COMPUTER MODELS FOR WATER-EXCESS MANAGEMENT

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1 INTRODUCTION

1.1 What is a Water-excess Management Computer Model?

This paper describes *water-excess management models* (These are also known as stormwater, hydrologic engineering, or flood-control models) The models simulate critical processes to provide information for

- Planning and designing new water-control facilities,
- Operating such facilities,
- Preparing for and responding to floods, or
- Regulating floodplain activities

For clarity, we make a distinction herein between mathematical models, computer models (also called programs), and applications A *mathematical model* is a symbolic representation of the behavior of a system For example, the combination of the continuity and momentum equations is a mathematical model of flow in an open channel To yield information, the equations of a mathematical model must be solved If the equations are relatively simple, they may be solved with pencil and paper and electronic calculator For example, the equations of the unit-hydrograph model can be solved in this fashion to predict runoff from a simple rain storm On the other hand, if the equations included in the model are too numerous or too complex to solve with pencil, paper, and calculator, they may be solved instead by translating the equations and an appropriate equation solver into computer code The result is a *computer model* or computer program When the equations of a mathematical model are solved with site-specific initial and boundary conditions and parameters, the model simulates the processes and predicts what will happen to the particular system This solution with specified conditions is an *application* of the model An application may use a computer model, or it may use the mathematical model with solution with pencil, paper, and calculator

1.2 Selecting a Water-excess Management Computer Model

Selection Problem and Solution. Ford and Davis (1989) write that water-resources planning and management is similar to home improvement In both, the appropriate tool must be selected to solve the problems at hand In the case of home improvement, the decision is what hand tool to use Should it be a hand saw or a chain saw? In the case of water management, the decision is what computer tool or model to use Jackson (1982) suggests that to select the best model, one should follow the procedure illustrated by Figure 1 1 In the case of water excess management, the information identified in step 1 of this procedure typically includes

- Stream-discharge time series or peaks,
- Volume time series or totals,
- River or reservoir water depth time series or maximums,
- Probabilities (frequencies) of extreme discharge, volume, or depth magnitudes,
- Inundated-area geometry,

- Landform changes due to erosion or deposition, or
- Economic, social, or environmental costs and benefits of any of these items

The remainder of this paper is devoted to step 2 identifying available models that can provide this information

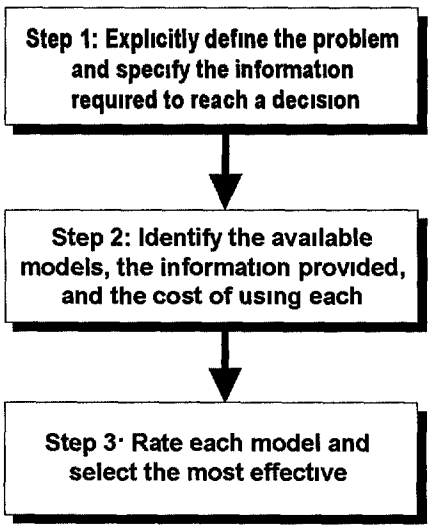

FIGURE 1.1 Steps in Selecting a Model

1.3 A Sample of Water-excess Management Computer Models

Computer models that provide the required information are described in theses and dissertations, in project reports, and in a number of journals, including AGU's *Water Resources Research*, ASCE's *Journal of Hydraulic Engineering*, ASCE's *Journal of Water Resources Planning and Management*, and AWRA's *Water Resources Bulletin* DeVries and Hromadka (1993), Renard, et al (1982), Larson, et al (1982), WMO (1975), Clarke (1973), and others have reviewed, summarized, and compared mathematical and computer models for water-excess management Here we follow their lead, except that we focus on the information provided, rather than on the specific details of the mathematical formulation and solution techniques We have selected a sample of the available computer models, summarized in Table 1 1, using the following criteria

- **Common usage.** The water-excess management computer models described herein are restricted to those used commonly by engineers other than the model developers, as this paper is written Further, the models described are those used in a variety of applications, rather than in a single setting Consequently, some models described in recent literature are omitted, and some models used predominately by a single entity or in a single application are omitted

- **General application.** The set of computer models reviewed includes only generalized computer models A *generalized computer model* is one in which the characteristics of the system (initial and boundary conditions, model parameters, and management decisions) are defined by the user's input For example, with computer model HEC-1, which is described in Section 2, the user defines, via input, all pertinent catchment characteristics and model parameters, plus the temporal and spatial distribution of the rainfall Thus runoff from any catchment due to any rainfall event can be estimated Computer models written for site-specific or

TABLE 1.1 Computer Models Described in This Paper

Computer model (1)	What is modeled *(primary use)* (2)	Whom to contact for information (3)	What is available (4)
HEC-1	Catchment runoff	US Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) 609 Second St. Davis, CA 95616 USA *or* National Technical Information Service U S Dept of Commerce 5285 Port Royal Rd Springfield, VA 22161 USA	Program in FORTRAN, source is available PC-version available Detailed user's manual available HEC technical reports, training documents, and project reports available HEC distributes to U S government users Vendors provide to others for fee, but program is public domain Program and documentation also available from U S National Technical Information Service (NTIS) Training available from HEC (federal) and universities (other users)
TR-20, TR-55	Catchment runoff	Soil Conservation Service (SCS) P O Box 2890 Washington, DC 20013 USA	PC versions of both TR-20 and TR-55 are available from offices of the Soil Conservation Service throughout the U S , along with documentation of the software Both programs are public-domain so are available from a variety of other sources, including vendors and academic institutions Technical reports describing math models are available from NTIS
SSARR	Catchment runoff	USACE North Pacific Division Attn CENPD-EN-WM HES P O Box 2870 Portland, OR 97208-2870 USA	The program was developed for and is used by the Corps on mainframe computers PC/workstation versions are available Program user's manuals and project reports are available
HSPF	Catchment runoff	Environmental Protection Agency (EPA) Environmental Research Laboratory Athens, GA 30613 USA	A PC version of HSPF is available, but as the program is written in FORTRAN, it may be compiled and executed on any computer for which a compiler is available Documentation is available from EPA
HEC-2	Fluvial	HEC (see above)	Same as for HEC-1 (see above)
WSPRO	Fluvial	U S Geological Survey (USGS) National Water Information Service Water Resources Division Reston, VA 22092 USA	FORTRAN source code, user's manual, and support documents are available A PC version is available WSPRO is available also from vendors
UNET	Fluvial	HEC (see above)	Same as for HEC-1 (see above)
DWOPER	Fluvial	NOAA National Weather Service Hydrologic Research Laboratory 1325 East-West Highway Silver Spring, MD 20910 USA	FORTRAN source code, user's manuals, and reports of applications are available A PC version is available from various vendors Training in application of DWOPER is available from various universities in the U S
HEC-6	Alluvial	HEC (see above)	Same as for HEC-1 (see above)
GSTARS	Alluvial	U S Bureau of Reclamation Denver Federal Center, Bldg 67 Denver, CO 80225 USA	Program source code, user's manual, and support documents are available Additional application-support documents are available
TABS-2	Alluvial	USACE Waterways Experiment Station (WES) P O Box 61 Vicksburg, MS 39180 USA	Program in FORTRAN, source is available PC version available Detailed user's manual is available WES technical reports, training documents, and project reports available PC version available to public from vendors
SWMM	Pressure flow	EPA (see above)	SWMM is available for a variety of platforms, including the PC It is available from EPA and from a variety of vendors Complete documentation is available from EPA and the vendors
HYDRA	Pressure flow	McTrans Center University of Florida 512 Weil Hall Gainesville, FL 32611-2083 USA	A PC version of the program is available, along with full documentation HYDRA is a component of HYDRAIN, which is also available for the PC
HEC-FFA	Statistical	HEC (see above)	Same as for HEC-1 (see above)
J407	Statistical	USGS (see above)	J407 is programmed in FORTRAN, so it is available for any computer for which a compiler is available A PC version and documentation available
EAD	Performance	HEC (see above)	Same as for HEC 1 (see above)
HEC-5	Performance	HEC (see above)	Same as for HEC-1 (see above)

problem-specific application typically do not have such flexibility Although these special-purpose computer models may embody the same mathematical models, the characteristics and parameters typically are "hard-wired " That is, they are fixed in the computer code An example of such a site-specific model is a FORTRAN program created by an operating agency for repeated forecasting of flood runoff from a single catchment In that case, the catchment characteristics and model parameters will not change, so these are included directly as a part of the code This makes for efficient analysis, but it limits the general utility of the computer model

- **Accessibility.** The models reviewed are limited to those that (1) are readily available to the reader from non-commercial sources, (2) will execute on commonly-available hardware, and (3) have documentation sufficiently detailed to permit use without specialized training or consulting

1.4 Classification of the Computer Models

The information provided by a computer model is correlated directly with the processes modeled For excess water management, the critical processes include those shown in Table 1 2

