CHAPTER 21

COMPUTER MODELS FOR SURFACE WATER

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21.1 PURPOSE OF CHAPTER

The purpose of this chapter is to describe computer program packages in hydrology that are generally available to hydrologists with access to standard computer systems such as personal computers (PCs) using the DOS or UNIX operating systems or to mainframes and minicomputers using standard operating systems and compilers. New programs are being written each year; some are variations of previous programs, while others use completely new techniques and provide the user with the great power of modern desktop computers, both in making a large number of computations very rapidly and in being able to deal with large volumes of data. It is not possible to include every existing model in a single chapter, and the discussion here is limited to several models of various types that have been found useful by practicing hydrologists and hydraulic engineers. Sufficient information is provided to permit the reader to make a judgment about the suitability of the program for specific hydrologic applications.

The programs covered in this chapter deal with surface water quantity and quality. The models are grouped into the following classes: (1) single-event rainfall-runoff and routing models, (2) continuous-stream-flow simulation models, (3) flood-hydraulics models, and (4) water-quality models.

The basic format of this chapter is as follows:

1. An overview of each model is provided.
2. The types of hydrologic problems and applications that the model is intended to deal with are discussed.
3. The required input for the model is briefly described.

4. Computer requirements are given.
5. Information on how the program can be obtained is provided.

21.1.1 General Remarks on Models in Hydrology

The models discussed in this section span the range from very simple, black-box-type models, the basic concepts of which were developed decades ago, through models that have been released for general use in just the last few years. The last group includes physically based distributed-parameter models, such as the SHE (European Hydrological System—Système Hydrologique Européen) model.

The data requirements of the models also vary over a wide range. In many design studies, standard design rainfall distributions and volumes are applied to catchments for which runoff response is characterized by synthetic unit hydrograph and generalized loss-rate functions. For physically based distributed-parameter models, large amounts of data are required for calibration of the model. However, the data are usually not available, because data collection is expensive and difficult. Also, as discussed by Abbott et al.[1,2] and Loague and Freeze,[22] a primary barrier to successful application of physically based models is the scaling problem. Field measurements are made at the point or local scale, while the application in the model is at the larger scale of the grid used to represent the hydrologic processes. This is especially true in the characterization of the spatial variability of precipitation and soil properties. In general, the larger the area considered, the larger is the variability of properties within that area.

The accuracy of model results is a function of the accuracy of the input data and the degree to which the model structure correctly represents the hydrologic processes appropriate to the problem. Complex models require complex data, and if the required data can be only roughly estimated, it may be better to use a model whose input data requirements are in tune with available data sources. Likewise, the modeling of the various hydrologic processes should be in balance. For example, continuous-stream-flow simulation requires accounting for both surface runoff and subsurface flow to streams in a balanced manner. A highly accurate model of surface runoff may not yield good stream-flow estimates if it is combined with a very approximate model of subsurface flows.

21.1.2 *Characterization of Models*

Simple, Single-Event, Rainfall-Runoff Models. Models that fall into this category include the Corps of Engineers HEC-1 model, the Soil Conservation Service TR-20 model, and similar models. Calculations proceed from upstream to downstream in the watershed, and the general modeling sequence is the following:

1. Subbasin average precipitation
2. Determination of precipitation excess from time-varying losses
3. Generation of the direct surface runoff hydrograph from precipitation excess
4. Addition of a simplified base flow to the surface runoff hydrograph
5. Routing of stream flow
6. Reservoir routing
7. Combination of hydrographs

In these models, the primary interest is the flood hydrograph, so it is [illegible] necessary to calculate evapotranspiration, soil moisture changes during and between storms, or detailed base flow processes.

Continuous-Stream-Flow Simulation Models. A second major class of hydrologic models is one that includes models that continuously account in time for all precipitation that falls on a watershed and the movement of water through the catchment to its outlet. During periods in which there is no precipitation, the main concern is the depletion of water stored in the watershed, with consequent emphasis on soil moisture accounting, evapotranspiration, and subsurface flows in the unsaturated and saturated groundwater zones.

Models which provide simulations of this type are called *continuous-stream-flow simulation models*. These models range in complexity from the very simple—antecedent precipitation index (API) and tank models—to the very complex—distributed-parameter models such as the HSPF and SHE models discussed below.

Physically based distributed-parameter models describe the major hydrologic processes which govern water movement through a catchment. These processes include, but are not limited to:

1. Canopy interception
2. Evapotranspiration
3. Snowmelt
4. Interflow
5. Overland flow
6. Channel flow
7. Unsaturated subsurface flow
8. Saturated subsurface flow

The spatial variation of these processes is represented by the spatial variation of precipitation, catchment parameters, and hydrologic response. Variability is modeled by representing the catchment by individual subbasins or by developing a grid of individual elements and prescribing the hydrologic characteristics of each element. Vertical variability is represented by subsurface zones or vertical layers of soil for each grid element.

Flood-Hydraulics Models. These models compute water surface profiles in open channels and represent flows in natural channels such as rivers and streams, where the geometry of the cross section changes from section to section. Programs in this group usually analyze flow through bridges and culverts, as well as on floodplains adjacent to the main river system.

Steady-flow models (such as HEC-2 and WSPRO) employ conventional step-backwater analyses. These programs assume that the flow is one-dimensional, gradually varied steady flow in the direction of the stream centerline. In situations where the flow is actually two-dimensional in nature or is rapidly varied (as at a bridge), hydraulic equations involving empirical head-loss coefficients are used to represent approximately these complicated flows. Both subcritical and supercritical flow profiles can be analyzed.

One class of unsteady-flow models is represented by the National Weather Service program FLDWAV and its predecessors DWOPER and DAMBRK. These programs are based on the one-dimensional St. Venant equations. The models provide many capabilities in addition to water surface profile calculation, such as dam breach simulation, embankment overtopping, and representation of structures and their operation schedules.

Some of the models which have been developed to analyze water-quality problems have detailed procedures for analyzing time-varying flows. For example, the EXTRAN block of the SWMM model described below has been frequently used for unsteady-flow analysis in stream systems. The MIKE11 model has similar capabilities.

Water-Quality Models. This group of models link the determination of water quantity and analysis of water quality. These models vary a great deal in their complexity. In general, the models require that relations between water-quality loading and the hydraulic features of the system be established. In most cases, empirical relations for defining chemical and biological reactions are used. Both lumped-parameter and distributed-parameter models are available, and the models may be single-event models or continuous models. Distributed-parameter models provide detailed information about local conditions, while lumped-parameter models are useful when large-scale systems are being studied. Single-event models are useful for evaluating water-quality conditions occurring with extreme flow events, while continuous models provide sequences of water-quality events that can be subjected to frequency analyses.

21.2 RAINFALL-RUNOFF AND ROUTING MODELS (SINGLE-EVENT MODELS)

21.2.1 HEC-1 Flood Hydrograph Package

Overview of Program. HEC-1 is a computer model for rainfall-runoff analysis developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers.[17,18] This program develops discharge hydrographs for either historical or hypothetical events for one or more locations in a basin. The basin can be subdivided into many subbasins. Uncontrolled reservoirs and diversions can also be accommodated. Figure 21.2.1 shows an example river basin and the schematic for the division of the basin into subbasins and routing elements for modeling by HEC-1.

The available program options include the following: calibration of unit hydrograph and loss-rate parameters, calibration of routing parameters, generation of hypothetical storm data, simulation of snowpack processes and snowmelt runoff, dam safety applications, multiplan/multiflood analysis, flood damage analysis, and optimization of flood-control system components.

The 1990 version of HEC-1 also has the capability to communicate with a data storage system (DSS) file. DSS is a database system that is designed for efficient storage and utilization of time series data between the various Hydrologic Engineering Center programs.[19] For example, observed precipitation and discharge data can be stored in a DSS file and retrieved automatically during an execution of HEC-1. Additionally, simulation results can be written to a DSS file. Utility programs develop graphs or tabulations of data. DSS also has programs for loading data from WATSTORE and other data sources, for data editing, and for producing reports. DSS provides a convenient means for transfer of data generated with one program (say HEC-1) to input to another HEC computer program (such as the reservoir system simulation program HEC-5).

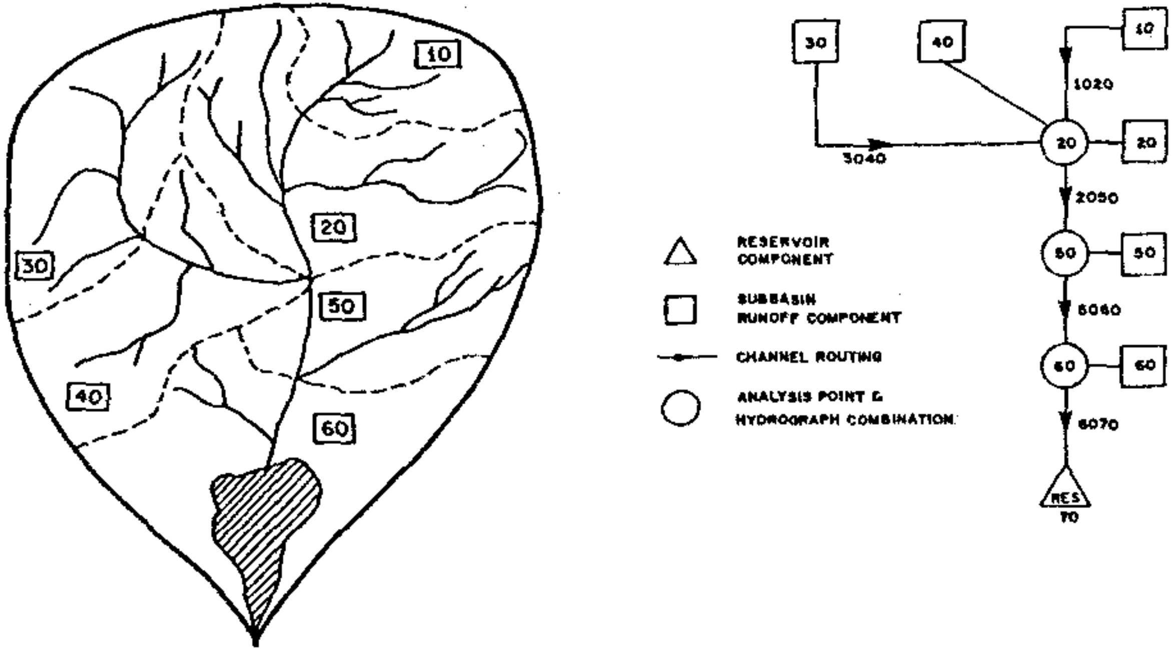

FIGURE 21.2.1 Example river basin and basin schematic for HEC-1 *(Source: Hydrologic Engineering Center.)*

HEC-1 allows a wide variety of options for specifying precipitation, losses, base flow, runoff transformation, and routing. A description of these options follows.

