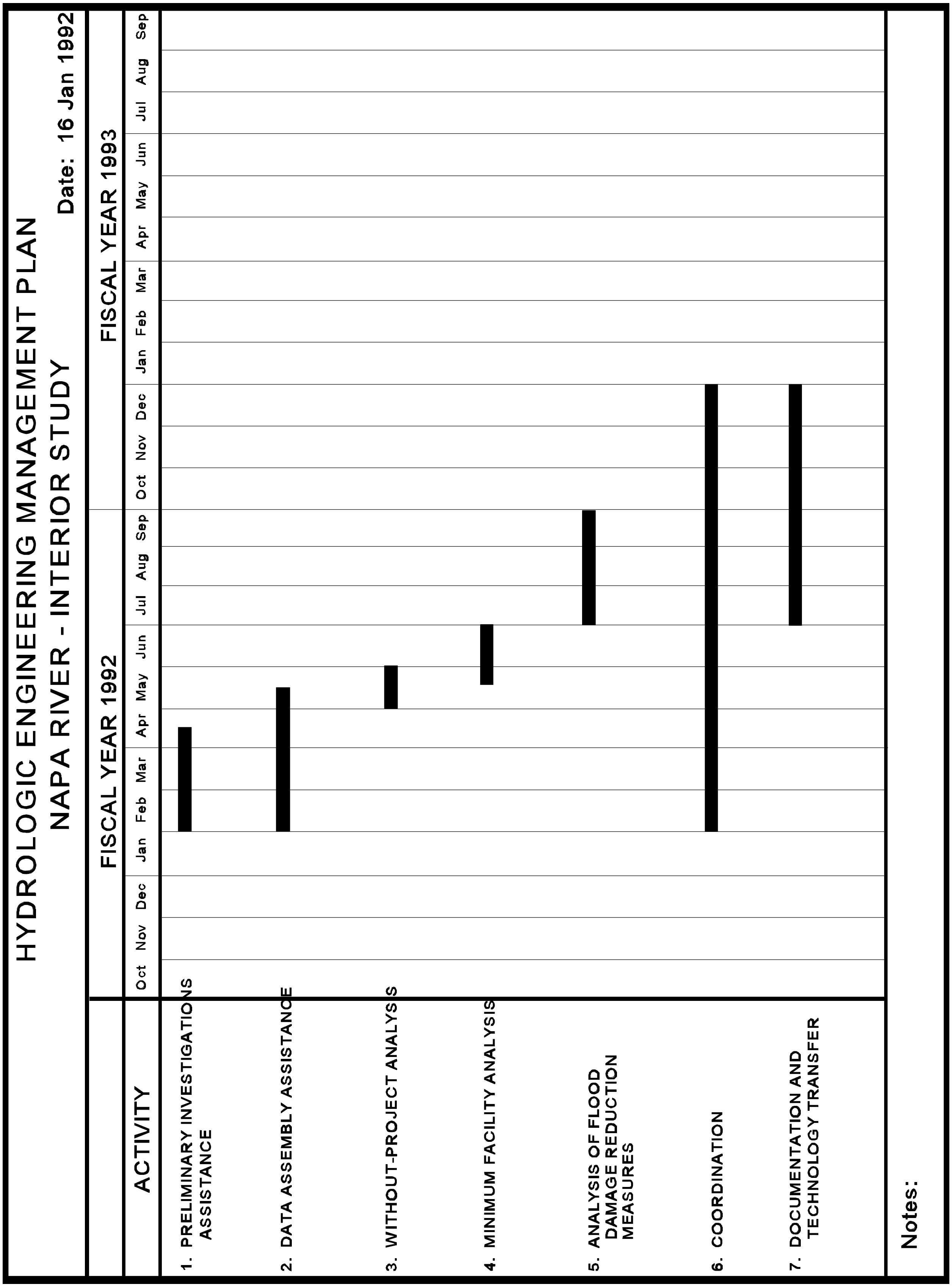


Figure C-1. (Concluded)

Appendix D
Case Study for Analysis of Interior Flood Damage Reduction Measures, Napa River, Napa, California

D-1. Introduction

a. This case study presents part of the hydrologic engineering analysis results of interior flood damage reduction measures for the City of Napa, CA. It was conducted by the Hydrologic Engineering Center (HEC) for the Sacramento District Corps of Engineers. The objective of the hydrologic engineering analysis was to determine the minimum outlet facility associated with the proposed line-of-protection, the stage-frequency relationships for the without-project conditions, and the stage-frequency relationships for a range of gravity outlet and pumping station sizes and configurations for the interior areas.

b. This case study presents the results of applying the HEC-IFH program for evaluation of one of the several interior areas involved in the overall investigation. The case study includes a description of the study area, the Napa River proposed flood damage reduction project, interior area data and information, without-project conditions analysis for minimum facility analysis, minimum facility analysis, and stage-frequency for interior flood damage reduction plans. The Sacramento District was responsible for developing data for the without-project conditions, including stage-damage relationships, cost estimates of the flood damage reduction measures, and other data required to perform the economic analyses of each plan. The design requirements for conveyance systems, inlet and outlet works, and the economic analyses of project components are beyond the scope of the case study presented herein.

D-2. Description of the Study Area

a. The Napa River basin is located about 50 miles north of San Francisco, CA. The basin is about 50 miles long on a north-south axis, varies between 5 and 10 miles in width, and has a drainage area of about 426 sq miles (see Figure D-1). The north, east, and west limits of the basin are formed by portions of the north coast mountain range. The southern limit is bounded by San Pablo Bay.

b. The Napa River originates near Mount St. Helena and empties into the Mare Island strait that flows into the tidal marshland and sloughs of San Pablo Bay. The City of Napa is located in the lower third of the basin and has a population of about 60,000. Basin land use consists mainly of vineyards in the valley area north of the City of Napa and limited mixed use in the marshland or reclaimed tidal land south of the city.

D-3. Description of the Proposed Flood Damage Reduction Project

a. Napa River and Napa Creek. The current recommended plan for the City of Napa provides for protection against the 1-percent chance event from the Napa River and Napa Creek. The proposed plan consists of channel excavation, sheet-pile walls, concrete floodwalls, setback earthen levees, a bypass channel, and related environmental mitigation measures.

b. Interior area measures. The interior flood damage reduction measures will consist of replacing approximately 21 existing storm sewers in 8 interior areas with minimum gravity outlets through the Napa River line-of-protection. Additional outlet capacity by gravity or pumps will be provided where economically justified. The proposed improvements for Napa Creek consist of channel excavation only and, therefore, will not include interior measures. The case study presented here will describe the analysis of interior measures for one of the areas.

D-4. Interior Area Data and Information Assembly

a. General.

(1) Hydrologic data and other information required for the analysis of the interior area were assembled. They include data for both the interior and exterior (Napa River) areas. The information is applicable for any analytical method, but was specifically targeted for application of HEC-IFH. Appropriate information was assembled to permit analyses using continuous simulation analysis (CSA) with period-of-record historical data and hypothetical event analysis (HEA) with synthetic storm event data.

(2) CSA is attractive because it preserves the relationship between Napa River stages at interior outlet locations and interior area runoff. A drawback of CSA is the difficulty of defining rare flood events when only a relatively short period-of-record is available as is the case for the Napa area. Therefore, HEA was adopted for this study to define the full range of flood events. The stage-frequency relationships from HEA and CSA were compared to help substantiate the reasonableness of the HEA results. Hydrologic data and other required information are described as an analyst would assemble and enter the data into HEC-IFH. Data sets and module information are shown by including representative program screens as figures where appropriate.

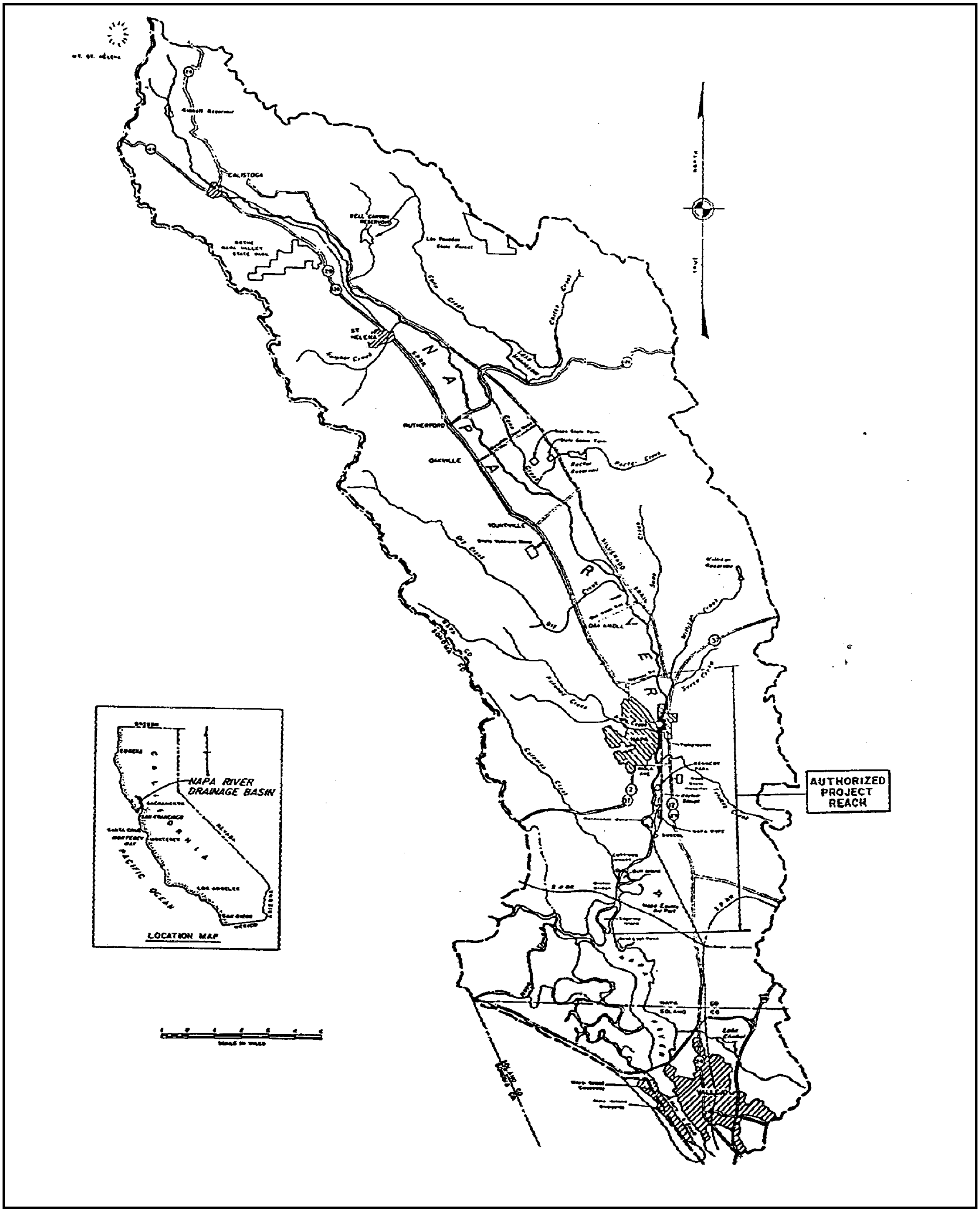


Figure D-1. Napa River basin

b. Rainfall data. Historical rainfall records were assembled for continuous simulation analysis (CSA) and hypothetical depth-duration-frequency relationships were developed for hypothetical event analysis (HEA).

(1) Historical rainfall records of nearby recording rain gauges were used to develop a continuous period-of-record rainfall record for Napa River interior areas. Recorded hourly incremental rainfall data were adjusted by the ratio of mean annual precipitation at the gauges to that for Napa River interior areas. A composite precipitation record for water year (WY) 1949 through WY 1989 was determined in this manner for use in CSA. The computed composite record was written to HEC-DSS and then imported into HEC-IFH. After importing the composite record, incremental rainfall can be plotted on a yearly, monthly, or daily basis. Figure D-2 shows daily total daily precipitation for WY 1986.

(2) Hypothetical frequency storm depth-duration-frequency relationships for general rain and local storms were developed from rainfall frequency data that were available for the Martinez 3S and Napa State Hospital gauges. Depths were adjusted by ratios of the mean annual precipitation (MAP) for the gauges and the MAP for the Napa River interior area estimated from a MAP isohyetal map. The adopted depth-duration-frequency rainfall relationships for a general rain storm are shown in Figure D-3. The development of precipitation data for computing exterior period-of-record discharge hydrographs is described in paragraph D-4*f*.

c. Delineation of interior areas.

(1) Interior areas were delineated based on alignment of the line-of-protection, minimum facility requirements, runoff topology, topography of local ponding areas, and present and potential future storm sewer and water collector/conveyance systems.

(2) Interior Area 5 is located on the right bank of Napa River just upstream from the mouth of Napa Creek (see Figure D-4). This 1.5-sq-mile area is bounded by the Napa River on the east, Highway 29 on the west, approximately Trancas Street on the north, and Napa Creek on the south. The area was divided into an upper and lower portion to accommodate the previously developed HEC-1 basin model. Runoff parameters and the existing storm sewer layout are described in subsequent sections.

d. Runoff characteristics.

(1) The Sacramento District developed a HEC-1 rainfall-runoff model for simulating historical flood events for Napa River interior areas during previous studies. The HEC-1 model used the kinematic wave technique for transforming rainfall to runoff. HEC-IFH does not use kinematic wave and therefore it was not possible to reproduce the modeling effort in HEC-IFH. It was important to preserve the timing of the interior runoff and the detail of the HEC-1 model because interior areas were divided into many subareas and reaches to

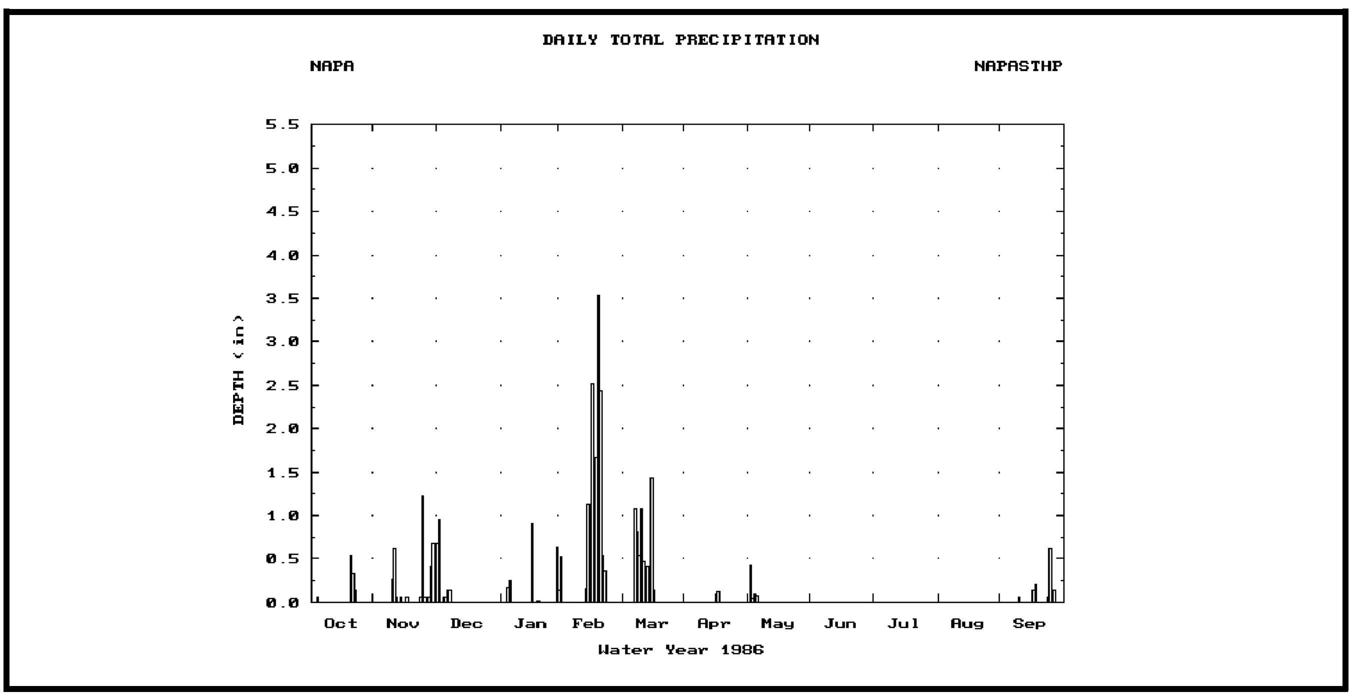


Figure D-2. Interior area composite historical precipitation data

HEA 01.04.00
Study ID NAPA
Module ID PRECHLOC

Basin Average Precipitation (PRECIP)

