Use of HEC-IFH Interior Flood Hydrology Package to Perform Interior Drainage Analysis

The U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) Interior Flood Hydrology Package (HEC-IFH), Version 2.01, is a DOS-based computer program that provides the capability to analyze flood characteristics on the landward side of flood mitigation structures, such as levees and floodwalls. These structures generally block the natural egress of floodwater from the interior areas, and the analyses of these conditions are an important part of Flood Insurance Studies (FISs). The HEC-IFH program includes the capacity to analyze gravity outlets and pumps for reducing flood damage due to interior runoff and allows the direct determination of interior stage-frequency relationships.

The USACE initially released its HEC-IFH Package, Version 1.0, in May 1992. Versions 1.01 through 1.04 were subsequently released. Version 2.0 was released in December 1998. Version 2.01 was released shortly thereafter with some minor changes. Although HEC-IFH will continue to be maintained by HEC, no further modifications will be made to the program. Interior area analysis capabilities will eventually be incorporated into the HEC's Hydrologic Modeling System (HEC-HMS), which will replace HEC-IFH.

Program Operational Environments

HEC-IFH 2.01 was tested under Windows NT, Windows 95, and Windows 98 operating systems. Because some existing Flood Insurance Studies were prepared using previous versions of the program, the compatibility of different versions was also tested. The tabulation below summarizes the operating systems required to run different versions.

	Operating System	
HEC-IFH	Windows NT	Windows 95, 98
Version 2.01	Can Run	Can Run
Versions 1.01-1.04	Cannot Run	Can Run

To assess the operational compatibility of Version 2.01 with analyses performed using previous versions of the IFH program, an attempt was made to duplicate the results from two case studies: a Continuous Simulation Analysis (CSA) created using Version 1.03 and a Hypothetical Event Analysis (HEA) created using Version 1.04.

CSA Case Study

The CSA case study was created using HEC-IFH Version 1.03 and used HEC-DSS Version 6-J for data file management, both of which were expected to be compatible with HEC-IFH Version 2.01. However, HEC-IFH Version 2.01 was unable to successfully load and run this CSA case study, although HEC-IFH Version 1.04 and HEC-DSS Version 6-J on a Windows 95 system produced duplicate results to the actual case study.

The tabulation below summarized duplicability of different versions under Windows NT and Windows 95 operating systems.

	Operating System	
HEC-IFH	Windows NT	Windows 95
Created using Ver. 1.03 *	Cannot Run	Did not test
Tested using Ver. 1.04 *	Cannot Run	Can Run
Tested using Ver. 2.01 *	Cannot Run	Cannot Run
*using HEC-DSS Version 6-J		

<u>HEA Case Study</u>

The HEA case study was created using HEC-IFH Version 1.04. Version 2.01 was tested for operational compatibility and it successfully duplicated the prior case study output. This test confirmed the capability of Version 2.01 for performing HEA analyses.

	Operating System	
HEC-IFH	Windows NT	Windows 95
Created using Ver. 1.04 *	Cannot Run	OK
Tested using Ver. 2.01 *	OK	OK
* using HEC-DSS Version 6-J		

Technical Capabilities

HEC-IFH provides two different analysis approaches, each of which is appropriate for certain studies, as presented below.

<u>Continuous Simulation Analysis (CSA)</u>

The CSA approach uses continuous historical precipitation and streamflow records. The procedure consists of sequential hydrologic simulation of inflow, outflow, and storage changes of the interior drainage ponding area. Inflow hydrographs into the interior drainage area in the simulated period are developed from the historical precipitation data. These inflows are used with the exterior stage data during the simulation period to model the response of the interior drainage system, including the operation of flood mitigation structures. The main result of the analysis is a continuous stage hydrograph for the interior drainage area. The program can then perform a frequency analysis to develop elevation-frequency relationships. The water-surface elevation for given recurrence periods can be determined from the relationship.

The CSA preserves the characteristics of the interior drainage area: the seasonality, persistence, and the dependence or independence of the exterior and interior flooding. It does not require the user to make important assumptions, such as the relationship of interior and exterior floods, based on engineering judgments. However, the procedure requires a large amount of data, primarily historical records for precipitation and the exterior stage or discharge hydrographs. A calibration is usually required. To determine the 1% annual chance water-surface elevation for an interior drainage area, a record of continuous precipitation and streamflow covering a time period of approximately 50 years is needed. For a short recording period, calibration to at least one historical event with a recurrence interval more than 10 years is required. These data requirements limit the applicability of the approach to only those interior drainage areas adjacent to large rivers where long historical stage or discharge records are available. Procedures for CSA are described in detail later.