Precipitation. Spatially averaged precipitation can be determined externally and supplied as program input. As an alternative, precipitation for individual recording and nonrecording gauges can be specified, along with weighting factors to calculate the average precipitation for each subbasin. The basin-average precipitation can be further adjusted if the gauges from which it is determined have a normal annual rainfall systematically different from the basin as a whole, for example, if the gauges are in the valleys and the precipitation is greater in the hills.

Losses. Losses can be computed from:

1. An initial loss and constant loss rate
2. A four-parameter exponential loss function unique to HEC-1
3. The Soil Conservation Service (SCS) curve number (with an optional initial loss)
4. The Holtan formula
5. The Green and Ampt method

Rainfall Excess to Runoff Transformation. Precipitation excess can be transformed to direct runoff using either unit hydrograph or kinematic wave techniques. Several unit hydrograph options are available. A unit hydrograph may be supplied directly or the unit hydrograph may be expressed in terms of Clark, Snyder, or Soil Conservation Service unit hydrograph parameters. The kinematic wave option permits depiction of subbasin runoff with elements representing one or two overland-flow planes, one or two collector channels, and a main channel.

Base Flow. Base flow is specified by means of three input variables: (1) a starting discharge at the beginning of the simulation, (2) an exponential recession rate term, and (3) a recession threshold discharge for the recession limb of the hydrograph. Once the discharge drops below this threshold, the discharge is based solely on the recession rate.

Routing through Stream Channels. The Muskingum-Cunge, kinematic wave, Muskingum, modified Puls, and normal depth methods can be used for stream-flow routing. For the Muskingum-Cunge and normal depth methods, a routing reach is specified in terms of length, slope, and Manning's n values (for the main channel and for the left and right overbanks), and the cross section is defined with eight pairs of x-y coordinate values.

Reservoir Routing. Storage routing techniques are used for routing of flows through uncontrolled reservoirs. The reservoir outflow may be computed by specifying spillway and low-level outlet hydraulic characteristics, or a discharge rating curve for the reservoir can be given. Program output includes a time history of water storage and water surface elevation.

Parameter Calibration Capabilities. A very useful option of HEC-1 is the ability to employ an automatic parameter calibration procedure for single basins (basins that are not subdivided) when both discharge data and precipitation data are available for historical flood events. Unit hydrograph and loss-rate parameters are optimized by using a univariate gradient procedure.

There is also an option to optimize routing parameters, given historical inflow and outflow hydrographs for a routing reach. This requires specification of a time distribution for lateral inflow (flow that enters the routing reach between the inflow and outflow locations). The optimized values for routing parameters are usually very sensitive to the time distribution of lateral inflow, especially when this flow is a substantial proportion of the total outflow.

Hypothetical Storm Generation. HEC-1 has capabilities to generate frequency-based hypothetical storms as well as U.S. Army Corps of Engineers standard project storms for regions in the continental United States east of the Rocky Mountains. Frequency-based storms can be developed from generalized rainfall criteria such as that found in various technical publications of the U.S. Weather Service of the National Oceanographic and Atmospheric Administration (NOAA). Point-to-area adjustments to average precipitation are made automatically. Adjustments from partial duration series to annual series data can also be made.

Snowpack/Snowmelt Simulation. Snow accumulation is computed within elevation zones specified for the subbasin. Air temperatures (specified for the bottom of the lowest zone) and a lapse rate are used to determine whether precipitation occurs as rain or snow. Two snowmelt routines are available: (1) an energy budget method which requires meteorological data such as solar radiation, wind speed, and dew point and (2) a simple temperature-index method requiring only air temperatures. Air temperatures are required at constant time increments and are supplied as time series input. The data do not have to be provided at the same time increment used for program computations; HEC-1 will interpolate time series data as required.

Dam Safety Applications. The reservoir routing procedures can also include the calculation of flows which overtop the dam, including the formation of a breach described by its final geometry after the breach is complete. Flow through the breach is calculated in addition to the flows over the top of the dam, through the spillway, and through the low-level outlet. The various components of dam outflow are combined and routed downstream. Flooding elevations downstream from the dam are computed by the hydrologic routing techniques in the program.

Multiplan/Multiflood Analysis. This option is useful for analyzing alternative future land use and/or project conditions. Various alternative sets of values for modeling parameters can be specified and runoff calculated in a single application of the program. Also, ratios can be applied to hydrographs or to historical or hypothetical storm hyetographs for evaluation of runoff response under a range of conditions. For example, in urban hydrology applications, three conditions can be simulated in a single run of the model: runoff from the existing watershed, runoff after development has occurred, and outflow from the developed watershed with flood detention structures.

Flood Damage Analysis. A flood-peak versus return-period curve can be specified for existing conditions at each basin outlet. Using the multiplan option, alternative land use or project proposals can be simulated and their effect on the flood frequency curve determined. By combining the flood frequency curve with a curve of damage cost versus flood discharge, the expected annual flood damage can be calculated for each alternative plan.

Optimization of the Size of Flood Control System Components. The required size or capacity of various components such as uncontrolled reservoirs, diversions, and pumping plants can be obtained by optimization. Data requirements include cost and grassed-area hydrographs are combined, and the result is then combined with hydrographs from other tributaries. If the program is in the design mode, the required pipe size is computed. Flow is then routed to the next combining point. Results are printed, and the program moves to the next subbasin.

Since the program requires only a little more design information than the rational method, it may serve as a next step beyond the rational method for the determination of urban runoff. Terstriep and Stall[32] give the results of ILLUDAS applications for 21 urban basins and two rural basins. The basins were all less than 8.5 mi^2 in size.

Required Input. ILLUDAS requires:

1. Identification information and run type
2. Basin parameters—paved- and grassed-area abstractions, minimum pipe size and Manning's n
3. Rainfall parameters—measured rainfall data or rainfall distribution, duration and return period, and antecedent moisture condition
4. Reach data—type of branch channel, section dimensions, and available storage
5. Subbasin data—subbasin area for paved and grassed areas, contribution area, slopes and path lengths, and hydrologic soil group.

Computer Requirements. ILLUDAS is written in FORTRAN IV. The program consists of over 700 lines of code, and on a mainframe computer the program requires 220 Kbytes of core. The program has also been compiled for operation on the IBM PC and compatible computers. The current version is ver. 2.16.

How Program Can Be Obtained. The ILLUDAS program is available to users in the State of Illinois from the Illinois State Water Survey, 2204 Griffith Dr., Champaign, IL 61820. Others can obtain the program from CE Software, Box 2472, Station A, Champaign, IL 61820.

21.2.4 DRM3—USGS Rainfall-Runoff Model

Overview of Program. The Distributed Routing Rainfall-Runoff Model (DR3M) was developed by the U.S. Geological Survey.[3] DR3M provides a detailed simulation of runoff from rainfall for user-selected storm periods. In DRM3 a drainage basin (or basin subarea) is represented by an overland-flow element, a channel element, and (optionally) reservoirs. Kinematic wave procedures are used to route overland flow over areas that are defined as contributing areas. Flow through the channel segments is also routed by using kinematic wave procedures.

Subareas can be arranged into a basin network to permit simulation of complex hydrologic basins. The model is intended primarily for simulation of urban watersheds (for which the kinematic wave procedures are most applicable), but the model has also been successfully applied to rural watersheds.

The currently available version of DR3M is version II. Program documentation is provided by Alley and Smith.[3]

Required Input. Input consists of short-interval precipitation and discharge data, daily precipitation and evaporation totals, subcatchment areas, roughness, and hydraulic data.

Computer Requirements. DRM3 is written in FORTRAN and can be run on PC systems as well as minicomputers and mainframe computer systems.

How Program Can Be Obtained. The DRM3 model can be obtained from the U.S. Geological Survey. For information contact the U.S. Geological Survey, WRD, 415 National Center, Reston, VA 22092.

21.3 CONTINUOUS-STREAM-FLOW SIMULATION MODELS

21.3.1 SWRRB—Simulator for Water Resources in Rural Basins

Overview. Simulator for Water Resources in Rural Basins (SWRRB) simulates hydrologic and related processes in rural (agricultural) basins. This computer model was developed by the U.S. Department of Agriculture[4] to predict the effect of various types of watershed management procedures on water and sediment yields in ungaged rural basins. The major processes which are included in the model are surface runoff, evapotranspiration, transmission losses, pond and reservoir evaporation, sedimentation, and crop growth. There is also a special component of the program that simulates the runoff of pesticides.

The model deals with large basins which are subdivided into as many as 10 subbasins, each of which can have a different rainfall input. There is no limitation on basin area. The soil profile can be divided into as many as 10 layers. The upper layer has a fixed thickness of 10 mm (0.4 in); the other layers are of variable thickness.

The model is physically based and is intended to be used for situations in which calibration data are not available. Periods of many years of daily flows can be simulated by SWRRB.

SWRRB has three major components: hydrology, weather, and sediment yield. These are discussed in the following paragraphs. A flowchart showing the major elements of the program is given in Fig. 21.3.1.

Hydrology Component. The SWRRB hydrology model is based on the water balance equation, and the change in soil water content is computed from rainfall, runoff, evapotranspiration, percolation, and return flow. Basins are subdivided to reflect differences in hydrologic characteristics, such as the different evapotranspiration rate for different crops, soils, and other factors. The runoff from each subbasin is computed separately.

Surface runoff is computed from daily rainfall values. Runoff volume is determined by using the Soil Conservation Service curve number approach. Peak discharge is estimated by using a modification of the rational formula. Rainfall intensity is related to the subbasin time of concentration, which is based on an average overland flow time of concentration computed from average overland and channel flow lengths, slopes, and Manning n values. If snow is present, it is assumed to melt on days for which the average temperature exceeds 0°C.

The percolation component of SWRRB uses a storage routing technique combined with a crack-flow model to predict flow through soil layers. Water which percolates below the root zone is moved to groundwater or shows up as return flow in downstream basins. The crack-flow model permits percolation of infiltrated rainfall for conditions where the soil water content is below field capacity.

