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SYSTEM OF GIS-BASED HYDROLOGIC AND HYDRAULIC APPLICATIONS FOR HIGHWAY ENGINEERING: SUMMARY REPORT

Francisco Olivera and David Maidment

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

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Francisco Olivera and David Maidment

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16. Abstract

A significant part of the cost of most highway projects is attributable to drainage facilities, such as bridges, highway culverts, storm drains, and water quality and quantity control structures. Design of these facilities involves a hydrologic analysis to determine the design discharge, and a hydraulic analysis of the conveyance capacity of the facility. Although most hydrologic and hydraulic calculation procedures are available in computer programs, the use of which has significantly reduced the mathematical effort involved, a substantial effort is still necessary to establish and manipulate the data required for input into those programs. In this research project, a geographic information system (GIS) for assisting in the design of highway drainage facilities has been developed. This GIS reduces the analysis time and improves the analysis accuracy by integrating digital spatial data describing the watershed with standard hydrologic and hydraulic computer packages. The focus has been on two main topics: (1) determining flood peak discharges and hydrographs, and (2) floodplain mapping.

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by
Francisco Olivera
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David Maidment

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System of GIS-Based Hydrologic and Hydraulic
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David Maidment, P.E. (Texas No. 53819)
Research Supervisor

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IMPLEMENTATION RECOMMENDATIONS

Based on the findings of this research project, the researchers recommend that TxDOT:

1. develop a training program in the form of short courses about Application of CRWR-FloodMap for Hydrologic and Hydraulic Modeling, to be given by CRWR researchers for TxDOT personnel, and
2. apply the CRWR-FloodMap for hydrologic and hydraulic modeling by CRWR researchers to two selected areas.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTIVATION</td>
<td>1</td>
</tr>
<tr>
<td>SPATIALLY DISTRIBUTED HYDROLOGIC AND HYDRAULIC MODELING</td>
<td>3</td>
</tr>
<tr>
<td>DETERMINING FLOOD PEAK DISCHARGES AND HYDROGRAPHS</td>
<td>4</td>
</tr>
<tr>
<td>FLOODPLAIN MAPPING</td>
<td>11</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>13</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>15</td>
</tr>
</tbody>
</table>
**SYSTEM OF GIS-BASED HYDROLOGIC AND HYDRAULIC APPLICATIONS FOR HIGHWAY ENGINEERING: SUMMARY REPORT**

**Motivation**

A significant part of the cost of most highway projects is attributable to drainage facilities, which can include bridges, highway culverts, storm drains, and water quality and quantity control structures. Design of these facilities involves a hydrologic analysis to determine the design discharge, as well as a hydraulic analysis of the conveyance capacity of the facility. Although most hydrologic and hydraulic calculation procedures are available in computer programs, the use of which has significantly reduced the mathematical effort involved, a substantial effort is still necessary to establish and manipulate the data required for input into those programs. In particular, the Texas Department of Transportation (TxDOT) has existing procedures for hydrologic and hydraulic analysis in the Texas Hydraulic System (THYSYS). Within these procedures, each application requires the computerization of the description of the watershed and the stream channel using data extracted manually from maps and cross sections contained in paper drawings.

Likewise, it was observed that, although there are many hydrologic and hydraulic models available, most of them are lumped models, making the distributed ones very limited in number and applicability. In many cases, the spatial variability of the hydrologic system, which precludes the modeler from applying lumped models, is addressed by subdividing the system into a series of subsystems, with each having different hydrologic properties. Although this is an improvement with respect to the lumped approach, this alternative cannot be considered pure distributed modeling.

In their efforts (1) to simplify the process of determining the input data for the computer programs and (2) to capture the spatial variability of the hydrologic system, some state departments of transportation are developing geographic information systems (GIS) for spatially distributed hydrologic and hydraulic modeling. By building a hydrologic digital spatial database and developing a GIS that operates off this database, these departments are
ensuring that the extraction of data and the application of design procedures are automated and efficient.

In this research project, a GIS for assisting in the design of highway drainage facilities has been developed. This GIS reduces the analysis time and improves the analysis accuracy by integrating digital spatial data describing the watershed with standard hydrologic and hydraulic computer packages. Focus has been made on two main topics: (1) determining flood peak discharges and hydrographs, and (2) floodplain mapping.

