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A literature review on flow hydrographs, peak discharges, and computer-based hydrologic and hydraulic modeling has been prepared. The first section deals with flow estimation, with special attention given to flood peak discharges (because they are a key design parameter for highway drainage structures). The second section addresses the use of computers for hydrologic/hydraulic analysis, the use of geographic information systems (GIS) for accounting for the spatial variability of the terrain, and the use of GIS-based hydrologic models for designing highway drainage structures.

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GIS-BASED HYDROLOGIC AND HYDRAULIC APPLICATIONS FOR HIGHWAY ENGINEERING: LITERATURE REVIEW

by

Francisco Olivera and David Maidment

Research Report Number 1738-1

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System of GIS-Based Hydrologic and Hydraulic Applications for Highway Engineering

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with

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FEDERAL HIGHWAY ADMINISTRATION

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CENTER FOR TRANSPORTATION RESEARCH

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THE UNIVERSITY OF TEXAS AT AUSTIN

August 1997

SUMMARY

A literature review on flow hydrographs, peak discharges, and computer-based hydrologic and hydraulic modeling has been prepared. The first section deals with flow estimation, with special attention given to flood peak discharges (because they are a key design parameter for highway drainage structures). The second section addresses the use of computers for hydrologic/hydraulic analysis, the use of geographic information systems (GIS) for accounting for the spatial variability of the terrain, and the use of GIS-based hydrologic models for designing highway drainage structures.

DISCLAIMERS

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GIS-BASED HYDROLOGIC AND HYDRAULIC APPLICATION FOR HIGHWAY ENGINEERING: LITERATURE REVIEW

This literature review has been subdivided into the following two sections: (1) flow hydrographs and peak discharges, and (2) computer-based hydrologic and hydraulic modeling. The first section deals with flow estimation, with special attention given to flood peak discharges (because they are a key design parameter for highway drainage structures). The second section addresses the use of computers for hydrologic/hydraulic analysis, the use of geographic information systems (GIS) for accounting for the spatial variability of the terrain, and the use of GIS-based hydrologic models for designing highway drainage structures

1. FLOW HYDROGRAPHS AND PEAK DISCHARGES

Because flow hydrographs and peak discharges constitute a description of the watershed for hydraulic design purposes, an extensive discussion of the published work in this field has been included.

1.1 Evolution of Runoff Hydrograph Models

The unit hydrograph, a method for estimating storm runoff, was first proposed by L. K. Sherman in 1932 (Chow et al. 1988, p.213); since then it has been used as a key concept. The unit hydrograph is defined as the watershed response to a unit depth of excess rainfall, uniformly distributed over the entire watershed and applied at a constant rate for a given period of time. In 1938, after studying watersheds in the Appalachian Mountains of the United States, Snyder proposed relations between some of the characteristics of the unit hydrograph, i.e., peak flow, lag time, base time, and width (in units of time) at 50% and 75% of the peak flow (Chow et al. 1988, p.224). Snyder's method was enhanced with the regionalization of the watershed parameters developed in 1977 by Espey, Altman, and Graves (Chow et al. 1988, p.227). A significant contribution to the unit hydrograph theory was made by Clark (1945), who proposed a unit hydrograph that is the result of a combination of a pure translation routing process followed by a pure storage routing process. Although Clark does not develop a spatially distributed analysis, the translation part of the routing is based on the time-area diagram of the watershed. The storage part consists of routing the response of the translation through a single linear reservoir located at the watershed outlet. The detention time of the reservoir is selected in order to reproduce the falling limb of observed hydrographs. Note that the actual travel time of a water particle, according to this approach, is the travel time given by the time-area diagram plus the detention time of the reservoir, which is somewhat inconsistent. Some years later, Nash (1957) proposed a unit hydrograph equation that is the response of a cascade of identical linear reservoirs to a unit impulse, i.e., a gamma distribution. It is important to note that the method proposed by Nash did not model the watershed itself, and was just a fitting technique based on the first and second moments of the calculated and observed hydrographs.

In 1972, the Soil Conservation Service (SCS) of the U.S. Department of Agriculture (USDA) proposed a unit hydrograph model based on a single parameter: the lag time between the center of mass of the excess precipitation hyetograph and the peak of the unit hydrograph. The shape of the hydrograph is given by an average precomputed dimensionless unit hydrograph curve or, as a simplification, by a triangular dimensionless unit hydrograph (Chow et al. 1988, p.228).

Yet, studying the storm rainfall-runoff relation involves much more than studying the unit hydrograph. Consequently, in trying to relax the unit hydrograph assumptions of uniform and constant rainfall, and to account for spatial variability of the catchment, considerable research has been done in recent years, and many articles dealing with these topics can be found in the literature.