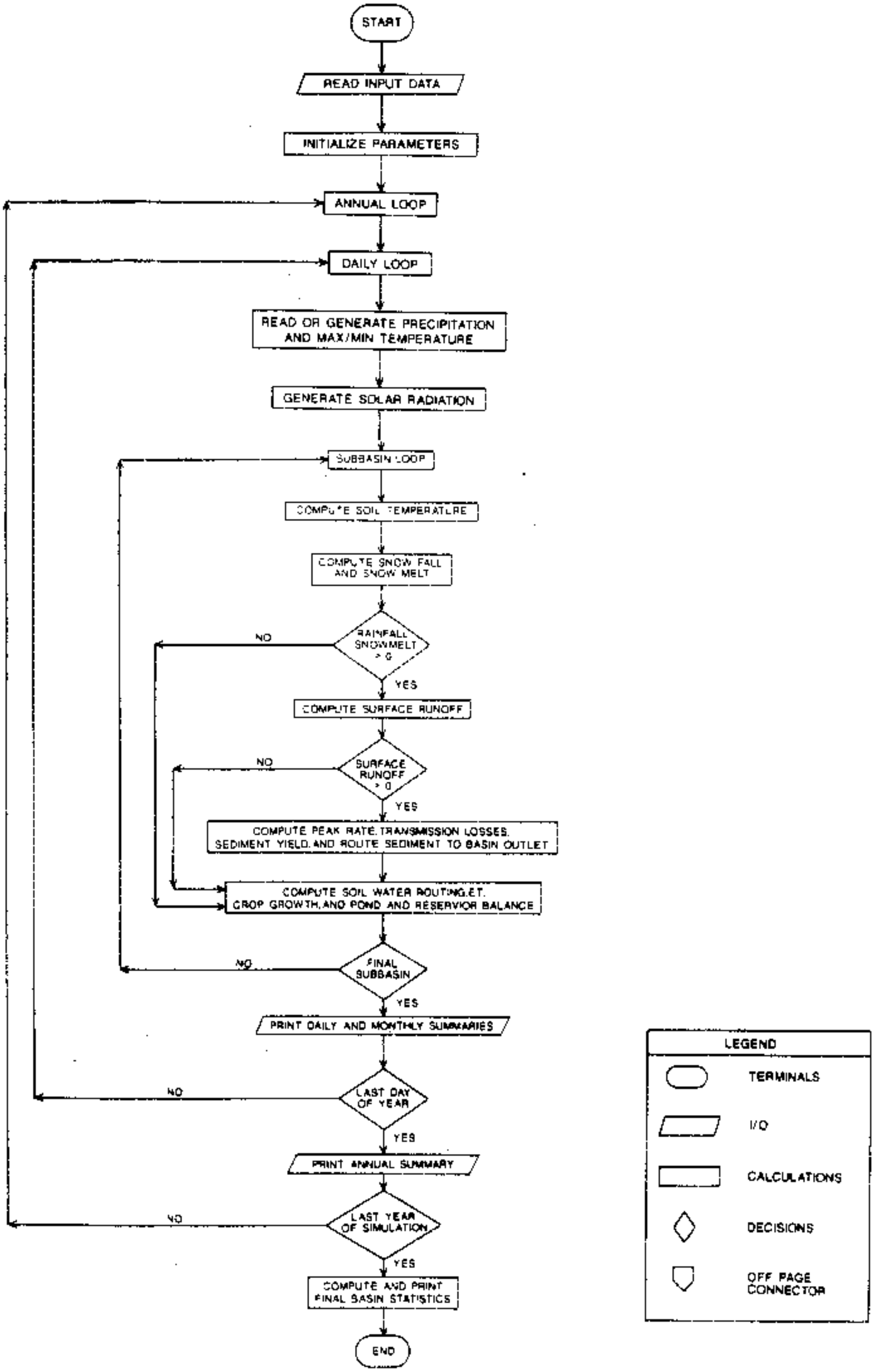

FIGURE 21.3.1 Schematic of the SWRRB program. *(Source: Arnold et al.*[4] *Used with permission.)*

Lateral subsurface flow is calculated to occur simultaneously with percolation, and lateral flow travel time is adjusted to account for variations in the soil water content and subsurface flow characteristics.

Potential evapotranspiration is related to daily solar radiation, mean air temperatures, crop cover and snow cover (if present). Soil and plant evaporation are computed separately. Soil evaporation is determined by the water content of the top 30 cm (12 in) of the soil. If soil water is limited, plant evaporation will be reduced accordingly.

Transmission losses in alluvial channels can be computed from stream channel data (width, depth, length, and the hydraulic conductivity of the channel alluvium).

Water yield in SWRRB is related to storage, seepage, evaporation, and outflow from ponds and reservoirs. The water balance equation is used for ponds and is based on the percentage of area occupied by ponds in the catchment employing an empirical pond storage-volume–surface-area relationship to compute daily inflows, outflows, seepage, and evaporation. The reservoir component is similar to the pond component. The reservoir calculations can also include flow from spillways.

Weather Component. SWRRB uses precipitation, air temperatures, and solar radiation for driving the weather component of the model. Two methods of providing precipitation data are available: daily precipitation can be used as a direct input, or precipitation can be simulated as a first-order Markov chain process which uses the probabilities of receiving precipitation if the preceding day was dry or wet. When no wet-dry probabilities are available, probabilities are estimated from the average number of days of precipitation in a month. Air temperatures and solar radiation for each day are generated from daily statistics of these variables.

Sediment Yield Component. Sediment yield for each subbasin is computed from the modified universal soil loss equation.[35] Sediment yield is computed from the surface runoff volume, the peak discharge, a soil erodibility factor, a crop management factor, an erosion control management factor, and a slope-length–steepness factor. The sediment yield from subbasins is used as an input to ponds and reservoirs.

Sediment is routed through the system, first through ponds and reservoirs, and then through stream channels by using a stream power concept described by Williams.[36]

SWRRB is used to predict the effects of various types of land uses on water yield (on a monthly or annual basis), on sediment production in the watershed, and on pollution. For example, sediment yields from a watershed can be compared for alternative management practices of fall plowing, conservation tilling, or no tilling. The model has been used to illustrate how various mixes of crops on the watershed and alternative management practices can affect water yield from the basin. SWRRB has been used to demonstrate the effects of reservoir storage on water and sediment yield in Oklahoma, and in another study it was used to determine the effect of urbanization on water and sediment entering a Texas lake.[4]

Required Input. The data used by the SWRRB program includes the following (specific input data formats are given in the program users manual):[4]

1. Program control codes governing the total length of simulation (1 to 100 years), number of subbasins, output codes, etc.
2. General watershed data such as rain-gauge correction factors, base flow parameters, and initial soil water storage

3. Subbasin centroid coordinates
4. General weather data
5. Monthly temperatures
6. Monthly solar radiation
7. Monthly rainfall
8. Parameters for generation of daily rainfall
9. Basin data such as SCS curve numbers, soil albedo, snow cover at start of simulation, overland and channel data, and surface erosion parameters
10. Channel routing data (including channel erosion parameters)
11. Pond data
12. Reservoir data
13. Soils data
14. Crop data
15. Irrigation data
16. Daily temperature and rainfall parameters

SWRRB provides access to meteorological statistics compiled for about a hundred first-order weather stations in the United States, and SWRRB contains a very extensive database of soil properties developed by the U.S. Department of Agriculture.

Computer Requirements. The SWRRB is written in FORTRAN 77. It runs on PC systems with 256 Kbyte RAM. Fortran source code is available. An interactive data editor is available for the program also.

How Program May Be Obtained. The program may be obtained from the Grassland, Soil, and Water Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, 808 East Blackland Rd., Temple, TX 76502.

21.3.2 PRMS—Precipitation-Runoff Modeling System

Overview. The Precipitation-Runoff Modeling System (PRMS) is a program developed by the U.S. Geological Survey (USGS) to simulate watershed response over time periods that are longer than those used with the USGS DR3M distributed-parameter watershed model discussed above. It was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. The model provides simulations on both a daily and a storm time scale by using variable time steps. In the storm simulation mode, the program simulates selected hydrologic components using time increments that can be as small as 1 min. Before and after the storm period a daily time step is used and a daily average or daily total is simulated for the hydrologic components. Stream flow is computed as mean daily flow.

Watersheds are partitioned into units based on specific characteristics. The USGS has developed maps for the United States that show watershed delineation into *hydrologic response units* (HRU). Parameters of these units include surface slope, aspect, elevation, soil type, vegetation type, and distribution of precipitation. Each hydrologic response unit is assumed to have homogeneous hydrologic characteristics. A water balance and energy balance are computed daily for each HRU. The sum of the responses of all HRUs gives the daily watershed response.

During storm periods, a second level of partitioning is used to permit the short-term response of the watershed to be determined. For this the watershed is assumed to be composed of a series of interconnected flow planes and channel segments. Each HRU can be represented by a single flow plane or by a series of flow planes. The watershed drainage network is represented by a system of channel segments, reservoirs, and junctions in a manner similar to the DR3M model. Kinematic flow routing is used for routing flows over flow planes and through the channel segments.

PRMS is used in conjunction with two other programs developed by the U.S. Geological Survey. A program named ANNIE provides computer data management and analysis capabilities for PRMS. Hydrologic forecasting capabilities are provided by a modified version of the National Weather Service program Extended Streamflow Prediction (ESP). PRMS, ANNIE, and ESP, when used together, form a complete watershed modeling system that gives the user the capability to reduce, analyze, and prepare data for model applications; to simulate and forecast watershed response; and to analyze model results statistically and graphically.

Required Input. Short interval precipitation and discharge data, daily precipitation and evaporation totals, subcatchment areas, roughness and hydraulic data.

Computer Requirements. The DRM3 program is written in FORTRAN and can be run on PC systems as well as on minicomputers and mainframe computer systems.

How Program Can Be Obtained. The DRM3 model can be obtained from the U.S. Geological Survey. For information contact the Office of Surface Water, U.S. Geological Survey, WRD, 415 National Center, Reston, VA 22092.

21.3.3 SHE—European Hydrologic System Model (Système Hydrologique Européen)

Overview. SHE is a physically based, distributed-parameter catchment modeling system that was produced jointly by the Danish Hydraulic Institute, the U.K. Institute of Hydrology, and SOGREAH (France). The development work was financially supported by the Commission of the European Communities, and the development of SHE was aimed at providing a strong European capability in hydrologic modeling. The background for the development of SHE is given by Abbott et al.[1] The process equations and model structure description can be found in Abbott et al.[2] and Bathurst.[5,6]

The model considers the major hydrologic processes of which govern water movement through a catchment, namely: snowmelt, canopy interception, evapotranspiration, overland flow, channel flow, and unsaturated and saturated subsurface flow. Spatial variability of hydrologic processes is described by using a rectangular grid of (x, y) points in the horizontal plane with vertical variation in properties represented by a series of horizontal planes of various depths.

SHE is applicable to a wide range of hydrologic processes and can be applied to a variety of hydrologic problems, including irrigation schemes, determination of land-use changes, water development studies, groundwater contamination, erosion and sediment transport, and flood prediction. See Table 21.3.1 for details.

Computer Requirements. SHE applications have been performed on mainframe computers. Applications of the program on PCs are limited because of the large number of computations that must be made.

TABLE 21.3.1 Suggested Applications for SHE at Different Operational Scales

Topic	Primary hydrologic process*	Possible scale of operation
Irrigation schemes:		
Irrigation water requirement	ET/UZ	Field
Crop production	ET/UZ	Project
Waterlogging	ET/UZ	Field
Salinity/irrigation management	UZ	Field
Land-use changes:		
Forest clearance	ET/UZ/SZ	Catchment
Agricultural practices	ET/UZ/SZ	Field/catchment
Urbanization	ET/UZ/SZ	Catchment
Water developments:		
Groundwater supply	SZ	Catchment
Surface-water supply	ET/UZ/SZ	Catchment
Irrigation	UZ/SZ	Project/catchment
Stream-flow depletion	SZ/OC	Catchment
Surface water/groundwater interaction	ET/UZ/SZ	Project/catchment
Groundwater contamination:		
Industrial and municipal waste disposal	UZ/SZ	Field/catchment
Agricultural chemicals	UZ/SZ	Field/project/catchment
Erosion/sediment transport	OC/UZ	Project/catchment
Flood prediction	OC/UZ	Catchment

* ET = evapotranspiration; UZ = unsaturated zone; SZ = saturated zone; OC = overland and channel flow.

