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The U.S. Army Corps of Engineers has broad, nationwide water resources planning and management responsibilities. In response to the needs of Corps planners, the Hydrologic Engineering Center (HEC) has developed and supports a family of computer programs designed to aide them in their work These programs include catchment, channel, alluvial, and statistical process models, system operation models, plan evaluation models, and data management programs. These models individually and collectively have been used throughout the Corps in a wide range of water resources planning studies.

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Papers in this series have resulted from technical activities of the Hydrologic Engineering Center. Versions of some of these have been published in technical journals or in conference proceedings. The purpose of this series is to make the information available for use in the Center's training program and for distribution with the Corps of Engineers.

HYDROLOGIC ENGINEERING CENTER PLANNING MODELS[1]

David T. Ford and Darryl W. Davis[2]

ABSTRACT: The U.S. Army Corps of Engineers has broad, nationwide water resources planning and management responsibilities. In response to the needs of Corps professionals, the Hydrologic Engineering Center (HEC) has developed and supports a family of computer programs designed to aid them in their work. These programs include catchment, channel, alluvial, and statistical process models, system operation models, plan evaluation models, and data management programs. These models individually and collectively have been used throughout the Corps in a wide range of water resources planning studies.
(KEY TERMS: planning; water resources; computer programs.)

CORPS OF ENGINEERS PLANNING RESPONSIBILITIES

Overview

The U.S. Army Corps of Engineers (USACE) has broad-in-scope, nationwide water resources planning and management responsibilities. These responsibilities are carried out in regionally-dispersed field offices by professionals working under the civil works arm of the Corps. The Corps water resources planning responsibilities are the result of accumulated congressional acts, court decisions, administrative directives, and interagency agreements. Likewise, the planning process that has evolved to meet these responsibilities is the result of decades of experience in performing a wide range of studies in an open public environment. The public mandate to Corps planning is to consider the broad range of water resources management issues and to develop plans that provide for balanced management of the Nation's water resources: comprehensive multi-objective planning is the charge. Policies governing Corps planning responsibilities and the multi-objective planning process are summarized in the Water Resources Policy Digest (USACE, 1983).

Planning Responsbilities

The planning responsibilities of the Corps fall into two categories, based on project purposes. In the first are project purposes for which the U.S. Congress has directed the Corps to assume a national leadership role, including navigation (inland waterways and ports), hurricane protection and beach-erosion control, and flood-damage reduction. One of these major functions must be addressed in a proposed plan before the Corps may request congressional authorization for construction. The Corps is, however, charged with considering the full range of multipurpose opportunities in all planning studies, whether or not the Corps has authority to recommend construction. Thus in the second category of planning responsibilities, the Corps considers potential for development of hydroelectric power, water supply, and recreation facilities, for stream-bank erosion reduction, for fish and wildlife enhancement, and for wetlands protection. Congress may authorize the construction of facilities in this second group as a component of a project with facilities in the first group, but cost sharing or reimbursement funding by local governments generally is required.

Planning Process

Corps planning studies are staged studies, with the analysis of each stage increasing in detail and the results of the analysis becoming increasingly specific in plan details. Figure 1 illustrates the interplay between stage of study and study emphasis. The **reconnaissance stage (Stage 1)** bounds the problem and determines if feasible solutions exist. Computer-model use in this stage is minor, but decisions regarding subsequent model use are made here. The **intermediate plan formulation stage (Stage 2)** is the major creative and screening stage and thus is the focus of many planning models. The most significant role for computer models is for plan evaluation in this second stage and early in the final stage. The final stage **(Stage 3)** is the **alternative selection and detailed evaluation stage.** In this stage the data displays are prepared, and coordination and other actions prescribed by law and by administrative regulations are performed. The computer models are more useful at this point for developing appropriate displays than for plan formulation. However, detailed and specialized programs can be important in this stage if noteworthy problems are examined in detail, particularly environmental-impact problems.