Pilgrim (1976) carried out an experimental study that involved tracing flood runoff from specific points of a 0.39 km^2 watershed, near Sydney, Australia, and measuring the travel time of the labeled particles to the outlet. A conclusion of his study is that "at medium to high flows the travel times and average velocities become almost constant, indicating that linearity is approximated at this range of flows." Pilgrim also states that time-variations of the tracer activity time curves "make an additional contribution to the non-linearity of the runoff process."

An attempt to link the geomorphological characteristics with the hydrologic response of a watershed was described by Rodriguez-Iturbe and Valdes (1979). In their paper, Horton's empirical laws (i.e., the law of stream numbers, lengths, and areas) are used to describe the geomorphology of the system. The instantaneous unit hydrograph is defined as the probability density function of the time a rainfall drop chosen at random takes to reach the outlet. This time is given by the sum of the times spent in each state (order of the stream in which the drop is located) on its way to the outlet. The time spent in each state is taken as a random variable with an exponential probability density function whose parameter depends on Horton's length ratio, mean velocity of the stream flow (dynamic parameter), and a scale factor.

Mesa and Mifflin (1986), Naden (1992), and Troch et al. (1994) present similar methodologies to account for spatial variability when determining the watershed response. The catchment response is calculated as the convolution of a network response and a hillslope response.

To calculate the network response, Mesa and Mifflin (1986) use the solution of the advection-dispersion equation, weighted according to the normalized width function of the network. In their paper, the normalized width function is defined as the number of channels at a given distance to the outlet, divided by the total length of all channels in the network. For the hillslope response, Mesa and Mifflin suggest a double travel time function, related to fast and slow flow, in the form of two isosceles triangles. The two functions are weighted (according to the probability that a water drop would take either path to the channel system) and added to give the final hillslope response. From the physical viewpoint, fast and slow hillslope responses are related to surface and subsurface flow, respectively. Their model was tested in a 1.24 km^2 sub-basin of the Goodwin Creek watershed in Mississippi. For the stream network, an average velocity of 1 m/s and a dispersion coefficient of 9.06 m^2/s were found. For the hillslope response, the average velocities of the fast and slow components were 0.25 m/s and 0.0046 m/s, respectively, and the fraction of the slow flow was taken equal to 90% of the total hillslope response.

For the network response, Naden (1992) suggests also the solution of the advection-dispersion equation, but weighted by a standardized width function of the network. In her paper, the standardized width function is defined as the number of channels at a given distance to the outlet, divided by the total number of channels in the network. She also recommends an additional weighting of the width function by the excess rainfall spatial distribution. Naden does not give a specific methodology to determine the hillslope response, and the one used in her paper "was selected by eye" as a single peak, reflecting the quick response, followed by an exponentially decaying curve for the slow component. For the case of the River Thames at Cookham in the United Kingdom, a stream flow velocity of 0.6 m/s and a dispersion parameter of 1 m^2/s were found. Additionally, because of the slow component of the hillslope response, which yields about 80% of the flow volume, the rainfall spatial variability is smoothed out, resulting in almost identical watershed responses for different rainfall spatial patterns. The ratio of the average velocities of the fast and slow components was found to be around 20.

Troch et al. (1994) propose a stream network response that is the same as that proposed by Mesa and Mifflin (1986). However, for the hillslope response they suggest a function given by the solution to the advection-dispersion equation, applied this time to the overland flow, and weighted according to a normalized hillslope function. The normalized hillslope function is interpreted as the probability density function of runoff generated at a given overland flow distance from the channel network. Contrary to Mesa and Mifflin's and Naden's hillslope response functions, Troch's does not account for the slow component.

An interesting approach to modeling the fast and slow responses of a catchment is presented by Littlewood and Jakeman (1992, 1994). In their model, the watershed is idealized as two linear storage systems in parallel, representing the surface and the subsurface water systems. The surface system is faster and affects mainly the rising limb of the resulting hydrograph, while the subsurface system is slow and determines the recession part of the response.

Although the linear unit hydrograph model has been used for more than sixty years, it is well known that flow, especially in the streams, exhibits a nonlinear behavior. Flow velocity, as modeled by Manning's or Chezy's equations, for example, is a function of the water depth, which implies that the duration of the watershed response depends on the volume of water flowing. Therefore, in principle, superposition, a well-known property of linear systems, does not apply to flow systems.