Source: Abbott.[3] Used with permission.

How Program Can Be Obtained. The program can be obtained through one of the sponsoring agencies: (1) The Danish Hydraulic Institute, Agern Alle 5, DK-2970 Horsholm, Denmark; (2) Institute of Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, Oxon OX10 8BB, United Kingdom; (3) Ministère de l'Environnement et du Cadre de Vie, 14, Bd. du General Leclerc, 95521 Neuilly-sur-Seine Cedex, France. Training in the use of the program is also available through these institutions.

21.4 FLOOD-HYDRAULICS MODELS

21.4.1 HEC-2 Water Surface Profiles

Overview. HEC-2 was developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers to compute steady-state water surface elevation profiles in natural and constructed channels.[20] Its primary use is for natural channels with complex geometry such as rivers and streams. The program analyzes flow through bridges, culverts, weirs, and other types of structures. Water surface elevation profiles can be computed for cases where there is a loss of flow from the stream because of levee or embankment overflows, overtopping of watershed divides, or flow through diversion structures (the split-flow option). Cross-section modifications can be easily analyzed by specifying a template for cut and fill to the cross section using the channel improvement option.

The encroachment computation option has been widely used in the analysis of flood-plain encroachments for the U.S. Federal Emergency Management (FEMA) flood insurance program. There are several types of encroachment calculation procedures, including the specification of encroachments with fixed dimensions and the designation of target values for water surface increases associated with floodplain encroachments.

HEC-2 uses the standard step method for water surface profile calculations, assuming that flow is one-dimensional, gradually varied steady flow. Either subcritical or supercritical flow profiles can be analyzed. The input data records for subcritical profile calculations are specified from downstream to upstream. The cross sections must be placed in reverse order in the data file for supercritical profile runs.

HEC-2 will compute up to 14 individual water surface elevation profiles in a given run. Usually a different discharge is used for each profile, although when the encroachment or channel improvement options are used, the section dimensions are changed rather than the discharge. The discharge can be changed at each cross section to reflect tributaries, lateral inflows, or diversions.

The water surface elevation at the starting cross section can be specified in one of four ways: as a given elevation, as critical depth, by a rating curve, or as a computation by the program, by the slope-area method, when the energy grade line slope is specified. The water surface elevation associated with critical flow is computed for conditions of minimum energy at the cross section.

The energy-loss term in the energy equation is computed from two factors: boundary resistance (friction loss) and eddy loss between sections (expansion or contraction loss). Friction losses are computed by using Manning's equation. Eddy losses are calculated by using a head-loss coefficient multiplied by the change in the velocity head between cross sections.

HEC-2 computes water surfaces as either a subcritical flow profile or a supercritical profile. Mixed subcritical and supercritical profiles are not computed simultaneously. If the computations indicate that the profile should cross critical depth, the water surface elevation used for continuing the computations to the next cross section is the critical water surface elevation.

The kinetic energy coefficient α is included in the energy equation and is calculated from a weighted sum of kinetic energies of the main channel and the overbank areas. The overbanks can be subdivided into individual flow sections by using the divisions established by the assigned distribution of Manning's n across the full section. The program requires that three flow path distances be used between cross sections: a channel length and left and right overbank lengths. The reach length used in friction-loss calculations is a discharge-weighted length based on the relative amounts of flow in each portion of the cross section. Friction loss is computed as the product of the reach length and the mean friction slope for the reach. The mean friction slope can be computed from the average conveyance, the average slope, the geometric mean slope, or the harmonic mean slope. An alternative method for defining frictional resistance is to use a *roughness height* based on the Colebrook-White approach. The roughness height can be varied horizontally across the section in the same manner as Manning's n.

Bridge Hydraulics. Head loss at bridges and other river structures is also computed by HEC-2. Bridge head loss is assumed to be due to two factors: contraction and expansion losses before and after the structure, and loss at the structure itself. Structure losses can be computed by either the *special bridge method*, which uses hydraulic formulas for pier losses, pressure flow when the bridge opening is submerged, and weir flow when the bridge and roadway embankment are overtopped, or by the *normal bridge method,* which computes bridge head loss as the sum of increased friction plus expansion and contraction losses at the structure. The special bridge method is usually easier to apply, since fewer cross sections are required. In bridge calculations, the weir may be described by using a fixed width and elevation or the weir crest may be defined using *x-y* coordinates to more closely represent the weir flow section produced by bridge approach roadway embankments and the bridge deck.

Culvert Flows. Single- or multiple-barrel box or circular culverts may be modeled. Culvert inlet control flow computations are based on Federal Highway Administration (FHWA) nomographs. The program uses hydraulic formulas for outlet control calculations (inlet and outlet losses plus friction in the culvert). Flows which pass over the roadway embankment are treated as weir flow in the same manner as in the special bridge method. There are limitations in the HEC-2 culvert procedures. Only circular or box culverts can be analyzed, and, when multiple culverts are used, they must all be identical.

Encroachment Analyses. The six methods for encroachment analysis of flood plains available in HEC-2 are listed in Table 21.4.1.

Required Input. The program is designed to operate in a batch mode, and a data file is prepared by using an editing program. The Corps of Engineers editor COED is supplied with the HEC-2 program package for the PC. COED has on-line help information for all input variables used by HEC-2. Individual data records have a two-character identifier at the beginning of each record. Multiple title records can be used, and comments can be inserted at any point in the data file. In addition to running identification data, the program requires job control information, discharge and loss data, and cross-section geometry data. The cross-section data make up the major portion of the input and include cross-section numbering, reach lengths, geometry data, and modifications to the basic cross-section data (points added to cross section, filling of all low areas to a specified elevation, blocking out of ineffective

TABLE 21.4.1 HEC-2 Floodplain Encroachment Calculation Methods

Method No.	Description
1	Encroachment elevations and stations specified
2	Top width of water surface specified and centered on the channel
3	Encroachment stations automatically computed for a specified percent reduction in conveyance
4	Encroachment stations automatically computed corresponding to a target difference in the water surface elevations of natural and encroached flows
5	Encroachment stations are optimized to achieve a target difference in the water surface elevations of natural and encroached flows
6	Encroachment stations automatically computed corresponding to a target difference in the energy grade line elevations of natural and encroached flows

Source: Feldman.[11] Used with permission.

flow areas). Manning's n values, and expansion and contraction loss coefficients, may also be changed at each cross section.

Data which do not change from section to section can be repeated from the previous cross section. Cross-section dimensions can be expanded or reduced in size and adjusted in elevation at the repeated cross section. The data can be entered in free format and transformed to fixed format by a program utility.

Program Output. The amount of output produced by an HEC-2 run can be controlled by input codes. HEC-2 can generate large volumes of output because detailed information about the computations is normally printed by the program. Various summary tables can be requested; for example, summary tables for bridge and culvert computations, for the channel improvement option, and for encroachment data are available. Special flood insurance study tables for displaying encroachment output that match the table format required by the U.S. Federal Emergency Management Agency's guidelines and specifications for flood insurance studies can be printed. User-defined tables can be produced which display any variable computed by the program.

The interactive screen plotting program PLOT2 can produce profile plots, cross-section plots, rating curves, and plots of other computed data. The plots can be sent to a graphics printer or to plotters which use the Hewlett-Packard (HP) graphics language format.

Computer Requirements. The HEC-2 program is written in ANSI-standard FORTRAN 77. Versions of the program are available in compiled form for personal computers and as source code for PCs, minicomputers, and mainframe computers. The PC source code package contains information for compiling the program. Some program utilities (such as PLOT2) are not written in FORTRAN and are supplied only in executable form. A math coprocessor is not required for the PC version, but it speeds up program operation significantly. A graphics monitor and hard disk are not mandatory, but make the program much easier to use effectively.

How Program Can be Obtained. HEC-2 is available directly from HEC only to U.S. government agencies. HEC provides lists of program vendors for the United States and other countries (Hydrologic Engineering Center, 609 Second St., Davis, CA, 95616).

21.4.2 WSPRO—A Model for Water Surface Profile Computations

Overview. WSPRO is a computer program which computes steady-state water surface profiles in open channels. It is intended for use with natural channels such as rivers and streams, where the geometry of the channel changes from section to section. The program analyzes flow through bridges and culverts, through multiple-opening stream crossings, and embankment overflows. Two Federal Highway Administration reports[27,28] provide the documentation for this model.

Conventional step-backwater analyses are used in this program. The program assumes that the flow is one-dimensional, gradually varied steady flow. Both subcritical and supercritical flow profiles can be analyzed. The input data records (which are usually ordered from downstream to upstream for a subcritical profile analysis) do not have to be rearranged for a supercritical profile run.

The program can compute 1 to 20 individual water surface elevation profiles in a given run. Usually a different discharge is used for each profile. The discharge can be changed at cross section. The water surface elevation at the starting cross section can either be specified by the user or be computed by the program. If a slope is specified, the program will compute the water surface elevation corresponding to normal depth using the slope-conveyance method. If neither elevation nor slope is specified, the program will assume the starting depth to be critical depth. The water surface elevation associated with critical flow conditions is based on occurrence of minimum energy at the cross section.

WSPRO allows simultaneous variation of bed roughness both across the cross section and with water depth. This type of roughness variation is fairly common in rivers;[28] however, this computational technique is not available in other models of *this type. Friction-loss computations are based on specified flow lengths between* cross sections. The user can select the technique used by the program for computing the average friction slope. Coefficients for energy losses associated with expansion and contraction of the flow may be specified as input.

Flow through Bridges. Flow through a bridge is treated as either free surface flow or pressure flow. When the water surface does not have significant contact with the underside of the bridge and the flow is subcritical or critical, a free surface flow profile is computed by techniques that are based on the USGS contracted-opening method,[26] in which a coefficient of discharge, reflecting the characteristics of bridge geometry and the flow, is determined for the bridge opening. The energy equation is then solved by using a minimum of three cross sections: an exit section located at least one bridge length downstream from the opening, a section at the bridge opening, and an upstream approach section. If spur dikes upstream from the bridge are present, a fourth section can be used.

Pressurized flow will exist when the water surface is in contact with the lower members of the bridge structure. WSPRO computes pressure flow conditions by one of two orifice-type discharge equations.[7] One equation represents unsubmerged orifice flow in which the water is in contact with only the upstream lower portion of the bridge. The second equation is used when the flow is in contact with both the upstream and downstream low-chord elements of the bridge.