Enter Partial-Duration Rainfall Depth-Duration-Frequency Data

Duration	Rainfall Depth (in) for each Hypothetical Event						
	50%	20%	10%	4%	2%	1%	0.2%
5 minutes	0.15	0.20	0.25	0.30	0.32	0.36	0.45
15 minutes	0.27	0.38	0.46	0.56	0.62	0.69	0.85
1 hour	0.57	0.80	0.97	1.16	1.30	1.44	1.78
2 hours	0.82	1.16	1.39	1.66	1.87	2.07	2.55
3 hours	1.02	1.42	1.70	2.04	2.29	2.54	3.14
6 hours	1.50	2.12	2.53	3.03	3.40	3.76	4.67
12 hours	1.98	2.79	3.33	4.00	4.48	4.96	6.15
24 hours	2.45	3.44	4.12	4.95	5.56	6.14	7.60
2 days	3.12	4.51	5.42	6.63	7.49	8.33	10.48
4 days	4.03	5.77	6.94	8.38	9.44	10.45	13.01
7 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 days	0.00	0.00	0.00	0.00	0.00	0.00	0.00

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit

Press <F10> to Save Data and Continue

Figure D-3. Interior area hypothetical precipitation data

represent sewered urban runoff. Therefore, the kinematic wave HEC-1 model was used with 1 in. of runoff to generate composite unit hydrographs for each interior area. Clark unit hydrograph parameters TC and R were estimated from these kinematic wave unit hydrographs using the parameter estimation capability in the HEC-1 program. These unit hydrograph parameters were used in HEC-IFH for computing runoff from the interior area during hypothetical event and continuous simulation analysis.

(2) The initial and uniform loss rate model was used for both CSA and HEA. There are no stream gauges in the interior area so calibration of runoff parameters was not possible. Other methods were used to ensure the reasonableness of the parameters as described below.

(a) For CSA, the initial loss was 0.4 in. and the uniform loss was 0.02 in. per hour. The monthly initial loss recovery rate for CSA was 0.04 in. per day. Test simulations with different initial loss recovery rates for CSA showed that peak interior runoff was not sensitive to this parameter. Examination of monthly precipitation, loss, and percent loss is possible in HEC-IFH and helps verify the reasonableness of selected loss rates (see Figure D-5).

(b) For HEA the adopted initial loss was 0.2 in. and the uniform loss was 0.02 in. per hour. These loss rates were held constant for all hypothetical events. These loss rates were consistent with those used by the district in previous studies and were considered reasonable for the highly urbanized areas. As expected, the HEA loss rates, which are representative of rare single events, are lower than the CSA rates. Peak interior runoff using the described adopted loss rate parameters was compared for CSA and HEA. Peak interior flow-frequency relationships for CSA and HEA are shown in Figure D-6 and compared closely for moderately rare events. This further substantiates the reasonableness of adopted parameters.

(3) No base flow was specified for either CSA or HEA. Base flow was considered to have little or no impact on peak runoff or volume for these small interior areas. Some runoff parameters for Interior Area 5 are shown in Figure D-7.

(4) No routing was used between the upper and lower subareas for Interior Area 5 due to the short travel time and the fact that the area is heavily sewered.

(5) The interior runoff computation time was 15 min for CSA and 5 min for HEA. The times of concentration for the upper and lower subbasins for Interior Area 5 were 0.79 and 1.1 hr, respectively. Accordingly, these time intervals were considered adequate to define the runoff hydrographs at the outlets.

Figure D-4. Napa Interior Area 5

CSA 01.04.00
Study ID NAPA
Plan ID PLAN5-3A

Hydrologic Analysis Summaries

Begin 01OCT1948/0015
End 30SEP1989/2400

K. Monthly Summaries - Average Monthly Rainfall

Month	Lower Sub-Basin			Upper Sub-Basin			Exterior Basin		
	Precip (in)	Losses (in)	Percent Loss	Precip (in)	Losses (in)	Percent Loss	Precip (in)	Losses (in)	Percent Loss
Oct	1.28	0.49	38.25	1.28	0.49	38.25			
Nov	3.37	1.09	32.30	3.37	1.09	32.30			
Dec	4.38	1.34	30.60	4.38	1.34	30.60			
Jan	5.02	1.47	29.21	5.02	1.47	29.21			
Feb	3.96	1.17	29.53	3.96	1.17	29.53			
Mar	3.43	1.20	34.90	3.43	1.20	34.90			
Apr	1.72	0.70	40.89	1.72	0.70	40.89			
May	0.41	0.25	61.46	0.41	0.25	61.46			
Jun	0.16	0.10	59.73	0.16	0.10	59.73			
Jul	0.06	0.03	43.31	0.06	0.03	43.31			
Aug	0.06	0.04	67.54	0.06	0.04	67.54			
Sep	0.38	0.19	49.00	0.38	0.19	49.00			

1Help 2PrtScr 3 4 5 6DOS 7 8 9Plot 10Exit
Press <F10> to Return

Figure D-5. Precipitation, loss and loss percent for Interior Area 5 - CSA

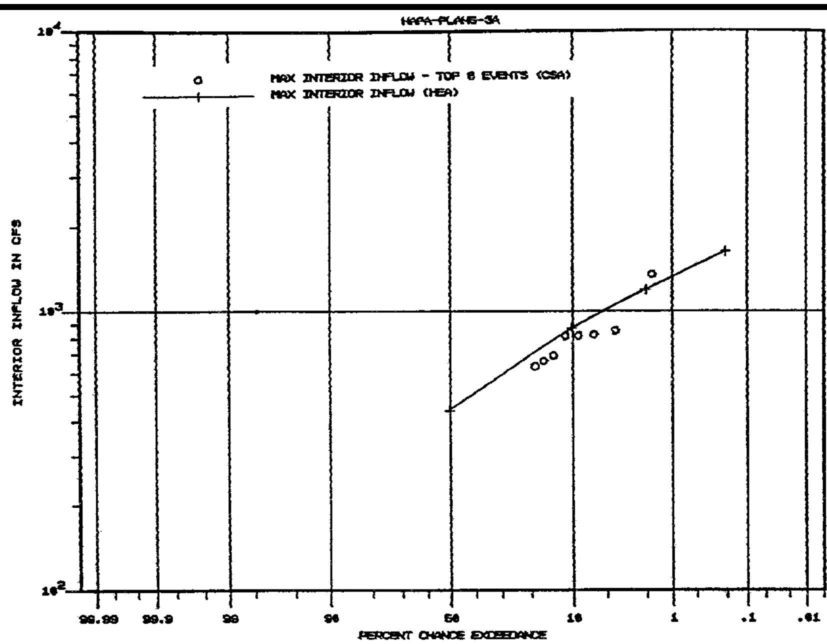


Figure D-6. Interior runoff discharge-frequency relationships - CSA and HEA

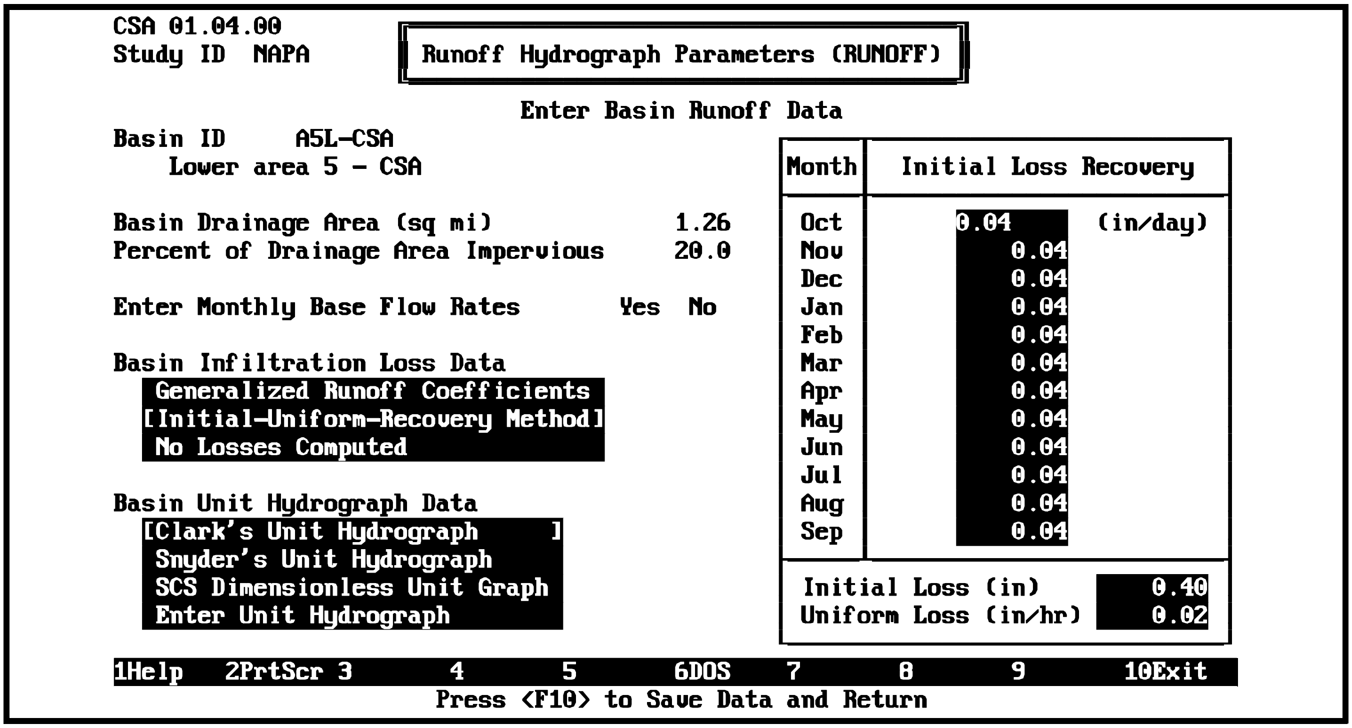


Figure D-7. Runoff parameters - Interior Area 5, lower subbasin, CSA

e. Interior ponding area. Elevation-area relationships were delineated for each ponding area adjacent to the line-of-protection at the flow concentration points. Relationships were taken from elevation-area tables generated from computerized topographic data of the project area. Elevation-area data were entered into HEC-IFH, which automatically generates the storage values from end-area approximations. The minimum value was established from the lowest invert elevation to be analyzed for Interior Area 5. The maximum value was established from the highest stage anticipated in the analysis, which in this case is the top of the levee embankment at the line-of-protection. A portion of the pond elevation-area-storage relationship for Interior Area 5, as implemented in HEC-IFH, is shown in Figure D-8.

f. Exterior stage data. Exterior stage hydrographs were required to establish the exterior conditions for both CSA and HEA methods.

(1) Exterior stage data for period-of-record CSA include continuous stage hydrographs that represent the historic patterns of Napa River discharge at the outlet locations of each interior area. A continuous discharge hydrograph was developed for the exterior from rainfall-runoff analysis. Historical rainfall records of nearby recording and nonrecording rain gauges were used with the PRECIP program to develop a continuous, period-of-record, composite rainfall record for the Napa River basin. Runoff parameters for the exterior basin were derived by calibration with the computed SPF hydrograph, the estimated peak discharge of the February 1986 flood event, and the project design discharge-frequency curve for Napa River below Tulucay Creek. Computed exterior runoff hydrographs were used with Napa River rating curves to determine continuous exterior stage hydrographs during CSA. The rating curves were defined at the outlet locations based on project channel water surface profiles provided by the district. Rating curves were slightly adjusted so that the peak flow of each hypothetical flood hydrograph matched the water surface elevation from the water surface profiles for the corresponding event. Figure D-9 shows some runoff parameters for the exterior basin.

(2)(a) Hypothetical storm analysis was conducted using general rain 96-hr local storms centered over the interior for unblocked, low Napa River conditions. For hypothetical interior and exterior analysis the general rain 96-hr hypothetical storms were centered over both the interior area and the Napa River basin.

(b) Hypothetical storm flood hydrographs at the outlet locations of each interior area were developed from HEC-1 data sets provided by the district. The data used consists of an S-curve unit hydrograph rainfall-runoff model upstream of the Oak Knoll stream gauge and a kinematic wave model downstream to Imola Avenue in Napa. The hydrographs were determined by taking ratios of the SPF. These HEC-1 rainfall-

CSA 01.04.00
Study ID NAPA

Interior Pond (POND)

Enter Surface Areas for Computing Volumes

Storage Table ID AREA5

Description
Area 5 natural pond at Soscal Ave.

Pond Elevation (ft)	Surface Area (ac)	Storage Volume (ac-ft)
-5.30	0.0	0.0
0.00	0.1	0.4
2.00	0.2	0.7
5.00	0.2	1.4
7.00	0.3	2.0
8.00	0.4	2.3
9.00	0.5	2.8
10.00	0.6	3.4
12.00	0.8	4.8
14.00	1.9	7.4
15.00	4.9	10.8
16.00	7.2	16.9
17.00	42.5	41.7

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit
Press <F10> to Save Data and Return

Figure D-8. Interior pond elevation-area-storage relationship for Interior Area 5

CSA 01.04.00
Study ID NAPA

Runoff Hydrograph Parameters (RUNOFF)

Enter Basin Runoff Data

Basin ID EXTUSNAP
Exterior Basin US of Napa Creek

Basin Drainage Area (sq mi) 266.00
Percent of Drainage Area Impervious 2.0

Enter Monthly Base Flow Rates Yes No

Basin Infiltration Loss Data
Generalized Runoff Coefficients
[Initial-Uniform-Recovery Method]
No Losses Computed

Basin Unit Hydrograph Data
[Clark's Unit Hydrograph]
Snyder's Unit Hydrograph
SCS Dimensionless Unit Graph
Enter Unit Hydrograph

Month	Initial Loss Recovery (in/day)
Oct	0.50
Nov	0.50
Dec	0.40
Jan	0.30
Feb	0.30
Mar	0.40
Apr	0.50
May	0.60
Jun	0.80
Jul	0.80
Aug	0.80
Sep	0.60

Initial Loss (in) 4.00
Uniform Loss (in/hr) 0.02

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit
Press <F10> to Save Data and Return

Figure D-9. Runoff parameters for the exterior basin - CSA runoff models were used by the district to develop project discharge-frequency relationships for the Napa River. Therefore, the HEC-1 model-developed hypothetical flood hydrographs were used for exterior conditions during HEA. The flood hydrographs were imported into HEC-IFH and used with rating curves to compute exterior stage hydrographs at interior outlet locations during HEA. Figure D-10 shows a portion of the imported hypothetical flood hydrographs for the exterior basin.

g. Existing and proposed storm sewer design and configuration. The details of existing and any proposed storm sewer layout, and discharge design capacities, including elevation of the inverts, were required to define drainage areas, minimum facilities, gravity outlet inverts, pumping station on-off elevations, and design criteria for inlet and outlet works. Layout and design of existing and proposed storm runoff conveyance systems were obtained from the Napa Public Works Department. The information included storm sewer location, length, size, and invert elevation. These data were provided on an areal photo (1 in. = 100-ft scale) with 2-ft contour intervals. Interior Area 5 is well sewered and has several existing gravity outlets that cross the line-of-protection and/or convey portions of the runoff to the Napa River. The outlets are shown in Figure D-4 and are described in the following subparagraphs. Numbered outlets refer to the primary and secondary outlet locations as shown in the figure.