Many distributed flow-routing methods can be found in the literature (Chow et al. 1988, Lettenmier and Wood 1993). Based on the Saint Venant continuity and momentum equations, the dynamic wave model, diffusion wave model, and kinematic wave model can be derived. The simplest among them, the kinematic wave model, neglects pressure and inertial forces in the flow and leaves friction equal to gravity forces. The diffusion wave model considers, additionally, pressure force terms, while the dynamic wave model includes also inertial terms. These models can be defined as linear or nonlinear, depending on the way the original equations are set.

In nonlinear systems, the terrain shall be analyzed continuously because its hydrologic behavior changes with time and superposition cannot be used. Not using superposition, though, implies determining the continuously changing response of the watershed, which might be complicated for uniform systems and eventually inapplicable for spatially variable systems.

1.2 Flood Peak Discharges

Estimates of the magnitude and frequency of flood-peak discharges and flood hydrographs are used for a variety of purposes, such as for the design of bridges and culverts, flood-control structures, and flood-plain management. These estimates are often needed at ungauged sites where no observed flood data are available for frequency analysis.

While available at-site systematic gauged records are the traditional and most obvious source of information on the frequency of floods, they are of limited length. Flood flows are predicted using plotting positions and curve fitting based on a graphical representation of systematic and historical flood peaks. Lognormal, Pearson type III, and generalized extreme value distributions are reasonable choices for describing flood flows. However, as pointed out by Stedinger et al. (1993), it is advisable to use regional experience to select a distribution for a region and to reduce the number of parameters estimated for an individual site.

Recommended procedures for flood-frequency analyses by U.S. federal agencies are described in Bulletin 17B (Interagency Advisory Committee 1982). Bulletin 17B describes a methodology for computing flood flow frequency curves using annual flood series with at least ten years of data, and recommends special procedures for zero flows, low outliers, historic peaks, regional information, confidence intervals, and expected probabilities for estimated quantiles. The recommended technique assumes that the decimal logarithms of the peak discharges have a Pearson type III distribution, and therefore the flood flow associated with a specific exceedance probability is a function of the sample mean, standard deviation, skew coefficient, and the exceedance probability itself.

For many years, the U.S. Geological Survey (USGS) has been involved in the development of regional regression equations for estimating flood magnitude and frequency at ungauged sites. Since 1973, regression equations for estimating flood-peak discharges for rural, unregulated watersheds have been published, at least once, for every state and for the Commonwealth of Puerto Rico. For some areas of the nation, however, data are still inadequate for defining flood-frequency characteristics. Regression equations for estimating urban flood-peak discharges for several metropolitan areas in at least thirteen states are also available. These regression equations are used to transfer flood characteristics from gauged to ungauged sites through the use of watershed and climatic characteristics as explanatory or predictor variables. Generally, these equations have been developed on a statewide or metropolitan-area basis as part of cooperative study programs with specific state departments of transportation or specific cities.

In 1994, the USGS, in cooperation with the Federal Highway Administration and the Federal Emergency Management Agency, compiled all the statewide and metropolitan area regression equations, as of September 1993, into a microcomputer program titled the *National Flood Frequency Program* (M. E. Jennings, W. O. Thomas, Jr., and H. C. Riggs 1994). The program includes equations — developed based on the statistical (regression) analysis of data collected at gauging stations — for estimating flood-peak discharges and techniques for estimating a typical flood hydrograph for a given recurrence interval for unregulated rural and urban watersheds.

The evolution of flood-peak discharge regionalization procedures within the USGS is described by discussing the following three procedures: (1) index-flood procedure used from the late 1940s to the 1960s, (2) the ordinary-least-squares regression procedure used in the 1970s and 1980s, and (3) the generalized-least-squares regression procedure that is being used today (1990s).

The index-flood procedure consisted of two major parts. The first was the development of basic, dimensionless frequency curves representing the ratio of flood discharges at selected recurrence intervals to an index flood (mean annual flood). The second part was the development of a relation between watershed and climatic characteristics and the mean annual flood, to enable the mean annual flood to be predicted at any point in the region. The combination of the mean annual flood with the basic frequency curve, expressed as a ratio of the mean annual flood, provided a frequency curve for any location.