TABLE 1.2 Processes Modeled by Water Excess Management Models

Process (1)	Description (2)
Catchment-runoff	These are the processes that govern how precipitation that falls on a catchment runs off of that catchment Runoff processes include evaporation, transpiration, infiltration, percolation, interflow, overland flow, and baseflow Modeling these processes provides information on stream-discharge time series or peaks, and volume time series or totals
Fluvial	These are the processes that govern fluid flow in an open channel when that fluid is subjected to external forces Modeling these processes provides information on river or reservoir depth time series or maximums, and inundated-area geometry
Alluvial	These are the processes that govern the erosion and deposition of sediment due to flow in an open channel Modeling these processes provides information on landform changes due to erosion or deposition, river or reservoir water depth time series or maximums, and inundated-area geometry
Pressure-flow	These are the processes that govern how water flows under pressure in closed conduits For water excess management in urban settings, these processes are often planned to function as pressure conduits for the design flow or greater events (ASCE/WEF, 1992)
Statistical processes	Physical, chemical, or biological processes exhibit randomness and variability that cannot be accounted for with models of the behavior of a system (Hirsch, et al, 1993) Models of statistical processes recognize this and seek to describe the randomness and variability by establishing an empirical relationship between probability and magnitude A statistical-process model yields information on probabilities associated with extreme discharge, volume, or depth magnitudes

Some computer models focus not on the processes but on system performance, so *performance models* are included in this paper as an additional classification Performance models may simulate critical processes as a secondary function, but their primary function is to use information from such a simulation to evaluate economic, social, or environmental benefits and costs

To provide further detail, the computer models reviewed herein are described, when appropriate, in terms of additional characteristics shown in Table 1 3

TABLE 1.3 Additional Characteristics for Model Classification

Event or continuous model?	This distinction applies primarily to models of catchment runoff processes An event model represents a single flood event that occurs over a period ranging from minutes to days A continuous model operates over a long period, predicting response during and between rainfall events
Measured-parameter or fitted-parameter model?	This distinction applies to all models A measured-parameter model is one in which parameters can be determined from system characteristics, either by direct measurement or by estimation from measurements For example, channel cross sections for a fluvial-process model can be determined by measurement A fitted-parameter model, on the other hand, includes parameters that cannot be measured Instead, these must be found by fitting the model with observed values of the hydrometeorological phenomena For example, the unit-hydrograph models have no explicit physical significance, so parameters cannot be measured Instead, for a given catchment, a unit graph is found by proposing model parameters, estimating runoff due to observed rainfall, and comparing computed with observed runoff If the values do not agree, the parameters are adjusted to achieve an acceptable fit
Distributed or lumped model?	This distinction applies to all models A distributed model is one in which the spatial variations of characteristics and processes are considered explicitly, while in a lumped model, these spatial variations are averaged or ignored For example, the UNET model accounts for variations of energy and mass along a stream reach, while many of the simple routing models in HEC-1 account only for the variation of mass between the points of inflow and outflow from a channel reach
Complete or partial model?	This is related to the distinction between distributed and lumped models A complete model represents in detail, more or less, all pertinent process A partial model represents only a portion of the process For example, HSPF attempts to represents all aspects of soil moisture, while the loss model of TR-55 accounts only for the distribution of rainfall volume between runoff and loss
Conceptual or empirical model?	This distinction is based on characteristics of the mathematical models included in the computer model A conceptual model is formulated from consideration of physical, chemical, and biological processes acting on the system input to produce the system output An empirical model, on the other hand, is formulated from observation of input and output, without seeking to represent explicitly the process of conversion Flood-frequency models are examples of the latter, while HSPF is an example of the former The frequency models do not consider the physical process, while HSPF attempts to represent mathematically the relationship of stimulus (rainfall) to response (runoff)

2 RUNOFF-PROCESS COMPUTER MODELS

2.1 HEC-1

Overview. HEC-1 is a single-event model that estimates runoff from precipitation with a spatially- and temporally-lumped description of a catchment (USACE, 1990b) HEC-1 incorporates a variety of conceptual or quasi-conceptual mathematical models, the user specifies through input which of these are used Parameters for the various mathematical models also are specified by user input HEC-1 incorporates procedures to estimate parameters of most of the runoff models that are included, if proper hydrometeorological data are available HEC-1 provides stream-discharge time series and peaks, and volume totals for decision making

Mathematical Models Included in the Computer Model. The runoff process, as represented in HEC-1, is illustrated by Figure 2 1

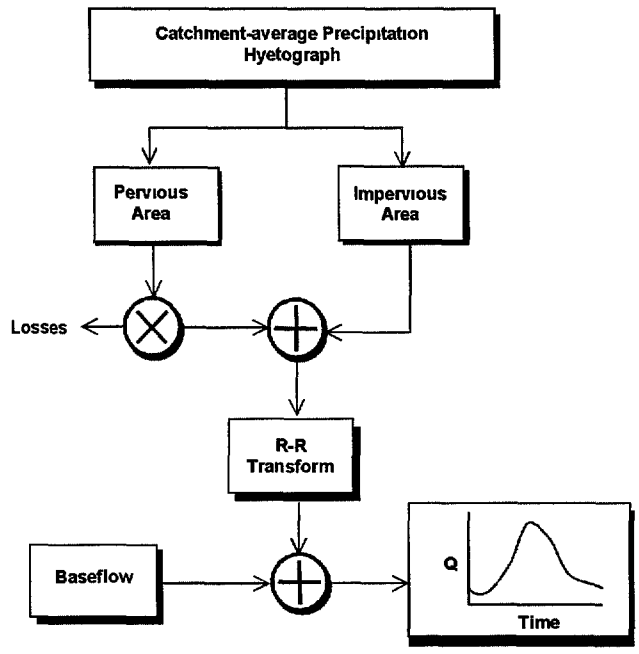

FIGURE 2.1 HEC-1 Representation of Runoff Process

The mathematical models incorporated include the following

- **Loss models.** To account for infiltration, depression storage, and other reductions in volume of runoff due to precipitation on pervious areas in a catchment, HEC-1 offers the alternatives shown in col 1 of Table 2 1 The user may select any one of these for a catchment For complex catchments that are subdivided for analysis, the user can select any combination of the loss models

- **Snowfall and snowmelt models.** These models simulate snowfall formation and accumulation and estimate runoff volumes due to snowmelt The snowfall model permits division of a catchment into elevation zones The user specifies a time series of temperatures for the lowest elevation zone, and the model estimates temperatures

for all others with a lapse rate Precipitation is assumed to fall as snow if the zone temperature is less than a user-defined freezing threshold Melt occurs when the temperature exceeds a user-defined melting threshold Snowfall is added to and snowmelt is subtracted from the snowpack in each zone Snowmelt may be computed with either a degree-day model or an energy-budget model

- **Runoff transforms.** Runoff volumes may be transformed to runoff hydrographs in program HEC-1 with either a UH model or via solution of the kinematic-wave simplification of the St Venant equations

- **Baseflow model.** HEC-1 incorporates a single model of baseflow, which is based on the assumption that drainage of water added to catchment storage (as soil moisture, etc) can be modeled well with an exponential decay function

TABLE 2.1 Runoff and Fluvial Process Models in HEC-1

Loss models (1)	Runoff transforms (2)	Routing models (3)
Initial loss & uniform rate	Unit hydrograph Clark's Snyder's SCS	Muskingum
Soil Conservation Service (SCS) curve number (CN)	Kinematic-wave	Kinematic wave
4-parameter exponential		Modified Puls (level pool)
Holtan's		Muskingum-Cunge
Green and Ampt		

In addition to runoff process models, HEC-1 includes the fluvial process models shown in col 3 of Table 2 1 for routing hydrographs The user may select any one appropriate for a given stream reach As with other mathematical models included in HEC-1, any combination of these may be used Parameters are defined with user input With the runoff and fluvial process models used in combination, large catchments in which parameters or precipitation vary spatially can be analyzed To do so. the catchment is subdivided, the runoff-process models are used to compute runoff at various locations, and the routing models are used to account for flow in stream channels to common points Figure 2 2 illustrates this approach First runoff is computed for subcatchment 1 with the runoff process models The resulting hydrograph represents the flow at control point A This hydrograph is routed from A to B with a fluvial process model The hydrograph of runoff from subcatchment 2 is computed and added to the routed hydrograph This yields an estimate of total runoff, accounting for spatial variation in rainfall and catchment characteristics

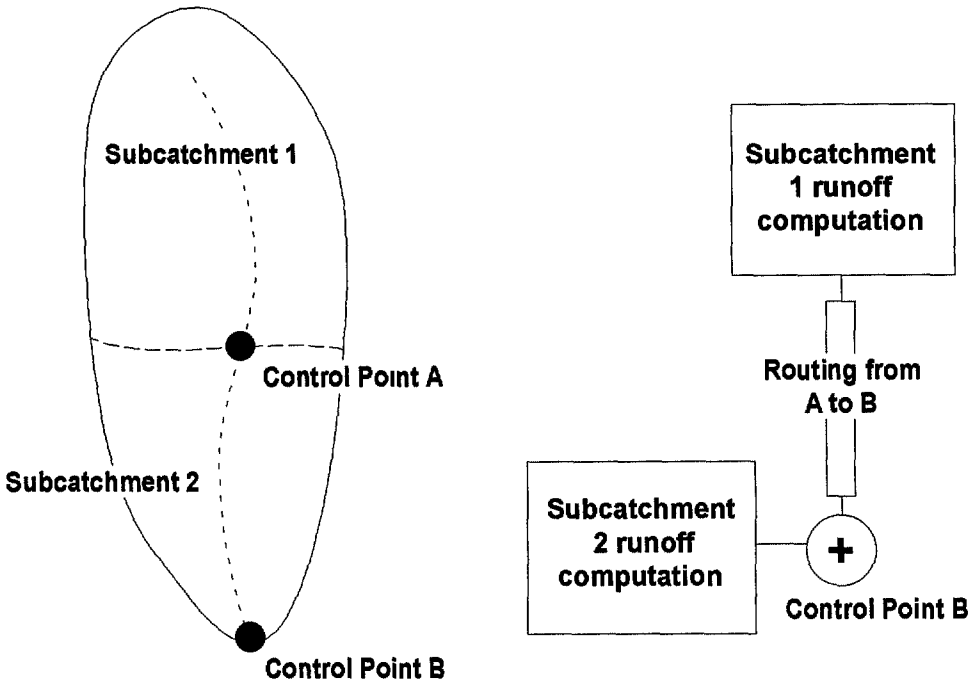

FIGURE 2.2 Illustration of Complex Catchment Modeling by Subdivision

Computer Model Input Requirements. To estimate catchment runoff with HEC-1, the user must provide the following input