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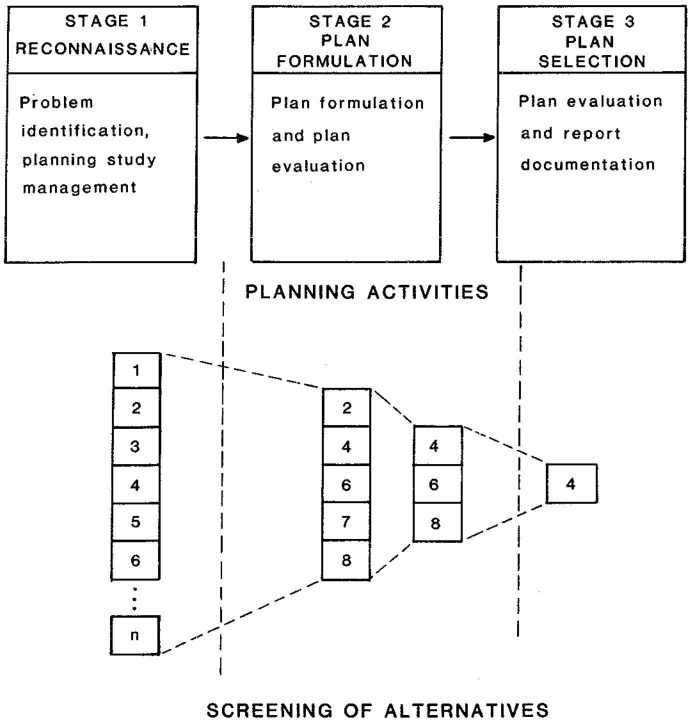

Figure 1. Corps Staged Planning Process.

ROLE OF HEC COMPUTER MODELS

Perspective

The process that produces water resources plans is under the control of and is performed by the professionals who individually contribute specialized information and insights while collectively conceiving of plan elements and assuring the "soundness" of the plans that emerge. Water resources planning models are used in this process for identification of alternatives and evaluation of plans. Planning models are not planners nor do they perform planning. Their role is to facilitate the process by assisting the responsible professionals. The models are not substitutes or replacements for professional judgment, and they do not short-cut the planning process. Instead, models develop data that provide information that, in turn, gives insight into problems and to opportunities for solution. Water resources planning models do not necessarily speed studies or reduce overall study cost. They do provide for analysis of many more alternatives than would be possible otherwise. They also permit evaluation of complex alternatives for solution of complex problems in significantly more detail and with an increasingly higher degree of confidence and repeatability than otherwise possible.

The emergence of a plan, from the perspective of technical modeling, is envisioned as requiring two essential elements. The first is the ability to emulate the physical processes and thus to understand the physical impacts of management plans. The second is the ability to evaluate the benefits and costs of managing the water and related resources. Plans, or elements of plans, are formulated by people and then are tested against efficiency criteria. The criteria are complex and emanate from various aspects of the planning process. The need, therefore, is to have the capability to evaluate proposed plan elements for comparison.

HEC Models and Planning

The Hydrologic Engineering Center (HEC) is a research, training, and consulting organization of the Corps of Engineers, with technical expertise in hydrology, hydraulics, and water resources planning. Since 1964, the HEC staff has developed, tested, supported, and applied computer programs that aid with the planning activities of the Corps. The HEC family of computer programs was developed and continues to expand in response to field office needs of the Corps. The HEC water resources planning models are categorized as: 1) physical and statistical process and system operation models, 2) evaluation models, and 3) data management programs. Figure 2 is a conceptualization of the planning and modeling process as discussed herein, with the role of these categories of models shown. The categorization is conceptual in terms relevant to planning as it is performed by the Corps.

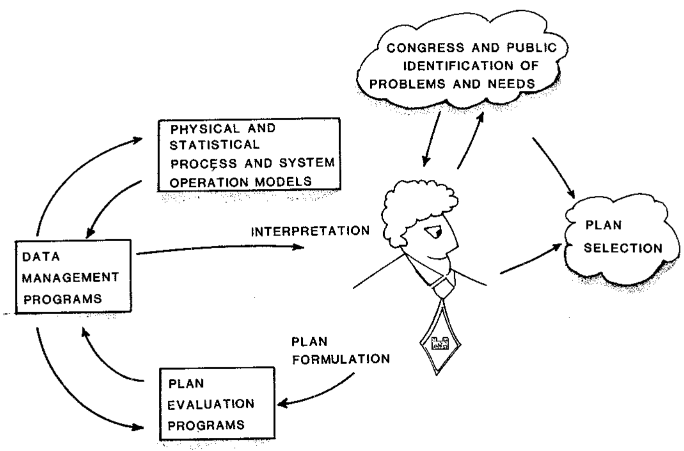

Figure 2. Model Use in the Planning Process.