In the following years, the use of ordinary-least-squares regression methods addressed some of the limitations of the index-flood procedure. Direct estimation of T-year floodpeak discharges, using ordinary-least-squares regression methods, avoided the following deficiencies in the index-flood procedure: (1) the flood ratios for comparable streams may differ because of large differences in the index flood; (2) homogeneity of frequency curve slope can be established at the ten-year level, but individual frequency curves commonly show wide and sometimes systematic differences at the higher recurrence levels; and (3) the slopes of the frequency curves generally vary inversely with drainage area. Additionally, it was observed that the flood ratios vary also with channel slope and climatic characteristics. T-year flood-peak discharges for each gauging station were estimated by fitting the Pearson type III distribution to the logarithms of the annual peak discharges. The regression equations that related the T-year flood-peak discharges to watershed and climatic characteristics were computed using ordinary-least-squares techniques. In ordinary-least-squares regression, equal weight is given to all stations in the analysis, regardless of record length and the possible correlation of flood estimates among stations. Additionally, in most statewide flood-frequency reports that used this method, the analysts divided their states into separate hydrologic regions.

Recent developments in the regionalization of flood characteristics have centered on accounting for the deficiencies in the assumptions of ordinary-least-squares regression and on more accurate and objective tests of regional homogeneity. Ordinary-least-squares regression procedures do not account for variable errors in flood characteristics that exist as a result of unequal record lengths at gauging stations, and both ordinary- and record-length weighted-least-squares regression methods do not account for the possible correlation of annual peak flow records between sites. A new procedure, generalized-least-squares regression, that accounts for both the unequal reliability and the correlation of flood characteristics between sites was developed. It was shown, in a Monte Carlo simulation, that generalized-least-squares regression procedures provided more accurate estimates of regression coefficients, better estimates of the accuracy of the regression coefficients, and better estimates of the model error than did ordinary-least-squares procedures.

In the case of the state of Texas, regional regression equations for calculating peak flood flows for different frequencies and potential extreme peak discharges have been developed. The peak flood flow is the maximum expected flow at a certain location for a given frequency. According to Asquith and Slade (1997), peak flood flows depend on the catchment area, the slope of the main channel, the basin shape factor, the hydrologic region, and on the return period. The potential extreme peak discharge is an estimate of the highest peak discharge expected to occur at a certain location and, according to Asquith and Slade (1995), is explained mostly by the area of the corresponding catchment and by the hydrologic region where the catchment is located.

2. COMPUTER-BASED HYDROLOGIC AND HYDRAULIC MODELLING

2.1 Hydrologic and Hydraulic Software

Many computer programs for hydrologic and hydrologic modeling are available to the engineering community. Some of these programs have been developed by the government and are in the public domain. DeVries and Hromadka (1993) have prepared a comprehensive summary of available software, in which programs are grouped in the following categories: (1) single-event rainfall-runoff and routing models, (2) continuous-streamflow simulation models, (3) flood-hydraulics models, and (4) water-quality models. Because of the widespread use of HEC-1, HEC-2 — and its Windows version HEC-RAS —

and TR-20, overviews of these programs are included in this review; however, the reader is referred to the software manuals for detailed information.

HEC-1: HEC-1 is a computer model for rainfall-runoff analysis developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. The program develops discharge hydrographs for either historical or hypothetical storm events for one or more locations in a basin. To account, to a certain extent, for spatial variability of the system, the basin can be subdivided into subbasins with specific hydrologic parameters.

The program options include 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. Uncontrolled reservoirs and diversions can also be accommodated.

Precipitation excess is transformed into direct runoff using either unit hydrograph or kinematic wave techniques. The unit hydrograph can be entirely supplied by the user or defined based on hydrologic parameters of the watershed, for which several built-in unit hydrograph options are available in the program (i.e., Clark, Snyder, or Soil Conservation Service unit hydrograph). 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.

HEC-2 and HEC-RAS: 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. Its primary use is for natural channels with complex geometry, such as rivers and natural streams. The program requires that three flow path distances be used between cross sections: a channel length and left and right overbank lengths. The program also analyzes flow through bridges, culverts, weirs, and other types of structures.

The encroachment computation option, widely used in the analysis of floodplain encroachments for the U.S. Federal Emergency Management (FEMA) flood insurance program, allows the user to specify encroachments with fixed dimensions or to designate target values for water surface increases associated with floodplain encroachments.

HEC-2 uses the standard direct step method for water surface profile calculations, assuming that flow is one-dimensional, gradually varied, and steady. The program 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.

HEC-2 computes up to fourteen 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.

In recent years, HEC has developed HEC-RAS, for River Analysis System, which has the same features as HEC-2 but with a Windows interface. Besides the user interface, no major differences between the programs have been observed.