Hypothetical Event Analysis (HEA)

Instead of using historical records, the HEA uses hypothetical storm events as the precipitation input. It is capable of analyzing conditions in which interior and exterior basin responses are dependent on the same meteorological events. A single storm event or a series of storm events is assumed to occur over both interior and exterior areas. Synthetic precipitation data are applied to subbasins of the interior drainage areas. The generated hydrograph as well as the exterior stage data are used to determine the interior ponding area and its associated water-surface elevation. In general, HEC-IFH provides similar options as in the HEC-1 program for computation of runoff hydrographs. For example, it provides initial-uniform, SCS Cover Number, Holtan, and Greeen-Apmt methods for loss rate calculation and Snyder, Clark, and SCS unit hydrograph methods. It also allows users to enter a unit hydrograph.

The HEA approach assumes that the peak discharge rate and the runoff volume of interior drainage area are statistically consistent with the annual chance of exceedance of the rainfall event. For example, a storm with a 1% annual chance exceedance rate would generate a 1% annual chance interior discharge. However, the 1% annual chance interior water-surface elevation will also be affected by exterior conditions. Exterior conditions can be provided as a constant stage or exterior stage hydrograph or be computed from a discharge hydrograph and a rating table. For an interior flood analysis, exterior stages of the exterior flooding source may be obtained from a FIS report . The HEC-IFH program also has the capability to compute exterior hydrographs from rainfall data. Procedures for HEA approach are described in detail later.

Neither of the analysis approaches described above simulates discharges associated with snowmelt in the interior drainage basin.

Documentation

Instructions for installation of the HEC-IFH program and detailed steps for data entry, program operation, and analysis summaries are provided in the *HEC-IFH Interior Flood Hydrology Users Manual*, CPD-31, January 1999, produced by the USACE. Additional information containing guidance and criteria for hydrologic analysis of interior areas can be found in EM 1110-2-1413, *Hydrologic Analysis of Interior Areas*, also produced by the USACE.

Use of HEC-IFH Program for FIS Interior Drainage Flood Analyses

The primary difference between interior flooding problems and other riverine flooding problems is that the water-surface elevation in the interior drainage area is determined by multiple flooding sources. In addition to the flood generated by local storms, the exterior stages also play an important role. Therefore, both locally generated runoff and the exterior stages must be considered. The HEC-IFH program provides a proper framework to incorporate both.

Both the CSA and HEA approaches can be used in FIS interior flood analysis. Selection of which method to use depends on the relationship of interior and exterior flooding sources. The USACE Engineering and Design Manual EM 1110-2-1413, *Hydrologic Analysis of Interior Areas* (http://www.usace.army.mil/inet/usace-docs/eng-manuals/cecw.htm) provides a detailed explanation of how to evaluate the relationship. Table 1 on the following page provides general guidance on how to select a proper method for an interior drainage analysis.

<u>Continuous Simulation Analysis (CSA)</u>

The basic procedures and capabilities for the application of HEC-IFH using the CSA are presented below.

- Subdivided Interior Drainage Basin: the interior drainage basin can be subdivided into upper and lower basins. The ponding area is located in the lower basin, separated from the exterior flooding source by flood protection structures. Only one upper basin is allowed; however, the user may use other programs, such as HEC-1, to estimate discharges from the upper basin in greater detail and input the hydrograph as the inflow to the lower basin.

- Rainfall and Rainfall Excess: the program uses long-term historical rainfall data as input. The rainfall data can come from a single gage or several gages. The program has the capability to compute composite basin precipitation. Rainfall excess of the interior drainage basin is computed using either the initial-uniform-recovery option, a simple soil moisture accounting method, or the generalized runoff coefficient option. No-loss option is also provided. However, for long-term simulation, loss rate should be included in the simulation. The model does not provide option for computing evapotranspiration loss.

- Runoff: rainfall excess is transformed by one of the following unit hydrograph methods: Snyder, Clark, or SCS dimensionless unit hydrograph. Baseflow can be added to the generated hydrograph.