Culvert Flows. Culvert flow computations in WSPRO are based on Federal Highway Administration design procedures.[33] Single- or multiple-barrel configurations of box, circular, and pipe-arch culverts of concrete, corrugated metal, and aluminum may be simulated. Culverts may also be included in the procedure for analyzing multiple openings in a roadway embankment described below. However, analyses are limited to using culvert data to compute headwater elevation on the basis of input data for discharge and downstream water surface elevations. The program does not determine a continuous water surface profile through the culvert.

Embankment Overflow. Roadway embankment overflow at a bridge is computed by treating the overflow sections as broad-crested weirs. Embankment overflow may occur in combination with either free surface flow through the bridge or with pressurized flow. In either case, a trial-and-error procedure is used.

For free surface flow, the following steps are followed:

1. An upstream water surface elevation is assumed.
2. The embankment overflow based on this elevation is computed.
3. Embankment overflow is subtracted from the total flow to give the flow passing through the bridge opening.

4. An upstream water surface elevation for the required flow through the bridge is computed.
5. The computed elevation from step 4 is compared with the assumed elevation of step 1.

The five steps are repeated until the elevation difference of step 5 is within an acceptable tolerance. The sign and magnitude of the difference is used to select the new assumed elevation in step 1 of the next iteration of the procedure.

A similar procedure is followed for pressurized flow. As for the free surface flow case:

1. An upstream water surface elevation is assumed.
2. The embankment overflow based on this elevation is computed.
3. In this case, however, pressure flow through the bridge opening is computed from the upstream elevation.
4. The computed flows from steps 2 and 3 are added.
5. The computed total discharge from step 4 is compared with the given discharge. Again, the five steps are repeated until the difference in step 5 is within an acceptable tolerance.

Multiple Openings. The WSPRO program is unique among programs of its type in that it provides capabilities for analyzing road crossings of streams in which there are two or more bridges or culverts at the crossing. In this analysis, flow is apportioned among the individual openings, and a water surface profile is computed for each individual opening using a representative strip of the valley. Flow apportionment is based on both the flow area of the openings and the distribution of flow conveyance across the total cross section. The valley strips are determined from flow division points which are based on the relative flow areas of adjacent openings. Iterations are made until the flow computed for each opening and a conveyance-weighted water surface elevation at a common upstream section do not change significantly on successive iterations.

Encroachment Analyses. Two options for channel encroachment analysis are available in the program. One method involves the analysis of fixed limit encroachments; the second determines encroachments based on conveyance removal to obtain a target rise in water surface elevation. In this latter method equal conveyance can be removed from each side of a cross section, with or without specified constraints. The procedures permit the analysis of the majority of encroachment problems encountered.

The WSPRO program was initially developed to provide bridge designers with a tool for analyzing alternative bridge openings and embankment configurations. Because of its usefulness for general stream profile computations, it is widely used in highway design, floodplain mapping, flood insurance studies, and developing stage-discharge relationships.

Required Input. The program is designed to operate in a batch process, in which a data file is generated by using an editing program. The individual data records use one- or two-character identifiers at the beginning of each record (this aspect of the program is similar to the input formats for HEC-2). The order in which the input records can be placed in the file is quite flexible. Also, the data can be entered in free format, if desired.

Types of input data used by the program are (1) title information, (2) job parameters, (3) profile control data, (4) cross-section definition, and (5) data display commands. Title information is used only for output identification. Up to three title information records can be used per run. Job parameters are provided on two records in each run to define error tolerances and test values, and to provide parameters for tables. Profile control data are discharges, starting water surface elevations or energy grade line slopes, information about subcritical or supercritical profile, and end of input.

Cross-section data make up the major portion of the input and include information on the type of cross section (unconstricted section, bridge, culvert, spur dike, etc.), cross-sectional geometry data, roughness data, and flow length data. Special data records for bridges, approach sections, road grades, and culverts are also used.

Data display commands are used to generate tables of cross-section properties and velocity/conveyance distributions and to produce plots. Data which do not change from section to section can be coded only for the first section to which they apply. Values which are not supplied are taken from the next downstream cross section. Template cross sections which can be expanded or reduced in size and adjusted in elevation can also be used.

Default values are provided for the parameters which govern the computational procedures, such as test values for computational tolerances.

Program Output. WSPRO generates a relatively large amount of output since it provides a detailed record of the processing of the input data and the results of all profile computations. This output is written to a file which can either be printed directly or be viewed on a terminal or personal computer screen by using a utility program. Three general types of information can be generated: (1) printer plots of cross sections, (2) cross-section property information, and (3) user-defined tables of computed quantities. The user can define which plots are to be included in the output. The model offers no option to suppress any output. However, an editing utility program could be used to produce smaller printed files. A wide selection of key input parameters and computed results are stored in a machine-readable direct-access file, and users can develop utility routines to access this file and generate additional tabular or plotted output.

Computer Requirements. The WSPRO program is written in American National Standards Institute (ANSI) standard FORTRAN 77. Program length is about 8000 lines of FORTRAN source code. Versions of the program are available for personal computers, minicomputers, and mainframe computers. Program execution requires about 200 to 250 Kbytes of memory on mainframe computers and about 400 Kbytes on PC systems. Three printer-compatible output files are automatically generated. Two direct-access files in machine-readable format are used. Additional output files can also be generated by the user.

How Program Can Be Obtained. The program can be obtained from the U.S. Geological Survey, WRD, 415 National Center, Reston, VA 22092, or from the Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. A number of vendors of hydrologic models will also supply the program, either in compiled form for use on personal computers or in ASCII format for other types of computer systems.

21.4.3 FLDWAV—NWS National Weather Flood Wave Model

Overview. The FLDWAV program is a generalized unsteady-flow simulation model for open channels. It was developed by D. Fread of the U.S. National Weather Service (NWS) and replaces the DAMBRK, DWOPER, and NETWORK models, combining their capabilities and providing new hydraulic simulation procedures within a more user-friendly model structure.[14]

The FLDWAV program is intended to be used on PC-type computers, minicomputers, or mainframe computers. It simulates a wide range of unsteady-flow applications for a dendritic (tree-shape) system of waterways subject to backwater effects, including real-time flood forecasting; dam breach analysis and inundation mapping; design of waterway structures such as levees, off-channel detention, etc.; floodplain mapping; analysis of irrigation systems with flows regulated by gates; analysis of storm sewer systems which can operated with both free-surface and pressure flows; and unsteady flows due to hydropower operations.

FLDWAV can simulate the failure of dams caused by either overtopping or piping failure of the dam. The program can also represent the failure of two or more dams located sequentially on a river.

The program is based on the complete equations for unsteady open-channel flow (St. Venant equations). Various types of external and internal boundary conditions are programmed into the model. At the upstream and downstream boundaries of the model (external boundaries), either discharges or water surface elevations which vary with time can be specified.

FLDWAV uses an expanded form of the original St. Venant equations to include the following hydraulic effects:

1. Lateral inflows and outflows
2. Nonuniform velocity distribution across the flow section
3. Expansion and contraction losses
4. Off-channel storage (which is referred to as *dead storage*)
5. Procedures for representing flow path differences between the sinuous main channel and the flood plain
6. Surface wind shear effects
7. Representation of internal viscous dissipation effects that occur in mud and debris flows

Special Features. FLDWAV's special features include:

1. A subcritical/supercritical mixed-flow solution algorithm
2. Levee overtopping calculations
3. Interaction between channel flow and the floodplain flow
4. Calibration of Manning's roughness parameters
5. Analysis of combined free-surface and pressure flow conditions
6. Automatic selection of time and distance steps.

Internal Boundaries. The St. Venant equations apply to gradually varied flow with a continuous profile. If features which control or interrupt the water surface profile exist along the main stem of the river or its tributaries, internal boundary conditions are required in the program. These features can include dams, bridges, roadway embankments, ., short steep rapids, weirs, etc. If a bridge is being simulated, the program uses a coefficient of discharge for flow through the bridge and another coefficient of discharge for flow over the roadway embankment. This latter flow is treated as flow over a broad-crested weir with a correction for submergence of the weir, if required.

If the structure is a dam, the total discharge past the structure is the sum of spillway flow, flow over the top of the dam, gated-spillway flow, flow through turbines, and flow through a breach in the dam, if a breach occurs. The spillway flow and dam overtopping are treated as weir flow, with corrections for submergence. The gated outlet can represent a fixed gate or one in which the gate opening can vary with time. These flows can also be specified by rating curves which define discharge passing through the dam as a function of upstream water surface elevation.

The turbine discharge can be either a fixed discharge or time-dependent. The dam breach flow is computed from a relationship expressing the time-varying characteristics of the dam breach. If the internal boundary is a waterfall or rapids, the water surface elevation at this location can be determined from a computation of critical depth.

External Boundaries. External boundary condition relationships must be specified at the upper and lower end of all unconnected stream reaches. The external boundary condition is the main factor driving the unsteady-flow conditions in many cases. The upstream boundary condition may be either a discharge hydrograph specified as a time series of flows or a stage hydrograph (a time series of water surface elevations). Downstream, the boundary condition could be a discharge or stage hydrograph, a rating curve which defines discharge as a function of water surface elevation, or a channel control loop-rating relationship based on Manning's equation in which the dynamic energy slope is related to the flow conditions at the last two cross sections at the downstream end of the river. Initial conditions (discharge and water surface elevation throughout the stream system at time zero) can be automatically obtained by using a steady-flow solution based on an initial discharge, or unsteady-flow conditions at time zero may be input directly.

If the river consists of a main stem and tributaries, the set of equations describing this case is solved by an iterative method[12] in which the flow at the confluence from or to the tributary is taken as the lateral inflow/outflow term in the St. Venant equations. If the river has bifurcations (such as islands) or is a dendritic system with tributaries connected to tributaries, a network solution scheme is used.[13]

Subcritical/Supercritical Mixed-Flow Solution Algorithm. When this algorithm is used, it automatically divides the routing reach into subreaches in which only subcritical or supercritical flow occurs. The Froude number is used to determine if the flow at a particular section is subcritical or supercritical. The transition locations where the flow changes from subcritical to supercritical are treated as external boundary conditions. At each time step, the solution begins with the farthest-upstream subreach and proceeds, subreach by subreach, in the downstream direction. The internal subreach boundary conditions are based on hydraulic conditions in the adjacent subreaches. Hydraulic jumps are allowed to move upstream or downstream prior to advancing to the next time step; this is done by comparing computed sequent water surface elevations with computed elevations in each section in the vicinity of the hydraulic jump. Using the subcritical/supercritical algorithm increases the computational time by about 20 percent.