(1) A major storm sewer system runs easterly along Trancas Street and discharges into the Napa River via a 54-in. circular pipe just downstream from the Trancas Street Bridge. This outfall is above the upstream limit of the project and therefore will not be disturbed. The outlet invert is not subject to blockage from high river stages due to the relatively high outlet invert elevation. It was estimated by the City of Napa that this outfall would pass a maximum of 50 cfs into the Napa River during flooding. This was simulated in HEC-IFH by diverting this flow from the upper subbasin to the river (see paragraph D-4*k*).

(2) The next downstream major storm sewer is a 72-in. circular pipe that enters the river at the north end of the Lake Park leveed area, just east of the intersection of Soscol and Pueblo Streets. It serves a major portion of the upper subbasin under pressure flow. This outlet is just upstream from the upper limits of the flood control project and, therefore, will be left undisturbed. The capacity of this pipe was estimated to be 300 cfs and this flow was diverted from the upper subbasin to the river for HEA and CSA (see paragraph D-4*k*).

(3) The Lake Park/Edgewater leveed area and its associated existing gravity outlets and pump station are considered independently and are not part of the Interior Area 5 analysis.

(4) The location 5.0 overflow ditch and 42-in. pipe north of the confluence of Napa Creek and the Napa River system includes a 72-in. pipe that empties into an overflow ditch that enters the Napa River just upstream from the confluence of Napa Creek and Napa River. At the outfall there is a 42-in.

HEA 01.04.00
Study ID NAPA
Module ID EXHYPUSN

Exterior Stage (EXSTAGE)

Index Location

Enter/Import Exterior Discharge Hydrographs (cfs)

Time Interval 15MIN

Number of Intervals 300

Da/HrMn	Hyp.Frq 50%	Hyp.Frq 20%	Hyp.Frq 10%	Hyp.Frq 4%	Hyp.Frq 2%	Hyp.Frq 1%	Hyp.Frq 0.2%	SPF
1/0015	81.	113.	139.	167.	191.	216.	296.	0.
1/0030	81.	112.	139.	167.	191.	216.	296.	0.
1/0045	81.	112.	139.	167.	191.	216.	296.	0.
1/0100	81.	112.	139.	167.	190.	216.	295.	0.
1/0115	81.	113.	139.	167.	191.	216.	296.	0.
1/0130	81.	113.	140.	168.	192.	217.	297.	0.
1/0145	82.	115.	141.	170.	194.	219.	301.	0.
1/0200	84.	117.	144.	173.	197.	223.	309.	0.
1/0215	86.	120.	147.	177.	202.	229.	322.	0.
1/0230	89.	124.	152.	183.	209.	237.	343.	0.
1/0245	92.	128.	158.	190.	217.	248.	370.	0.
1/0300	95.	134.	164.	199.	228.	261.	421.	0.
1/0315	100.	140.	172.	208.	240.	276.	471.	0.

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit

Position with <PgDn>, <PgUp>, <Dn>, <Up>, <Home>, <End>

Figure D-10. Portion of hypothetical flood hydrographs for exterior basin - HEA

circular pipe that runs beneath the overflow ditch. This outfall location is the flow concentration point for Interior Area 5 and was designated as the ponding area (see paragraph D-4*d*) and the primary gravity outlet location for this interior area.

(5) Additional existing outlets. There are three additional existing outlets that cross the line-of-protection and are to be replaced with new gravity outlets with drop inlets. They are all upstream from the primary gravity outlet and are designated and analyzed as secondary outlets for HEA and CSA. These outlets are described below:

(a) Location 5.1. One 24-in. pipe at Imperial Way.

(b) Location 5.2. One 18-in. pipe at North Bay Drive (to be replaced by a 24-in. drop inlet).

(c) Location 5.3. One 30-in. pipe at Lincoln Avenue.

There are a few small outlets that convey a minor portion of interior runoff from Interior Area 5 into Napa Creek from the left bank (north side). These outlets will not be cut off by the project because they are upstream from the Napa River tieback levee where channel excavation is the only project feature. The effects of these outlets were considered negligible in the analysis of Interior Area 5.

h. Field reconnaissance. Two field trips were made to locate outlet inverts and ditches that will be cut off by the line-of-protection, bridges, hydraulic structures, and floodplain channels and overbank areas. Several meetings were held with the Napa Public Works Department and Sacramento District to discuss existing and proposed storm conveyance systems and proposed interior features that would convey storm runoff through the line-of-protection.

i. Gravity outlets.

(1) The characteristics and configuration of typical new gravity outlets were defined to establish gravity outlet parameters and to develop rating curves for the outlets. This information included culvert length, size, etc., invert elevations and slopes of existing storm sewers, culvert type (box or circular, concrete or corrugated metal pipe, etc.), and entrance and exit configurations.

(2) The typical outlet through the line-of-protection was defined, after coordination and agreement with the study manager, as a concrete box culvert with a grated drop inlet. The outlet inverts of the drop inlets are established by the existing storm sewer inverts entering the drop inlets. Lengths of the box culverts were dependent on whether the line-of-protection consisted of a setback levee, sheet-pile wall, or concrete flood wall at the outfall. Slopes of the box culverts were set to maintain the slopes and outlet invert elevations of the existing outlets as close as possible. Required information was taken from project drawings provided by the district and existing storm sewer layouts provided by the City of Napa. Manual gate closure valves, as well as flap gates, will be included as part of each new outlet. The minimum head differential required for gravity flow was specified as 0.5 ft. No special gate closure requirements were established. A typical layout of a drop inlet box culvert at the primary location for Interior Area 5 is shown in Figure D-11.

j. Pumping Stations.

(1) Typical pumping station configuration and operation were determined through coordination with the district. Criteria for number of pumps and pumping station capacity were that each pumping station would have a total of three pumps, each having two-thirds of the total designated station capacity. Two of these pumps would be operated as needed and one would be for backup in case one of the other pumps went out of service. For example, a 300-cfs pumping station would include three (200-cfs or 90,000-gpm) pumps, two of which would be operating for a maximum possible station capacity of 400 cfs. Pump head-capacity-efficiency relationships were determined from pump performance curves provided by the district. Figure D-12 shows the relationships for a 200-cfs (90,000-gpm) pump unit.

(2) Pump on and off elevations were determined so that the pumps would come on to effectively reduce damaging stages and turn off when stages dropped below damaging levels. However, pumps should not cycle on and off over very short periods of time. Pump on/off elevations were determined based on the "zero damage" elevation and rate of rise for specific ponding areas for a specific interior area. Pump on/off elevations may need adjusting depending on the final design configuration of the pumping station. Preliminary on/off elevations for the two operating pump units for a 100-cfs station are shown in Figure D-13 and are based on a "zero damage" elevation of 14.0 ft for Interior Area 5.

k. Auxiliary flow. Auxiliary flow includes auxiliary inflow to the interior subbasin, diversions out of the system, seepage inflow from the exterior (Napa River) to the interior area, and overflow out of the interior area. As indicated in paragraph D-4*f*, the effect of the existing 54-in. and 72-in. pipes located upstream from the upper limits of the flood protection project was represented by a diversion from the upper subbasin in Interior Area 5. Specified diversions for Area 5 are shown in Figure D-14. Seepage was not considered a factor because the inundation time for the earthen embankments would be minimal and sheet-pile and concrete floodwalls along the line-of-protection would be extensively used.

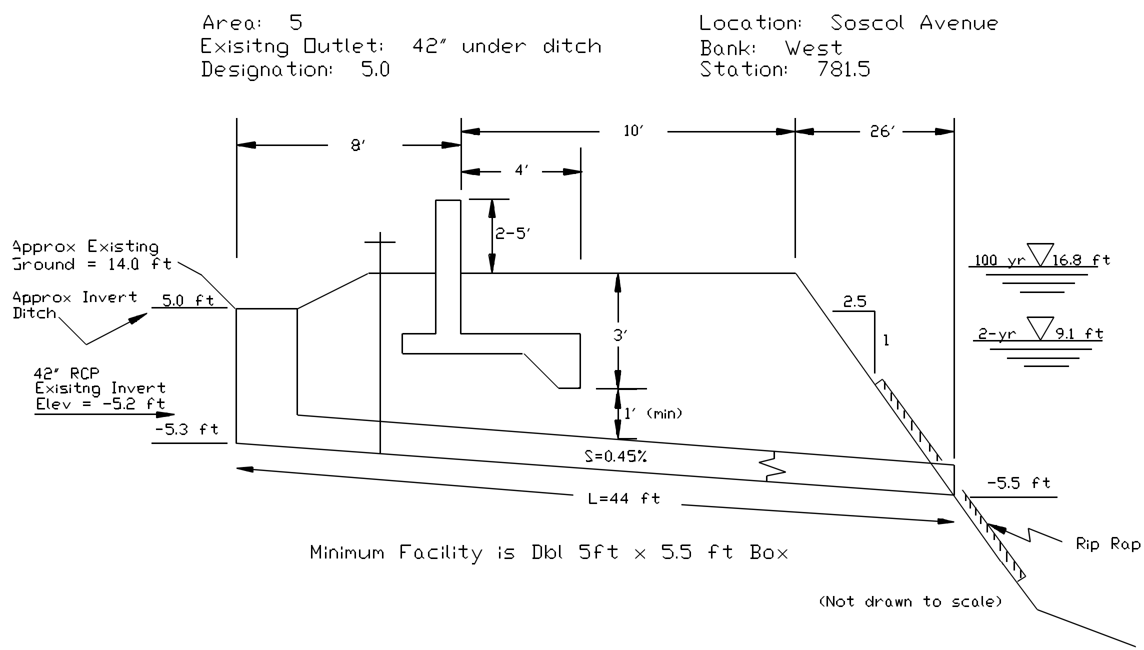
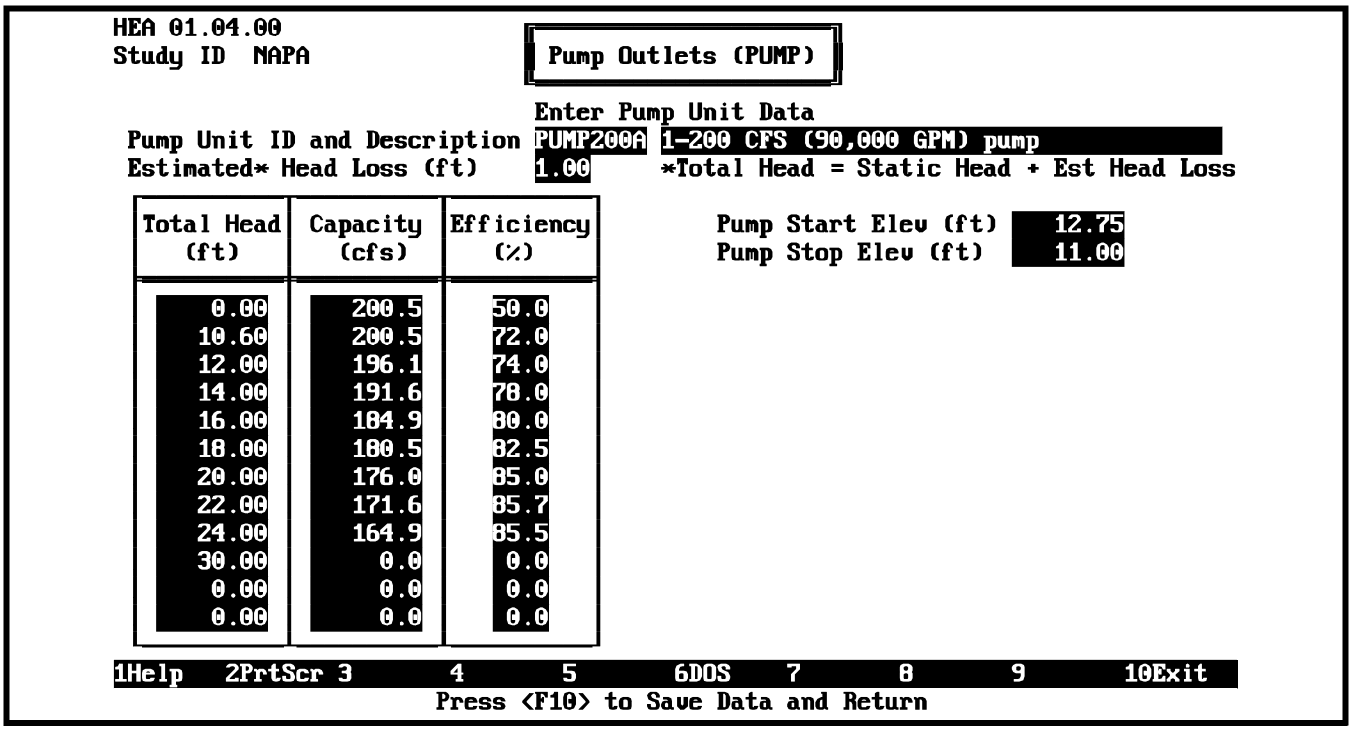


Figure D-11. Typical layout - new box culvert with drop inlet Area 5



HEA 01.04.00
Study ID NAPA

Pump Outlets (PUMP)

Enter Pump Unit Data
Pump Unit ID and Description PUMP200A 1-200 CFS (90,000 GPM) pump
Estimated* Head Loss (ft) 1.00 *Total Head = Static Head + Est Head Loss

Pump Start Elev (ft) 12.75
Pump Stop Elev (ft) 11.00

Total Head (ft)	Capacity (cfs)	Efficiency (%)
0.00	200.5	50.0
10.60	200.5	72.0
12.00	196.1	74.0
14.00	191.6	78.0
16.00	184.9	80.0
18.00	180.5	82.5
20.00	176.0	85.0
22.00	171.6	85.7
24.00	164.9	85.5
30.00	0.0	0.0
0.00	0.0	0.0
0.00	0.0	0.0

1Help 2PrtScr 3 4 5 6DOS 7 8 9 10Exit
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Figure D-12. Pump unit head-capacity-efficiency data

```
HEA 01.04.00                 Hydrologic Analysis Summaries          Begin 01/0005
Study ID  NAPA                                                      End   07/0600
Plan ID   PLAN5-4A
                 D. Analysis Input Summaries - Pump Station Data

     PUMP Module ID PMOD100     100 cfs station (2-67 cfs pumps oper.)
```

Pump Number	Pump Unit ID	Maximum Capacity (cfs)	Pump Start Elevation (ft)	Pump Stop Elevation (ft)	Maximum Total Head (ft)
1	PUMP67A	66.8	12.75	11.00	30.00
2	PUMP67B	66.8	13.25	11.75	30.00
3					
4					
5					
6					
7					
8					
9					
10					

```
1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
                          Press <F10> to Return
```

Figure D-13. Pumping station data for Interior Area 5

```
HEA 01.04.00
Study ID  NAPA              Auxiliary Inflow/Outflow (AUXFLOW)

                   Enter Diversion Rate for Upper Sub-Basin

Diversion Table ID  AREA5U

Description
  Outflow to Napa R via Pueblo & Trancas.
```

Runoff + Aux. Inflow (cfs)	Diverted Flow (cfs)
0.0	0.0
10.0	10.0
50.0	50.0
100.0	100.0
200.0	200.0
350.0	350.0
10000.0	350.0
0.0	0.0
0.0	0.0
0.0	0.0
0.0	0.0
0.0	0.0
0.0	0.0

```
1Help   2PrtScr 3       4       5       6DOS    7       8       9       10Exit
                   Press <F10> to Save Data and Return
```

Figure D-14. Diversion rate for the upper subbasin - Interior Area 5 *l. Water surface profile data.* Water surface profiles for with-project conditions were developed by the district using the HEC-2 program. These profiles were used to determine rating curves for the Napa River at interior area outlet locations. The water surface profiles were also used to determine exterior stage transfer relationships for transferring the computed exterior stage at the primary outlet location to the secondary outlet locations. The rating curve for Napa River at the Area 5 primary location is shown in Figure D-15.

m. Stage-damage relationships. Representative stage-damage relationships for the interior areas at runoff concentration points are required for economic analysis and identification of interior plans that maximize net flood damage reduction benefits. Economic analysis is not part of this investigation; therefore, complete stage damage relationships were not required. The elevation where significant damage begins or "zero damage" was required in order to establish the size of the minimum facility and to set pump on/off elevations. These elevations were provided by the district.