- **Precipitation.** The precipitation may be provided as catchment average depth or as depths observed at gages The user must provide a temporal distribution of precipitation this may be the historical observation at a gage, or it may be a design-storm distribution

- **Catchment physical characteristics, including characteristics of water-control facilities.** The user must delineate catchment boundaries and define, via input, the catchment area If the catchment is subdivided for analysis, the user must define, through the sequence of input, how the system is schematized for modeling If the stream system includes water-control facilities, such as detention ponds, the performance-governing characteristics of these must also be specified

- **Model parameters.** The user must specify all appropriate loss-model, runoff transform model, baseflow model, and routing model parameters

- **Simulation specification.** HEC-1 was designed for maximum flexibility, therefore, it relies on the user to specify the time step and duration of the simulation, subject to constraints imposed by the available computer memory

Computer Model Output. Output from HEC-1 includes the following A summary report of the user's input, for each subcatchment, a report of the average-precipitation depth, the loss, and the excess for each simulation step,

plus a report showing the computed runoff hydrograph ordinates, for each stream reach modeled, a report of the outflow (downstream) hydrograph ordinates, various summary output tables that show the discharge peaks and times of peak at system control points

Applications. The Hydrologic Engineering Center (HEC) and US Army Corps of Engineers (USACE) offices nationwide have used HEC-1 extensively, results of these applications are described in reports available from these offices Additional applications have been described by Russell, et al (1979), Bedient, et al (1985), Bhaskar (1988), and Melching, et al (1991)

Utility Programs and Specialized Versions. The HEC has developed utility programs that simplify use of HEC-1 or provide additional capabilities Several are identified in Table 2 2

TABLE 2.2 Utility Programs for and Specialized Versions of HEC-1

Program (1)	Description (2)
HEC-DSS	This is a time-series database management system (DBMS). It creates specially-formatted random-access files, with a hierarchical system of record names to expedite storage and retrieval of data in the files Data in the DBMS may be accessed through a set of front-end utility programs that permit data entry, reporting, charting, and database housekeeping Further, the data can be accessed via a FORTRAN library of routines that read, write, and otherwise interact with database files It is through this library that HEC-1 (and many other models from HEC) retrieves data from and files data in the database
HMR-52	This program computes catchment-average precipitation for probable maximum design storms (PMS), using criteria established by the National Weather Service (NWS) for catchments east of the 103rd meridian in the United States The storm may be used, in turn as input to HEC-1 to estimate the probable maximum flood (PMF) runoff This extreme discharge is the basis for dam-safety analysis
HEC-1F	This specialized version of HEC-1 is designed for real-time flow forecasting It includes a subset of the runoff process models of HEC-1, plus algorithms for updating model parameters during an event and for adjusting computed hydrographs to match observed discharge at the time a forecast is made A companion program, PRECIP, estimates catchment average precipitation for the forecasts

2.2 TR-20 and TR-55

Overview. Programs TR-20 and TR-55 are single-event computer models that estimate design-event discharge time series, peaks, and volumes (USDA, 1983, 1986) Both programs use runoff process models developed by the Soil Conservation Service, these mathematical models are described in the National Engineering Handbook (USDA, 1971) Program TR-55 computes the peaks, volumes, and time series for a single catchment Program TR-20 uses identical procedures to compute peaks, volumes, and time series, plus fluvial-process models to route and to combine catchment runoff hydrographs, in a manner similar to that illustrated by Figure 2 2

Mathematical Models Included in the Computer Model. The runoff process, as represented in TR-20 and in TR-55, is essentially the same as illustrated by Figure 2 1 A catchment-average precipitation hyetograph is specified, losses are computed, and a runoff transform converts the runoff volume to discharge TR-20 and TR-55 do not include a baseflow model The features of the mathematical models are summarized in Table 2 3

TABLE 2.3 Mathematical Models in TR-20 and TR-55

Component (1)	Details of mathematical model (2)
Loss model	SCS curve number model Cumulative runoff volume is a function of cumulative rainfall volume Model has two user-supplied parameters initial abstraction and maximum retention Programs include empirical relationships to estimate parameters from catchment characteristics
Runoff transform	SCS one-parameter unit hydrograph Programs include empirical relationship to estimate parameter from catchment travel time plus quasi-physically based models to estimate travel time
Routing	TR-20 includes a linear channel-routing model and a storage routing model for detention TR-55 does not include a routing model

Computer Model Input Requirements. To estimate catchment runoff with either TR-20 or TR-55, the user must provide the following input

- **Precipitation.** TR-20 and TR-55 are intended as tools for estimating runoff from rainfall Consequently, both require specification of a catchment average hyetograph The SCS design storms are incorporated in both models, either directly in the code or as input files

- **Catchment physical characteristics and/or runoff model parameters.** The user must define the catchment area, the catchment-average rainfall, and the parameters of the loss model and the unit hydrograph model Relationships are incorporated in both models to estimate the parameters from catchment characteristics, if those are to be used, the user must provide information on catchment soils, land use, overland flow surfaces, and channels

- **Fluvial model parameters.** If the routing models of TR-20 are required, the user must provide model parameters and channel descriptions If the stream system includes detention structures, the characteristics of these must be provided also

Computer Model Output. Depending on user preferences and the program version used, output from programs TR-20 and TR-55 may include the following a summary of user's input, a report of estimated model parameters if the SCS empirical relationships are used, and a report of catchment runoff hydrographs and peaks

Applications. Due to their simplicity and availability, programs TR-20 and TR-55 are used widely in the US for planning and design Engineers of local SCS offices use the models extensively and will provide information on various applications McCuen (1987) describes application DeBarry and Carrington (1990) describe integration of a geographic information system (GIS) and TR-55 to estimate runoff with existing and future-condition land use

2.3 SSARR

Overview. SSARR, the Streamflow Synthesis and Reservoir Regulation model, was developed by the USACE for planning, designing, and regulating water-control projects in the Columbia river basin, USA (USACE, 1991c) SSARR is primarily a runoff-process model, but it includes also fluvial process and performance evaluation models SSARR is a continuous-accounting model, with fitted parameters The model is spatially-distributed in the sense that it permits the user to subdivide a basin to represent spatial variation of characteristics and processes, again as illustrated by Figure 2 2

Mathematical Models Included in the Computer Model. The mathematical models included in SSARR are a combination of conceptual and empirical models These models simulate the following

- **Snowmelt, snow accumulation.** Precipitation is defined by the user at intervals from 0 1 to 24 hr If this can occur as snow, the user indicates a base temperature for snow formation The snowpack can be defined by either elevation band or a snow-cover depletion function SSARR computes snowmelt from the accumulated snowpack with either a temperature-index approach or USACE generalized snowmelt equations

- **Soil moisture accumulation and evapotranspiration.** When rainfall and snowmelt volumes are determined, SSARR estimates runoff volume with an empirical relationship in which runoff is a function of an accumulated soil-moisture index (SMI) and rainfall intensity Evapotranspiration is estimated as a function of either mean monthly or daily evaporation data, the SMI is adjusted to account for this evapotranspiration

- **Baseflow.** Total runoff is determined with the SMI relationship The runoff volume then is distributed to either baseflow or surface/subsurface flow with an empirical baseflow infiltration index (BII) relationship The baseflow contribution is routed with a storage-routing model to estimate contribution to total streamflow

- **Surface and subsurface flow.** Runoff volume that does not contribute to baseflow is considered surface or subsurface flow An empirical relationship, the surface-subsurface separation curve, defines the contribution to each Both are routed with storage-routing models, and the results are added to routed baseflow to estimate the total streamflow

The interaction of these processes in the SSARR model is illustrated by Figure 2 3

Computer Model Input Requirements. The input required for the SSARR model is similar to that required for the other runoff-process models (hydrometeorological data, stream system configuration, etc) In addition the user must define the SMI relationship, BII relationship, and surface-subsurface separation curve, the initial-conditions for the SMI and BII, and the routing-model parameters Because of the empirical nature of these, they are best determined via fitting with recorded streamflow and precipitation