Levee Overtopping Calculations. The program will compute the amount of flow which overtops levees along either or both sides of the mainstream of the river or its principal tributaries. The overtopping is represented by the lateral flow term in the St. Venant equations (a discharge per unit channel length). The levee is treated as a broad-crested weir in the computation of the amount of flow leaving the river. Because the amount of flow passing over the levee is affected by the water depth in the adjacent floodplain, the FLDWAV program has three options for analyzing the flow. In the first option the presence of the floodplain is ignored. For the second option, the receiving floodplain is treated as a storage area having a user-specified storage-elevation relationship, and level-pool routing procedures are used to compute the flow into and out of the floodplain. In the third option, the floodplain is treated as a tributary and the St. Venant equations are used to determine water surface elevations and discharges. In each option, a breech in the levee may be specified at some location.

Interaction between Channel Flow and the Floodplain Flow. The program also allows the floodplain to be separated into compartments where there are levees or roadway embankments perpendicular to the flow paths. The flow from compartment to compartment is computed by using the broad-crested weir equation. If the upstream water levels drop below the downstream levels, flow reversals are computed.

Calibration of Manning's Roughness Parameters. An optional feature of the FLDWAV program allows an automatic determination of Manning's *n* values when measured stage hydrographs are available. The program computes the Manning *n* as a function of either discharge or water surface elevation within river subreaches bounded by water-level recording stations.

Computer Requirements. The FLDWAV program is written in standard FORTRAN IV. Versions of the program are available for personal computers, minicomputers, and mainframe computers. The PC version requires a minimum of 600 Kbytes of RAM and requires a math-coprocessor chip for the program to run.

The program has more than 80 subroutines. Arrays are coded with a variable dimensioning technique within a single large array which is the only array of fixed size. When the program is executed, the large array is automatically partitioned into individual variable arrays required for a particular application. The size of each array is determined by the input which describes the application. In this way the maximum utilization of computer memory is assured, since arrays which are not used in a specific application are not assigned to memory.

Related Programs. DAMBRK, DWOPER, and other NWS models have been very widely used and are still in general distribution. DWOPER is the original form of the program. It was modified into the NETWORK program to deal with stream networks, such as those encountered in branching river systems, rivers with islands, and canal networks.

DAMBRK, the Dambreak Flood Forecasting Model (latest revision in 1988), is an unsteady-flow dynamic-routing model which uses the one-dimensional St. Venant equations to route reservoir outflow and dambreak floods through the downstream river valley. The program develops an outflow discharge hydrograph due to spillway and/or dam-failure flows.

SMPDBK, the Simplified Dam-Break Model, is an interactive simplified dambreak model which computes the peak discharge, water surface elevation, and time of occurrence of flooding at selected cross sections downstream from a breached dam.

BREACH, the Breach Erosion Model, is a deterministic model of the erosion-formed breach in an earthen dam caused by overtopping of the dam or initiated by a piping failure of the dam. The dam may be a manmade structure or formed by a landslide. BREACH computes the outflow and the breach parameters used in NETWORK and SMPDBK.

CROSS, a Cross-Section Reduction Plot Program, is for development of data to be used with the NWS models FLDWAV, NETWORK, and DAMBRK. It computes top-width–elevation tables from cross-section data in x-y coordinate format and also computes distance-weighted average cross-section data. CROSS can be used to convert data that are in HEC-2 format to the NWS format used by FLDWAV, NETWORK, and DAMBRK.

How Program Can Be Obtained. The FLDWAV program can be obtained from the National Weather Service, Hydrologic Research Laboratory, 1325 East-West Highway, Silver Spring, MD 20910. FLDWAV is available in executable form for PCs and as FORTRAN source code for other computer systems. A number of vendors of hydrologic models also supply the programs described above, either in compiled form for use on personal computers or as source code for other types of computer systems.

21.4.4 DHM—Diffusion Hydrodynamic Model

Overview. The DHM program is a coupled topographic and channel flow simulation model for two-dimensional floodplain analysis. It was developed for a two-dimensional dam-break floodplain study of a hypothetical failure of a large dam, and it was subsequently extended to include channel flow analysis and the exchange of water between stream channels and the topography. Hromadka and Yen[15] describe the application of the DHM to one-dimensional open-channel floodwave analysis; two-dimensional floodwave analysis; rainfall-runoff modeling of dam breaks, reservoirs, and estuaries; and coupled topographic and open-channel flow modeling.

The DHM is intended for use on PCs and larger systems. Recent applications of the DHM include river overflow floodplain studies, alluvial fan analysis, water reservoir dam-break analysis, and regional flood control deficiency analysis. Most of these studies were accomplished on PCs.

The DHM is based on the noninertial form of the St. Venant equations for two-dimensional flow. Various types of external and internal boundary conditions are available in the model such as spatially distributed rainfalls, hydraulic parameters, stage-discharge curves, and critical flow control. Kinematic wave techniques for flood routing calculations can be used in place of the diffusion routing calculations if desired.

Special Features. DHM's special features include:

1. Two-dimensional unsteady-flow topographic-flow modeling
2. Open-channel unsteady-flow modeling
3. Coupling of flow exchange between the open-channel and topographic-flow models
4. Modeling of backwater and storage effects by the use of the noninertial form of the St. Venant equations
5. The model can be switched to the kinematic wave technique
6. A small amount of program code

7. Availability of various output forms such as flow depth versus time or discharge versus time

The model reduces to a set of two-dimensional point estimates in the limit as the grid area approaches zero. Each grid element is connected to other grids by a north, south, east, west local coordinate system. Parameters required are area-averaged local elevations, Manning's *n* factor, effective area ratio (i.e., ratio of grid area with respect to area available to store water), and initial flow depth.

The open-channel flow model permits one-dimensional unsteady-flow routing of an interconnected channel network through the topographic model. Overflow from the open channels or drainage into the channel is modeled as a simple source-sink term within the two-dimensional topographic model.

The program advances the topographic and open-channel flow models forward in time independently, using an interface between models defined at prescribed intervals by the user. The interface algorithm simply provides coincident water surfaces at grid points where channel flows occur, while conserving mass. Excess channel flows spill into the surrounding grid as a source term contribution, whereas water stored in a grid element spills into a channel as a sink term with respect to the grid.

The model is initiated by flow versus time inputs at grid or open-channel locations, or by runoff distributed over the topography. Generally, small time steps are used because of the nonlinearity of the flow equations and model stability considerations. Using a 80486-type PC processor, a 60-mi^2 DHM simulation, with 1000-ft by 1000-ft grids and channel link network, requires about 1 h to simulate a 24-h storm event.

Computer Requirements. The DHM program is written in standard FORTRAN IV. The program runs on most modern PC-type systems. Because the model can utilize a large database, it can be very effectively used in geographic information system (GIS) applications.

How Program Can Be Obtained. The DHM program can be obtained from the Computational Hydrology Institute, 1510 Red Hill Ave., Tustin, CA 92680.

21.5 WATER-QUALITY MODELS

21.5.1 SWMM—Storm Water Management Model

Overview. The Storm Water Management Model (SWMM) was originally developed for the Environmental Protection Agency in 1971 by Metcalf and Eddy Inc., Water Resources Engineers Inc., and the University of Florida.[24] It was initially designed as a single-event model for the simulation of both runoff quantity and water-quality processes associated with urban runoff and in combined sewer systems for prediction of flows, stages, and pollution concentrations. The model has more recently been adapted to permit continuous simulation of urban storm water flows in addition to single-event simulations.[17,24]

The SWMM program consists of a number of segments or *blocks*. These include:

1. *RUNOFF Block.* Generates runoff from rainfall and routes flows to combining points. Water which infiltrates through the ground surface may also be routed as subsurface flow.

2. *TRANSPORT block.* Routes flow through watershed channels using the kinematic wave method.
3. *EXTRAN block.* Routes channel flow using an explicit finite-difference solution of the St. Venant equations. This is the only block in which water quality cannot be simulated along with runoff.
4. *STORAGE/TREATMENT block.* Routes flow through reservoir-type storages using a storage-routing procedure.
5. *STATISTICS block.* Separates the continuous hydrograph record and pollutographs (concentration as a function of time) into independent storm events. It also calculates statistics and performs frequency analyses.

SWMM permits simulation of a wide range of features of urban hydrology and water-quality processes including rainfall, snowmelt, surface runoff, subsurface contributions to runoff, flow routing, storage, and treatment of flows. SWMM deals with the movement of pollutants from the land surface of the modeled area to combined sewers or storm drainage outfalls. Hydrographs developed in the hydrologic portions are input to the water-quality part of the model. Output is in the form of pollutographs for each pollutant modeled. The hydrographs and the pollutographs are read into the TRANSPORT block where they are combined with the dry weather and infiltrated flow components to produce outflow graphs of water quality and quantity. SWMM predicts concentrations of suspended solids, nitrates, phosphates, and other pollutants in storm water runoff. For each time step, the runoff rate is computed in the hydrologic part of the model. The amount of pollutant removed by runoff is also computed for the time interval, and this can be related to the quantity of runoff to produce a pollutograph. Calibration data are considered essential to permit credible simulations of pollutographs. Without calibration, the computed pollutographs should be considered to provide only relative comparisons between control approaches.

Types of Problems. SWMM has been applied to nearly all aspects of urban hydrology. Huber, Heaney, and Cunningham[16] have published a bibliography of SWMM usage. A SWMM users group holds annual conferences on applications of the SWMM model.

In planning studies, the model can be used to simulate a period of a number of years using long-term precipitation data. The STATISTICS block can be used for a frequency analysis of the long-term record of hydrographs and pollutographs.

The EXTRAN block has been frequently used as a stand-alone modeling element for hydraulic analysis of drainage flows.[25] Hydrographs generated by another model can be supplied as input, and the unsteady-flow behavior of flood control system elements like pumping plants, storage reservoirs, and conveyance channels and conduits can be modeled in detail.

Computer Requirements. SWMM version 4 is distributed for use primarily on PC systems. A math coprocessor is recommended, but not mandatory. For simulations of large problems, execution times can be lengthy, and an 80386- or 80486-based computer is recommended for these applications. The program is written in FORTRAN 77, which permits it to be compiled on mainframe computers and microcomputers.

How Program Can Be Obtained. The program can be obtained from the Center for Exposure Assessment Modeling, Environmental Research Laboratory, Environmental Protection Agency, College Station Rd., Athens, GA 30613. Various software vendors also supply the program.

21.5.2 HSPF—Hydrologic Simulation Program—Fortran

Overview. The Hydrologic Simulation Program—Fortran (HSPF) model simulates both watershed hydrology and water quality.[21] It allows an integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The program provides a time history of runoff rate, sediment load, and nutrient and pesticide concentration, along with a time history of water quality and quantity at specific points in a watershed. HSPF simulates sand, clay, and silt sediments and a single organic chemical and transformation products of that chemical. Transfer and reaction products modeled are hydrolysis, oxidation, biodegradation, volatilization, and sorption. Resuspension and settling of silts and clays are based on the computed shear stress at the sediment-water interface. Resuspension and settling of sand is determined from the difference between the sand in suspension and the stream's total transport capacity for sand. Calibration of the model requires data from each of the sediment types. Exchanges of chemicals between benthic deposits (bottom sediments) and the overlying water column are also allowed.