MODELS OF PHYSICAL AND STATISTICAL PROCESSES AND SYSTEM OPERATION

HEC's physical and statistical process models allow the water resources professionals to simulate these processes and thus to quantify the effects of alternative solutions to water-related problems. The characteristics of the physical system, statistical process, or water uses are described by the model user with input data. The response of the system is predicted by solution of the equations describing the process. Models currently available from HEC are categorized as models of catchment processes, of channel processes, of alluvial processes, of statistical processes, and of system operation. Several of the models are capable of simulating processes in more than one category. Additional detailed information on these models is presented by Feldman (1981).

Catchment Processes

The primary HEC tool for evaluation of catchment processes is program **HEC-1, the Flood Hydrograph Package** (USACE, 1980a). **HEC-1** is a single-event model which uses a spatially and temporally-averaged description of the catchment to estimate the runoff from discrete storm events. Complex catchments may be modeled by subdividing, analyzing independently the subdivisions, and combining the results. Historical precipitation data are provided by the program user, or hypothetical storm data are derived by the program with National Weather Service procedures (U.S. Department of Commerce, 1956, 1961, 1977) or Corps of Engineers procedures (USACE, 1952). Catchment snowfall may be specified, and snowmelt runoff may be computed. Interception, infiltration, and other rainfall and snowmelt abstractions are estimated using common techniques. The magnitude and timing of runoff is simulated using a unit hydrograph technique, or the kinematic wave procedure (Harley, 1975). If desired, estimated baseflow is then added to the computed runoff to yield total flow at the catchment outlet. The results of computations are tabulated and may be plotted, as in Figure 3. The capability to simulate various catchment processes is available also in smaller, single-purpose programs from which program **HEC-1** was developed (USACE, 1966a, 1966b, 1966c, 1966d, 1966e, 1966f) and in the **STORM** program (USACE, 1977c).

Channel Processes

The models of channel processes developed and supported by HEC may be categorized as channel routing, reservoir routing, flood-inundation, and dam-overtopping models. The flood-inundation model, **HEC-2**, computes water-surface elevation at any cross section of a natural channel for subcritical or supercritical steady flow. The standard-step method (USACE, 1979c) is used to solve the one-dimensional energy equation, with adjustments and extensions for obstructions and for channel expansion and contraction. Flow through bridges and culverts may be simulated, and the impacts of channel improvements, embankments, and levees may be evaluated with the model. Results are tabulated and may be plotted.

The **Gradually-varied Unsteady Flow Profile** program (USACE, 1977a) and the **DWOPER** program (Fread, 1978) are available for simulation of unsteady channel flow or for simulation of flow in channels in which structures or flood-plain geometry cause rapid variation of water surface elevation. Channel routing models simulate the movement of a flood wave in a natural channel by solution of the continuity and energy equations. This may be accomplished with either of the unsteady flow models, but most often is accomplished with a model which solves a simplification of the equations. Programs **HEC-1** and **HEC-5** (USACE, 1982a) and the **Hydrograph Routing and Combining** (USACE, 1966c) program provide the capability to solve, with alternative techniques, the simplified equations and thus, to define the translation and attenuation of a flood wave in a channel.

HEC's *reservoir routing* models simulate the movement of a flood wave through an uncontrolled reservoir or a detention structure. Program **HEC-1** includes this capability, as does program **HEC-5**. In both cases, the characteristics of the reservoir are described through program input, and a simplification of the continuity and energy equations is solved to determine the reservoir outflow hydrograph, given the inflow hydrograph. Program **HEC-5** can also be used to simulate long-term controlled reservoir operation for water supply and for other conservation purposes.

The capability to simulate dam overtopping or dam failing is provided by a component of program **HEC-1** and by program **DAMBRK** (Fread, 1980). **HEC-1** uses simplified procedures to simulate dam overtopping and, if desired, to simulate the formation and expansion of a breach. The previously described reservoir and channel routing components of this model are employed for the simulation. The **DAMBRK** program, developed by the National Weather Service and supported by the staff of the HEC, simulates the failure of a series of dams on a river, solving the continuity and energy differential equations with a finite-difference numerical scheme. With either model, the results of the simulation are the discharge or stage hydrographs due to the overtopping or failing.