Table 1 - Assessment of Coincidence of Interior/Exterior Floods and Method Selection

Coincidence[1]	Dependence[2]	Examples/Comments	Method Selection
High	High	Hurricanes, large regional events. Interior and exterior areas of similar magnitude.	HEA is often proper for urban areas. Blocked gravity outlet associated with high exterior stages is common.
High	Low	Storm/flood season of small interior area coincides with snowmelt runoff in a large basin.	CSA is preferred. HEA can be used with coincident frequency analysis.
Medium	High	Relatively high likelihood of interior and exterior events occurring simultaneously. The most common situation.	CSA or HEA, depending upon the data availability. Gravity outlets are likely blocked during critical interior events. Coincident frequency analysis procedure usually is required.
Medium	Low		
Low	High	Interior and exterior flood events rarely coincide, such as when the exterior stage is regulated by upstream control structures.	CSA or HEA, depending upon the data availability. Coincident frequency analysis usually is required for HEA. It may provide a lower interior water-surface elevation than the one estimated by using a given high exterior stage.
Low	Low	Rare condition. Interior flooding rarely if ever coincides with high exterior stage.	HEA with a selected exterior stage is often enough. Average exterior stage often is proper. Studies generally focus on gravity outlet assessments.

1. Coincidence – If the interior and exterior events produce stages that coincide, i.e., the exterior stage is high when an interior flood event occurs, then coincidence is said to occur.
2. Dependence – If the physical and meteorological processes of the interior and exterior flood events are related , they are said to be dependent.

- Auxiliary Flows: auxiliary flows are defined as inflows from adjacent areas, such as a diversion from an upper basin of interior drainage area or seepage.

- Channel Routing: three options, Lag, Modified Puls, and Muskingum routing methods, are provided to route the total discharge hydrograph from the upper basin of the interior drainage area to the interior ponding area.

- Exterior Stages: exterior stage data can be defined through the use of an exterior stage hydrograph or an exterior discharge hydrograph and channel rating curve. The program also provides an option to compute the exterior discharge hydrographs by using the same rainfall-runoff procedures described for interior discharge hydrograph computations.

- Pond Routing: the interior flows are routed through the interior ponding area then discharged through the line-of-protection, such as levees or floodwalls, by gravity outlets, pumping stations, or a combination of both. The program is limited to simulate flows for a single ponding area. Multiple ponding areas may be considered only if they are hydraulically linked; thus, the water-surface elevations in all ponding areas rise and fall together.

- Gravity Outlet Computation: the program provide two options: circular and box culverts for gravity outlet computation. It can use up to 25 gravity outlets in each interior analysis. Rating tables of gravity outlet can be computed by the program or provided by the users.

- Frequency Analysis: the program can develop elevation-frequency relationships. It provides annual water year summaries, which include maximum interior and exterior elevations and the maximum flooded area. These annual maximums can form partial series or annual series for frequency analyses. For FISs, the frequency analysis must be based on annual series data.

The HEC-IFH program includes very extensive reporting capabilities. For CSA, the output includes summaries for input data, calculation summaries for rainfall, interior and exterior stage, inflow, outflow, gravity outlet and pumping flows for the interior ponding area and the areas flooded during the entire simulation period. The program also provides monthly and annual (water year) summaries and detailed output as user-defined.

<u>Hypothetical Event Analysis (HEA)</u>

- Subdivided Interior Drainage Basin: as described in the previous CSA section.

- Rainfall and Rainfall Excess: user enters hypothetical storm depth-duration-frequency data for individual or multiple hypothetical events. These data are available from National Weather Service publications TP-40, TP-49, Hydro-35 and NOAA Atlas 2. Four methods are available to compute rainfall excess values: SCS Curve Number, Holtan, Green-Ampt, and the Initial-Uniform Loss Rate.

- Runoff: rainfall excess is transformed into a runoff hydrograph by using either a user-provided unit hydrograph or one of the following unit hydrograph methods: Snyder, Clark, or SCS dimensionless unit hydrograph. Baseflow can be added to the generated hydrograph.

- Auxiliary Flows: auxiliary flows are defined as inflows from adjacent areas, such as a diversion from an upper basin of interior drainage area or seepage. However, the auxiliary flow must not be large enough to affect the statistical consistency of runoff and storm events. If a significant amount of auxiliary flow is involved, the HEA is not the proper approach to use for the analysis.

- Channel Routing: route the discharges from the upper basin of the interior area to the ponding area. Three options, Lag, Modified Puls, and Muskingum routing method, are available.