The water-quantity routines in HSPF are a FORTRAN version of the Hydrocomp Simulation Program which was developed from the Stanford Watershed Model (SWM) originally developed in 1959. The model has undergone a great deal of modification since its initial development.[8] A commercial version of the Stanford Watershed Model was developed by Hydrocomp, Inc.[9] The most recent versions of the HSPF model contain all of the basic computational routines of the SWM-IV as well as various routing routines and water-quality simulation routines.

HSPF computes a continuous hydrograph of stream flow at the basin outlet. Input is a continuous record of precipitation and evaporation data. Rainfall is distributed into interception loss, rainfall on impervious areas which contributes directly to runoff, and an infiltrated portion. The infiltration is divided into (1) surface runoff and interflow which moves through the upper soil zone to channel flow and (2) flow into the lower soil zone or groundwater storage which contributes to active and inactive groundwater storage. The model utilizes three soil moisture zones: an upper soil zone, a lower soil zone, and a groundwater storage zone. Rapid runoff is accounted for in the upper zone. Both the upper and lower zones influence factors such as overland flow, infiltration, and groundwater storage. Water that is computed as moving into the lower zone can move into deep groundwater storage, some of which can become base flow to the stream. Total stream flow is a combination of overland flow, interflow, and groundwater flow.

The program user must supply parameters for each of the various processes. More than 20 parameters are needed to describe merely the hydrologic parameters, some of which cannot be directly measured (such as the various soil moisture parameters). Without calibration data, it can be difficult to verify the flows computed by this model.

Computer Requirements. The HSPF model is available for use on PC systems with 640 Kbytes of RAM and a hard disk. A math coprocessor is required to run the program. Because the program is written in FORTRAN 77, it can be compiled on mainframe computers and microcomputers.

How Program Can Be Obtained. The current public domain version of the program (HSPF) was developed for the U.S. Environmental Protection Agency. The program can be obtained from the EPA's Center for Exposure Assessment Modeling, Environmental Research Laboratory, Athens, GA 30613. Various software vendors also supply the program.

21.5.3 QUAL2E—Stream Water-Quality Model

Overview. QUAL2E is the Enhanced Stream Water Quality Model and is the latest in a series of water-quality management models initially developed by the Texas Water Development Board in the 1960s. QUAL-I was required by the Environmental Protection Agency during the 1970s for the development of basin-specific water-quality models. Several improved versions of QUAL were developed as part of this effort, and the QUAL-II series of models have been widely used after extensive review and testing. Present support is by the Environmental Protection Agency's Center for Exposure Assessment Modeling (CEAM).

QUAL2E simulates several water-quality constituents in branching stream systems. The model uses a finite-difference solution of the advective-dispersive mass transport and reaction equation. A stream reach is divided into a number of subreaches, and for each subreach a hydrologic balance in terms of discharge, a heat balance in terms of temperature, and a materials balance in terms of concentration is written. Both advective and dispersive transport processes are considered in the materials balance. Mass is gained or lost from the subreach by transport processes and by waste discharges and withdrawals. Mass can also be gained or lost by internal processes such as benthic sources or biological transformations.

The program simulates changes in conditions in time by computing a series of steady-flow water surface profiles, that is, the stream is conceived as a series of reaches, with water passing from one reach to the next, and water-quality processes take place in each reach separately from its neighbors upstream and downstream. The basis for mass transport calculations is the stream-flow rate; velocity, cross-sectional area, and water depth are computed from the flow, and the mass-flow rate of constituent moving from one tank to the next is found as the product of the stream-flow rate and the mass concentration of the constituent in the water. Time-varying computations are made by the program from climatological variables that primarily affect temperature and algal growth. QUAL2E simulates the major interactions of the nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration, and their effect on the dissolved oxygen balance. The program determines mass balances for conservative minerals, coliform bacteria, and nonconservative constituents such as radioactive substances. QUAL2E uses chlorophyll *a* as the indicator of planktonic algae biomass. The nitrogen cycle is divided into four compartments: organic nitrogen, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen. In a similar manner, the phosphorus cycle is modeled by using two compartments. The primary internal sink of dissolved oxygen in the model is biochemical oxygen demand (BOD). The major sources of dissolved oxygen are surface reaeration, algal photosynthesis, and atmospheric reaeration.

Description of a stream network in QUAL2E requires dividing the streams into headwaters, reaches, and junctions. For each reach, as many as 26 physical, chemical, and biological parameters must be defined. The modeler must define more than 100 individual inputs when developing model input data. Model calibration and evaluation is not an easy task with such a complex model, and the developers of the program have used the principles of uncertainty analysis to assist users in the model calibration process. A version of the program named QUAL2E-UNCAS incorporates three uncertainty analysis techniques: sensitivity analysis, first-order error analysis, and Monte Carlo simulation. Selected input variables are changed by the program, and the user selects the specific variables and locations on the stream where the uncertainty analysis is to be applied.

Computer Requirements. The QUAL2E model is designed to be used on PC systems with 640 Kbytes of RAM and a hard disk. The program is written in FORTRAN 77, which permits it to be compiled on mainframe computers and microcomputers.

How Model May Be Obtained. The QUAL2E model is available from the U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling (CEAM), Environmental Research Laboratory, Athens, GA 30613.

21.5.4 WASP4—Water-Quality Simulation Program

Overview. WASP4 is a simulation program for modeling contaminant fate and transport in surface waters. There has been a series of models designated as WASP—WASP4 is the latest in this series. WASP4 is designed for use by modelers who have a background in water-quality modeling. It is a sophisticated model that permits a good deal of flexibility in its application. WASP4 can be used to simulate one-, two-, or three-dimensional flows. The program is designed to allow users to substitute their own subroutines in the program. WASP4 input can also be linked to other models, such as HSPF, whose output files can be reformatted and read by WASP.

Two water-quality models are provided with WASP: (1) TOXI4, a simulation of transport and transformation of toxic substances and (2) EUTRO4, a model of dissolved oxygen and phytoplankton dynamics affected by nutrients and organic material.

WASP represents a body of water as a series of computational segments. Environmental properties and chemical concentrations are assumed to be spatially constant within each segment. Segment volumes and type (surface water, subsurface water, surface benthic, and subsurface benthic) and hydraulic coefficients must be specified. WASP4 uses several mechanisms for describing transport: advection and dispersion in the water column; advection and dispersion in pore water; settling, resuspension, and sedimentation of one to three classes of solids; evaporation; and precipitation.

The simulation of advection requires specification of each inflow or circulation pattern for the flow routed through each water-column segment. The flow can vary with time. Dispersion requires cross-section areas for model segments, characteristic mixing lengths, and dispersion coefficients to be specified.

The user must also specify loads, boundary concentrations, and initial concentrations. Only particulate concentrations are transported as solids, and only dissolved concentrations can be transported as pore water.

Advection and dispersion between each segment are computed for each variable by the model, and exchange with surfical benthic segments is determined. Sorbed or particulate fractions can settle through the water column and deposit to or erode from the surfical benthic segments. Dissolved materials may migrate downward or upward through the bed by percolation and pore water diffusion. Sorbed materials may migrate downward or upward as a result of sedimentation or erosion.

The TOXI4 Component. TOXI4 simulates transport and transformation of one to three chemicals and one to three types of particulate material. The model is composed of as n as six systems—three chemical and three solid—for which the WASP4 mass-balance equation is solved. The chemicals may be independent, or they may be linked through chemical reactions, such as a parent-compound–daughter product sequence.

Transfer processes defined in the model include sorption, ionization, and volatilization. Transformation processes include biodegradation, hydrolysis, photosynthesis, and chemical oxidation. Sorption and ionization are treated as equilibrium reactions. All processes are described using rate equations which may be described either by first-order constants or by second-order chemical-specific constants and time-varying environment-specific parameters that also vary in space.

Sediment is treated as a conservative constituent that is advected and dispersed among water segments. It may settle to or erode from benthic segments and may move between benthic segments through erosion and deposition.

The EUTRO4 Component. EUTRO4 simulates the transport and transformation of as many as eight state variables in the water column and sediment bed, including dissolved oxygen, carbonaceous biochemical oxygen demand, phytoplankton carbon and chlorophyll *a*, ammonia, nitrate, organic nitrogen, organic phosphorus, and orthophosphate. The model can be used to simulate any or all these variables and the interactions between them. Each variable may exist in both dissolved and particulate phases in each stream segment, as specified by the user. Settling and resuspension of organic solids, phytoplankton solids, and inorganic solids may be specified.

The program can deal with simulations at various levels of complexity. The simplest level allows the computation of final BOD, dissolved oxygen (DO), and sediment oxygen demand (SOD). At the next level, BOD is divided into carbonaceous (CBOD) and nitrogenous (NBOD) fractions. The third level is a linear dissolved oxygen balance influenced by photosynthesis and respiration of phytoplankton and nitrification of ammonia to nitrate besides SOD and CBOD. The fourth level adds the phosphorus cycle and simulates phytoplankton dynamics. Level 5 adds benthic interactions.

WASP4 and its predecessors have been used in a wide range of studies for the U.S. Environmental Protection Agency. Some of the applications have been validated by using field data or verified by model experiments.

Computer Requirements. The WASP4 model is written in FORTRAN 77, and versions are maintained both for PC systems (available on diskette) and for DEC and VAX systems using the VMS operating system (on nine-track magnetic tape). To use the model on PC systems, 640 Kbytes of RAM and a hard disk are required. A math coprocessor is desirable.

How Model May Be Obtained. The WASP4 models are available from the U.S. Environmental Protection Agency, Center for Exposure Assessment Modeling (CEAM), Environmental Research Laboratory, Athens, GA 30613.

21.5.5 AGNPS—Agricultural Non-Point-Source Pollution Model

Overview. The Agricultural Non-Point Source (AGNPS) model[37] simulates runoff water quality from agricultural watersheds. It was developed by the U.S. Agricultural Research Service (ARS) in cooperation with the Minnesota Pollution Control Agency and the U.S. Soil Conservation Service (SCS).[38] Other models of this type (such as SWRRB discussed above) are limited in the size of watershed which can be used because of the large amount of input data required. AGNPS is designed to be a simple, easy-to-use model which can run on a PC and deal with watersheds ranging in size from a few acres to 50,000 acres (20,000 hectares) or larger. Estimates of runoff water quality can be made with AGNPS to evaluate potential pollution problems for a watershed, and remedial measures can be recommended on the basis of an assessment of the effects of applying alternative management practices. Data representing these management alternatives can be used as program input, and the resulting watershed responses can be evaluated and compared.

AGNPS is an event-based model which uses geographic data cells of 1 to 40 acres (0.4 to 16 hectares) to represent land surface conditions. Within the framework of the cells, runoff characteristics and transport processes for sediment, nutrients, and chemical oxygen demand (COD) are simulated for each cell. Flows and pollutants are routed through the channel system to the basin outlet. Point source inputs (such as nutrient COD from animal feedlots) can also be simulated and combined with the non-point-source contributions.