Alluvial Processes

Reservoir sedimentation and erosion and sediment deposition in rivers can be simulated with HEC's alluvial process models. Program **HEC-6** (USACE, 1977b) simulates the transport of sediment in a river, accounting for scour and deposition within the channel. This simulation is accomplished by linking a model of the channel processes with appropriate equations that simulate the interaction of the water-sediment mixture and the river-bottom sediment material. The **Deposit of Suspended Sediment in Reservoirs** (USACE, 1967a) program simulates deposition of sediment as a function of sediment grain size, reservoir temperature, discharge, reservoir geometry, inflowing sediment load, and the sediment-trapping efficiency of the reservoir. The **Reservoir Delta Sedimentation** program (USACE, 1967b) and the **Suspended Sediment Yield** program (USACE, 1968) also simulate deposition and transport of alluvial material.

Statistical Processes

Statistical process models developed in HEC permit estimation of the probability of various magnitudes of annual maximum discharge and generation of alternative sequences of monthly streamflow for project evaluation. The **Flood Flow Frequency Analysis** program (USACE, 1976) implements the Water Resources Council's guidelines for frequency analysis of annual maximum discharge with the log-Pearson type III distribution (U.S. Department of the Interior, 1981). The distribution parameters are estimated for a single streamflow station, considering the impact of broken and incomplete records, zero-flow years, outliers, and historic events. The