Figure 1 shows the framework of hydrologic and hydraulic modeling using GIS. According to the figure, after a spatial database of the hydrologic system is developed, a hydrologic model is generated using CRWR-PrePro, and flood discharges are calculated using HEC-HMS. These flood discharges are then used to calculate water levels with HEC-RAS. Finally, the water levels are mapped on the digital spatial data using AVRAS to generate floodplains. CRWR-PrePro has been developed as part of this research project at the Center for Research in Water Resources (CRWR); HEC-HMS and HEC-RAS have been developed by the Hydrologic Engineering Center (HEC); and AVRAS has been developed by the Environmental Systems Research Institute (ESRI). CRWR undertook to integrate the pieces into a consistent system.
**Spatially Distributed Hydrologic and Hydraulic Modeling**

Distributed hydrologic and hydraulic modeling require a distributed model and a spatial database to support it. A distributed model is a set of rules (i.e., mathematical equations) that represent the physical processes that take place in a system and that account for the spatial variability of the properties of the objects that undergo these processes. A spatial database is a consistent set of spatial data of the system that includes the properties of the objects that undergo the physical processes.

Although creating mathematical representations of the distributed physical processes is a complex task by itself, storing and handling the amount of data required by distributed models is even a more difficult task. Thus, it has become apparent that software specifically developed for managing large amounts of spatially distributed data, such as that associated with a GIS, is necessary and that, ideally, the distributed hydrologic models should be developed to operate within the GIS environment.

Another difficulty found in the process of accounting for the spatial variability of the system is the lack of spatial data for large areas. In other words, it is possible that, after successfully developing a distributed model and its corresponding computer code, an engineer would be unable to populate the model parameters because of a lack of information. This difficulty, though, always confronts the modeling community since, as more data become available, models become more complex and more data are needed. Fortunately, a significant amount of digital spatial data of Texas has been developed by different federal, state, and local agencies and made available to the public. Development of spatial data, however, will be an ongoing task.

Finally, presenting the engineering community — a community of professionals with well-established working habits — with a new approach to hydrologic and hydraulic modeling also constitutes a challenge. Engineers have been working successfully for years using standard hydrologic and hydraulic models, through which they have been making a significant contribution to society. It is, therefore, understandable that some would be reluctant to change their modeling philosophy in favor of a new — though arguably better —
modeling philosophy. A transition period, in which the new GIS approach is coupled with the traditional models, is therefore necessary. In fact, it has been observed that making a connection between ArcView and standard software packages like HEC-HMS or HEC-RAS allows the modeler to get the most out of GIS (i.e., to capture the spatial variability of the system) while continuing to work using familiar tools.

**Determining Flood Peak Discharges and Hydrographs**

Determination of flood peak discharges and hydrographs is a complex problem that could not be approached all at once. As explained below, the case of peak flows that depend solely on location was addressed first, followed by the case of peak flows that depend on location and return period; finally, the case in which time is also a variable and a hydrograph has to be determined.

A raster map of precomputed values of potential extreme peak discharges (i.e., the highest peak discharge expected to occur at a certain location) was developed. These discharges can be expressed as a function of drainage area and hydrologic region only. Thus, GIS functions that operate on raster data were used to develop raster data sets of the drainage area of each terrain pixel and of the hydrologic region in which each pixel is located. These raster data sets were then used as input for the discharge equations and were applied to each pixel, a process that resulted in a raster map of precomputed discharge values. Retrieval of these values is immediate because no “on-the-fly” calculations are involved.

This raster map is a powerful tool that obviates having to delineate the watershed, calculate its area, and apply the corresponding equation. It tends, though, to overestimate flows, since some watershed characteristics, such as land use, soil type, and geology, have been ignored and worst-case values have been predicted. The effect of reservoirs and cities on the downstream water bodies has not been considered either. However, it does not seem to imply a drastic change of methodology, since only the areas in downstream proximity to dams and urban centers would have to be corrected. A disadvantage of the concept of potential extreme peak discharge is that discharges are estimated for worst-case scenarios and
are not related to a specific return period. Because worst-case scenario discharges might be too conservative for design purposes, a new method was proposed to account for the discharge frequency, which is explained next.

Figure 2: Digital raster map of potential extreme peak discharges. The Identify Results window indicates that, at the selected point (click of the mouse), a potential extreme peak discharge of 152,000 cfs is expected.