D-5. Without-project Conditions Analysis for Minimum Facility Evaluation

a. General. The without-project analysis involves evaluation of conditions without and with the line-of-protection in place. Degrees of flooding for these conditions are needed to select a minimum facility. The without-project condition used to formulate and evaluate the interior flood damage reduction measures will assume that the adopted minimum facility is in place and is described in paragraph D-6.

b. Napa River flooding without line-of-protection. The source of serious flooding in the City of Napa is the Napa River and to a lesser extent Napa Creek. The recommended flood damage reduction project protects the city from flooding up to the 1-percent chance flood for both the Napa River and Napa Creek. The basis for sizing the minimum facility is to assure that flooding from local storm runoff, when the Napa River and Napa Creek are below bank full, is not more frequent with the line-of-protection in place than without the line-of-protection in place.

c. Local runoff flooding without line-of-protection. Local flooding was evaluated without the line-of-protection in place, assuming the present storm sewer system in place, and Napa River and Creek below flood stage. Stage-frequency relationships for this condition were not developed due to lack of data. Storm sewer system design criteria for the City of Napa, for existing and new systems, were well-documented and were used to establish the target condition for the minimum outlet facility analysis. The first criterion used was that only minor street and gutter flooding should occur up to the 10-percent chance (10-year) flood event. Minor street and gutter flooding in this case is defined as not exceeding a depth that would result in flooding more than 10 ft from the street gutter. The second criterion was that no significant damage from flooding would occur in residential and commercial areas from floods up to the 4-percent chance (25-year) flood event.

HEA 01.04.00
Study ID NAPA
Module ID EXHYPUSN

Exterior Stage (EXSTAGE)

Enter Exterior Channel Rating Curve

Discharge (cfs)	Elevation (ft)
0.0	0.00
13800.0	9.00
19400.0	11.00
23500.0	12.50
28700.0	13.80
33000.0	15.10
37200.0	16.80
52100.0	19.00
0.0	0.00
0.0	0.00
0.0	0.00
0.0	0.00
0.0	0.00
0.0	0.00

1Help 2PrtScr 3 4 5 6DOS 7 8 9Plot 10Exit
Press <F10> to Save Data and Exit

Figure D-15. Exterior rating curve for Interior Area 5

This second criterion was interpreted that the interior stage resulting from the 4-percent chance event should not exceed the start of significant damage elevations determined by the district office. Based on the past performance of the existing sewer system and the overall reasonableness of the criteria, the storm sewer system design criteria were adopted for sizing the minimum facilities.

d. Assess future without-project conditions impacts. Future conditions that could affect Napa River interior area local runoff flooding were considered. Hydrologic and/or hydraulic conditions are not expected to significantly change over the project life and, therefore, no changes needed to be incorporated into the hydrologic and hydraulic analysis. The interior areas are fully urbanized, so future urbanization would have minimal effect on watershed runoff. Proposed and planned improvements in the existing storm sewer system, as described by the City of Napa, were evaluated and incorporated in the interior areas where appropriate. There were no planned changes to the existing storm sewer system in Interior Area 5.

D-6. Minimum Facility Analysis

a. General. The adopted minimum facility, sized according to the criteria described in paragraph D-5*c*, is a justified part of the line-of-protection. Stage-frequency relationships for the condition with the minimum facility in place become the condition without the minimum facility in place for evaluating potential interior flood damage reduction measures over and beyond the minimum facility. The residual damage with the minimum facility in place becomes the target for damage reduction of proposed additional interior flood damage reduction measures. As described previously, the minimum facility was sized to provide interior flooding relief so that during low exterior stages (unblocked gravity outlet conditions) the local interior area runoff will pass the design storm sewer outflow without an increase in interior stages over natural or without line-of-protection conditions.

b. Selecting the minimum facility for Interior Area 5. A series of analyses of gravity outlet capacities and configurations using local storm hypothetical events analysis (HEA) and assuming unblocked conditions were conducted using HEC-IFH. Physical characteristics of the gravity outlets were described in paragraph D-3*i*. A new plan was defined for each gravity outlet capacity to be evaluated and the interior stage-frequency relationship was developed for each outlet. Plan components as defined in HEC-IFH for one of the plans evaluated for Interior Area 5 are shown in Figure D-16. Stage-frequency relationships of gravity outlets were compared to the storm sewer design criteria described previously and the outlet size that came closest to meeting the criteria was selected. For Interior Area 5, the selected minimum facility was a double 5- by 5.5-ft box culvert. The "zero damage" elevation is 14.0 ft, and the 4-percent chance elevation based on the results of the HEA unblocked condition simulation is 13.55 ft. The stage-frequency relationship with the minimum facility in place is shown in Figure D-17. The 10-percent chance stage is below the criterion elevation for street flooding and therefore this minimum facility is adequate.

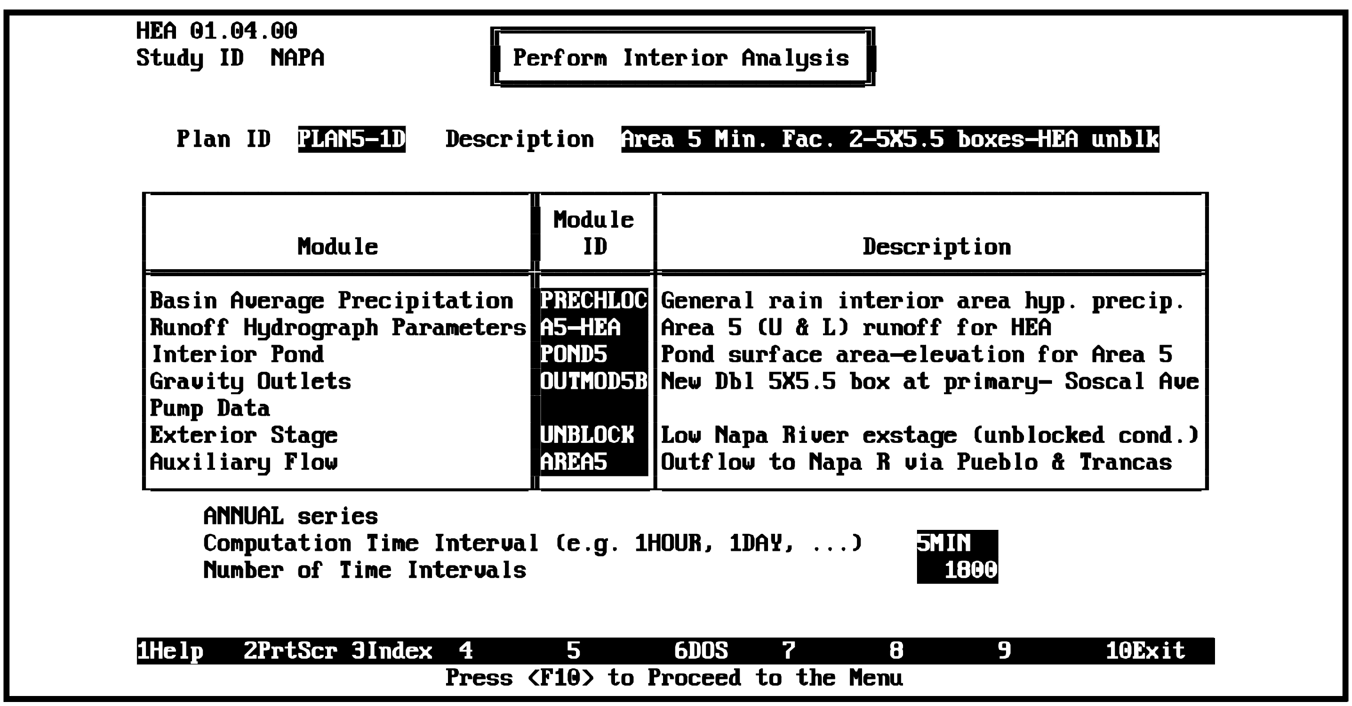

Figure D-16. Plan components, minimum facility - HEA, unblocked

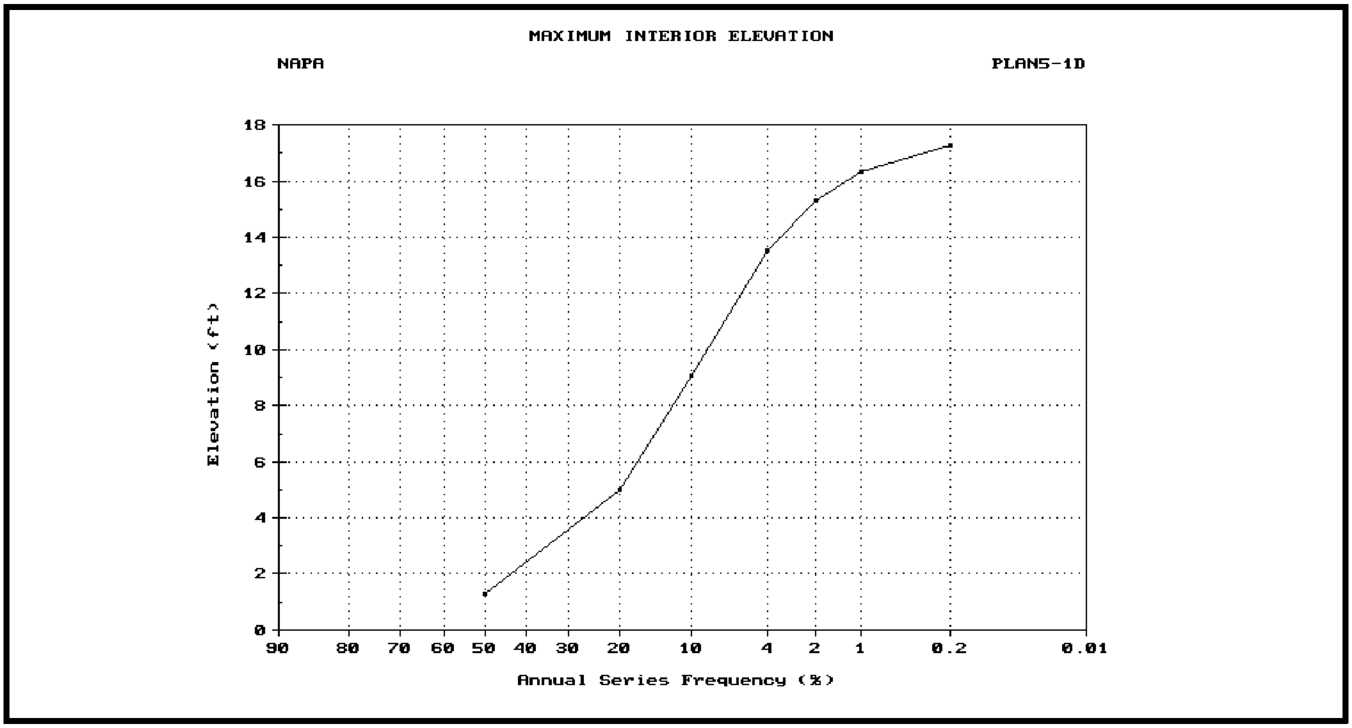

Figure D-17. Stage-frequency for minimum facility - Interior Area 5 - HEA, unblocked

c. Without-project condition stage-frequency relationship with the minimum facility in place.

(1) After the minimum facility was selected, it was evaluated using general rain hypothetical event analysis (HEA). A new general rain HEA plan (Plan 5-2A) was defined using precipitation depth-duration-frequency data for general rain events occurring over the Napa River watershed as well as the interior area. Exterior stages were computed from imported hypothetical flood discharge hydrographs and a stage-discharge rating for the Napa River at the interior area outlet as previously described. The results of the analysis were used to test the effectiveness of the minimum facility gravity outlet. HEC-IFH assessed local runoff flooding that occurs during blocked conditions (e.g., with general rain storms centered over the interior and exterior basin causing flooding on both the interior and exterior). The resulting stage-frequency relationship is shown in Figure D-18. Plan 5-1D is HEA with unblocked exterior conditions and Plan 5-2A is HEA with interior and exterior flooding conditions.

(2) Continuous simulation analysis (CSA) was performed using previously described period-of-record composite rainfall. The purpose of evaluating CSA in addition to HEA is to compare the resultant stage-frequency relationships. CSA captures the relationship between interior runoff and exterior stage, whereas HEA assumes interior and exterior flooding are coincident.

(3) Examination of CSA results for several historical events shows that interior and exterior flooding are typically coincident, as illustrated in Figure D-19 for the February 1986 event. An exception to this was the January 1973 event, where the 41-year record interior rainfall and resultant runoff occurred while Napa River stages were very low (see Figure D-20). Timing of the peak interior runoff and the maximum exterior stage is critical in the Napa study due to the small ponding area storage available. Due to this fact and the fact that the historical CSA shows that the peak interior runoff can occur before, after, or simultaneous to the exterior peak stage, HEA stage-frequency relationships were adopted for the evaluation of interior features. HEA captures the critical combinations of interior runoff and exterior stage that can occur, but are not always well-represented in the historical record. Figure D-21 shows a comparison of the stage-frequency relationships for CSA and HEA. The differences in stage are minor considering a 2-ft difference in stage (17.0 ft minus 15.0 ft) is equivalent to less than 0.25 in. of runoff from the interior area. The relatively good comparison between the relationships helps prove the reasonableness of the HEA-developed stage-frequency relationship. The HEA stage-frequency was adopted to establish the base plan or without-project condition stage-frequency relationships for evaluating additional interior flood damage reduction measures as described in paragraph D-7.