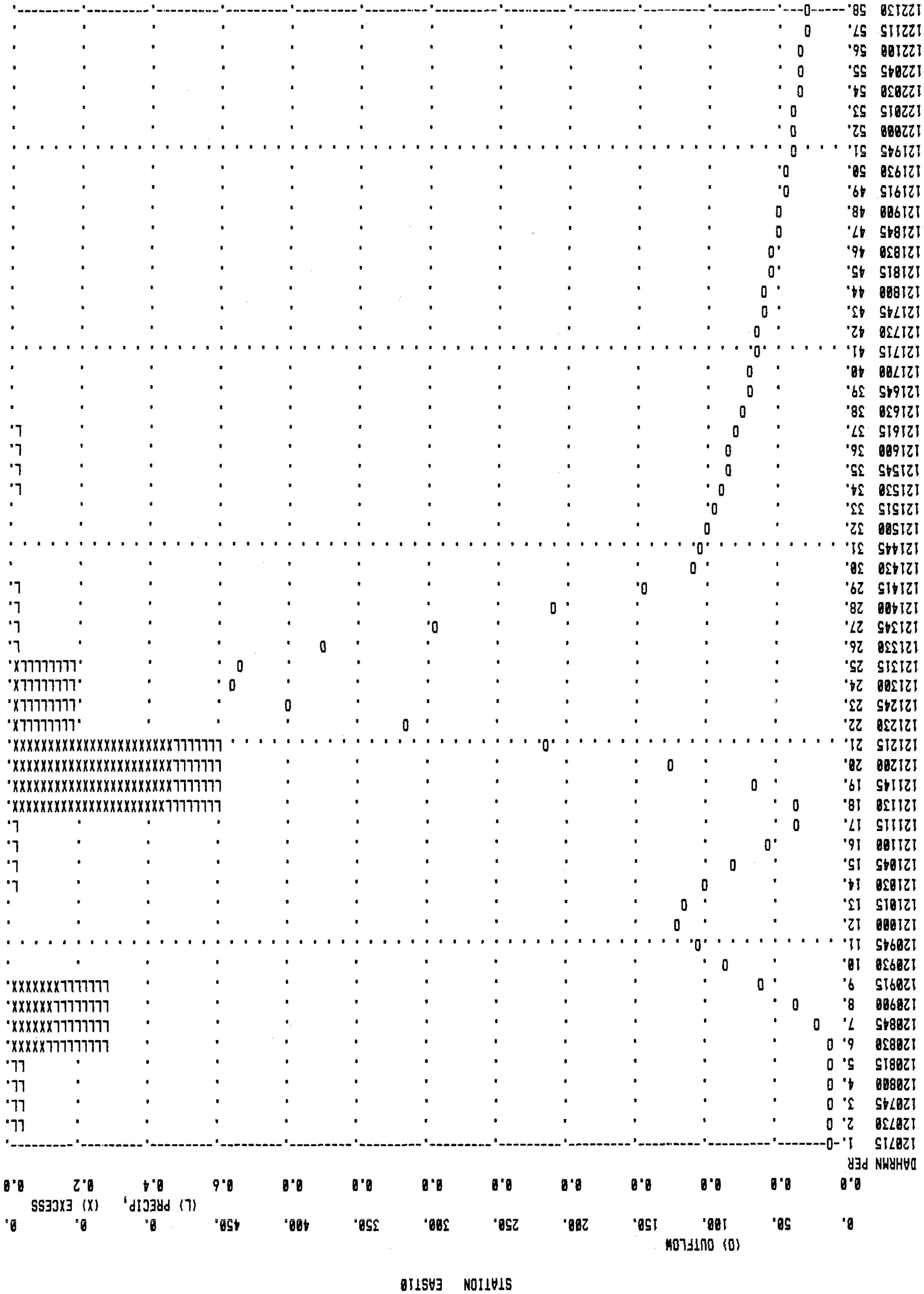

Figure 3. Plot of Hydrograph and Hyetograph Computed with HEC-1.

fitted annual maximum discharge frequency curve is tabulated and plotted.

The **HEC-4** (USACE, 1971) program was developed recognizing that performance evaluation of a complex water resources system with only available historical data will not adequately reflect the expected long-term system benefits. This program analyzes monthly streamflow data to estimate the parameters for modeling the discharge-frequency relationship with a log-Pearson type III distribution. An autoregressive model is used to generate sequences of monthly discharge. The response of a water resources system to the various sequences subsequently may be analyzed with a model of the physical processes or system of interest, thereby permitting evaluation using long-term performance averages.

System Operation

In some applications, existing process simulation models did not satisfy planning study requirements, so specialized models of system behavior were developed. Examples of such models are programs **HEC-5** and **D2M2** (USACE, 1983a).

The **HEC-5** program simulates the operation of a multipurpose water resources system consisting of reservoirs, points of demand (control points), and interconnecting channels. The system demands may be specified at any of the system reservoirs and at any of the control points; these demands may include hydroelectric power requirements, requirements of water for water quality maintenance and for water supply, and requirements for capacity to store flood waters. Given the demands, a sequence of reservoir inflows, channel capacities, and the inter-reservoir operating rules, the program selects reservoir releases to satisfy the requirements. The system operation is simulated with these releases, and the resulting system status is reported. This report of system status includes tabulations of volume of water stored in each reservoir each period, release from each reservoir each period, discharge at each control point each period, and a summary of the demands satisfied system-wide.

The **Dredged-material Disposal Management Model (D2M2)** was designed for systematic simulation and evaluation of alternative disposal system long-term management policies. With the model, disposal-site dewatering rates, containment dike heights, and other characteristics of the disposal system are specified by the model user, so management schemes that involve changes in these parameters can be simulated by systematic variation and re-execution of the model. **D2M2** simulates disposal system behavior as flow through a network and solves for the least-costly operation with a mathematical programming formulation. The mathematical programming formulation includes continuity constraints for material sources and for disposal sites, transportation link and disposal site capacity constraints, and carry-over storage constraints.

MODELS FOR PLAN EVALUATION

Models for plan evaluation quantify the efficiency of alternative plans, using results of physical and statistical process simulation or of simulation of system operation. The output reports of the process simulation models allow direct quantification of plan efficiency by permitting comparison of simulated performance with performance targets. For example, to select the best reservoir operation policy, the target rates of reservoir withdrawal for water supply can be compared to rates simulated with program **HEC-5** with a candidate inter-reservoir operating policy. As an alternative to using directly the physical criteria of system performance, a plan evaluation model may be used, and the physical performance may be related to economic benefits or to another index of performance. The HEC's **Expected Annual Damage (EAD) Program** (USACE, 1979a), the **HEC-1 Program,** the **Structure Inventory for Damage Analysis Program (SID)** (USACE, 1982b), and the **Interactive Nonstructural Analysis Program (INA)** (USACE, 1980b) use the results of the process models to perform such an evaluation.