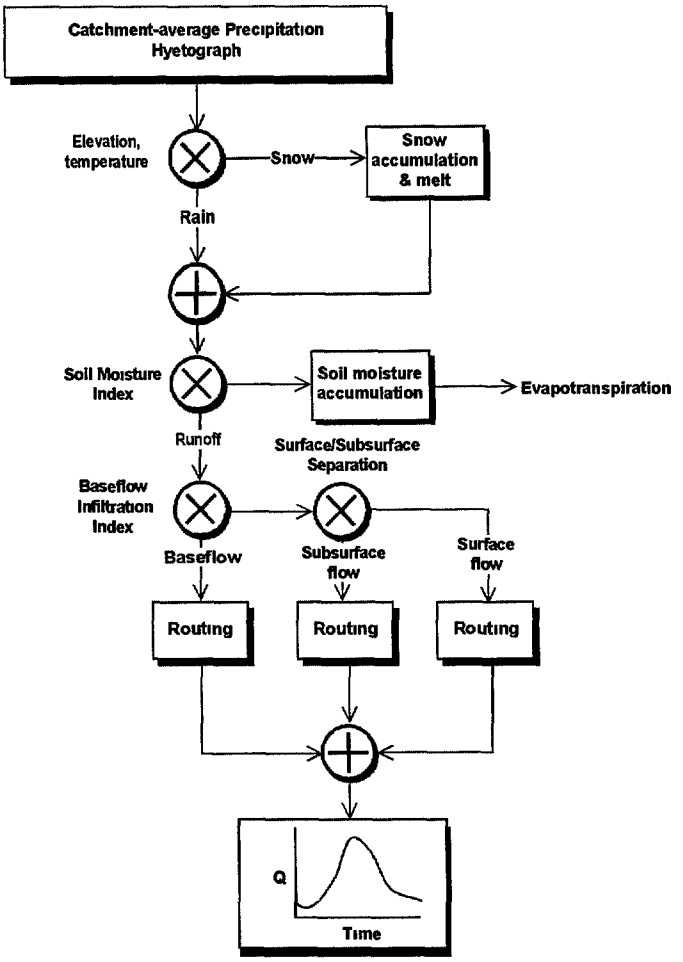

FIGURE 2.3 Structure of SSARR Runoff-process Model

Computer Model Output. The SSARR model forecasts streamflow time series at locations throughout a basin, so the primary output is a tabulation of the forecasted discharge Various report formats and plots of results may be selected by the user

Applications. The USACE has used SSARR continuously and successfully since its development for operational forecasting in the 622,000 km^2 Columbia basin, a variety of reports on application are available from the North Pacific Division of USACE Larson, et al (1982) describe other applications to catchments ranging in size from 12 6 km^2 to 370,000 km^2

2.4 HSPF

Overview. HSPF, the Hydrologic Simulation Program - FORTRAN, is a recent incarnation of Stanford Watershed Model (Crawford and Linsley, 1966) HSPF was developed for the US Environmental Protection Agency (EPA) by Hydrocomp, Inc in 1980, has been revised extensively by a variety of contractors, and currently is available in its tenth release (Bicknell, et al , 1992) HSPF is a continuous, quasi-conceptual, distributed, fitted-parameter model of all aspects of catchment response to rainfall In addition to the runoff-process model embodied in HSPF, this computer model includes mathematical models of fluvial, alluvial, chemical, and biological processes critical to the

work of the EPA HSPF provides information on stream-discharge time series or peaks, volume time series or totals, river or reservoir water depth time series or maximums, and landform changes due to erosion or deposition

Mathematical Models Included in the Computer Model. Like SSARR, HSPF computes catchment runoff volume by accounting continuously for the spatial distribution of system moisture, as illustrated by Figure 2 4 The computer model employs a combination of empirical and conceptual mathematical models in this accounting For example, simulation of infiltration is based on the conceptual model developed by Philip, while overland flow, interflow, and groundwater flow are modeled with empirical storage-outflow relationships The HSPF user's manual describes the various mathematical models and their parameters in detail

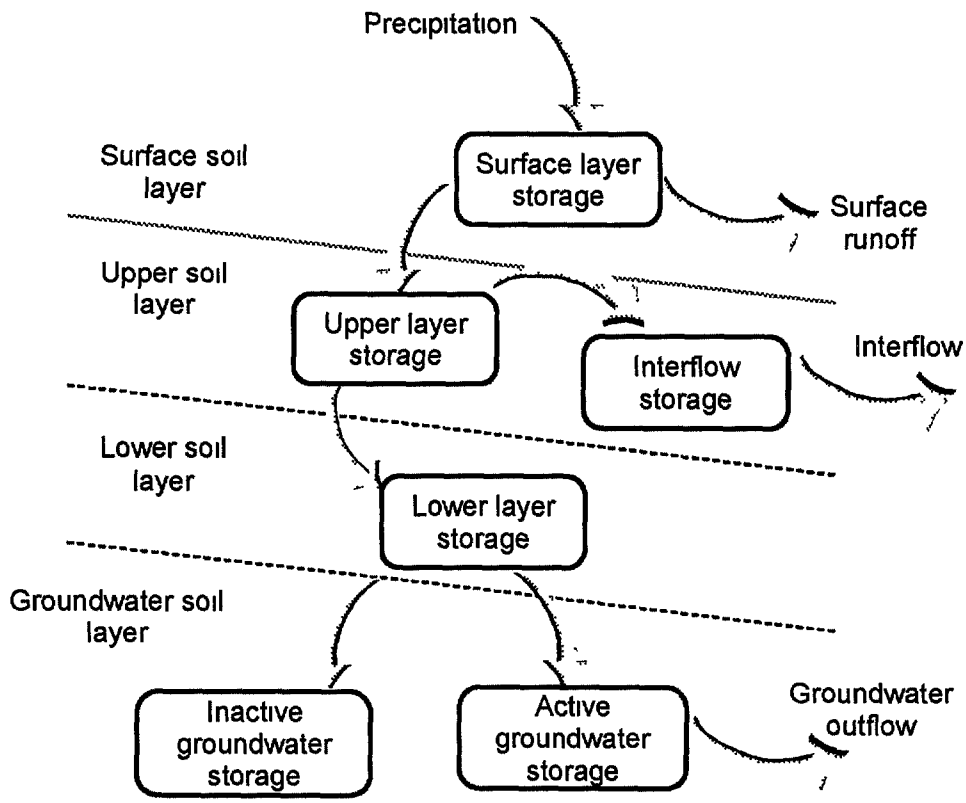

FIGURE 2.4 Structure of HSPF Runoff-process Model

Computer Model Input Requirements and Output. Like other catchment runoff models, HSPF requires input of hydrometeorological time series In the case of a continuous simulation model, these series are lengthy, so data management could be a formidable task To minimize data management effort and problems, HSPF includes a time-series database management system

In addition to time series input, the HSPF user must define values of the approximately 20 parameters of the various mathematical models As many of these are parameters of empirical models, they are estimated from experience or via calibration with observations of precipitation and runoff HSPF output includes hydrographs at system locations plus an accounting of moisture storage and flux throughout the hydrologic system

3 FLUVIAL-PROCESS MODELS

3.1 HEC-2

Overview. HEC-2 solves the equations of one-dimensional, steady, gradually varied flow to predict water-surface elevation along a natural or constructed open channel (USACE, 1982a) Water surface profiles in either subcritical or supercritical regime can be computed HEC-2 also incorporates conceptual and empirical models that allow analysis necessary for common designing, planning, and regulating problems These special capabilities are summarized in Table 3 1

TABLE 3.1 Special Capabilities of HEC-2 Model

Capability (1)	Description (2)
Treatment of effective flow areas	Several options are available to restrict flow to certain portions of a given cross section This is often required because of sediment deposits, floodplain encroachments, oxbow lakes, etc
Analysis of bridge and culvert losses	The energy loss due to bridge piers and culverts can be estimated
Analysis of channel encroachments	Six methods of specifying floodplain encroachments are available The equal conveyance reduction method is used to determine the floodway boundaries for a flood insurance study
Evaluation of channel improvement	Natural river cross section data may be modified simply with the channel improvement option This allows simulation of the effects excavating a compound trapezoidal channel section into the natural section
Calibration to high water marks	When high water marks are known for a specified discharge, HEC-2 can estimate the effective Manning's n value necessary to reproduce this observed elevation
Development of storage-outflow function	HEC-2 includes the capability to develop a storage volume v relationship for a river reach This can, in turn, be used for streamflow routing with the modified Puls and other simple fluvial process models
Analysis of split flow	For flow splits (such as at diversion structures, levee overtoppings, etc) HEC-2 balances the energy grade line elevations at the split and downstream confluence Weir flow, normal depth, or a diversion rating curve may describe the hydraulics of the split
Simulation of flow in ice-covered streams	Water surface profiles with a stationary, floating ice cover can be estimated The user must provide the thickness and effective n value of the ice cover

Mathematical Models Included in the Computer Model. Given a complete description of the geometric boundaries which contain the flow in an open channel, HEC-2 estimates the average flow depth and velocity in the prescribed cross sections by solving the one-dimensional energy equation This formulation relies on the assumptions shown in Table 3 2 (Violation of one or more of these assumptions does not necessarily mean that

results of analysis with HEC-2 are wrong Instead, it means that the user must evaluate the relative effect of these assumptions upon the results of a particular application)

TABLE 3.2 Assumptions of HEC-2

Flow is steady and gradually varied, with localized rapidly varied flow, such as at weirs or culvert inlets
Flow is turbulent, and fully rough, with viscous forces playing a minor role
Flow is homogeneous, with constant fluid density throughout the flow field
Flow can be adequately characterized by movement in a single direction
Pressure distribution at a cross section is hydrostatic