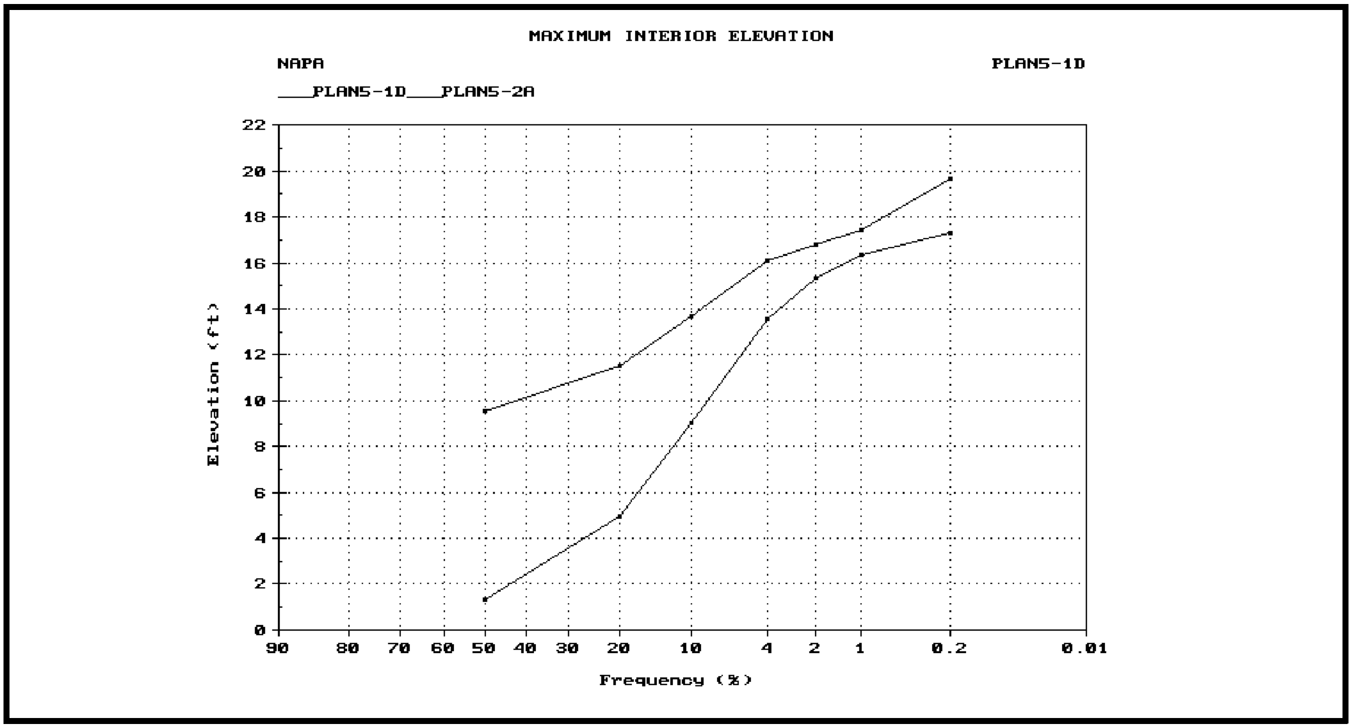

Figure D-18. Stage-frequency relationships - HEA unblocked and interior/exterior

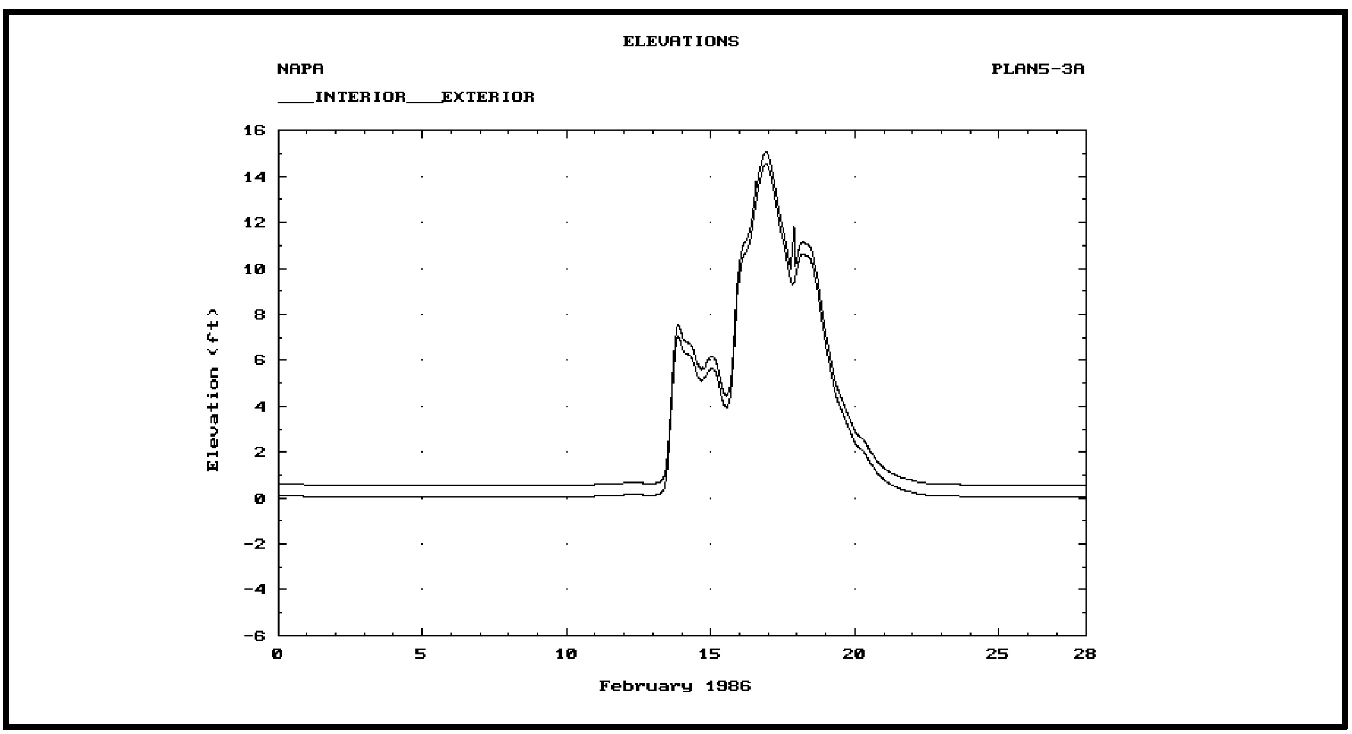

Figure D-19. Interior and exterior elevation - February 1986, CSA

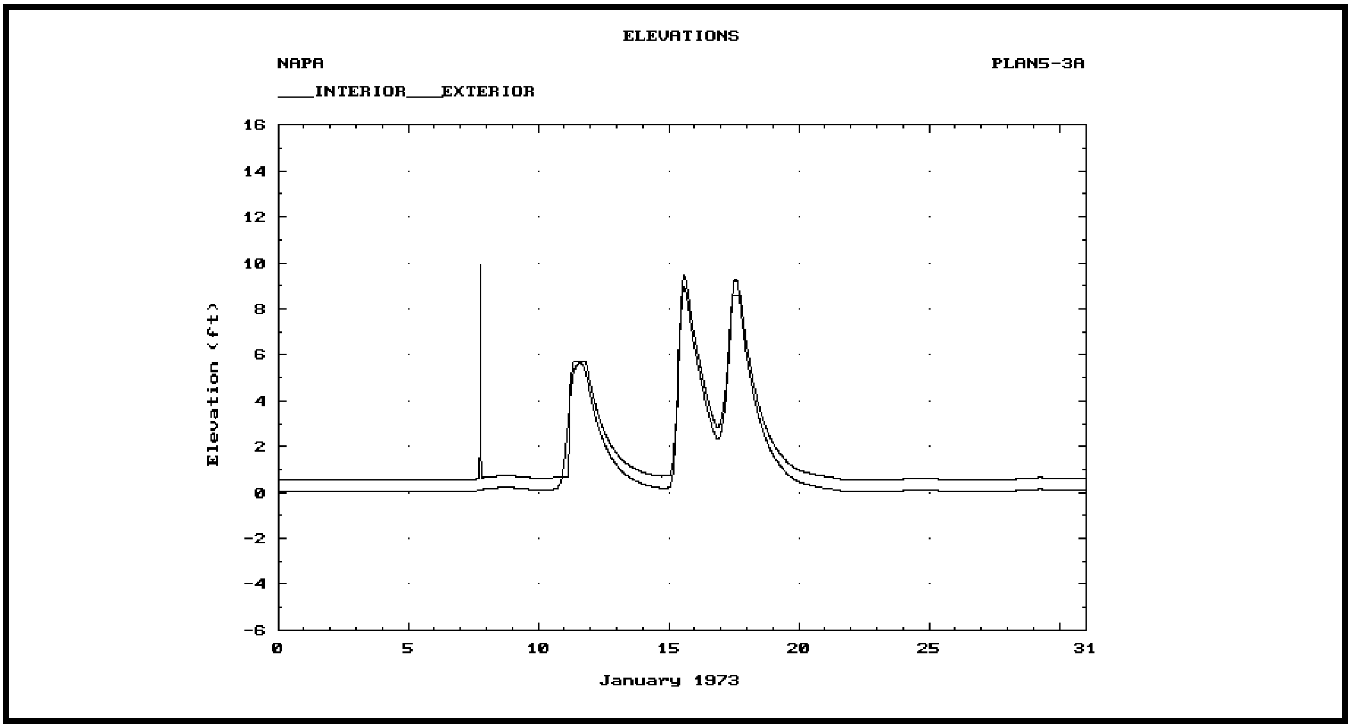

Figure D-20. Interior and exterior stages - January 1973 event, CSA

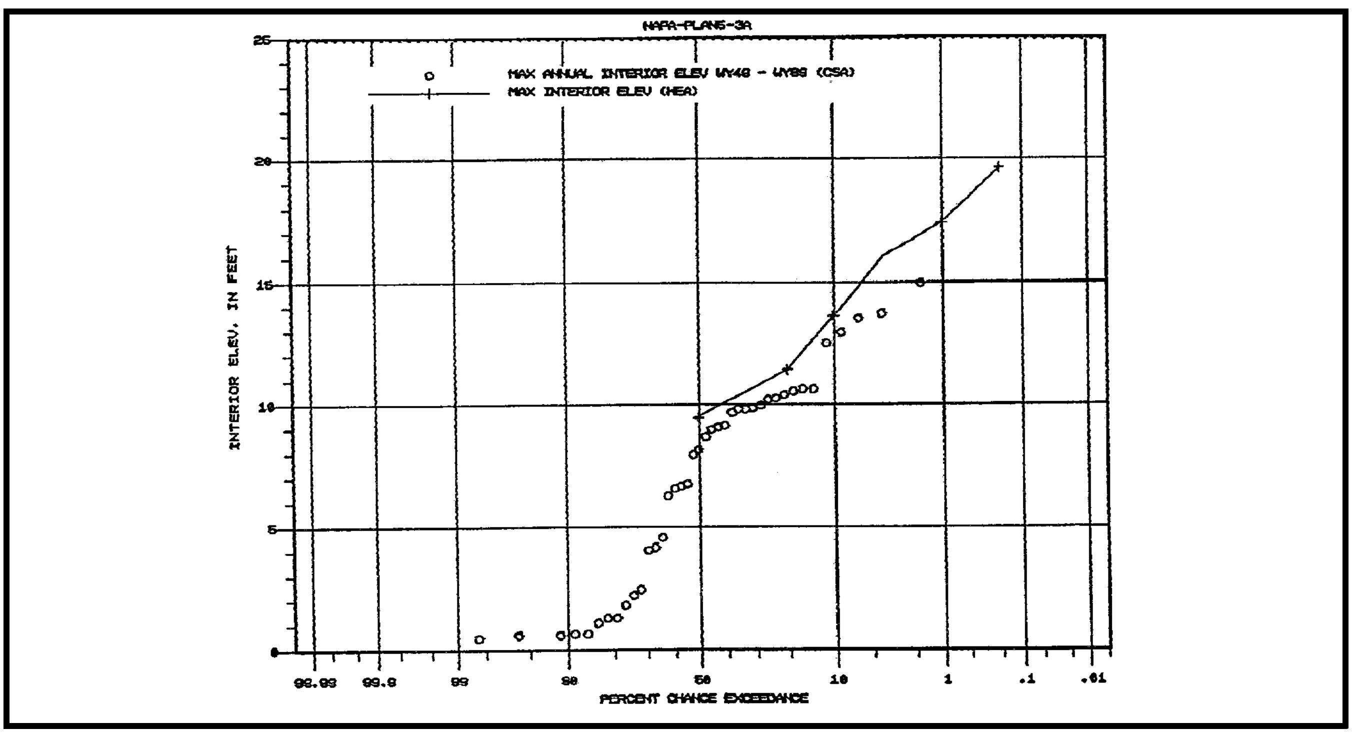

Figure D-21. Interior stage-frequency relationships for CSA and HEA - Area 5

D-7. Stage-Frequency for Interior Flood Damage Reduction Plans

a. General. The objective of this task is to develop stage-frequency relationships that can be used to formulate a set of flood damage reduction plans for each interior area. The condition with the line-of-protection and the selected minimum gravity outlet in place becomes the without-project condition for evaluating additional features, such as additional gravity outlets, pumping stations, additional ponding area storage, and nonstructural measures.

b. Stage-frequency relationships for additional gravity outlet capacity. New plans for evaluating additional gravity outlet capacity using data previously developed for the HEA with the minimum facility in place were defined. Only the gravity outlet data needed to be changed to define plans with a range of outlet sizes. Four or five gravity outlet configurations (modules), with one or more gravity outlets in addition to the minimum facility outlet, were defined. Each module represented an incremental increase in total outlet capacity. Several plans that incorporated the gravity outlet modules were defined and interior stage-frequency relationships were developed for each plan. The HEA results were adopted to establish a final stage-frequency relationship for each gravity outlet plan. These relationships will be used in the economic analysis to select an optimal plan. A plan summary for the four different Area 5 plans analyzed is shown in Figure D-22. Figure D-23 shows a comparison of the plan stage-frequency relationships.

c. Determine stage-frequency for added pumping capacity.

(1) General. The analysis for Area 5 shows that additional gravity outlet capacity is not effective, due to considerable coincidence between interior runoff and high exterior stages. Residual damages may be significant, and pumps may be justified. The same steps described for evaluating additional gravity outlet capacity are appropriate for evaluating added pumping capacity. Some differences in the analysis are described below.

(2) Base condition. The base condition for evaluating pumping capacity is with the minimum facility and, most likely, the economic optimal gravity outlet configuration, in place. Several plans are evaluated against the base plan, each with an incremental increase in pumping capacity. At the time of this writing the preliminary economic optimal gravity outlet was selected as four 5- by 5-ft box culverts (Plan 5-C). HEA plans for Area 5 with the selected outlet and three different size pumping stations were defined and analyzed. The plan configurations are shown in Figure D-24 and the stage-frequency relationships are shown in Figure D-25. These relationships will be used to define the optimal pumping station size for interior Area 5.

