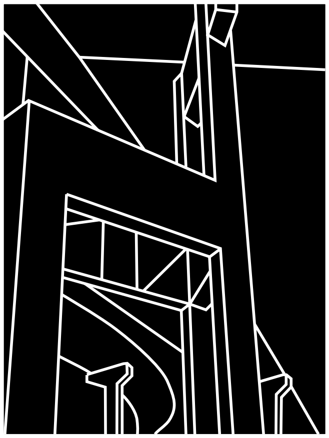
PROJECT SUMMARY REPORT 1738-S

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
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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

and

David Maidment

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Research Project 0-1738
System of GIS-Based Hydrologic and Hydraulic
Applications for Highway Engineering

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1999

DISCLAIMERS

David Maidment, P.E. (Texas No. 53819)
Research Supervisor

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The researchers acknowledge the invaluable assistance provided by Anthony Schneider (BRG), TxDOT project director for this study. Also appreciated is the guidance provided by T. D. Ellis (PAR), the other member of the TxDOT project monitoring committee.

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.

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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.

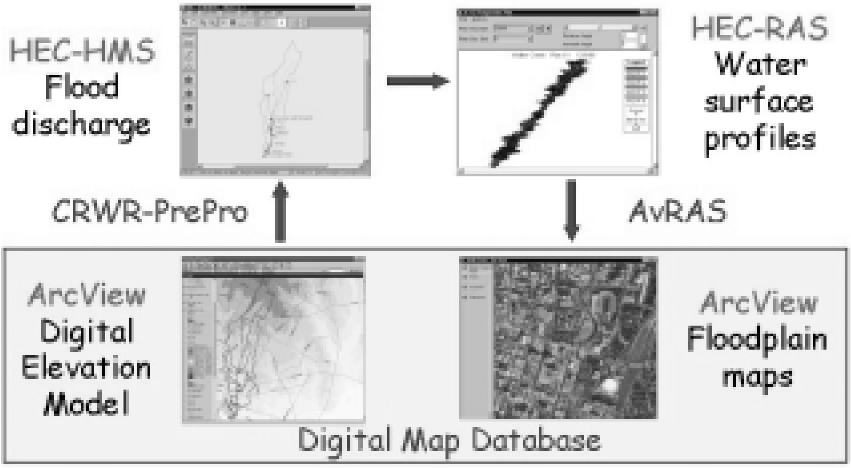


Figure 1: Framework of hydrologic and hydraulic modeling using GIS.

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 —

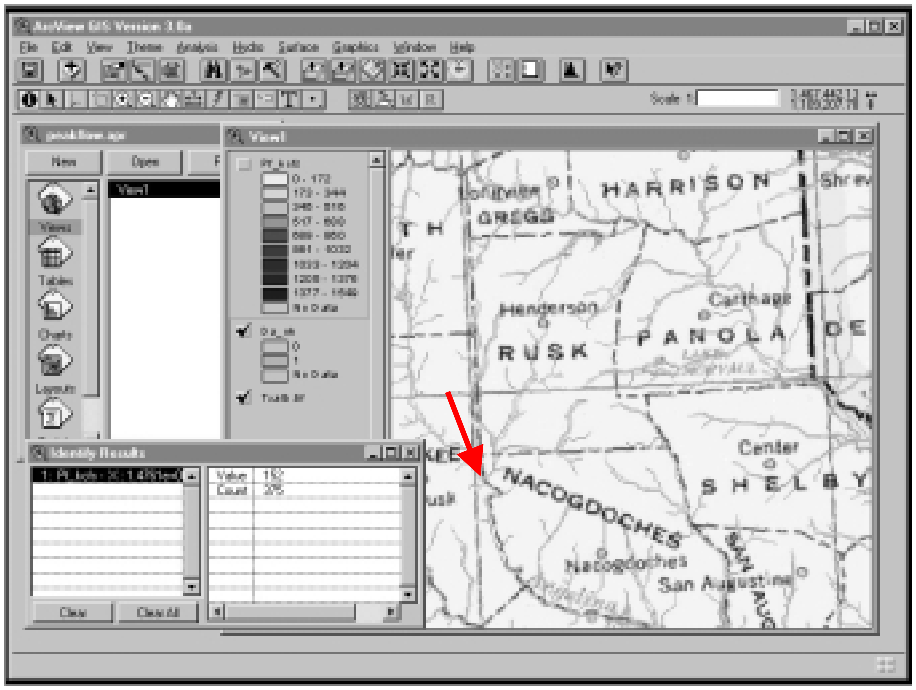
modeling philosophy. A transition period, in which the new GIS approach is coupled with the traditional models, is therefore necessary. In fact, it has been observed that making a connection between ArcView and standard software packages like HEC-HMS or HEC-RAS allows the modeler to get the most out 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.