By computing the energy loss between a river cross section with a known water surface elevation and an adjacent cross section, the water surface elevation at the adjacent section can be determined For subcritical flow, the computations start with a known relationship between discharge and water surface elevation at the downstream boundary of the fluvial system and proceed in an upstream direction until the water surface elevation is computed at each cross section For supercritical flow, the computations start with a known water surface elevation at the upstream boundary and proceed in a downstream direction

HEC-2 estimates the total energy loss between two adjacent sections as the sum of frictional energy loss due to channel roughness, form energy loss due to expansion and contraction, and energy loss due to flow through structures, such as a bridges, culverts, or weirs The frictional energy loss is the product of the average energy grade line slope and the distance between cross sections This energy grade line slope at a section is computed with Manning's equation Several schemes are available in HEC-2 for determining the average energy grade line slope between two cross sections arithmetic, geometric, or harmonic mean energy slope at adjacent cross sections, or the average conveyance at adjacent cross sections HEC-2 includes a contraction/expansion energy loss model that estimates that loss as a function of the difference in velocity head between two cross sections

Computer Model Input Requirements. HEC-2 is a generalized computer program The user must therefore provide all stream characteristics and boundary conditions via input For a simple application, the basic input requirements are shown in Table 3 3

Computer Model Output. A variety of output data may be selected by the user The basic output includes a report of computed water-surface elevation, velocity, and other pertinent characteristics of flow at each channel cross section HEC-2 will prepare an electronic file with the computed results for subsequent access by a graphing utility

Applications. HEC-2 is claimed to be the most-commonly-used water excess management model in the US In most communities, HEC-2 is the model used to delineate the inundated area for establishing the 100-year floodplain This floodplain, in turn, serves as the basis for most floodplain land use controls Reports of the delineation are available from the Flood Insurance Administration Additional reports on HEC-2 application are available from the HEC

TABLE 3.3 Input Required for HEC-2 Model

Input item (1)	Description (2)
Flow regime	The user must assess the location of normal depth relative to critical depth for each application For a subcritical flow regime, cross section data are specified progressing upstream For supercritical flow regime, data are specified progressing downstream For unknown or mixed regimes, multiple input data sets are prepared and results combined, as discussed in HEC-2 user's manual
Starting boundary condition	HEC-2 solves the one-dimensional energy equation for a given stream, so the starting water surface elevation must be specified This can be input directly or estimated by the program
Discharge	The steady flow discharge must be specified for each stream segment This may change along the profile in order to include effects of tributaries, diversions, etc
Energy loss coefficients	For a basic application of HEC-2, user must specify Manning's n for the main channel Manning's n for the left and right overbanks, contraction loss coefficient, and expansion loss coefficient
Cross section geometry	Boundary geometry for the analysis is provided by a series of elevation v station coordinate points at each cross section Cross sections are required at representative locations throughout the reach, but especially where slope, conveyance, or roughness change significantly
Reach length	The distance between cross sections must be specified to permit computation of the turbulent energy loss due to boundary roughness HEC-2 allows input of separate reach lengths for the main channel, left and right overbanks to describe curved channels, river meanders, etc

3.2 WSPRO

Overview. WSPRO is a one-dimensional steady state backwater model developed by the US Geological Survey (USGS), under contract to the Federal Highway Administration for the evaluation and design of bridge waterways (Sherman, 1986, 1988) Federal Highway Administration policy on design of floodplain encroachments is to consider the impact of encroachment alternatives on the floodplain, rather than to determine the bridge opening size necessary to pass a given design discharge WSPRO is formulated for such analysis

Mathematical Models Included in the Computer Model. WSPRO solves the one-dimensional steady equation using a standard step-backwater approach, much like that used by HEC-2 In addition to the backwater solution, WSPRO includes empirical models for determining the effect of culvert, spur dike, and bridge abutments

Computer Model Input Requirements and Output. Input requirements for WSPRO are similar to those of HEC-2 Special input describes typical highway bridge structures, including spur dikes, road grades, culverts, and bridges with multiple openings For situations where the flow regime changes along a given profile, WSPRO has the capability to change from subcritical to supercritical flow computation schemes Output from WSPRO includes

computed conveyance, water surface elevation, and velocity at each channel cross section, and results of computation for flow through bridge openings and other highway structures

3.3 UNET

Overview. UNET simulates one-dimensional, unsteady flow through either a simple open channel, a dendritic system of open channels, or a network of open channels (USACE, 1993). This permits analysis of diversions and confluences in a looped system, including systems in which the direction of flow may reverse UNET has the capability to model also flow in lakes, bridges, culverts, weirs, and gated spillways, using mathematical models that are essentially the same as those included in HEC-2 These capabilities are summarized in Table 3 4

TABLE 3.4 Special Capabilities of UNET Model

Capability (1)	Description (2)
Flow regime	UNET simulates subcritical flow in a network of open channels Supercritical flow can be simulated if specified as a part of an interior boundary condition
Channel geometry	Cross-section geometry is specified in HEC-2 format Data are arranged in groups corresponding to reaches of a network
Internal boundaries and special conditions	Internal boundary conditions, such as levee failures, gated spillways, weir overflow structures, bridge and culvert hydraulics, and pumped diversions can be simulated Connection of facilities to another reach or to a ponding area can be simulated
Output	UNET uses HEC-DSS for data storage and retrieval

Mathematical Models Included in the Computer Model. The numerical solution procedures employed by UNET were developed assuming that computational speed and computer memory resources are relatively minor constraints for a given application The full one-dimensional unsteady-flow equations are reformulated and solved with a linearized finite-difference approximation (Barkau, 1985) The solution algorithm employs sparse matrix techniques with Gaussian reduction

Computer Model Input Requirements and Output. The input required for UNET is similar to that required for HEC-2, but additional input is required to describe the interconnection of stream segments, and location of lakes and storage elements These requirements are summarized in Table 3 5 UNET uses the HEC-DSS described in Table 2 2 to store boundary conditions, such as rating curves and hydrographs, and results of computations, including time series of water-surface elevation at various stream locations

TABLE 3.5 Input Required for UNET Model

Input item (1)	Description (2)
Channel geometry	Each cross section is input in HEC-2 format The cross section data are arranged in a reach-by-reach order, with upstream and downstream connectivity specified This allows analysis of supercritical and subcritical flow regimes without data reordering
Boundary conditions	Discharge hydrograph or rating function must be specified for each terminal reach boundard
Initial conditions	Initial depth and velocity must be specified for each cross section The model can store results of application for use as subsequent initial condition
Energy-loss parameters	User must specify Manning's n for each cross section Contraction and expansion loss coefficients and overflow weir coefficients may be specified

Unsteady flow models typically produce large reports of computational results, and UNET is not an exception The model computes and reports depths, velocities, and other pertinent flow characteristics at each cross section for each time step of the discretized solution of the flow equations These results may be filed with the HEC-DSS and subsequently plotted with DSPLAY, the graphing program of the database management system

Applications. UNET has become the USACE standard for analyses in which an unsteady flow model is required, consequently, project reports are readily available from offices nationwide (See, for example, USACE, 1990c)

3.4 DWOPER

Overview. The Dynamic Wave Operational model (DWOPER) was developed by the National Weather Service for use in riverine flood forecasting (Fread, 1987) DWOPER can be used for analysis of flow in a single channel, or a dendritic or bifurcated (looped) river system Optional features include the simulation of locks and dams, lateral inflows, pressurized flows in storm drains, and wind effects An automatic calibration feature is also available to estimate model parameters from observations of flow and water-surface elevation

Mathematical Models within the Computer Model. DWOPER uses a four-point implicit finite difference scheme to approximate the complete one-dimensional unsteady flow equations The resulting nonlinear algebraic equations are solved using the Newton-Raphson method, along with Gaussian elimination with sparse-matrix techniques

Computer Model Input Requirements and Output. Input for DWOPER includes channel cross section geometry, expressed as elevation v top width, a description of the network configuration, energy loss model parameters, descriptions of structures, and flow hydrographs Extensive reports of discharge, velocity, and depth at channel cross sections are available Computed water surface elevations can be filed electronically and graphed with utility programs

Applications. Because of its widespread availability, DWOPER is in common use Fread (1987) describes several applications

4 ALLUVIAL-PROCESS MODELS

4.1 HEC-6

Overview. HEC-6 models the effects of river sediment transport and resulting changes in the flow boundaries with a one-dimensional representation of the open-channel flow (USACE, 1991b) The program computes changes in river bed profiles for a single flood event or for a long-term sequence of flows It provides information on depths and landform changes due to erosion or deposition Thus HEC-6 can be used to evaluate the lateral movement of a stream.