Expected Annual Damage Program

The **EAD** program was developed for economic analysis of inundation-damage reduction plans. The program follows the requirements and guidelines of the "Evaluation of Beneficial Contributions to National Economic Development for Flood Plain Management Plans" (USACE, 1975). Expected annual flood damage may be computed for a specific location in a specific year with particular hydrologic, hydraulic, and economic conditions in that year, or for a series of future years, to permit discounting to estimate long-term benefits with changing conditions. The input data for **EAD** consists of floodplain management plan description, damage reach delineation, damage category identification, flow-frequency, flow-stage, stage-damage relationship specification, and identification of the time frame for analysis. A similar procedure that analyzes seasonal and duration effects is incorporated into **HEC-5.**

HEC-1 Plan Evaluation Capability

Computer program **HEC-1** includes the capability to evaluate simultaneously the expected annual damage for alternative catchment conditions or with alternative flood-damage reduction measures. Furthermore, the program includes an algorithm to identify the optimal sizes of damage-reduction measures that have been described in general detail by the program user. The algorithm selects trial sizes for system components, repeatedly simulates the physical processes with a range of storms to define the damage-frequency function, computes expected damage with the intergration procedures of the **EAD** program, determines an index of performance that includes component cost, damage reduction, and a measure of risk, and reiterates as necessary to identify the "best" series of all proposed components.

Structure Inventory for Damage Analysis Program

The **SID** program aggregates the depth-damage relationships for individual structures in a section of flood plain to provide a single relationship for flood damage computation. This aggregated depth-damage relationship is combined with the results of channel process simulation, reservoir operation simulation, and statistical process simulation to permit expected damage computation with the **EAD** program. The effects of nonstructural flood-damage mitigation measures that alter the depth-damage relationship can be evaluated by describing those measures; the aggregated depth-damage relationship is modified accordingly.

Interactive Nonstructural Analysis Package

The computer programs of the **Interactive Nonstructural Analysis Package** were developed to manage large amounts of data for nonstructural planning and to perform the calculations to assess the efficiency of alternative nonstructural flood-damage mitigation measures. The programs focus on individual structures or on user-defined groups of structures as the elements of analysis. Alternative nonstructural measures are evaluated on a structure-by-structure basis, just as these measures would be implemented. For each structure in the flood plain, basic and computed information are stored in a data bank. This information characterizes the structure and the nature of the flood problem at the structure. These structure attributes are used for identifying structures for which nonstructural measures may be appropriate. The program interacts with the **EAD** program to compute expected annual damage with existing or with proposed modified conditions.

DATA MANAGEMENT TOOLS

Data management tools provide a systematic means for organizing, storing, retrieving, manipulating, and sorting data for process models and for plan evaluation models. HEC's data management tools include a spatial data management system, **HEC-SAM**, and a general-purpose data storage system, **HEC-DSS.**

HEC-SAM

The **HEC-SAM** is a system of general-purpose data management models which store, access, update, and manipulate geographically-oriented data (Davis, 1981). The system has two distinct functional components: file management and file-processing interface. The file management element comprises computer programs that manipulate and process geographic data so the data are represented in a grid cell format. The file-processing interface component includes programs that sort and reformat data so those data may be analyzed with the appropriate process simulation or evaluation models. Programs in this category are **HYDPAR** (USACE, 1978a), which estimates catchment model parameters from land-use data stored in grid-cell format, and **DAMCAL** (USACE, 1979b), which develops depth-damage relationships from damage data stored in grid-cell format. Other special-purpose display and attractiveness and impact analysis programs are available for analysis of the stored data (USACE, 1978b). Figure 4 is an example attractiveness map produced by these programs. The previously described simulation and evaluation models are employed for technical analysis.

The objective of the **HEC-SAM** programs is to provide the data-management capability for systematic assessment of alternative land-use patterns and flood-damage mitigation plans. **HEC-SAM** programs manage data required to evaluate damage from a specific storm and to develop elevation-frequency relationships for expected damage computation for modified flood plain conditions. The programs can be used also to develop data in the format required to evaluate physical or statistical process modifications, and to evaluate damage or damage reduction due to changes in flood plain occupancy, changes in catchment and stream channel characteristics, changes in structural construction practices, changes in development-control policies, and changes in values and damage potential of flood plain structures. The damage-reduction due to structural and nonstructural damage-mitigation measures can be evaluated also. **HEC-SAM** programs manage data required to perform a variety of environmental evaluations for management alternatives and modified catchment conditions.

HEC-DSS

The HEC data storage system, **HEC-DSS,** is a file management system that allows convenient, orderly exchange of data between **HEC** planning programs (USACE, 1983b). Figure 5 illustrates an application of HEC-DSS to exchange data between physical process and plan evaluation models. The **HEC-DSS** consists of a library of FORTRAN-callable subroutines that store data in a standard format and retrieve those data on demand. References to the library routines can be added to any existing or newly-developed programs. The files created are random-access files with a hierarchical system of names to control data flow and to expedite storage and retrieval. In addition to allowing convenient data transfer between programs, the **HEC-DSS** system allows centralization of utility functions commonly used by process simulation and evaluation models. These utility functions include data editing routines, report generation and data tabulation and display routines, and statistical summary routines.