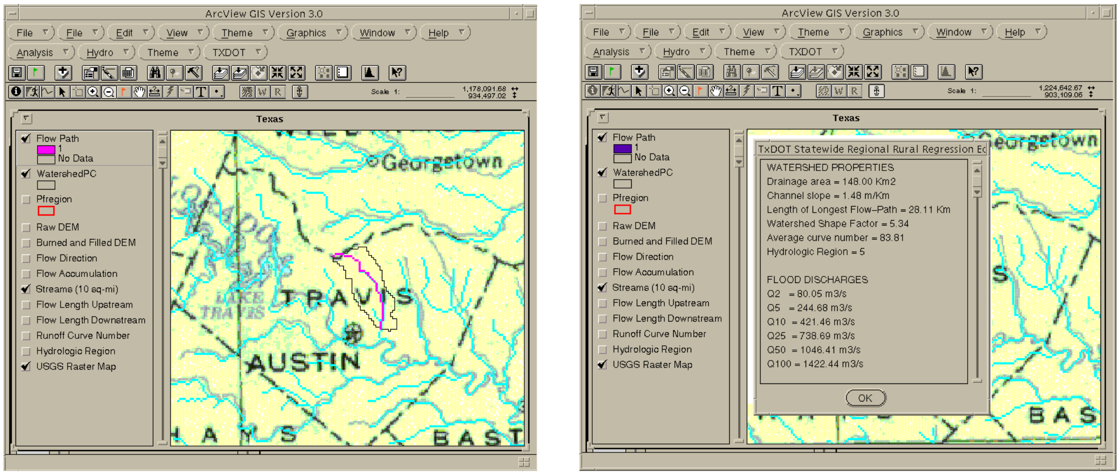
This raster map is a powerful tool that obviates having to delineate the watershed, calculate its area, and apply the corresponding equation. It tends, though, to overestimate flows, since some watershed characteristics, such as land use, soil type, and geology, have been ignored and worst-case values 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.



Value 152
Count 275

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).



```
TxDOT Statewide Regional Rural Regression Ec
WATERSHED PROPERTIES
Drainage area = 148.00 Km2
Channel slope = 1.48 m/Km
Length of Longest Flow–Path = 28.11 Km
Watershed Shape Factor = 5.34
Average curve number = 83.81
Hydrologic Region = 5

FLOOD DISCHARGES
Q2   = 80.05 m3/s
Q5   = 244.68 m3/s
Q10  = 421.46 m3/s
Q25  = 738.69 m3/s
Q50  = 1046.41 m3/s
Q100 = 1422.44 m3/s
```

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.