Mathematical Models Included in the Computer Model. HEC-6 solves the one-dimensional energy equation (3 1) using a computation technique similar to that included in computer model HEC-2 HEC-6 does not include the empirical models for bridge and culvert energy losses, but it does allow for the specification of an internal elevation-discharge boundary condition, the development of which can be accomplished using HEC-2 Transport calculations are made for a control volume defined using the cross-section locations and an assumed depth of alluvial deposits The computed energy slope, depth, velocity, and shear stress at each cross section are used to compute the sediment transport capacity at each cross section These rates, along with sediment supply rate and armoring potential, are used for volumetric accounting of sediment movement through the system The amount of scour or deposition is computed by dividing the surface area of the mobile boundary into the change in sediment volume A new water surface profile is then computed for the updated channel geometry

Sediment transport rates in HEC-6 are computed for 20 different grain size categories ranging from clay (less than 0 004 mm) through silt (less than 0 063 mm) up to large boulders (2,048 mm) A variety of sediment transport equations, based on either cohesive or non-cohesive theory, can be selected for the transport capacity calculations Mathematical models of incipient motion, channel bed armoring, grain size sorting, and particle entrainment are also included in HEC-6

To account for unsteady flow, a hydrograph is discretized into a series of steady flows, and a water-surface profile is computed using a standard step backwater approach This procedure is repeated until the entire flow hydrograph has been routed

Due to the one-dimensional formulation, HEC-6 does not represent the multi-dimensional nature of sand bar formation, secondary flow currents, and stream bank failure

Computer Model Input Requirements. HEC-6 requires also all of the information necessary for a one-dimensional fluvial model, including a complete description of the geometric boundaries of the channel that contains the flow, definition of the flow regime, and specification of energy loss coefficients. In addition, the information shown in Table 4 1 must be developed and provided by the user

Computer Model Output. HEC-6 provides reports of both hydraulic and sediment-transport calculations The basic level of output data includes a report of initial conditions, hydraulic calculations, sediment transport calculations, accumulated sediment volumes, and overall bed elevation changes

Applications. Vanoni (1977) and Fan (1988) report on applications of this and other alluvial process models In addition, a number of project reports are available from the HEC

TABLE 4.1 Input Required for HEC-6 Model

Category (1)	Input requirement (2)
Sediment grain size distribution	Sediment grain sizes transported by streams vary over a wide range HEC-6 considers the transport of sediment in the size range between clay size particles and 2,048 mm boulders The user must stipulate the grain size distribution of both the streambed material and the inflow sediment load Vanoni (1985) provides guidance on preparation of these data
Sediment properties	In addition to the grain size, the user must specify the specific gravity, shape factor, unit weight of deposits, and fall velocity of the sediment
Other boundary conditions	HEC-6 computes the changes in a stream bed over time, so a time series of discharge must be provided The discharge may be modified along the application reach to account for tributaries or diversions

4.2 GSTARS

Overview. The Generalized Stream Tube Model for Alluvial River Simulation, GSTARS, is a one-dimensional alluvial process model developed by the USGS (Molinas and Yang, 1986) GSTARS provides information on river water depths, inundated area geometry, and landform changes

Mathematical Models Included in the Computer Model. Like HEC-6, GSTARS solves the one-dimensional energy equation to determine the stream hydraulics at a given cross section for a given discharge, but it uses the concept of stream tubes to describe differences in the lateral distribution of conveyance along the stream cross section Since the stream tube flow distribution is based on the computed horizontal water surface elevation, the model does not explicitly include lateral stream processes, such as sand bar formation, secondary currents and bank failure The stream tube approach is useful however for certain applications, such as simultaneous occurrence of deposition and scour at a cross section

Computer Model Input Requirements and Output. Input requirements for GSTARS are similar to those of HEC-6 Unlike HEC-6, GSTARS permits specification of lateral and vertical differences in the initial bed material gradations for each cross section if the data is available GSTARS output includes reports of the hydraulic and sediment transport computations It includes also convenient plots of streambed elevation *v* time

4.3 TABS-2

Overview. TABS-2 is fully two-dimensional model of sediment movement in an open channel (Thomas and McAnally, 1985) Consequently, it will model sand bar formation, secondary currents, and other flow and transport cases not well-modeled with the one-dimensional representations

Mathematical Models Included in the Computer Model. TABS-2 solves the two-dimensional, depth averaged momentum and continuity equations, for either steady or unsteady flow TABS-2 uses a finite element technique and computes, for each node of the finite-element representation, flow depth and longitudinal and lateral velocities The sedimentation component of the model then computes the transport capacity using the two-dimensional convection-diffusion equation with bed source terms The actual transport is based on sediment availability TABS-2 can handle both cohesive and non-cohesive sediment transport

Computer Model Input Requirements and Output. In addition to the grid network data, each element requires information on initial bed material sizes As with the other alluvial process models, the inflowing sediment load and hydrograph must be specified by the user TABS-2 will provide detailed reports of all computations To aid the user in digesting this mass of output, TABS-2 includes also a post-processor that displays the results of computations graphically This graphical output includes velocity vector plots, contour plots of scour/deposit depths, and shear stress variations

Applications. This model is readily available, so is widely used by USACE, various other government agencies, and consultants Thomas and Heath (1983) describe application of TABS-2

5 PRESSURE-FLOW PROCESS MODELS

Flow of water in modern drainage systems typically consists of both open-channel and closed-conduit flow Open channel flow always has a free surface, and is modeled with the fluvial-process computer models of Section 3 Water in a closed-conduit, on the other hand, may flow with a free surface, or, if the discharge exceeds the capacity, it may flow under pressure This section describes models that are appropriate for simulation of the pressure flow In fact, most computer models in this category account for both free-surface and pressure-flow In the first case, the computer models use mathematical models identical to those incorporated in the fluvial-process models In the latter case, the computer models include additional mathematical models to account for energy losses due to pipe friction, entrances and inlets, bends, expansions, contractions, manholes, and valves, meters, and other appurtenances

5.1 SWMM

Overview. The Storm Water Management Model, SWMM, is a comprehensive program developed by the EPA for analysis of water quantity and quality in a combined sewer system (Huber and Dickinson, 1988) For water excess management, SWMM provides information on discharge time series and peaks, and on hydraulic grade elevation series or maximums

SWMM is constructed of computational "blocks," as shown in Figure 5 1 The Runoff block uses nonlinear storage routing to estimate runoff due to specified rainfall The Transport block solves a kinematic-wave simplification of the St Venant equations to account for open channel flow The EXTRAN block routes inlet hydrographs through a network of pipes, junctions, and flow diversion structures The Storage/Treatment block models flow-control devices The service blocks manipulate data, report results, and provide for statistical analysis of results The blocks are linked through an executive routine Each of the components may be used independently In particular, the EXTRAN block may be used to simulate flow in a system whenever it is important to represent severe backwater conditions and special flow devices such as weirs, orifices, pumps, storage basins, and tide gates (Roesner, et al , 1988)

Mathematical Models Included in the Computer Model. EXTRAN is a distributed, conceptual model of open channel and closed conduit flow With it, a drainage system is represented in link-node form This representation may include parallel pipes, looped systems, weirs, orifices, pumps, diversions due to surcharging, manholes, and storage facilities

EXTRAN solves the gradually varied, one-dimensional form of the unsteady flow equations for the system For the link-node representation of the system, it uses the momentum equation in the links and a special lumped form of the

continuity equation in the nodes A finite difference solutions scheme is used, with solution time step governed by the wave celerity in shorter channels or conduits in the system

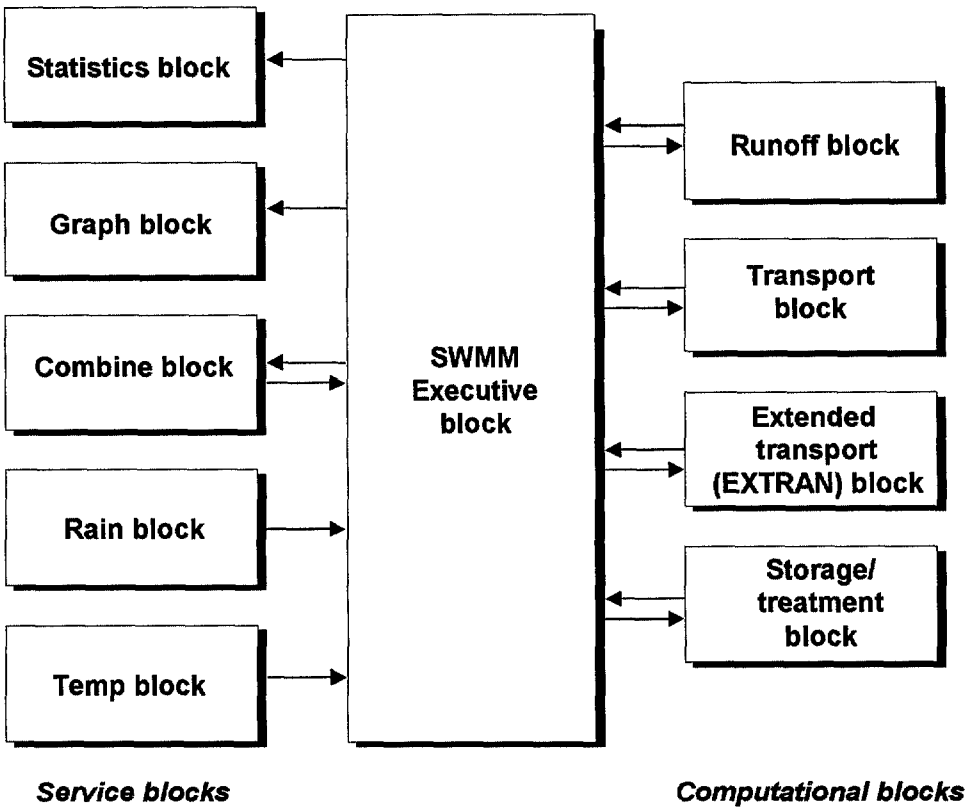

FIGURE 5.1 Structure of Storm Water Management Model (SWMM)