Soil Conservation Service TR-20: The U.S. Soil Conservation Service (SCS) TR-20 computer model is a single-event rainfall-runoff model that is normally used with a design storm as rainfall input. The program computes runoff hydrographs, routes flows through channel reaches and reservoirs, and combines hydrographs at confluences of the watershed stream system. Runoff hydrographs are computed using the SCS curve number method (based on land-use information and soil maps indicating soil type) and the SCS dimensionless unit hydrograph defined by a single parameter, the watershed lag. TR-20 utilizes the SCS methods given in the "Hydrology" section of the *National Engineering Handbook.*

Watersheds are usually divided into subbasins having similar hydrologic characteristics and which are based on the location of control points through the watershed. Control points are locations of tributary confluences, a structure, a reservoir, a diversion point, a damage center, or a flood-gauge location.

Historical or synthetic storm data are used to compute surface runoff from each subbasin. Excess rainfall is applied to the unit hydrograph to generate the subbasin runoff hydrograph. Base flow can be treated as a constant flow or as a triangular hydrograph. A linear routing procedure is used to route flow through stream channels. The modified Puls method (storage-indication routing) is used for reservoir routing. As many as 200 channel reaches and 99 reservoirs or water-retarding structures can be used.

TR-20 has been widely used by SCS engineers in the United States for urban and rural watershed planning, for flood insurance and flood hazard studies, and for the design of reservoirs and channel projects. The SCS methodology is also accepted by many local agencies. TR-55 is a simplified version of TR-20 that performs rainfall-runoff modeling.

2.2 GIS for Hydrologic and Hydraulic Modeling

In a relatively short time, geographic information systems (GIS) have gained fairly widespread use in a variety of engineering applications. Originally envisioned (and used) as a geographic mapper with integrated spatial database, GIS is increasingly being used in modeling applications, where geographic data can be readily accessed, processed, and displayed. GIS has been implemented mostly by large entities (e.g., federal, state, and local government agencies) for mapping and management of spatial data. However, there is increasing interest in the potential application of GIS in engineering design and analysis, especially in hydrology and hydraulics.

Given that geographic information systems are not yet widely used for hydrologic modeling, the practicing engineering community has had only limited exposure to this technology. This was verified by a survey, developed as part of Smith's master project (1995), sent out to the fifty state highway agencies to assess the current use (state of the practice) and expected use of GIS for hydraulics-related highway work. From the thirty-two responses that were received, it became evident that those state highway agencies that have implemented GIS (ten states) are using it for mapping and data management only. Most of them recognize the potential of GIS for engineering analysis, but only the state of Maryland has implemented a system that supports hydrologic analysis, i.e., GISHYDRO (Ragan 1991). To some extent, the distinction between GIS and computer-aided design (CAD) seems to be blurred. GEOPAK, for example, listed by one responder as a GIS, is a roadway design CAD package that has digital elevation model (DEM) capability.

Within the hydrologic environment, GIS is a tool that allows one to move from lumped pre-GIS models to spatially distributed models. The line between lumped and distributed models is not sharp, and there are pre-GIS attempts to deal with spatially distributed terrain attributes. For example, the U.S. Army Corps of Engineers flood model HEC-1, well known as a lumped model, allows the user to subdivide the watershed into smaller subbasins for analysis purposes, and then route their corresponding responses to the watershed outlet. In this case, neither the concept of a purely lumped model applies, nor can the model be considered fully spatially distributed. It is therefore advisable to keep in mind the extent to which a given model is lumped or distributed.

Digital Terrain Data for Hydrologic Modeling: Several pioneers are worthy of note for their foresight and work in the development of hydrology-related application of GIS for engineering applications. DeVantier and Feldman (1993) presented a general review of the connection between GIS and hydrologic modeling, one that "summarizes past efforts and current trends in using digital terrain models and GIS to perform hydrologic analysis." The link between GIS and hydrologic modeling becomes more natural as the concern about spatially distributed terrain parameters and the use of computers for hydrologic analysis become more widespread. Digital terrain models (DTM) are used by GIS to describe the spatially distributed attributes of the terrain, which are classified as topologic and topographic data (although, strictly speaking, topographic is part of topologic data). Digital elevation models (DEM), in particular, refer to the topographic data, while all other attributes, not related to elevation, constitute the topologic data. It can be expected that, because of the large amount of information required to describe the terrain, GIS is a memory- and computation-intensive system. However, storing and handling the data are not necessarily the critical point when working with GIS, because the acquisition and compilation of the information can be an even more difficult task.