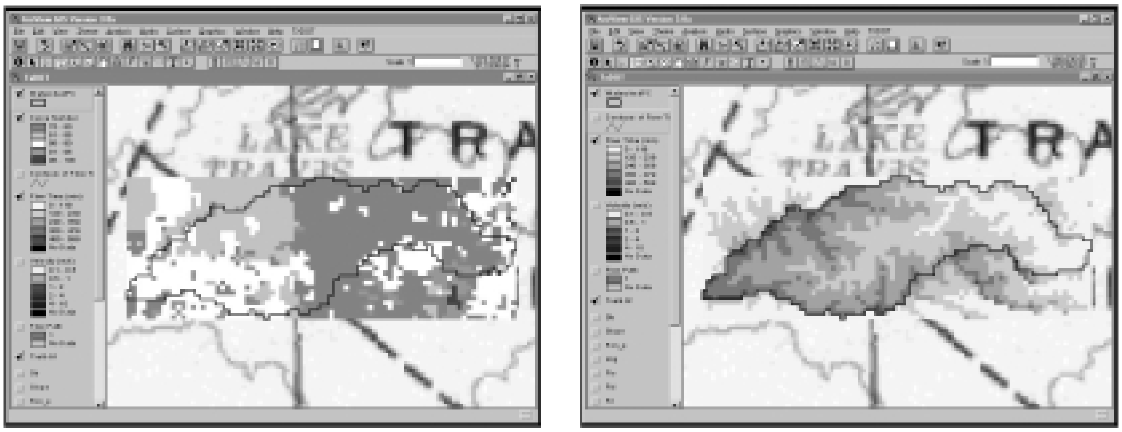
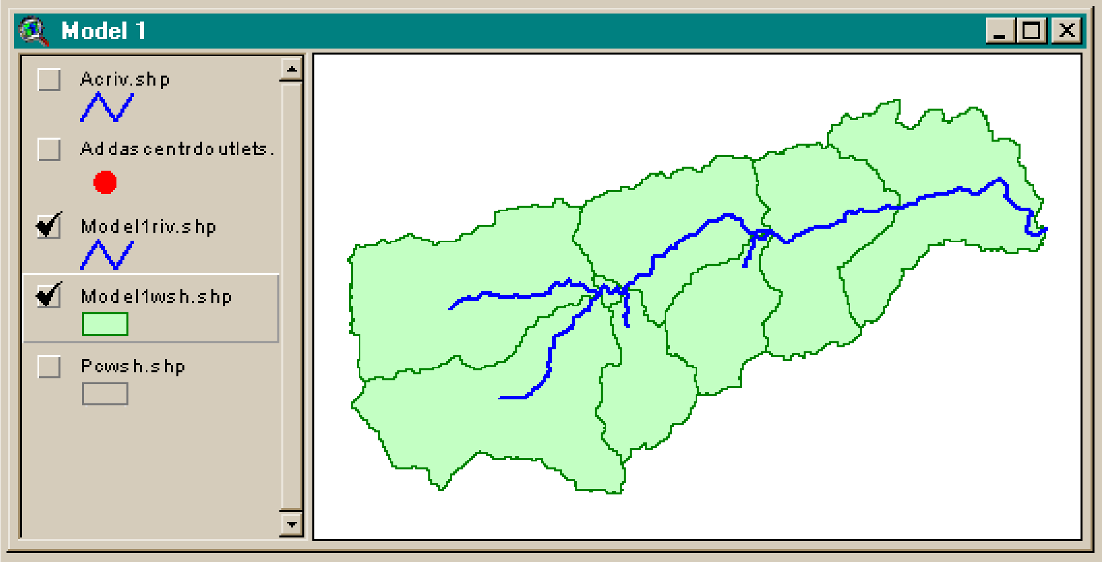


Figure 4: Left*: Curve number grid generated with the Flood Flow Calculator.*
Right*: Flow time to the watershed outlet grid generated with the Flood Flow Calculator.*

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.


Model 1

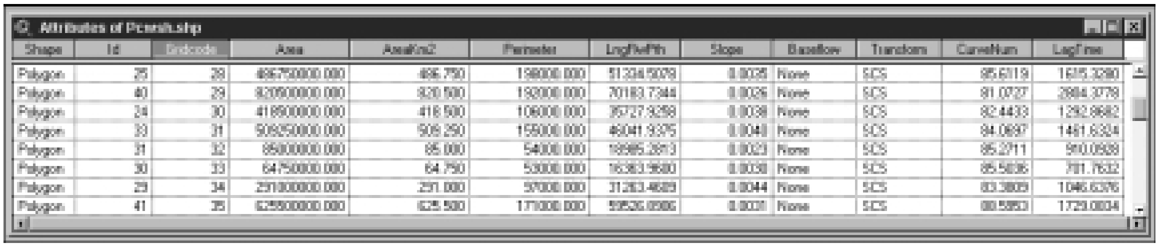
☐ Acriv.shp

☐ Addascentrdoutlets.