The Flood Flow Calculator, an ArcView extension for calculation of peak discharges for different return periods, was developed according to the TxDOT Statewide Regional Rural Regression Equations. According to these equations, peak discharges are a function of drainage area, length and slope of the longest flow-path within the watershed, shape factor of the watershed (ratio of the square of the length of the longest flow-path to the area of the watershed), average curve number, and return period. In this case, since the input parameters for the discharge equations must be calculated on a cell-by-cell basis, no raster map of
precomputed discharge values can be developed. Instead, discharges are calculated on-the-fly, after the user selects the location from the map. This time, GIS functions that operate on raster data were used to develop the necessary raster data sets and calculate the necessary watershed parameters before estimating peak discharges for different design return periods with the equations (see Figure 3).

Figure 3: Left: Delineated watershed and longest flow-path for the selected outlet. Right: Watershed parameters and peak flows for different return periods.

Also included are tools used (1) to generate raster maps of curve numbers and flow-time to the watershed outlet and (2) to calculate average values of a physical property within a watershed.
Although this method is more developed than the previous one, dependence of flow on time is still not considered. A model that generates hydrographs is presented next.

A connection between GIS data sets describing a hydrologic system and HEC’s Hydrologic Modeling System (HEC-HMS) was developed in this project. This model, dubbed CRWR-PrePro, extracts topographic, topologic, and hydrologic information from digital spatial data and prepares an input file for the basin component of HEC-HMS, which, when opened, automatically creates a topologically correct schematic network of subbasins and reaches, and attributes each element with selected hydrologic parameters. Figure 5 shows the data — maps and tables — in GIS format displayed by ArcView. Figure 6 shows pieces of the basin input file for HMS in ASCII format, and their corresponding hydrologic elements in the HMS schematic. Figure 7 shows the complete HMS schematic and the parameter window for one reach. Note that the hydrologic parameters calculated and stored in tables within GIS are transferred to HMS.
Figure 5: Watershed and stream data in ArcView. Top: Spatial data sets in vector format. Middle: Attribute table of the polygon data set of watersheds. Bottom: Attribute table of the polyline data set of streams.
Figure 6: Connection between the text file prepared by CRWR-PrePro (based on the GIS data) and the basin schematic in HEC-HMS.

Figure 7: Left: Basin schematic in HMS. Right: Reach attributes in HMS, after being calculated in GIS and transferred to HMS.
CRWR-PrePro also generates an input file for the precipitation component of HEC-HMS. Two methods to interpolate precipitation records are supported: Thiessen polygons to calculate average precipitation at the subbasins (see Figures 8 and 9), and GridParm to calculate routing parameters of the precipitation cells for use with the ModClark subbasin routing method.

![Diagram of ArcView with gage and volume weight highlighted]

*Figure 8: Calculation of a gage volume weights with ArcView. These volume weights are then written to an ASCII file that can be read by HMS.*
Figure 9: The information written to the ASCII file is transferred to HMS.

At the moment, CRWR-PrePro calculates or imports parameters for: (1) the Soil Conservation Service (SCS) curve number method and the initial plus constant loss method for loss rate calculations; (2) the SCS unit hydrograph model for subbasin routing, for which the lag-time can be calculated with the SCS lag-time formula or as a fraction of the length of the longest channel divided by the flow velocity; and (3) the Muskingum method and the lag method for flow routing in the reaches (depending on the reach length). Using CRWR-PrePro, the determination of physical parameters for HEC-HMS is a simple and automatic process that accelerates the setting up of a hydrologic model and leads to reproducible results.

Floodplain Mapping

A methodology for automated floodplain mapping has also been developed. The work provides a link joining hydraulic modeling using HEC-RAS with spatial display and analysis of floodplain data in ArcView. As inputs, the model requires a completed HEC-RAS model simulation and a GIS stream centerline representation. The procedure consists of several steps: (1) data import from HEC-RAS, (2) stream centerline representation, (3) cross-section
georeferencing, terrain modeling, and (4) floodplain mapping. The output is a digital
floodplain map that shows both extent and depth of inundation.

The process developed for automating terrain modeling and floodplain delineation
has several noteworthy benefits. First, it has a user friendly interface. Use of the menu items
automates and simplifies floodplain mapping. Second, it has a digital output. Rendering the
floodplain in digital format allows the floodplain data to be easily compared with other
digital data, such as digital orthophotos and GIS coverages of infrastructure, buildings, and
land parcels. Finally, the process results in resource savings. Many floodplain maps need to
be revised because they become outdated. The automated mapping approach developed for
this research saves time and resources versus conventional floodplain delineation on paper
maps. Thus, floodplain maps can be updated more frequently, as changes in hydrologic and
hydraulic conditions warrant. (See Figure 10.)