Terrain data can be handled in different ways, depending on the type of model to be used. The grid approach involves subdividing the terrain into identical square cells arranged in rows and columns; triangular irregular networks (TIN) involve selecting a set of representative irregularly distributed points and connecting them by straight lines to produce triangles; and in digital line graphs (DLG), elevation contour lines are digitally represented as a set of point-to-point paths. Accordingly, it is expected that grid data, because of their geometric structure, lead to finite difference methods, while TIN data lead to finite element methods of runoff computation. The extra effort required in working with TINs and finite element methods is offset by the fact that TINs are less memory demanding, because their resolution is not fixed and can be suited to local terrain characteristics. On the other hand, although modeling with grid and finite difference methods is less complex, it is, because of its fixed geometric structure, more memory demanding. DLGs appear mainly as a natural way to store information and as a data source for analysis with grid or TIN.

Stream-Watershed Delineation Based on Digital Terrain Data: Much research has focused on stream-watershed delineation and, in general, on watershed analysis based on topographic data, say, DEMs or DLGs. Hutchinson (1989) presents an interpolation algorithm to determine the DEM from elevation data points and stream lines. This algorithm produces DEMs that are consistent with the stream lines and has proven to produce DEMs more accurate than those obtained with previous methodologies. Jensen and Domingue (1988) and Jensen (1991) outlined a grid scheme to delineate watershed boundaries and stream networks to defined outfalls (pour points). The scheme uses digital elevation data to determine the hypothetical direction of flow from each cell in a grid to one of its eight neighboring cells. The cells contributing flow to the pour point can be counted (representing area) and the cells having no contributing flow define drainage boundaries. Cells having a flow accumulation in excess of a threshold establish stream network cells.

Tarboton et al. (1991) computed stream slopes and stream lengths using a similar grid system. In addition, the authors proposed criteria for proper selection of the threshold based on statistical properties of the terrain. Jones et al. (1990) employed a triangulation scheme on digital elevation data to determine watershed boundaries and flow paths. Procedures for delineating streams and watersheds from DEMs, as well as for correcting DEM's depressions produced by data noise, can be found in Maidment (1997), Meijerink et al. (1994), ESRI (1992), Garbrecht and Martz (1995a, 1995b), and Martz and Garbrecht (1992).

Maidment et al. (1996b) present the watershed delineation of the Niger River basin based on a 1-km DEM. In this delineation, a stream is identified on the DEM wherever the upstream drainage area exceeds 10,000 km^2, and subwatershed boundaries are delineated from outlets at each stream junction, which produces a drainage network with a single stream for each subwatershed. To avoid long reaches between junctions, outlets were also placed on streams 250 km long. A total of 167 streams with their corresponding drainage areas were determined in this way. Before delineating the watersheds, the DEM had to be corrected to account for the Lake Chad inland catchment, at the northeast of the Niger basin. Since the standard delineation process involves filling up terrain depressions, a pour point at the lowest point of the Lake Chad basin was defined to avoid filling up the whole catchment and making it overflow toward the Niger basin.

Rinaldo et al. (1992) analyzed the similarities between stream networks derived from DEMs and optimal channel networks (OCN) obtained by minimizing the energy spent in the system. Likewise, an automated procedure, fully based on topographic data, for subdividing catchments into smaller elements and for calculating hydrologically relevant attributes of the elements is described by Moore et al. (1988) and by Moore and Grayson (1991). This catchment partitioning is done in order to apply lumped models that represent particular hydrologic processes at an element level. The integration of the element responses gives the spatially distributed response of the entire catchment.

Runoff Modeling Using GIS: Grid-based GIS appears to be a very suitable tool for hydrologic modeling, mainly because "raster systems have been used for digital image processing for decades and a mature understanding and technology has been created for that task" (Maidment 1992a). The ESRI Arc/Info-GRID system and the U.S. Army Corps of Engineers' GRASS system use a grid data structure. Grid systems have proven to be ideal for modeling topographically driven flow, given that a characteristic of this type of flow is that flow directions do not depend on any time-dependent variable. This characteristic is what makes topographically driven flow easily modeled in a grid environment. Accordingly, grid systems include hydrologic functions as part of their capabilities. At present, hydrologic functions, available in GRID and GRASS, allow one to determine flow direction and drainage area at any location, stream networks, watershed delineation, etc. (Maidment 1992a).