- Exterior Stages: exterior stage data can be defined through the use of an exterior stage hydrograph or an exterior discharge hydrograph and a rating curve. The program also provides an option to compute the exterior discharge hydrographs by using the same rainfall-runoff procedures described for interior discharge hydrograph computations.

- Ponding Area Routing: the interior flows are routed through the interior ponding area then discharged through the line-of-protection, such as levees or flood walls, by gravity outlets, pumping stations, or a combination of both.

- Gravity Outlet Computation: discussed in the procedures for CSA.

- Frequency Plot: the underlying assumption of HEA is that the storm and the discharge generated by the storm are statistically consistent. Frequency plots for maximum total interior flow, maximum interior elevation, and maximum interior area flooded are based on this assumption. However, when the assumption is not proper, e.g., when a coincident frequency analysis is needed, those frequency plots should not be used to determine the 1% annual chance water-surface elevation. Instead, results of the coincident frequency analysis should be used, as discussed in the following section.

Coincident Frequency Analysis

Coincident frequency analysis is directly applicable to areas where interior and exterior floods rarely occur simultaneously, i.e., these two events are independent. These areas often include small interior drainage areas protected by a levee next to large rivers and lakes. The method applies the total probability theorem to create a stage-frequency relationship for the interior area affected by coincidental interior and exterior flooding.

Coincident frequency analysis is not part of the HEC-IFH program. The user can utilize the HEC-IFH to generate a series of hypothetical event hydrographs and interior elevations. From these interior elevations, the user can develop a series of interior elevation frequency plots for given exterior stage frequencies.   The stage-frequency relationship for the exterior flooding source can be generated by the HEC-IFH or from historical river stage records. Procedures of coincident frequency analysis are described below.

- Develop a stage-frequency relationship for exterior stages, then divide exterior stages into appropriate intervals. Estimate probability for each interval. For example, exterior stages are divided into 5 intervals, B_1, B_2, …, B_5. For an exterior stage interval B_1 with the elevation range from 100 to102 feet, when historical data showed that 60% of the river stages were within this range, then the probability of exterior stage at this interval, $P(B_1)$, is estimated as 0.60. The sum of the probabilities for all intervals must equal 1.

- Conduct HEA for each of the exterior stage conditions. Develop a stage-frequency relationship, $P(A/B_i)$, for each exterior stage condition. $P(A/B_i)$ is the conditional probability of the interior stage A given the exterior stage B_i.

- Develop a relationship of coincident interior water-surface elevation vs. exceedance probability from the conditional probability curve as below:

$$P(A) = \sum_{i=1}^{n} [P(A/B_i) * P(B_i)]$$

Where: P(A) = probability of exceeding a given interior elevation.

$P(B_i)$ = probability of exterior flood source at the specific stage interval i; for interval i, assume the full range of values affecting the interior ponding elevation.

P (A/B_i) = probability of exceeding a given interior elevation if the exterior flood source is at the stage interval i.

- Plot interior stage vs. exceedance probability to arrive at the coincident frequency curve.

Critical Aspects of HEC-IFH Applications

The HEC-IFH program provides an excellent tool for interior area hydrologic analyses. It requires technical skills in hydrology, hydraulics, and probabilistic analysis. The most critical aspect of the HEC-IFH application concerns the assessment of interior/exterior basin dependence and flood coincidence. In many cases, the study areas do not have the detailed precipitation and stream gage records necessary for a CSA; therefore, an HEA will be the only feasible approach for performing an interior analysis. When using an HEA, the assessment of interior/exterior basin dependence will have great influence on the selection of method to model the exterior stage. The choice of exterior stage representation coupled with a coincident frequency analysis can affect, sometimes significantly, the computed interior flood elevations and boundaries of interior floodplains.

<u>Exterior Stages</u>

There are essentially two methods of modeling the exterior stage hydrograph in an HEA: a constant exterior stage for the entire duration of the flood event, and a variable exterior stage as determined from a rainfall-runoff model of the exterior basin. The appropriate method for a particular study depends on the assessment of interior/exterior basin dependence. For this assessment, consideration should be given to the relative areas of the interior/exterior basins, their associated topographic conditions, individual basin response times, and the size of the basins relative to the area of storm events typical for the study area.

If the assessment indicates a low dependence between the interior and exterior basins, then it is appropriate to model the exterior stage as a constant elevation for the duration of the flood event. An example is a small interior drainage area protected by a levee along a major river. The interior floods are often caused by local thunderstorms while the exterior elevation is determined by upstream conditions of the river. Interior and exterior basins are basically independent. The exterior stage may be determined by analyzing gage records. The HEC- IFH program provides an option to transfer gage stage in distance into the exterior elevation at locations of outlets.