Computer Model Input Requirements and Output. To use the EXTRAN block to simulate flow in a system of closed-conduits, the user must provide the following a link-node description of the system, geometric description of the components of the system, including pipe sizes, shapes, slopes, and locations and dimensions of inlets, diversions, and overflows, and the system inflow hydrographs, computed either with SWMM or a catchment-runoff model

Output from the EXTRAN block includes reports and graphs of discharge hydrographs and velocities in selected conduits and flow depths and water surface elevation at selected junctions A data interface with other SWMM blocks permits transfer of the hydrographs to those blocks for subsequent analysis

Applications. Jewell, et al (1977) prepared a detailed SWMM application guide Huber, Heaney, and Cunningham (1988) published a summary of SWMM applications A SWMM users group meets annually to share information on applications

5.2 HYDRA

Overview. HYDRA was developed for the US Federal Highway Administration (FHWA) for analysis and design of storm drain, sanitary sewage, and combined flow systems (FHWA, 1993) It is a component of the FHWA

HYDRAIN integrated drainage design system HYDRA will analyze flow in an existing or proposed system of closed conduits and/or open channels If that system is overloaded (flow exceeds capacity), HYDRA will identify flow-reduction solutions HYDRA also will select pipe size, slope, and invert elevations to satisfy user-specified design criteria

Mathematical Models Included in the Computer Model. HYDRA is a complete design/analysis package that includes catchment process, fluvial process, and pressure-flow process models The pressure flow model is derived from the EXTRAN module of SWMM (FHWA, 1993) However, the model has been expanded to include water-control facilities common in highway drainage

Computer Model Input Requirements and Output. HYDRA is designed for maximum flexibility and generality, thus permitting analysis of almost any reasonable drainage system The user-prepared input file consists of commands, dimensions, and parameters to describe the drainage system and how it is to be modeled As with EXTRAN, a link-node scheme is employed to describe system layout The system's tailwater boundary condition is specified by the user For pressure flow computations, the user must identify each conduit's roughness and dimensions

HYDRA computes the hydraulic gradeline throughout the system To do so, it computes major and minor losses within the system

6 STATISTICAL-PROCESS COMPUTER MODELS

Statistical models that provide information for decision making are all empirical, fitted-parameter models When these are employed in water-excess management studies, either of two approaches is common (1) special-purpose computer software is created to satisfy the needs of the particular study, perhaps using a library of statistical analysis routines, or (2) the water-management problem is formulated in general terms and one of the readily-available general-purpose statistical analysis software packages is used The exception is *annual maximum discharge frequency analysis*, in which the probability of the annual maximum discharge exceeding a specified magnitude is estimated Because of the critical role of and recurrent need for such analysis, and due to the wide-spread use of a single statistical model proposed by the Water Resources Council, generalized computer models have been developed This section describes two of those models

6.1 HEC-FFA and Program J407

Overview. In the United States, a number of federal agencies conduct annual maximum discharge frequency analysis for decision making Until 1967, each agency established its own methods and procedures for the analysis, leading to occasional differences in estimates of quantiles or probabilities To promote a consistent approach, a multi-agency committee of the US Water Resources Council (WRC), studied alternatives and recommended the log-Pearson type III distribution for use by US federal agencies (Interagency Advisory Committee, 1982) The committee recommended also procedures for treating small samples, outliers, zero flows, broken and incomplete records, and historical flood information The USACE and USGS developed computer models to implement the guidelines The USACE computer model is designated HEC-FFA (USACE, 1992), and the USGS model is designated J407 These models are essentially identical, with minor differences to meet the unique needs of the agencies

Mathematical Models Included in the Computer Model. HEC-FFA and J407 fit a Pearson type III statistical model (distribution) to logarithms of an observed flood series, using modified method-of-moments parameter

estimators Bulletin 17B and various hydrology texts describe the statistical model and fitting procedures in more detail Table 6 1 shows the analysis procedures used by the models in fitting the distribution

TABLE 6.1 HEC-FFA and J407 Features

Feature (1)	Analysis Procedure (2)
Parameter estimation	Estimate parameters with method of moments, assuming that sample mean, standard deviation, skew coefficient = parent population mean, standard deviation, and skew coefficient To account for variability in skew computed from small samples, use weighted sum of station skew and regional skew
Outliers	These are observations that " depart significantly from the trend of the remaining data " Models identify high and low outliers If information available indicates that high outlier is maximum in extended time period, it is treated as historical flow Otherwise, they are treated as part of systematic sample Low outliers are deleted from sample, and conditional probability adjustment is applied
Zero flows	If the annual maximum flow is zero (or below a specified threshold), the observations are deleted from the sample The model parameters are estimated with the remainder of the sample The resulting probability estimates are adjusted to account for the conditional probability of exceeding a specified discharge, given that a non-zero flow occurs
Historical flood information	If information is available indicating that an observation represents the greatest flow in a period longer than that represented by the sample, model parameters are computed with "historically" weighted moments
Broken record	If observations are missing due to ". conditions not related to flood magnitude," different sample segments are analyzed as a single sample with size equal the sum of the sample sizes
Expected probability adjustment	This adjustment is made to the model results " to incorporate the effects of uncertainty in application of the [frequency] curve "

Computer Model Input Requirements. Both HEC-FFA and J407 provide information on probabilities (frequencies) of extreme discharge magnitudes To do so, both require as input a sample series of unregulated, annual-maximum flows that is free of climatic trends, representative of constant watershed conditions, and from a common parent population In addition to the systematic time series, HEC-FFA and J407 require the following

- **Model execution specifications.** The user may select from amongst various plotting positions for visually inspecting the goodness-of-fit, and from amongst various reports and plots of results
- **Model parameters.** Both computer models estimate the log Pearson type III parameters from sample statistics The sample statistics are computed from the input series However, if desired, the user may specify the sample statistics, thus overriding the computation Further, the user must specify the regional skew coefficient if the weighting scheme of Bulletin 17B is to be used

- **Historical data.** If historical flow data are available, the user must identify these

Computer Model Output. Output from HEC-FFA and J407 includes the following A summary report of the user's input, computed sample statistics and estimated model parameters a report of the computed frequency function, showing selected quantiles, and plots of the frequency function

7 PERFORMANCE MODELS

The computer models described in earlier sections of this paper provide information on *system behavior*, they simulate processes by which a system input is transformed to a system output But for informed water-resources planning, we need often information on *system performance* the consequence of a particular system output or a particular state of the system Several of the models described include the capability to assess performance For example, HEC-1 and TR-20 include routines to model detention-structure performance, given hydrographs computed with the runoff process models they include But for more detailed analysis, computer models designed especially for evaluation are available Two are described here EAD, a flood-damage evaluation model, and HEC-5, a reservoir-system evaluation model

7.1 EAD

Overview. The objective of the HEC EAD (Expected Annual Flood Damage) program is to compute inundation damage and inundation-reduction benefit , thus permitting evaluation of existing flood hazard and of the anticipated performance of proposed damage-reduction measures (USACE, 1984a) The *Principles and Guidelines* (USWRC, 1983), a document that provides the "rules" for federal water resource planning in the US, stipulates that the economic benefit of a flood-damage-reduction project is the sum of location, intensification, and inundation-reduction benefit *Location benefit* is associated with addition of activity to a floodplain, while *intensification benefit* is a consequence of modified operation of existing activity in a floodplain due to the protection provided *Inundation-reduction benefit* is the difference between damage due to flooding without and with the project The *Principles and Guidelines* further requires that the damage estimates should be " potential average annual dollar damages to activities affected by flooding [estimated] using standard damage-frequency integration techniques "

Mathematical Models Included in the Computer Model. Average annual damage, also properly called the expected annual damage, is computed by integrating the cumulative distribution function (cdf) of annual damage In the simplest application, EAD uses a numerical integration scheme to integrate a user-provided damage-frequency function and reports the results These computations can be performed for various damage categories for any number of *reaches* (subdivisions of the floodplain) Damage-frequency functions are not commonly available, but are derived from statistical, fluvial, and economic data or models, as illustrated in Figure 7 1 The functions may represent the existing without-project, existing with-project, future without-project, and/or future with-project state of the floodplain EAD will perform this manipulation for any alternative conditions defined by the user

The functions shown in Figure 7 1 may change with time EAD includes the appropriate discounting formulas as required by the *Principles and Guidelines* to " convert future monetary values to present values "

Computer Model Input and Output. Table 7 1 shows the input required for EAD EAD output includes a report of the derived damage-frequency functions, sorted by reach, for each damage category, plus the aggregate function, for the existing, without-project condition, and for each alternative condition defined by the user It includes also a report of the computed average annual damage, sorted by reach, for each damage category, plus the aggregate function The inundation-reduction benefit of each with-project condition is displayed