Recently, there have been attempts to take advantage of GIS capabilities for runoff and nonpoint-source pollution modeling. Vieux (1991) reviews water quantity and quality modeling with GIS and, as an application example, employs the kinematic wave method to an overland flow problem. GIS is used to process the spatially variable terrain while the finite element method (FEM) is used to solve the mathematics. Maidment (1992a, 1992b, 1993) presents a grid-based methodology for determining a spatially distributed unit hydrograph that assumes a time-invariant flow velocity field. According to Maidment, the velocity time invariance is a requirement for the existence of a unit hydrograph with a constant time base and relative shape. In Maidment's articles, from a constant velocity grid, a flow time grid is obtained and, subsequently, the isochrone curves and the time-area diagram are determined. The unit hydrograph is obtained as the incremental areas of the time-area diagram, assuming a pure translation flow process. A more elaborated flow process, accounting for both translation and storage effects, is presented by Maidment et al. (1996a). In their paper, the watershed response is calculated as the sum of the responses of each individual grid cell, which is determined as a combined process of channel flow (translation process) followed by a linear reservoir routing (spreading process). Although an approximate method, the model shows a good fit for the unit hydrograph of the Severn watershed at Plynlimon in Wales. Olivera et al. (1995) and Olivera and Maidment (1996) present a grid-based, unsteady-flow, linear approach that uses the diffusion wave method to model storm runoff and constituent transport. According to these papers, the routing from a certain location to the outlet is calculated by convolving the responses of the grid cells of the drainage path.

Sensitivity of model results to the spatial resolution of the data has been addressed by Vieux (1993), who discusses how the grid-cell size affects the terrain slope and flow-path length and, accordingly, the surface runoff. Vieux and Needham (1993) conclude that increasing the cell size shortens the streams length and increases the sediment yield.

Water Balance of the State of Texas: A water balance of the state of Texas, using GIS, was prepared by Reed and Maidment (1997), in which a 5-km precipitation grid, a 500-m digital elevation model (DEM), gauged streamflow data, and other spatial data sets were used to generate spatially distributed maps of mean annual runoff and evaporation. In this effort, 166 gauged watersheds were delineated from a 500-m DEM and hydrologic attributes were compiled for each of them. To estimate the runoff in ungauged locations, plots of watershed average annual rainfall (mm) versus annual runoff per unit watershed area (mm) were analyzed. By eliminating watersheds having a large amount of reservoir evaporation, urbanization, recharge, or springflow, a clear trend emerged in the rainfall-runoff data and a *runoff coefficient* function was derived. Because runoff values were normalized by watershed area, this runoff coefficient function is scale independent and represents watersheds having drainage areas ranging from 270 to 50,000 km^2. Next, an expected runoff grid was created by applying the runoff coefficient function to the precipitation grid. Finally, a grid of *actual runoff* was created on a 500-m grid by combining gauged streamflow data with expected runoff information. By applying a flow accumulation function to the runoff maps, the expected and actual flows were calculated at each 500-m DEM cell. Flow maps created using these results show statewide spatial trends (e.g., the increased density of stream networks in East Texas) and also capture localized phenomena (e.g., such as large springflows and agricultural diversions). A map of the differences between actual and expected runoff shows where human activities have altered natural runoff.

Floodplain Modeling with GIS: In the area of floodplain management, the U.S. Army Corps of Engineers has developed an integration of HEC-2, a widely used floodplain determination package, and GRASS, a software program developed to work with raster data (Walker et al. 1993). The integration package accesses HEC-2 output in tabular form and converts it to GRASS format. For floodplain determination, Talbot et al. (1993) developed a GIS application that takes water elevations as input. Their approach is intended to be nonspecific, accepting stage values from any model that can determine water elevations along a stream channel. HEC-1 and HEC-2 are mentioned as valid sources of stage values. The application involves the intersection of two TINs, one representing the terrain and the other the channel's water elevations, so that the banks of the floodplain can be established. The authors indicate that the resulting floodplain is locally reasonable and indicative of the overall floodplain. Beavers (1994) has developed ARC/HEC2, a set of AMLs (Arc/Info Macro Language) and C programs, which work to extract terrain information from contour coverages, insert user-supplied information (such as roughness coefficients or location of left and right overbanks), and format the information as HEC-2 readable data. Following HEC-2 execution, ARC/HEC2 is capable of retrieving the HEC-2 output (in the form of water elevations at each cross section) and creating an Arc/Info coverage of the floodplain. This process allows the resulting floodplain to be stored in a coverage format that is readily accessed by users who wish to use the floodplain information in conjunction with other Arc/Info coverages. ARC/HEC2 requires that a terrain surface be generated so that accurate cross-sectional profiles are provided to HEC-2. These terrain surfaces, in the format of TINs or grids, are created within Arc/Info based on contour lines, survey data, or on other means of establishing terrain relief. The accuracy of the surface representation is crucial for accurate floodplain calculations.

Watershed Modeling System: The Watershed Modeling System (WMS) is a hydrologic software package developed at the Engineering Computer Graphics Laboratory (ECGL) at Brigham Young University. The package is divided logically into six integrated and task-oriented modules: TIN Module, DEM Module, Tree Module, Grid Module, Scatter Point Module, and Map Module. These are described below.