Basic model components include hydrology, erosion, sediment transport, and chemical transport. In the hydrology component, runoff volume is calculated by the SCS curve number procedure. Peak flow rate is estimated by using an empirical equation which takes into account drainage area, channel slope, runoff volume, and watershed length-width ratio. Erosion is computed from a modified form of the universal soil loss equation. Soil loss is calculated for each cell of the watershed. Eroded soil and sediment yield are subdivided into particle size classes; sediment routing is based on the effective transport capacity of the stream channels. In the chemical transport part of the model the transport of nitrogen, phosphorus, and COD is calculated throughout the watershed. Chemical transport calculations are divided into soluble and sediment-adsorbed phases. COD is assumed to be soluble and to accumulate without losses.

In AGNPS applications, a uniform grid of cells is placed over the watershed. Storm rainfall and runoff produce erosion through sheet and rill erosion processes, soil loss and sediment yield is calculated for each cell, and the upland transport of sediment and nutrients is determined for each cell outlet. Calculations for AGNPS occur in three loops: initial calculations for all cells are made in the first loop, runoff volume is calculated for cells containing impoundments and sediment yields for cells that no other cells drain into are computed in the second loop, and sediments and nutrients are routed through the watershed in the third loop.

Required Input. Model input consists of watershed data (area, number of cells, precipitation) and cell parameter data. Twenty-two cell parameters are used. These include: SCS curve number, average land slope, slope shape factor, field slope length, channel data (slope, length, side slope, and roughness), universal soil-loss equation data (erodibility, cropping, and practice factors), soil texture, fertilization level, point-source indicator, gully source parameters, chemical oxygen demand factor, and a channel indicator for the presence of a defined channel in a cell.

Computer Requirements. AGNPS is written in FORTRAN 77 and consists of about 2000 lines of source code. On a minicomputer system, the model requires 400 Kbytes of storage memory for a watershed containing 3200 cells. The PC version of the program operates from a shell which provides access to a full-screen data editor, help screens, viewing of output on the computer monitor, and control of printed output. Graphical output display is also available, and the program supports several types of graphics printers and plotters.

How Progra an Be Obtained. The program is available from the North Central Soil Conservation Research Laboratory, Soil Conservation Service, U.S. Department of Agriculture, Morris, MN 56267. The AGNPS developers publish a quarterly AGNPS newsletter and conduct several training sessions throughout the United States each year.

21.5.6 MIKE11—Microcomputer-Based Modeling System—Rivers and Channels

Overview. MIKE11 was developed by the Danish Hydraulic Institute for the simulation of flows, water levels, and transport of sediment and dissolved or suspended materials.[10] MIKE11 is a general-purpose microcomputer-based model that simulates not only rainfall-runoff processes, but also river hydraulics, sediment transport, and water quality. MIKE11 can be used in design, management, and operation of river systems and channel networks.

MIKE11 is based on the Danish Hydraulic Institute program System 11, which provides a similar set of modeling system capabilities for the mainframe environment.

The MIKE11 model consists of several individual modules, allowing the user to add specific modules for various types of hydrologic simulation as the need for these features arises in the application. The model is menu-driven. It is configured with a core component termed the *basis module* plus a series of other add-on modules. The basis module includes the menu portion that deals with data handling and program execution; a catchment database that includes river cross-section data; a database for rainfall time series and water level and discharge data; computational modules for rainfall-runoff simulation and for river flow; and a module that permits plotting of input and output data. Figure 21.5.1 shows a simplified flow chart of the system.

The catchment and stream channel network system is modeled by the rainfall-runoff module. Complex river systems can be simulated. Runoff computations are based on a lumped-conceptual-type model that continuously accounts for the moisture content in four storage zones: (1) surface storage, (2) lower zone storage, (3) upper groundwater storage, and (4) lower groundwater storage. Runoff to stream channels is assumed to consist of overland flow, interflow, and base flow. The river

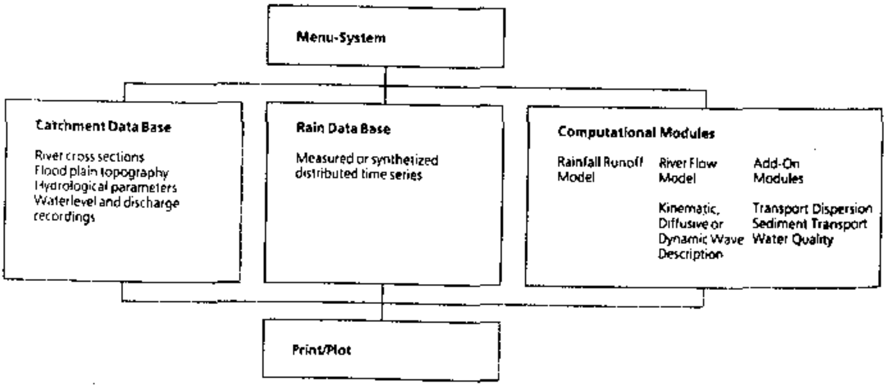

FIGURE 21.5.1 Simplified flow chart of the MIKE11 program. *(Source: Danish Hydraulic Institute.[10] Used with permission.)*

flow module permits the use of a variety of computational procedures. The full nonlinear one-dimensional unsteady-flow equations are normally used, while simplified channel routing equations (kinematic wave or diffusion wave equations) can be employed as deemed suitable in specific parts of the full model. Complex channel configurations can be accommodated, including looping channels. Channel computations can also include lateral discharges, free and submerged flow at weirs, flooding and drying of overflow areas, flow over embankments, and two-dimensional floodplain flows. Culverts and other stream structures can also be simulated. Irregular cross-section geometry can be used, flow-related roughness and local head losses can be employed, and the model can deal with both subcritical and supercritical flow conditions.

Sediment Transport Module. A sediment budget accounts for erosion and deposition, and the resulting changes in model geometry are used in the hydrodynamic calculations by the model. The model can account for sediment transfer between the river and floodplains. MIKE11 also has an option for computing bedform dimensions and the resistance coefficients associated with bedform roughness.

Transport-Dispersion Module. This module solves the one-dimensional conservation of mass equation. Transport and dispersion are simulated for any dissolved or suspended material. The behavior of conservative materials with linear decay characteristics can be simulated. Cohesive sediment transport can also be simulated.

Water-Quality Module. This module is an extension of the transport-dispersion module. It simulates the reaction processes of multicompound systems, and models a wide variety of biochemical interaction processes, ranging from simple BOD and DO computations to multicompound simulations including nutrients, macrophytes, and plankton.

MIKE11 has been used in the analysis of a number of river systems throughout the world. Applications include flood control planning, reservoir operation, design of river structures, irrigation system hydraulics, studies of tides and storm surges in rivers and estuaries, dam-break simulation, and detailed design of channel systems.

Required Input. Required data for the catchment and river data module include hydrologic parameters, river cross sections, floodplain topography, and discharge and water level records. For the rain database, either measured rainfall time series data or synthesized rainfall time series are required.

Computer Requirements. MIKE11 is specifically designed for the PC environment and is supplied in compiled form to run as a single-user program on 16-bit and 32-bit systems under MS-DOS and the CPM/86 operating systems or in a multiuser system under UNIX. MIKE11 supports plotters using HP graphics language conventions.

How Program Can Be Obtained. The program can be purchased from the Danish Hydraulic Institute, Agern Alle 5, DK-2970 Horsholm, Denmark.

21.6 COMPUTER MODELS AVAILABLE THROUGH THE HOMS PROGRAM

The Hydrological Operational Multipurpose System (HOMS) of the World Meteorological Organization (WMO) provides a program for the transfer of technology used by hydrologists throughout the world. A number of computer programs for hydrologic analysis are included in the series of HOMS *components*. Also available as HOMS components are technical manuals and descriptions of hydrologic instruments. The HOMS Reference Manual provides guidance in the use of the components and user requirements. The manual provides what are termed *sequences*, or *logical aggregations of components that are compatible with each other and may be* used together.

There are about 430 components available; a number of these are hydrologic models of the type discussed in this chapter. Summaries are available for each component, either from the HOMS Office, WMO, Geneva, Switzerland (address below), or from HOMS National Reference Centers (HNRC) located in over 100 countries. The address of the HNRC for a particular country can be obtained from the WMO Secretariat.

There are a number of models which are described by HOMS. HOMS lists hydrologic models in two categories: (1) hydrologic models for forecasting and design and (2) analysis of data for planning, design, and operation of water resources systems. A list of some of the models available through HOMS follows, using the HOMS classification number for the component.

Section J: Models for Forecasting Stream Flow

J04.1.01 Tank model (Japan)

J04.1.04 Snowmelt-runoff model (United States)

J04.1.06 Microcomputer-based flood forecasting system (Philippines)

J04.2.01 Conceptual watershed model for flood forecasting (China)

J04.2.02 Conceptual watershed model (the HBV model) (Sweden)

J04.2.03 Model to forecast rainfall floods (Russia)

J04.3.01 Sacramento soil moisture accounting model (SAC-SMA) (U.S. National Weather Service)

J04.3.03 Snow accumulation and ablation model (SNOW-17) (U.S. National Weather Service)

J15.2.01 Streamflow synthesis and reservoir regulation (SSARR) (U.S. Army Corps of Engineers)

J15.2.02 Nonlinear cascade hydrologic model (Czechoslovakia)

J15.2.03 CLSX (constrained linear system extended) model (Italy)

J15.3.02 Multipurpose unsteady-flow simulation system (MUFSYS 3) (Czechoslovakia)

J15.3.05 General-purpose flood forecasting modeling system—NAMS11/FF (Denmark)

Section K: Hydrologic Analysis Models

K22.1.04 Computer program for structure site analysis—DAMS2 (United States)

K22.1.05 Model CA HYDRO (Colombia)

K22.2.02 Semiconceptual watershed model (Italy)

K22.2.05 Rainfall-runoff model for medium-sized urban basins (France)

K22.3.03 General-purpose rainfall-runoff model—NAM (Denmark)

K35.3.07 WSP2 computer program for water surface profiles (United States)

K35.3.09 Microcomputer modeling package for rivers and estuaries—MIKE11 (Denmark)

K55.2.06 Water-quality simulation model—WATQUAL (United States)

K55.3.01 Storage, treatment, overflow, runoff model—STORM (United States)

K55.3.02 Water quality for river-reservoir systems—WQRRS (United States)

How Models May Be Obtained. For further information on HOMS and the HOMS components, including the address of the HOMS National Reference Centers in your country, write to: HOMS Office, Hydrology and Water Resources Department, WMO Secretariat, Case postale No. 2300, *CH-1211 GENEVA 2*, Switzerland. In the United States the HNRC is located at the National Weather Service, NOAA, 1325 East-West Highway, Silver Spring, MD 20910.

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