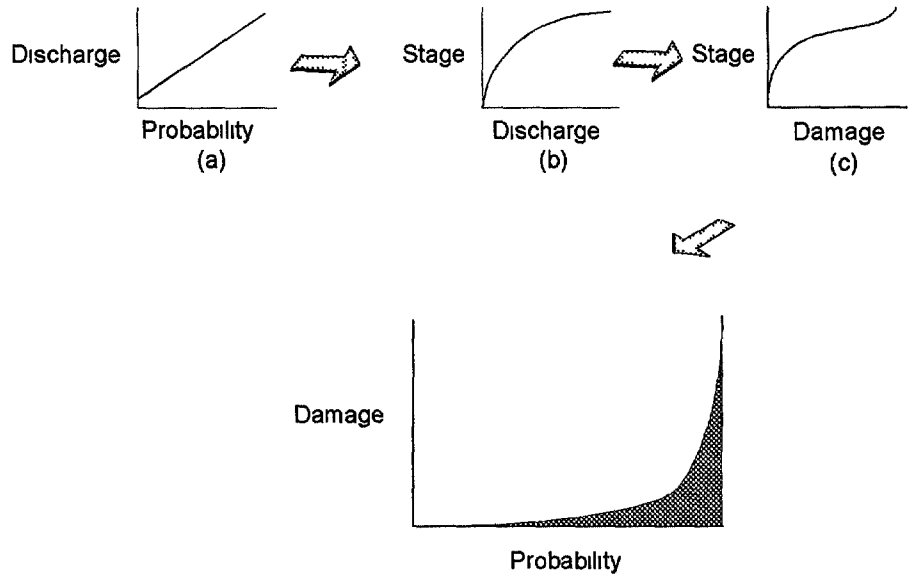

FIGURE 7.1 Derivation of Damage-frequency Function

TABLE 7.1 Input Required for HEC EAD Model

Category (1)	Input requirement (2)
Job specification	User must define discount rate, period of analysis
Statistical function	User must define either discharge v probability, stage v probability, or damage v probability function
Other functions	Depending on the form of the statistical function provided, user must provide other functions necessary to derive a damage v probability function These may include stage-damage and/or stage-discharge functions

Utility Programs. The HEC has developed utility programs that simplify use of EAD or provide additional capabilities The *SID* (Structure Inventory of Damage) program provides data management capabilities for the numerous stage-damage functions typical of a major flood-control study (USACE, 1989) It yields input in the format required for EAD The *FDA* (Flood Damage Analysis) package is a complete ensemble of flood-damage analysis models (USACE, 1988) It includes EAD, SID, and utility programs that permit linkage with statistical and fluvial process models through the HEC-DSS

7.2 HEC-5

Overview. Program HEC-5 models the performance of a reservoir or system of reservoirs operated to manage excess water (USACE, 1982b) Other computer models, including HEC-1 and TR-20, can simulate the operation of a detention structure in which the performance is a function of the properties of the outlet works HEC-5, however, simulates performance that is a function of both the properties of the outlet works and an operator's specification of the manner in which the reservoirs should be operated With HEC-5, storage in each reservoir in a system is divided into zones, as illustrated by Figure 7 2 Within each zone, the user defines indexed storage levels The model will simulate operation to meet specified system constraints and to keep system reservoirs in balance, with each at the same index level System constraints that may be modeled are summarized in Table 7 2

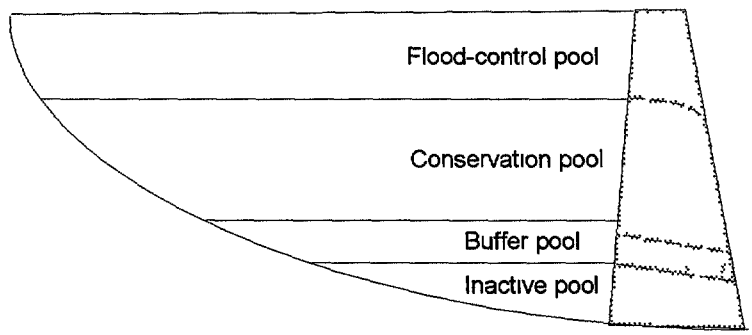

FIGURE 7.2 Reservoir Storage Zones for Program HEC-5

In addition to modeling reservoir flood-control operation, HEC-5 includes algorithms for modeling reservoir system operation for conservation purposes

Mathematical Models Included in the Computer Model. HEC-5 includes various simplified models for streamflow routing and a reservoir storage routing model For reservoirs with hydroelectric power generation facilities, an energy production model is included

Computer Model Input Requirements. Table 7 3 shows the input required for HEC-5 for analysis of performance of a flood-control reservoir system

TABLE 7.2 HEC-5 Flood-control Operation Rules

Constraint on release made (1)	Condition (2)
Release to draw storage to top of conservation pool without exceeding channel capacity at reservoir or downstream points for which reservoir is operated	Storage is between top of conservation pool and top of flood-control pool
Release equal to or greater than minimum desired flow	Storage greater than top buffer storage
Release equal to minimum desired flow	Storage between top inactive and top of buffer pool
No release	Storage below top of inactive pool
Release required to satisfy hydropower requirement	If that release is greater than controlling desired or required flows for above conditions
Release limited to user-specified rate of change	Unless reservoir is in surcharge operation
No release that will contribute to flooding downstream	If flood storage available
Release to maintain downstream flow at channel capacity	If operating for flood control
Release from reservoir at greatest level	If two or more reservoirs on parallel streams operate for common downstream point
Release to bring upper reservoir to same index to same index level as downstream reservoir	If two reservoirs in tandem

TABLE 7.3 Input Required for HEC-5 Model

Category (1)	Input requirement (2)
Job specification	Output requirements
System hydrological data	Reservoir inflows and intermediate area runoff, reservoir evaporation data
Fluvial model parameters	Routing coefficients
System layout	Description of individual reservoirs and physical relationship of reservoirs, channels, etc
Operating policy	Reservoir storage zones and levels

Computer Model Output. HEC-5 output includes the following A summary of the user's input, for each reservoir, a summary of inflows, releases, and storages for the period of analysis, for each system control point, a

summary of flows for the period of analysis, and if flood-damage relationships are provided, a summary of damage at each location HEC-5 also includes links to HEC-DSS, the database management system described in Section 2 1 Thus flood hydrographs can be computed and filed in the database by a catchment-process model, then retrieved for reservoir-performance analysis with HEC-5

8 WARNINGS

8.1 Watch for Rapid Changes in Technology

Scott McNeally, chairman of a Sun Microsystems, suggests that " the shelf life of biscuits and technology is about the same (*NY Times*, 27 March 1993) " Accordingly, the reader is cautioned that the state-of-practice in water-excess modeling changes rapidly He or she should contact sources of models and review the current water-resources literature for information on computer model updates or new computer models before selecting for application one of the models described in this paper

8.2 Avoid Pitfalls in Analysis

Biswas (1979), Ford and Davis (1989), and many others have written about the potential problems in applying models for water resource decision making. They note that, although mathematics and the computer are now essential ingredients of decision making, great care must be exercised to insure that results provide the information necessary to make the decisions Quade (1980) provides a list of common pitfalls in formulation and modeling, these are summarized in Table 8 1, the reader is encouraged to consider these when applying the models described herein

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TABLE 8.1 Pitfalls in Formulation and Modeling (after Quade, 1980)

Pitfall (1)	Description (2)
Insufficient attention to formulation	Modeler gets in hurry to get on with "real work" and pays insufficient attention to formulation Ends up working on problem that has little relation to real issue
Unquestioning acceptance of stated goals and constraints	Uncritical acceptance of client's or policy maker's statement of objectives and constraints on actions to be considered
Measuring achievement by proxy	Danger is that measure of achievement is a product of the modeler's judgment of the decision maker's values, rather than the decision maker's judgment of values
Misjudging the difficulties	Analysis is, necessarily, based on an abstraction of reality Attempts to include everything result in ambiguity, confusion, and intractability
Bias	Beware hidden bias introduced by data used, alternatives evaluated, and model selected
Equating modeling with analysis	Models are only one ingredient and modeling only one step in policy analysis analysis, searching out the right problem, designing a better alternative for consideration, and skillfully interpreting the computations from the model and relating them to the decision maker's problem are equally significant
Improper treatment of uncertainties	Impact of unpredictabilities in factors that affect outcome of a course of action must be considered, including uncertainties that are not stochastic in nature
Attempting to simulate reality	Heed the principle that the problem (the question being asked), as well as the process being modeled, determines what should be modeled
Belief that a model can be proved correct	Models can, at best, be invalidated Aim of validation tests is to increase degree of confidence that events inferred from application of model will, in fact, occur under the conditions assumed Modeler should also check data
Neglecting the by-products of modeling	The results of computation with model are not the only valuable output "Building a model is valuable because of what one learns about the problem and because of the guidance that a model can provide to the judgement and intuition of the analyst and policy maker
Overambition	Large-scale models designed for many purposes are likely to serve none
Seeking academic goals, rather than policy goals	Applications or development of models should focus on decision-making needs (relevance, reliability, usability, cost-effectiveness), rather than on tenure-granting needs (nontriviality, power, computational efficiency, elegance)
Internalizing the policy maker	Model cannot be made so comprehensive that it captures the preferences and constraints on the policy makers, so that it can designate the best alternative in a credible and acceptable manner
Not keeping the model relevant	Modeler must work to insure that the model's "knobs" represent the policy variables under the control of the policy maker
Not keeping the model simple	Model should be no more complicated than needed, and analyst should be able to exhibit in simplified form the key structrural elements of the model and their most important relationships Thus client can understand both how results came about and how to incorporate logic of analysis into continued thinking about the problem
Capture of the user by developer	Full documentation is critical Otherwise user is at mercy of model developer

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