Conversely, if the assessment indicates a high dependence between the interior and exterior basins, it is appropriate to simulate the exterior stage hydrograph by either using the HEC-IFH program, or, for more complicated situation, other programs such as HEC-1. The exterior stage hydrograph can be imported into the HEC-IFH model.

Using a constant exterior stage in cases where the interior/exterior basin dependence is low simplifies the modeling approach without compromising the validity of results. Similarly, using a variable exterior stage allows an accurate consideration of the individual basin response times and the associated opportunities for gravity drainage of the interior area.

The determination of basin dependence depends on the judgement of the engineer performing the analysis. Users are encouraged to investigate hydrologic and watershed conditions for both interior and exterior watersheds to arrive at a site-specific conclusion. While this is not necessarily an undesirable scenario, some engineers will not feel comfortable making this determination and would prefer some minimum guidance on this matter. As such, the relative sizes of the interior/exterior basins can be considered in determining probable dependence.

The criteria below may be used as a general guidance only when other meteorological, hydrologic, and watershed data are not available:

- If the exterior basin is at least 50 times larger than the interior basin in area, then the interior/exterior basins may be considered to have a low dependence. This guidance should only be applied to exterior basins greater than 100 square miles in area.

- If the exterior basin has an area less than 100 square miles or has a ratio to interior area of less than 50, then the interior/exterior basins may be considered to have high dependence.

When performing an interior analysis, the most conservative results (i.e., higher water-surface elevation) would be generated by assuming a constant exterior stage with the same frequency as the interior flood (such as using Base Flood Elevation for the exterior stage) for the entire analysis period. This assumption usually generates the highest interior flood elevation and the largest interior floodplain. This assumption also is applicable to the situation where the interior and exterior floods are caused by the same regional event or are highly coincidental, and where the exterior peak lasts longer than the interior peak, thus making the variation in exterior stage negligible. In most cases, however, the exterior stage changes significantly during the modeling period. When the exterior stage is high; the interior area is blocked and, thus, unable to discharge interior runoff. When the exterior stage is low, the interior area is able to discharge interior runoff. Use of a constant exterior stage cannot reflect this change. As a result, the interior water-surface elevation and flooding areas will be overestimated.

The HEA case study provides evidence of this concept. The difference in the interior flooding elevation between using the Base Flood Elevation as the constant exterior stage vs. variable exterior stage hydrograph generated by the HEC-IFH exterior watershed modeling is shown in the following tabulation.

	Exterior Stage Hydrograph	
	Constant	Variable
1% Annual Chance Exceedence Interior Water-Surface Elevation (ft)	741.36	740.30

For this case, the interior area is 29 acres, the exterior area is 8,448 acres, and the modeling period is 24 hours.

The duration of the rainfall event used in the simulation must be long enough to reflect the true nature of the interior drainage flooding. A 24-hour rainfall is recommended for use as a minimum. A longer rainfall period must be used if the interior flooding for the area is typically associated with a long period of interior rainfall and a coincidental high exterior elevation.

Coincident Frequency Analysis

The HEC-IFH program can be used as an analysis tool with a coincident frequency analysis (not performed by the HEC-IFH program) to provide a more accurate determination of probable interior flooding. If it is determined that the interior and exterior floods usually occur coincidentally, the user may use a 1% annual chance water-surface elevation, either from a FIS or from another analysis, as the exterior elevation in an HEA. Otherwise, the user must be cautious not to simply use the frequency plot from the HEA to determine the 1% annual chance interior water-surface elevation. Instead, a coincident frequency analysis should be performed to determine the 1% annual chance coincident interior water-surface elevation. The user must conduct a series of HEA runs to obtain frequency plots of interior elevations for different constant exterior stages. A detailed example of coincidental frequency analysis is presented in EM 1110-2-1413.

Conclusions

The HEC-IFH program provides an excellent tool for interior area hydrologic analyses for use in FISs because of its technical capability and flexibility. The program can be used to determine the water-surface elevation for interior drainage areas adjacent to the levee. It can simulate the rainfall-runoff process, stream flow routing, and complex configurations of gravity outlets and pumping facilities. It provides options to develop the elevation-frequency relationship for the interior drainage area, and summaries study results in various tables and graphics.