The main limitation of this approach is the assumption of straight-line cross sections.
The HEC-RAS model requires cross sections to be defined such that they are perpendicular
to the flow lines in both the floodways and main channel. As a result, land surveys of river
cross sections observe the perpendicularity requirement. Within relatively straight portions of
the channel, this equates to straight-line cross sections. However, near bends in the stream,
the cross sections are surveyed perpendicular to the channel, but “doglegged” in the
floodways to ensure perpendicularity to flow. Unfortunately, information concerning the
orientation of each cross section is indicated on survey maps, but is not routinely stored by
HEC-RAS cross-section data. Consequently, because no information on cross-section
doglegging is available, the approach in this research assumes that all cross sections occur in
straight lines. The effect of the straight-line assumption on the accuracy of the resulting
terrain models and floodplain maps varies with the distance from the stream channel.

It was also observed that 30-m and 10-m DEMs do not provide sufficiently detailed
channel representations to be used as the source of cross-sectional data for floodplain
modeling. In addition, because of the small distances with which floodplain mapping works,
map projection consistency is of significant importance. The number of cross sections should
also be sufficient to capture bends and sharp elevation changes in the channel. The appropriate density of cross sections should be determined based on the shape of the channel and on the requirements for hydraulic modeling. To increase the density of cross sections in HEC-RAS, the cross-section interpolation menu option can be employed.

![Image of Walker Creek view]

*Figure 10: Floodplain (in blue) overlaid on the digital orthophoto of downtown Austin, Texas. Dark blue corresponds to deep areas.*

Further development on the use of GIS for hydrologic and hydraulic modeling should include support for more modeling options of the software packages, as well as development of a more efficient and GIS-supported connection between the hydrologic and hydraulic packages for flow value transfers. Future development in this field, though, is strongly dependent on the availability of terrain data at a resolution consistent with its use.

**Conclusions**

Given the feasibility of developing tools for automated hydrologic and hydraulic distributed modeling, as well as the availability of digital spatial data for different parts of the
country, GIS appears to be an excellent environment for developing water resources planning and management.

In this research project, GIS-based tools for determining flow hydrographs at different locations of a hydrologic system have been developed, as have tools for calculating the corresponding water levels within the channels and flooded areas. The model uses digital spatial data that in most cases have already been developed for the whole country and that are of public domain. Thus, it takes advantage of already available data and minimizes the need to recreate data at a local level. The model makes a connection between GIS data and standard computer packages, such as HEC-HMS and HEC-RAS, that are used by TxDOT.
BIBLIOGRAPHY


ESRI (1992), Cell-based Modeling with Grid 6.1: Supplement — Hydrologic and Distance Modeling Tools, Environmental Systems Research Institute, Redlands, CA.

Garbrecht, J., and L.W. Martz (1995a), TOPAZ; Rep. # NAWQL 95-1; USDA, Agricultural Research Service, Durant, OK.


Reed, S. M., D. R. Maidment, and J. Patoux (1997), Spatial Water Balance of Texas, Center for Research in Water Resources Online Report 97-1, The University of Texas at Austin.


USGS a, 7.5-Minute Digital Elevation Model Data,

USGS b, 1-Degree Digital Elevation Models,

USGS c, Global 30 arc-second Elevation Data Set,


**INTERNET BIBLIOGRAPHY**

Global 30 Arc-Second Elevation Data Set:

USGS - Metadata for GCIP Reference Data Set (GREDS):

1-Degree USGS Digital Elevation Models:
http://edcwww.cr.usgs.gov/glis/hyper/guide/1_dgr_dem

The U.S. EPA Reach File Version 3.0 Alpha Release (RF3-Alpha) Technical Reference:
http://www.epa.gov/owowwtr1/NPS/RF/techref.html

Hydrologic Unit Maps: http://nsdi.usgs.gov/nsdi/products/huc.html
1 to 2,000,000 Hydrologic Unit Map of the Conterminous United States:
http://nsdi.usgs.gov/nsdi/wais/water/huc2m.HTML

Hydrologic Unit Maps of the Conterminous United States:


USGS Land Use and Land Cover Data - Procedures for Obtaining Data:
http://edcwww.cr.usgs.gov/glis/hyper/guide/1_250_lulc

Metadata for COUNTY100: http://nsdi.usgs.gov/nsdi/wais/water/county100.HTML

Major Aquifers (e00 format):
http://www.tnris.state.tx.us/pub/GIS/hydro_geology/major_aqu_e00

Transportation - USDOT Data (e00 format):
http://www.tnris.state.tx.us/pub/GIS/highway/usdot_e00

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