ACCESS

The HEC planning programs are developed with public funds and are available to the public from the HEC. FORTRAN source files and standard test data files are distributed on magnetic tape. Executable versions of the programs are maintained by the HEC staff on government-owned or leased computers for use by Corps professionals. The programs also are available for use through computer time-sharing vendors. Users manuals are available from HEC for all programs, and programmers manuals and supplementary documentation are available for many of the programs. HEC staff conducts training courses for Corps professionals on program application; similar courses are offered to the public by universities. Video tapes of selected HEC training courses and

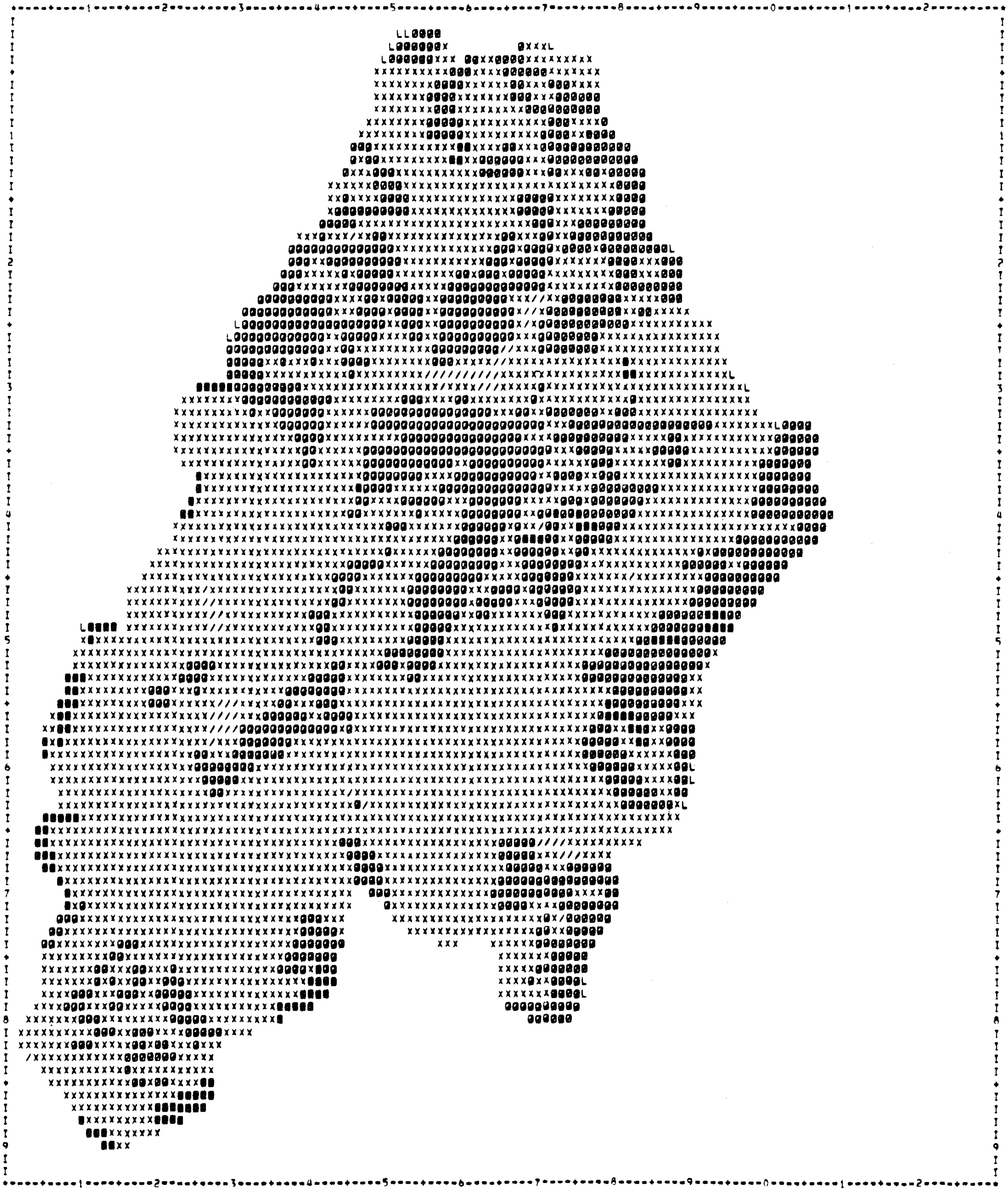

Figure 4. Attractiveness Map from HEC-SAM Programs.

accompanying course materials are available for loan to the public. Catalogs of all these materials are available.