TIN Module. A triangular irregular network (TIN) is a set of elevation points connected to form a network of triangles in a manner that simulates the face of the land. The TIN module is used for terrain modeling, automated basin delineation, and drainage analysis. Once basin boundaries have been delineated, geometric attributes, such as area, slope, and runoff distances, can be calculated for each basin.

DEM Module. A digital elevation model (DEM) is a regular gridded elevation representation of the topography of the terrain that can be imported into WMS and used as background elevation information.

Map Module. The Map Module is used to define stream channels, ridges, boundaries, and any other important terrain feature present in the model. TINs can be constructed from these feature objects using an existing TIN or a DEM as a background elevation map. Within the Map Module there are several tools that can be helpful in either setting up models or presenting results. Tools for reading and writing DXF files, mapping TIFF images, and annotating text are part of this module.

Tree Module. Traditionally HEC-1 and TR-20 models are developed around a topologic representation — or tree diagram — of a watershed. Nodes or icons for each component, such as outlet points (confluences), basins, diversions, and reservoirs, are linked according to the underlying stream network of the watershed. Using WMS, tree diagrams can be established in one of two ways: automatic creation from TIN geometry, or manually defining outlets, basins, diversions, etc., and linking them. Preferably a TIN is used, since it can help supply important geometric information that would otherwise have to be determined manually from maps. Once the tree diagram for a watershed is established, all necessary data and methods to run an HEC-1 simulation can be defined.

Grid Module. The Grid Module is used for surface visualization and for the development of a CASC2D rainfall/runoff analytical model. The user can discretize a watershed into a number of grid cells and then define hydrologic properties at grid cells in preparation for running CASC2D. Parameters may be interpolated from a set of scattered data points to the grid. Results of the 2-D analysis can then be contoured on the grid or displayed with hidden surface removal and color fringes to display the variation in the computed results.

Scatter Point Module. The Scatter Point Module is used to interpolate from groups of scattered data points to grids. A variety of interpolation schemes are supported.

2.3 Use of GIS for Design of Highway Drainage Structures

For TxDOT, as well as for other highway agencies, a continuing concern is the need to apply current engineering hydrologic and hydraulic design and analysis procedures that balance simplicity with accuracy. Although most hydrologic and hydraulic calculation procedures are now available in computer programs, the use of which has substantially reduced the mathematical effort involved, a substantial effort is still necessary to establish and manipulate the data required for input into those programs. In trying to simplify the process of determining these input data, the departments of transportation in Texas and Maryland have developed GIS packages that calculate spatial hydrologic parameters that can then be used by standard hydrologic software packages.

GISHYDRO: GISHYDRO, a geographic information system structured for hydrologic analysis, was developed and installed in the Maryland State Highway Administration's (MSHA) Division of Bridge Design in Baltimore in 1991 (Ragan 1991). The objective of GISHYDRO was to improve the efficiency and quality of hydraulic design by allowing the user to quickly assemble the land use, soil, and slope data for any watershed in the state, and then make the necessary interfaces to define the required input parameters and run the SCS TR-20 hydrologic model for existing or proposed watershed conditions. A digitizer was used to delineate watershed and subwatershed boundaries; define details of the stream, swale, and overland flow paths; and enter areas proposed for land use change. GISHYDRO then sets up the files for entry into the Soil Conservation Service computer program TR-20, so the model can be run for existing or proposed conditions. The same files are used to run a nonpoint-source pollution model that estimates BOD, nitrate, phosphate, and other loadings in terms of the watershed land use and soil types.

Hydrologic Data Development System: The Hydrologic Data Development System (HDDS) (Smith 1995) is a prototype system intended to demonstrate the potential for using GIS for highway-based hydrologic data development and analysis. This system employs data that are now widely available (or that will become more prevalent).

The focus of HDDS is on the development of an integrated set of Arc/Info programs and associated data. Although the HDDS programming is specific to Arc/Info, the data are transferable and the general methodology should be applicable to any GIS package that has similar capabilities. The system provides the user with the capability of establishing some of the most important hydrologic parameters used in hydrologic analysis methods, such as the drainage basin boundaries, areas and subareas, the maximum flow path length, the estimated travel time, the watershed average slope, the hydrologic soil group, the design rainfall, the weighted runoff coefficients, and other hydrologic parameters of a catchment defined by a highway/stream crossing. The data may be passed automatically from HDDS to the TxDOT Hydrologic and Hydraulic System (THYSYS) to calculate the relationships between design floods and their frequency. The resulting data may then be manipulated to create drainage area maps, tables, and other documentation.

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