HEA 01.04.00
Study ID NAPA

Comparison of Plans

A. Plan Summary

Plan ID	Type of Series	Storm Area (sq mi)	Storm Duration (hr)	Area of Primary Grav.Out (sq ft)	Min Pump Start Elev. (ft)	Min Pump Stop Elev. (ft)	Total Pump Capacity (cfs)
PLAN5-2A	ANNUAL	266.00	96.00	55.00	0.00	0.00	0.0
PLAN5-2B	ANNUAL	266.00	96.00	72.00	0.00	0.00	0.0
PLAN5-2F	ANNUAL	266.00	96.00	90.75	0.00	0.00	0.0
PLAN5-2C	ANNUAL	266.00	96.00	100.00	0.00	0.00	0.0
PLAN5-2D	ANNUAL	266.00	96.00	126.75	0.00	0.00	0.0

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Figure D-22. Summary of plans for evaluating additional outlet capacity - HEA

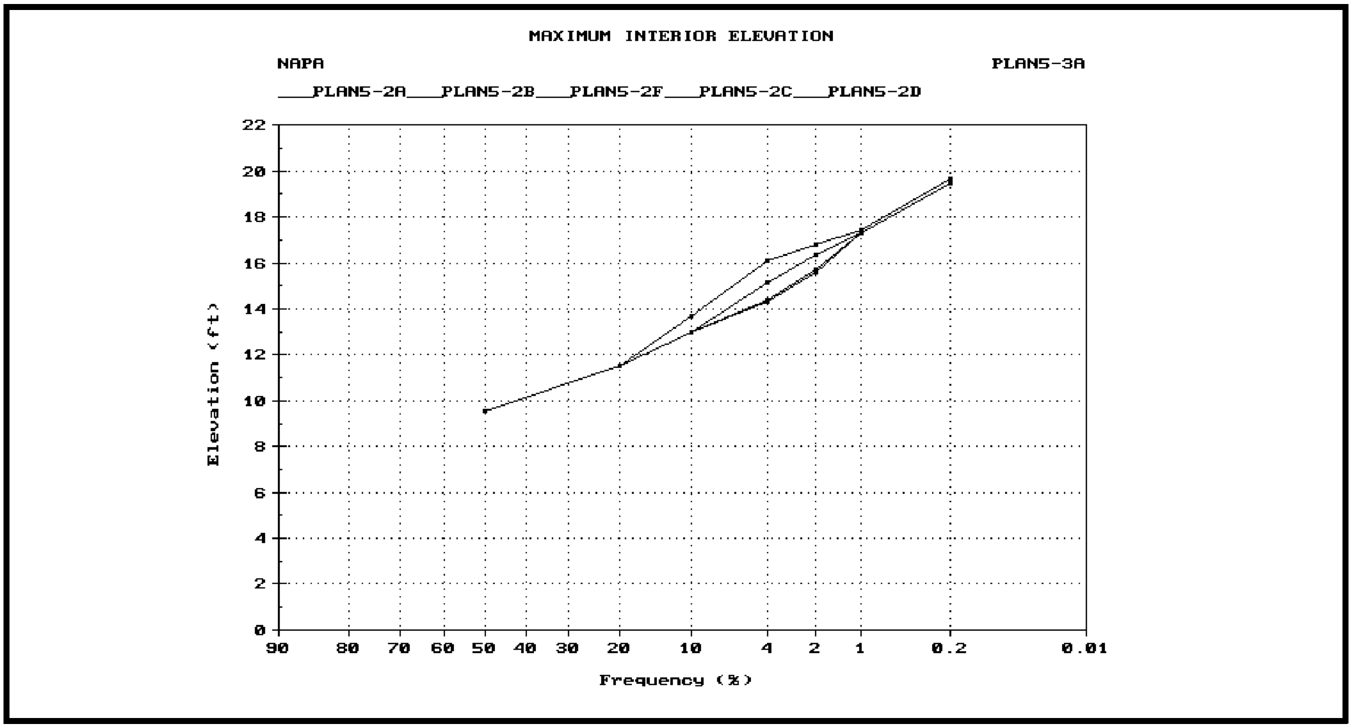

Figure D-23. Stage-frequency relationships for a range of gravity outlet sizes

HEA 01.04.00
Study ID NAPA

Comparison of Plans

Plan No.	Plan ID	Plan Description
1	PLAN5-2C	Area 5 - 4-5X5 Boxes - HEA int/ext
2	PLAN5-4A	Area5 4-5X5 w/100 cfs pump - HEA int/ext
3	PLAN5-4B	Area5 4-5X5 w/200 cfs pump - HEA int/ext
4	PLAN5-4C	Area5 4-5X5 w/300 cfs pump - HEA int/ext
5		
6		
7		

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Figure D-24. HEA plans for evaluating pumping capacity

HEA 01.04.00
Study ID NAPA

Comparison of Plans

B. Maximum Interior Elevation-Frequency

Plan ID	Peak Elevation (ft) vs. Percent Chance Exceedance							
	50%	20%	10%	4%	2%	1%	0.2%	SPF
PLAN5-2C	9.54	11.51	13.01	14.33	15.62	17.29	19.49	0.00
PLAN5-4A	9.54	11.51	13.01	13.80	15.05	16.48	19.15	0.00
PLAN5-4B	9.54	11.51	13.00	13.56	14.52	15.93	18.79	0.00
PLAN5-4C	9.54	11.51	12.99	13.54	14.15	15.54	18.57	0.00

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Figure D-25. Stage-frequency relationships for evaluating pumping capacity

d. Nonstructural measures. Temporary evacuation, relocation, flood proofing, and other nonstructural measures that reduce susceptibility to damage, as well as the increase in available storage, will be evaluated by the district and considered in the final recommended plan.

e. Final plan selection. Other social, institutional, and environmental issues, including the management of future development, and flood warning and preparedness programs, will need to be evaluated in the final plan selection for each interior area.

Appendix E
Case Study for Interior Flood Damage Reduction Measures, Valley Park, Missouri

E-1. Background

Valley Park is an incorporated community of about 4,300, situated in southwestern St. Louis County, Missouri. A portion of the city lies in the Meramec River floodplain, and is subject to flooding from events rarer than about a 10-percent annual chance of flooding. Valley Park is located about 22 miles upstream from the mouth of the Meramec River, which empties into the Mississippi River just downstream from St. Louis. The drainage area of the river at Valley Park is about 3,800 sq miles. Periodic flooding has been a problem, with significant flooding occurring in 1915, 1945, and 1957, and lesser amounts in other years. In December 1982, the flood of record occurred. Estimated as a 1-percent chance flood at that time, it flooded many low-lying areas of the community with 8 to 10 ft of water. In May 1983, another significant event (about a 4-percent chance flood) resulted in widespread flooding. In the mid-1980's, the St. Louis District investigated various flood mitigation projects for Valley Park and other communities along the lower 50 miles of the Meramec. Only a levee for Valley Park showed the necessary economic justification and a sponsor willing to cost-share the project. The Design Memorandum for the levee and accompanying interior flood control project was completed in February 1993. Construction began in the autumn of 1993.

E-2. General

The proposed levee project will protect about 461 acres of the city of Valley Park. It will protect against the 1-percent chance event from the Meramec River, and from coincident flooding from two tributaries: Fishpot Creek and Grand Glaize Creek. Almost no hillside area is included within the levee alignment. The protected interior area will be drained by six gravity outlets, with five ponding areas providing storage during blocked gravity outlet conditions. Open channels and drainage structures were also sized to convey the storm waters to the ponding areas. Although the interior analysis was fairly routine, it was the first application of the HEC-IFH computer program to analyze and design an interior system. The original beta test version of HEC-IFH was first used, with the updated versions incorporated as they became available.

E-3. Strategy

a. Interior flood control analysis is an essential part of the complete levee design, with a "minimum facility" being the first step. Because of several borrow areas and some natural storage located inside the levee alignment, it was believed that a minimum facility would mainly consist of gravity outlets and existing ponding. The duration of flooding for the Meramec River is short, with 4 to 6 days duration above flood stage for both actual and hypothetical events. Because of the short duration of blocked drainage, it was believed that interior facilities beyond the minimum would not be needed.

b. The approximate quantities of material to be removed from the potential borrow sites, as well as the amount of undeveloped areas usable for ponding, were known early in the interior analysis. The volume of the 1-percent chance flood, 4-day-duration storm was estimated, with the resulting runoff volume (about 200 acre-ft) filling the ponding storage. Consequently, it was decided to initially size the interior system for this storage, using a 1-percent chance event as the design standard. No economic incremental analysis was judged necessary for the interior analysis, because the borrow pit storage would be available for any design flood and changes in gravity outlet size(s) would be expected to show little reduction in peak ponding stages.

c. To fully test the design and the new program, both the HEA and CSA methods were used. A series of 4-day-duration hypothetical storms was used in the HEA to establish stage-frequency analysis for both open and closed gravity outlet conditions. The continuous period-of-record method (CSA) was then applied to establish the minimum facility and to compare against the stage-frequency relationship developed through the HEA.

E-4. Basic Data Requirements

Interior flood hydrology analyses are very data intensive, especially when both HEA and CSA techniques will be used. The following paragraphs identify the major data needs:

a. Subareas. Five interior drainage basins were identified, based on urban storm drainage systems and topographic contour mapping. These areas are identified as: the Fishpot, Highway 141, Glass Plant, Simpson Lake, and Grand Glaize interior areas. The Highway 141 subarea consisted of two subbasins, with a diversion to the Fishpot subarea during blocked outlet conditions. The other four subareas each consisted of a single subbasin. Separate HEC-IFH analysis would be performed for each of the five subareas, with each including gravity outlet and ponding storage. Table E-1 gives pertinent data for the interior areas and Figure E-1 shows a schematic diagram. Two-foot contour interval topographic mapping was available for the lower 50 miles of the Meramec from the earlier analysis.

Table E-1
Interior Unit Hydrograph Parameters

Interior Location	Designated Interior Basin*	Drainage Area (sq mi)	Runoff Coefficient (percent)	SCS T(LAG) (HR)
Fishpot	FPI	0.08	85	0.11
Highway 141	HYW & HYW1	0.05	90	0.17
Highway 141 with Outlet Closed	HYW1	0.02	95	0.06
Glass Plant	GPT	0.37	85	0.31
Simpson Lake	SIM	0.11	85	0.13
Grand Glaize	GG1	0.09	85	0.11

*From Figure E-1

b. Precipitation. Both hypothetical and continuous precipitation data would be necessary for the analysis.

(1) Hypothetical storm time series were developed from the appropriate National Weather Service publications with a 10-minute time interval used, due to the short concentration times of the interior basins. The 50- through 0.2-percent chance exceedance hypothetical storms were generated.

(2) Because of the short duration of flooding for both the tributary and the interior streams, time increments less than 24 hrs were needed for the CSA. Hourly precipitation records were available at the St. Louis, Missouri, rainfall station from 01 October 1948 to 30 September 1988. This precipitation data stream could be readily transferred to the Valley Park site for use with the CSA portion. Because of the short time of concentration of the interior unit hydrographs, it was initially felt that a 1-hr duration was too long to accurately define the interior hydrographs. The initial CSA analysis used a 10-min time-step and each 1 hr of rainfall data was subdivided into 10-min increments.

c. Subarea runoff parameters. SCS unit hydrographs and simple runoff coefficients were used to generate interior runoff hydrographs based on expected future conditions. Adopted values are shown in Table E-1.

d. Exterior river stage. Long record stage and discharge information was available for the Meramec at the Eureka gauge, located at River Mile 34.1, beginning in 1922. Daily stage data for the period October 1948 through September 1988 was assembled and transferred 12 to 14 miles downstream to simulate exterior river stages at each Valley Park outlet site. Transfer relationships between the Eureka gauge and each outlet site were developed through water surface profile analysis and are shown in Table E-2.

Table E-2
Eureka Gauge Transfer Curves

Eureka Gauge Elevation (NGVD)*	Fishpot Creek Elevation** (NGVD)	Glass Plant Elevation (NGVD)	Grand Glaize Creek Elevation*** (NGVD)
429.09	415.52	415.14	413.54
435.89	421.43	420.97	419.10
440.64	424.73	424.19	422.18
444.73	429.30	427.87	425.75
446.55	431.69	430.55	428.38
447.23	432.66	431.76	429.63
448.29	434.07	433.17	430.97
452.99	440.95	439.09	436.83
456.36	444.12	442.70	440.73

* National Geodetic Vertical Datum.
** Also used for Highway 141 subarea analysis.
*** Also for the Simpson Lake subarea analysis.

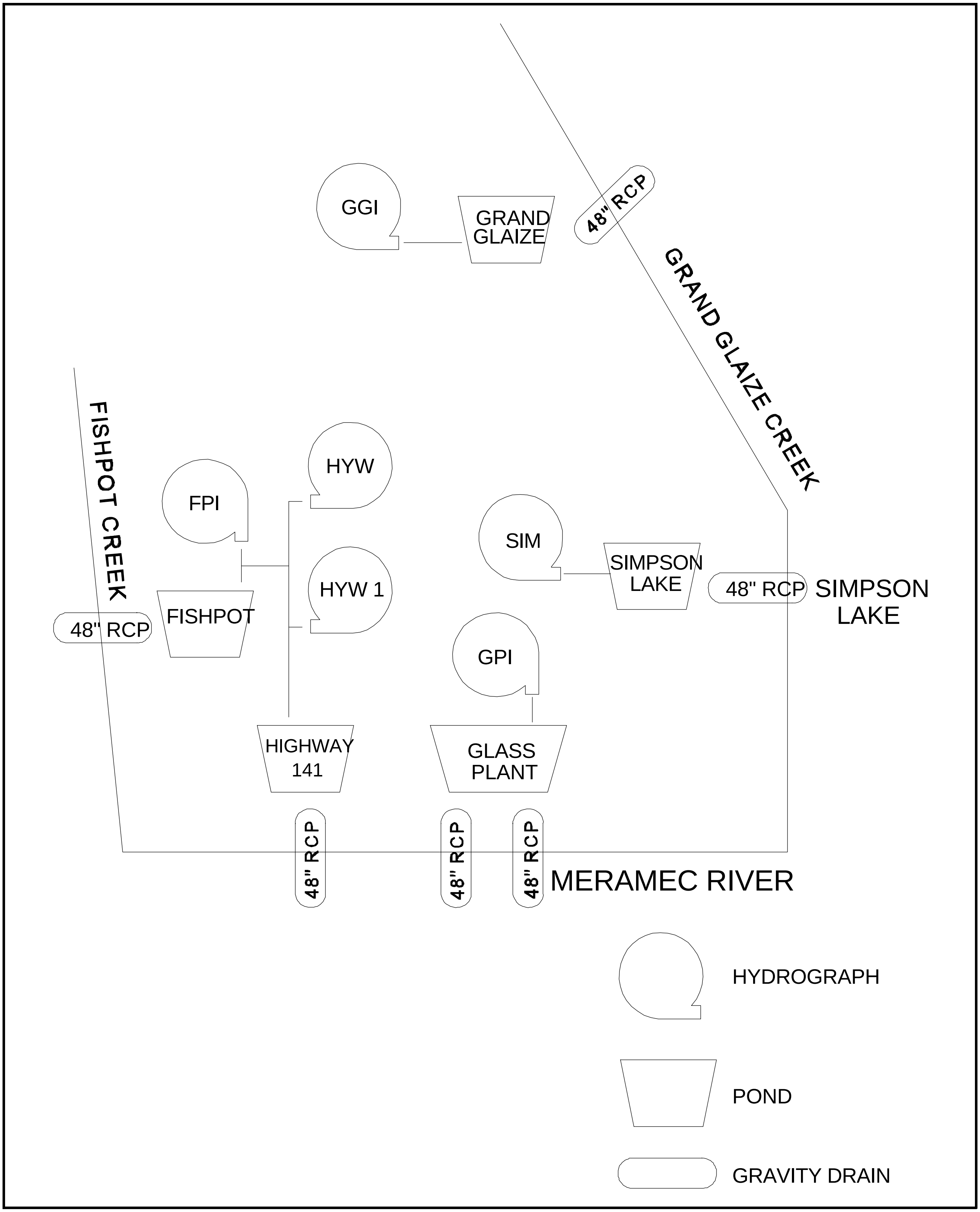

Figure E-1. Schematic of Valley Park interior hydrology project

e. Interior storage areas. Preliminary borrow requirements, along with any natural storage available, were identified at each site. As borrow requirements became more specific throughout the course of the levee investigation, elevation-storage relationships were developed and refined. Elevation-storage relationships are shown in Table E-3.

f. Gravity outlet rating curves. Discharge-stage relationships were developed for 48-, 54-, and 60-in. reinforced concrete pipes (RCP). A minimum diameter of 48 in. was used because each subarea's existing storm outlet system entering the area consisted of 24- to 48-in. pipes. The invert elevations for each outlet were selected based on evaluating the stage-duration data available through HEC-IFH for the period of record and the necessary interior storage. Invert elevations selected represent a 7-percent exceedance duration or less for the Meramec and do not decrease the desired storage volumes. The gravity outlets would be expected to be unblocked at least 93 percent of the time, lessening the need for supplementary pumping. Gravity outlet rating curves are generated automatically by HEC-IFH, with typical output illustrated in Figure E-2.