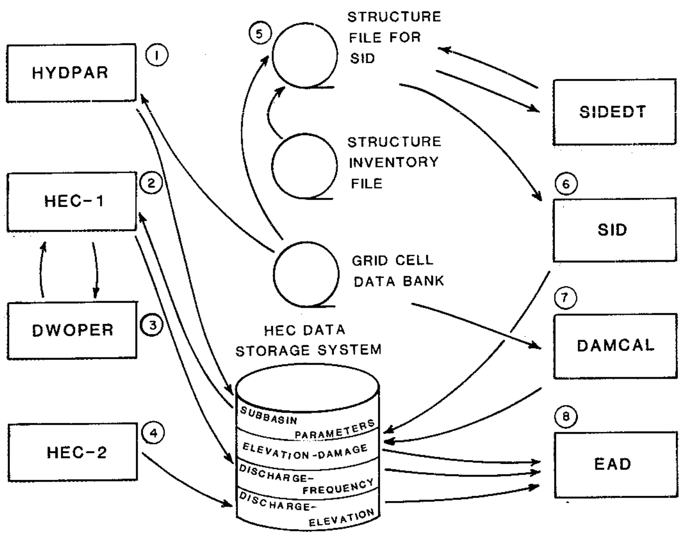

Figure 5. Application of HEC-DSS to Exchange Data Between Models.

FUTURE PLANS

Future plans at HEC include improving existing models, converting existing models to execute on microcomputers, and developing new models to meet the needs of Corps study requirements. All new models developed now follow software engineering guidelines that are intended to yield programs that are reliable, easily transported from one computer system to another, readily modified, and easily supported and maintained. Certain existing programs are being rewritten to conform to these guidelines. The capability to transfer data via the HEC-DSS and HEC-SAM is being added to many of the existing models, thereby allowing integrated application of the programs in planning studies.

Historically, HEC programs have been designed for and executed in batch mode on large main-frame computers. In response to the needs of Corps field offices, HEC staff is converting several of the most commonly used programs to execute on 16-bit microcomputers, including HEC-1, HEC-2, EAD, and SID. Gradual conversion of other programs to execute on 16- or 32-bit microcomputers is planned.

Development of new planning models continues at HEC in response to the needs of Corps field offices. No grand design exists for an ultimate set of HEC programs. Instead, as analysis needs emerge, existing programs are modified or new programs are produced and added to the set.

SUMMARY

In response to needs of Corps planners, the Hydrologic Engineering Center has developed and supports a set of computerized planning models. The set includes models for simulation of physical and statistical processes, models of water-resources system operation, models for plan evaluation, and programs for data management as shown in Table 1. These models have been used Corps-wide to aid professionals in formulation and selection of solutions to water resources planning problems.

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TABLE 1. Summary of HEC Planning Models.

Physical and Statistical Processes and Systems Simulation Models (1)	**Plan Evaluation Programs (2)**	**Data Management Programs (3)**
HEC-1 (USACE, 1980a)	EAD (USACE, 1979a)	HYDPAR (USACE, 1978a)
HEC-1 Predecessors (1966a, b, c, d, e, f)	SID (USACE, 1982b)	DAMCAL (USACE, 1979b)
	INA (USACE, 1980b)	RIA (USACE, 1978b)
	HEC-1	HEC-DSS (USACE, 1983b)
STORM (USACE, 1977c)		
HEC-2 (USACE, 1979c)		
Gradually-Varied Unsteady Flow (USACE, 1977a)		
DWOPER (Fread, 1978)		
HEC-5 (USACE, 1982a)		
DAMBRK (Fread, 1980)		
HEC-6 (USACE, 1977b)		
Deposit of Suspended Sedimentation Reservoirs (USACE, 1967a)		
Reservoir Delta Sedimentation		
Suspended Sediment Yield (USACE, 1967b)		
Flood-Flow Frequency Analysis (USACE, 1976)		
HEC-4 (USACE, 1971)		
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