Table E-3
Interior Storage Areas

Fishpot		I-141		Glass Plant		Simpson Lake		Grand Glaize	
Elev (ft) (NGVD)	Vol (acre-ft)	Elev (ft) (NGVD)	Vol (acre-ft)	Elev (ft) (NGVD)	Vol (acre-ft)	Elev (ft) (NGVD)	Vol (acre-ft)	Elev (ft) (NGVD)	Vol (acre-ft)
405.0	0.0	415.0	0.0	407.0	0.0	408.0	0.0	410.0	0.0
406.0	0.2	416.5	0.2	409.0	5.4	409.0	0.4	412.5	1.0
407.0	0.9	422.0	2.3	413.0	35.8	412.0	6.3	414.0	4.4
408.0	2.0			420.0	119.1	414.0	25.6	419.0	20.2
420.0	26.0					417.0	59.6	420.0	23.5

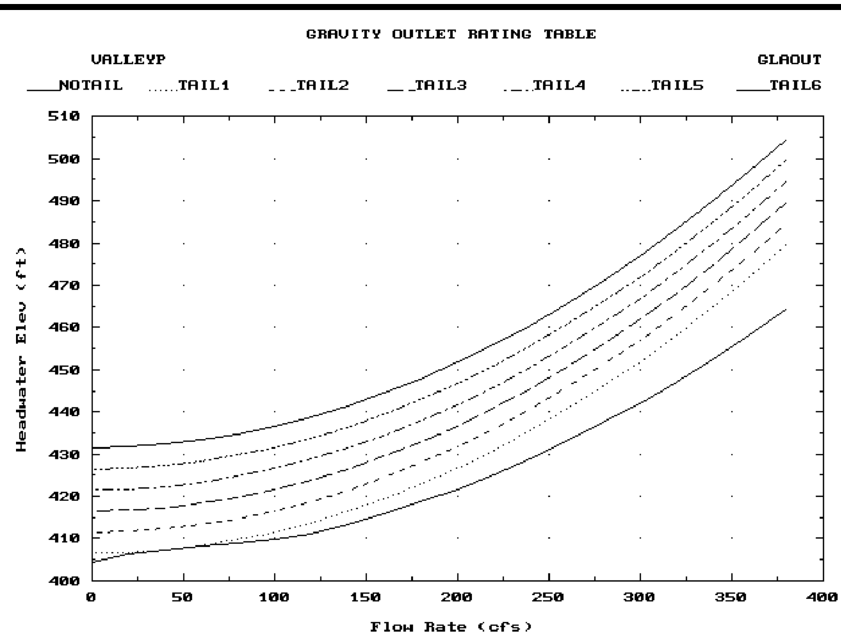

Figure E-2. Gravity outlet rating table for two 48-in. culverts

g. Seepage. Seepage curves for each interior ponding area were supplied by geotechnical personnel to estimate seepage inflow during blocked outlet conditions. These relationships are shown in Table E-4.

h. Auxiliary outflows. One diversion was incorporated to transfer inflow from the upper subarea for the Highway 141 basin to the Fishpot subarea during blocked outlet conditions at the Highway 141 site. Figure E-1 shows the diversion location.

i. Flank levee exterior elevations. Because some gravity outlet structures discharge into Fishpot and Grand Glaize Creeks, exterior river elevations for these structures can change rapidly during local rainfall events independent of the Meramec elevations. Consequently, the blocked outlets at these sites could be caused by either Meramec River backwater, by Fishpot or Grand Glaize Creek flows, or a combination of the two. Water surface profile analyses were performed for a variety of tributary discharges coincident with the full range of Meramec River backwater elevations. Unit hydrographs and runoff coefficients were used to generate hydrographs at each flank levee outlet site. With HEC-IFH, one can enter a family of curves with the tributary discharge and Meramec backwater elevation to determine the corresponding elevation at the tributary gravity outlet site. Figures E-3 and E-4 illustrate this procedure. Consequently, blocked outlets from either the Meramec or from the tributary could be included. Grand Glaize and Fishpot Creek parameters are shown in Table E-5.

E-5. Minimum Facility

A minimum facility was evaluated at each of the five subareas using both the HEA and the CSA techniques.

a. HEA. HEA was performed for both blocked and unblocked outlet conditions, using hypothetical storm rainfall, subarea runoff, available interior storage, and a minimum gravity outlet diameter. Stage-frequency relationships for both blocked and unblocked conditions were determined. Larger gravity outlets were evaluated, but essentially no improvement in interior peak stages was noted, due to the ponding storage available at each site.

Table E-4
Seepage Curves for Ponding Areas

Fishpot		I-141		Glass Plant		Simpson Lake		Grand Glaize	
Head (ft)	Seepage (cfs)	Head (ft)	Seepage (cfs)	Head (ft)	Seepage (cfs)	Head (ft)	Seepage (cfs)	Head (ft)	Seepage (cfs)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24.1	1.0	24.1	0.8	1.0	0.8	1.0	0.6	24.0	0.8
26.1	1.1	26.1	1.0	2.0	1.5	3.0	1.8	26.7	1.0
29.7	1.2	29.7	1.1	3.0	2.3	4.0	2.4	29.7	1.1
36.2	1.3	36.2	1.2	5.0	3.8	5.0	3.0	36.2	1.2
				10.0	7.5	10.0	6.0		
				15.0	11.3	15.0	9.0		
				20.0	15.0	20.0	12.0		
				25.0	18.8	30.0	18.0		
				30.0	22.5				

Table E-5
Exterior Unit Hydrograph Parameters

Exterior Location	Drainage Area (sq mi)	Runoff Coefficient (percent)	SCS T(Lag) (hr)
Fishpot Creek	10.1	85	.90
Grand Glaize Creek	23.7	85	1.58

CSA 01.04.00
Study ID VALLEYP
Module ID COINFPME

Exterior Stage (EXSTAGE)

Tributary Rating Table

Tributary Flow (cfs)	Tributary Elevations (ft)						
	Main River Elev (1) 392.00	Main River Elev (2) 400.00	Main River Elev (3) 408.00	Main River Elev (4) 416.00	Main River Elev (5) 424.00	Main River Elev (6) 432.00	Main River Elev (7) 436.00
0.0	395.60	400.00	408.00	416.00	424.00	432.00	436.00
500.0	399.83	400.70	408.04	416.01	424.01	432.01	436.01
1000.0	401.80	402.10	408.15	416.02	424.02	432.02	436.02
2000.0	404.60	404.59	408.58	416.10	424.03	432.03	436.03
3000.0	406.59	406.57	409.24	416.22	424.06	432.04	436.04
4000.0	408.30	408.26	410.06	416.39	424.10	432.05	436.05
5000.0	409.80	409.77	410.94	416.60	424.16	432.07	436.06
6000.0	411.10	411.11	411.85	416.86	424.23	432.31	436.31
7000.0	412.30	412.28	412.72	417.15	424.32	432.43	436.42
8000.0	413.30	413.29	413.59	417.48	424.41	432.56	436.54

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Figure E-3. Tributary rating table

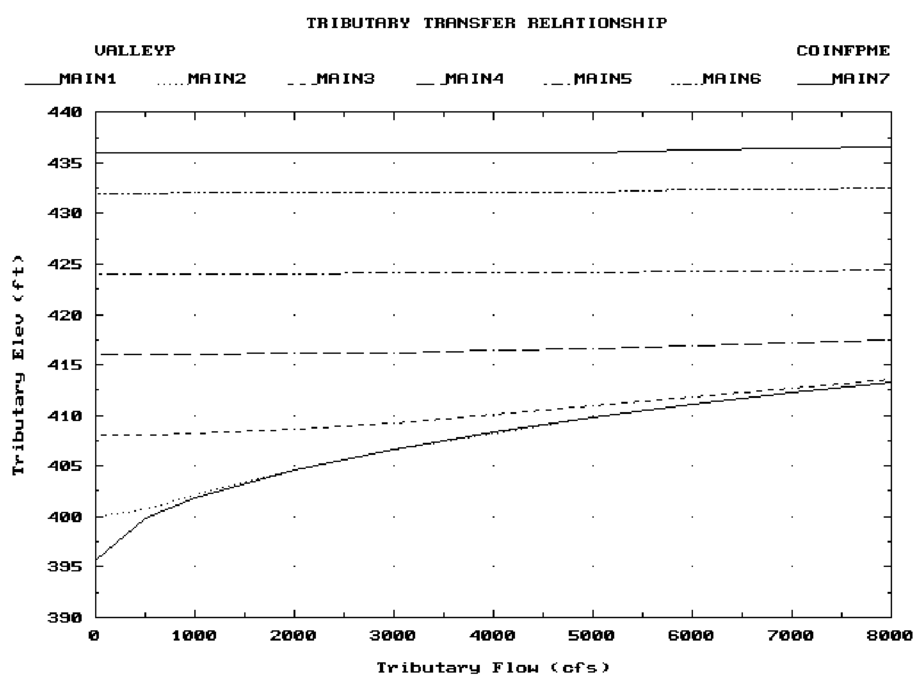

Figure E-4. Plot of tributary rating table *b. CSA.*

(1) Data were used to prepare a CSA for each of the five subareas. Trial runs of HEC-IFH initially were made on an expanded memory 386/25 PC using a 10-min time increment. These early trials resulted in extremely lengthy run times. Runs of 8 to 10 hr were typical, with the run aborting before completion of the CSA due to inadequate computer storage. The acquisition of a 486/33 PC during this phase lessened the problem; however, it was decided to modify the time-step to 1 hr to improve the computation performance. The interior inflow hydrographs would not be adequately defined; however, the inflow volume would be acceptable for routing through the storage areas and out the gravity outlet(s). Using a 1-hr time step for the 40 years of record resulted in about 3 hr of computation time for a 486/33 PC. The CSA gave a continuous stage-hydrograph of ponding elevations and the drain outflow for each site. Annual peak values could then be extracted for graphical display. The stage-frequency relationships resulting from the CSA method were very comparable with the HEA results, falling between the HEA stage-frequency relationships for blocked and unblocked conditions.

(2) The results of the CSA were used to determine the minimum facility, which is shown in Table E-6. Table E-7 compares the results of the HEA and CSA for the 100-year average return period event at one site. Each gravity outlet was analyzed similarly. The hydraulic design details for the gravity outlets planned for the minimum facility are shown in Table E-8.

Table E-6
CSA Interior Analysis Summary (Minimum Facility)

Area Location	Gravity Outlet Size (in.)	Ponding Size (acre-ft) (1% Chance)	Maximum Pond Elev (NGVD) (1% Chance)
Fishpot	1-48	24.8	419.4
Highway 141	1-54	1.9	421.2
Glass Plant	2-48	100.5	418.2
Simpson Lake	1-48	42.7	415.5
Grand Glaize	1-48	20.6	419.2

Table E-7
Comparison of HEA and CSA for the 1-Percent Event

Area Location	HEA Results Closed Outlet (acre-ft)	CSA Results (acre-ft)
Fishpot	32.0	24.8
Highway 141	8.4	1.9
Glass Plant	148.2	100.5
Simpson Lake	44.0	42.7
Grand Glaize	36.1	20.6

Table E-8
Gravity Outlets

Location	RCP Size (in.)	Invert: Inlet (NGVD)	Invert: Outlet (NGVD)	Length (ft)
Fishpot Creek	48	405.0	403.00	198
Highway 141	54	414.4	412.74	163
Glass Plant				
3rd Street	48	405.0	400.89	574
5th Street	48	405.0	397.79	1128
Simpson Lake	48	408.0	405.57	341
Grand Glaize	48	410.5	408.50	152

E-6. Plan Summaries

Individual CSA runs are obviously quite lengthy. One CSA run for a Valley Park subarea, using 1-hr intervals with 40 years of record, yields about 3,900,000 bytes of output. The total output for the various Valley Park plans now retained in the computer requires about 85 MB of storage, a veritable "mountain" of paper. Thus an extremely valuable feature to analyze output is the plan summary tables available within HEC-IFH, which allow the easy comparison of several different plans or scenarios. Examples of some plan summary displays are shown in Figures E-5, E-6, and E-7. These results compare interior elevations, area flooded, stage-frequencies, etc. for the Glass Plant subarea for gravity outflow conditions of two 48-in. outlets (GLASMOD1), two 54-in. outlets (GLASMOD2), and two 60-in. outlets (GLASMOD3). As is readily apparent, there is no significant improvement in the results for larger gravity outlets than the minimum facility (two 48-in. outlets).

E-7. Graphical Displays

Another valuable feature of the HEC-IFH Package is the ease of preparing report quality graphical displays of key information. Figures E-8 through E-13 give examples of graphical information used for the Valley Park FDM. These figures show the monthly maximum, average and minimum ponding stages, and exterior river stages for the period of record. They also show the stage-duration curves for both annual maximum outflow and acres flooded in the ponding area, and the interior stage-frequency relationship from the CSA.

E-8. Summary

HEC-IFH proved to be a useful tool in analyzing the Valley Park interior area. The St. Louis District will continue to use HEC-IFH for interior studies.

CSA 01.04.00
Study ID VALLEYP

Comparison of Plans

A. Analysis Summaries - Maximum Values

Plan ID	Exterior Elev. (ft)	Interior		Head Differential		Pump Data	
		Elev. (ft)	Area Flooded (ac)	Maximum (ft)	Minimum (ft)	Head (ft)	Outflow (cfs)
GLASMOD2	430.21	417.76	15.3	14.95	-18.89	0.00	0.0
GLASMOD3	430.21	417.76	15.3	16.54	-18.89	0.00	0.0
GLASMOD4	430.21	417.76	15.3	14.33	-18.89	0.00	0.0

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Figure E-5. Maximum values for study plans

CSA 01.04.00
Study ID VALLEYP

Comparison of Plans

F. Interior Analysis - Maximum Interior Elevations

Plan ID	Area Prim. Grav. (sqft)	Total Pump Cap. (cfs)	Peak Elevation (ft) vs. Percent Chance Exceedence Frequency Event						
			50%	20%	10%	4%	2%	1%	0.2%
GLASMOD2	25.1	0.0	410.87	413.79	414.94	417.38	417.71	417.95	418.53
GLASMOD3	31.8	0.0	410.91	413.79	414.94	417.38	417.71	417.95	418.53
GLASMOD4	39.3	0.0	410.87	413.79	414.94	417.38	417.71	417.95	418.53

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Figure E-6. Maximum interior elevations for study plans

CSA 01.04.00
Study ID VALLEYP

Comparison of Plans

H. Interior Analysis - Maximum Interior Area Flooded

Plan ID	Area Prim. Grav. (sqft)	Total Pump Cap. (cfs)	Maximum Interior Area Flooded (ac) vs. Percent Chance Exceedence Frequency Event						
			50%	20%	10%	4%	2%	1%	0.2%
GLASMOD2	25.1	0.0	0.0	0.0	0.0	0.0	0.1	3.1	14.8
GLASMOD3	31.8	0.0	0.0	0.0	0.0	0.0	0.1	2.9	14.7
GLASMOD4	39.3	0.0	0.0	0.0	0.0	0.0	0.1	2.8	14.7

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Figure E-7. Maximum interior area flooded for study plans

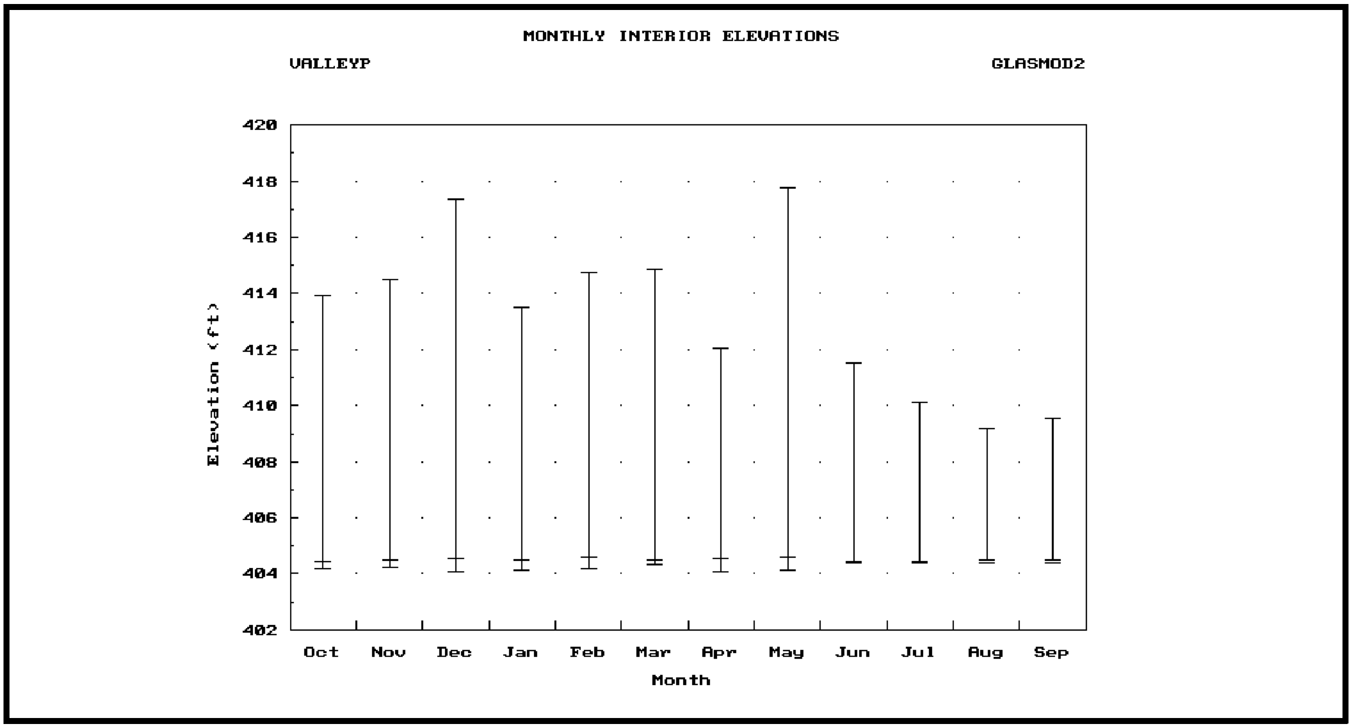

Figure E-8. Monthly interior elevations for glass plant basin

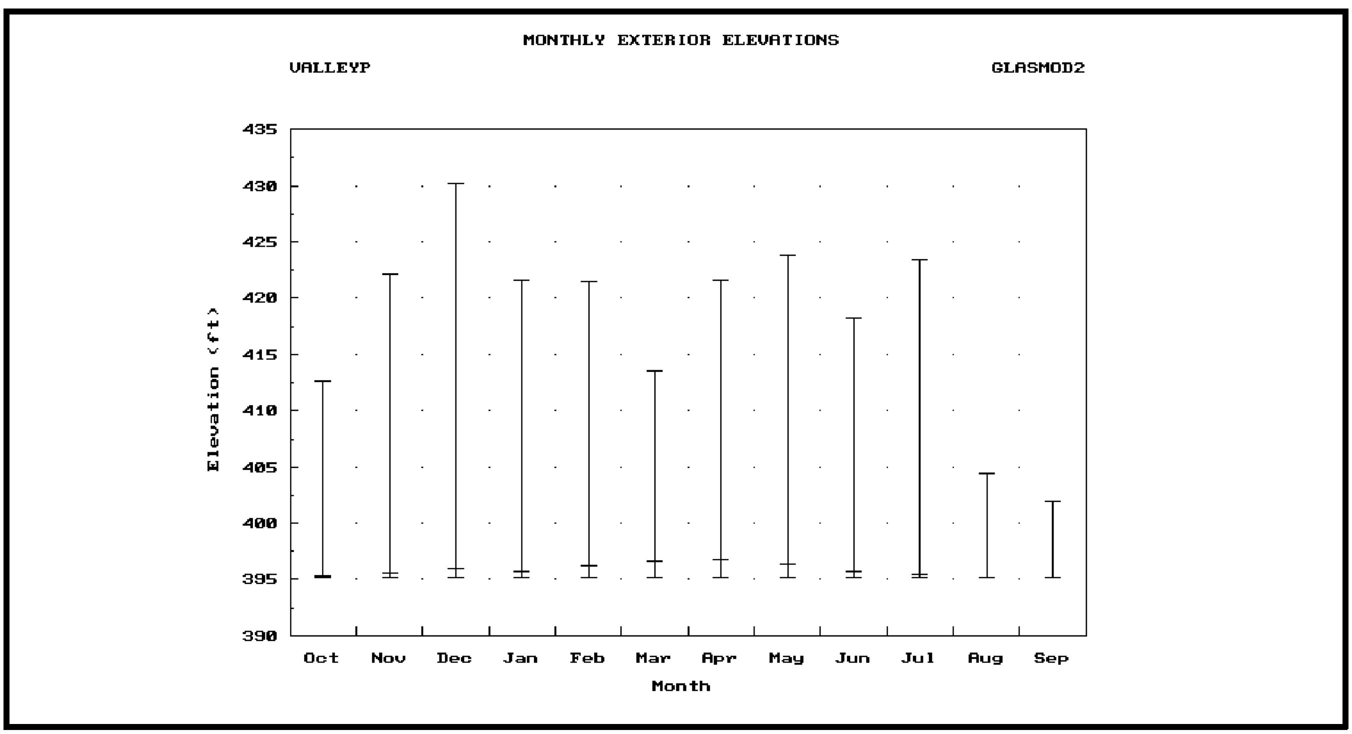

Figure E-9. Monthly exterior elevations for glass plant basin

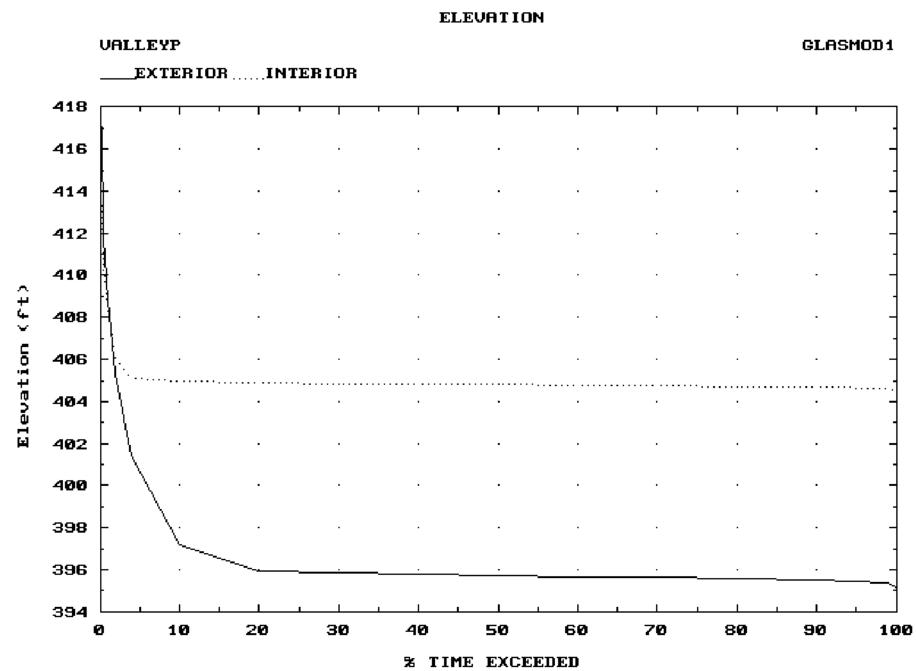

Figure E-10. Interior and exterior stage duration relationships for glass plant basin

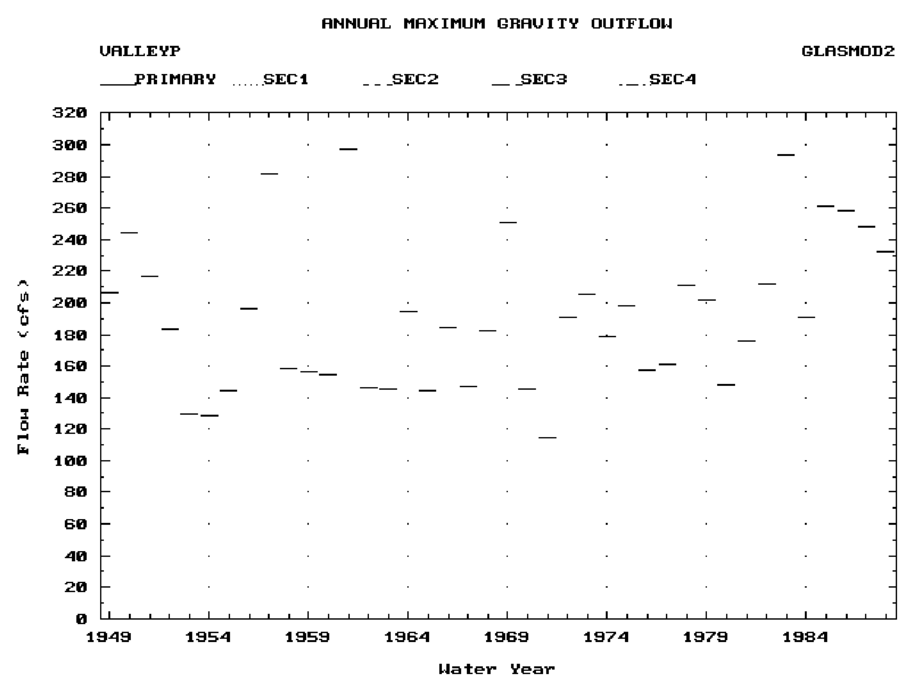

Figure E-11. Maximum annual gravity outflow

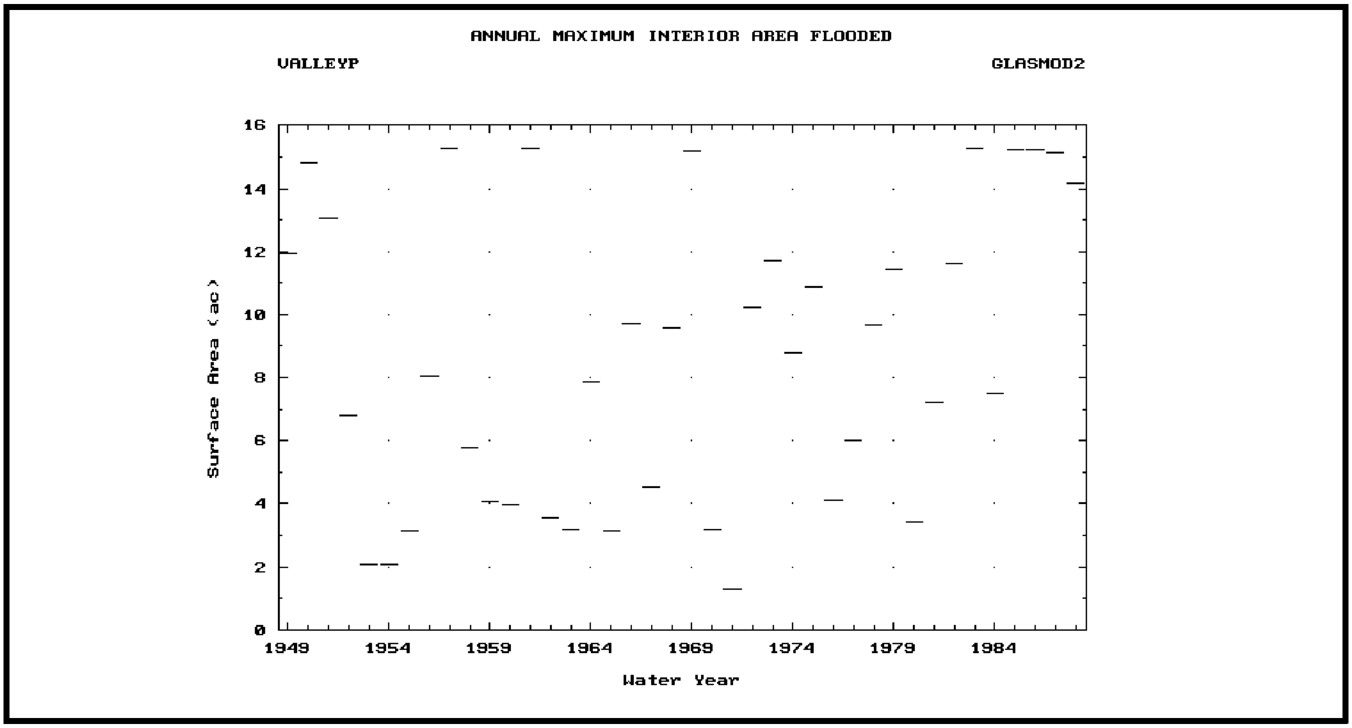

Figure E-12. Maximum annual interior area flooded

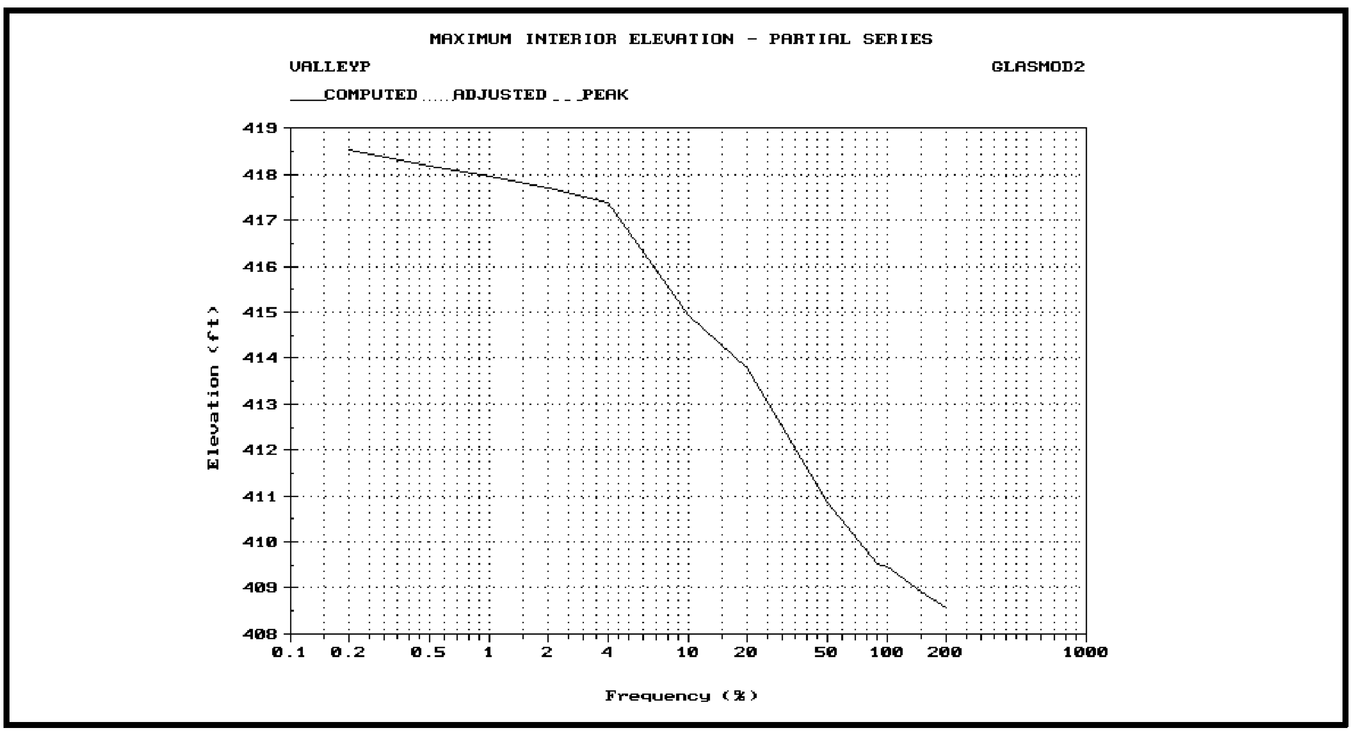

Figure E-13. Interior elevation - frequency for glass plant basin