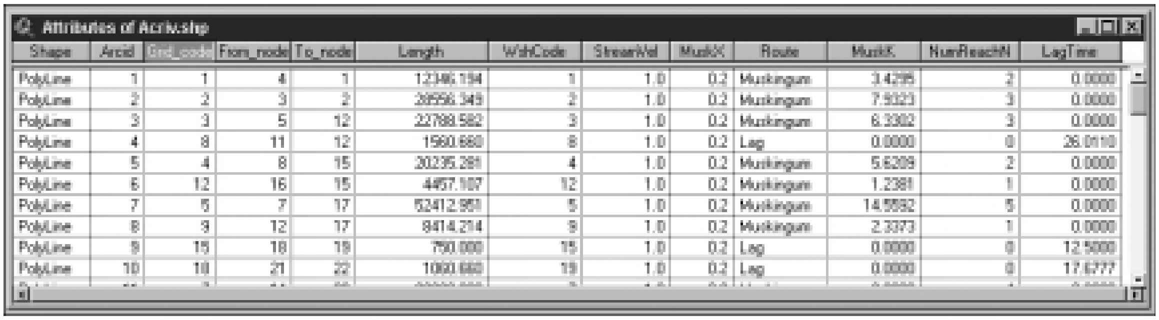
☑ Model1riv.shp

☑ Model1wsh.shp

☐ Pcwsh.shp

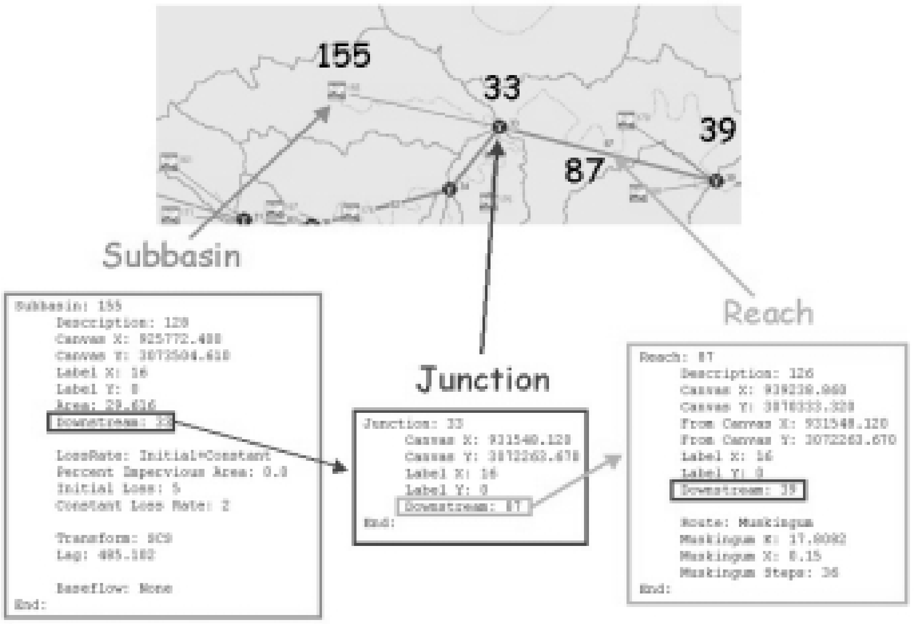

Attributes of Pcwsh.shp

Shape	Id	Gridcode	Area	AreaKm2	Perimeter	LngFlwPth	Slope	Baseflow	Transform	CurveNum	LagTime
Polygon	25	28	486750000.000	486.750	198000.000	51334.5078	0.0025	None	SCS	85.6119	1615.3280
Polygon	40	29	820500000.000	820.500	192000.000	70183.7344	0.0026	None	SCS	81.0727	2884.3778
Polygon	24	30	418900000.000	418.500	106000.000	35727.9258	0.0038	None	SCS	82.4433	1292.8682
Polygon	33	31	909250000.000	909.250	159000.000	46041.9375	0.0040	None	SCS	84.0897	1461.6324
Polygon	31	32	85000000.000	85.000	54000.000	19985.2813	0.0023	None	SCS	85.2711	910.0938
Polygon	30	33	64750000.000	64.750	53000.000	16383.9600	0.0030	None	SCS	85.5036	701.7632
Polygon	23	34	231000000.000	231.000	57000.000	31283.4609	0.0044	None	SCS	83.3809	1046.6376
Polygon	41	35	625500000.000	625.500	171000.000	59526.0586	0.0021	None	SCS	80.5953	1729.0004


Attributes of Acriv.shp

Shape	Arcid	Grid_code	From_node	To_node	Length	WshCode	StreamVel	MuskX	Route	MuskK	NumReachN	LagTime
PolyLine	1	1	4	1	12346.194	1	1.0	0.2	Muskingum	3.4295	2	0.0000
PolyLine	2	2	3	2	28556.349	2	1.0	0.2	Muskingum	7.9323	3	0.0000
PolyLine	3	3	5	12	22788.582	3	1.0	0.2	Muskingum	6.3302	3	0.0000
PolyLine	4	8	11	12	1560.660	8	1.0	0.2	Lag	0.0000	0	26.0110
PolyLine	5	4	8	15	20235.281	4	1.0	0.2	Muskingum	5.6209	2	0.0000
PolyLine	6	12	16	15	4457.107	12	1.0	0.2	Muskingum	1.2381	1	0.0000
PolyLine	7	5	7	17	52412.951	5	1.0	0.2	Muskingum	14.5592	5	0.0000
PolyLine	8	9	12	17	8414.214	9	1.0	0.2	Muskingum	2.3373	1	0.0000
PolyLine	9	15	18	19	750.000	15	1.0	0.2	Lag	0.0000	0	12.5000
PolyLine	10	19	21	22	1060.660	19	1.0	0.2	Lag	0.0000	0	17.6777

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.*

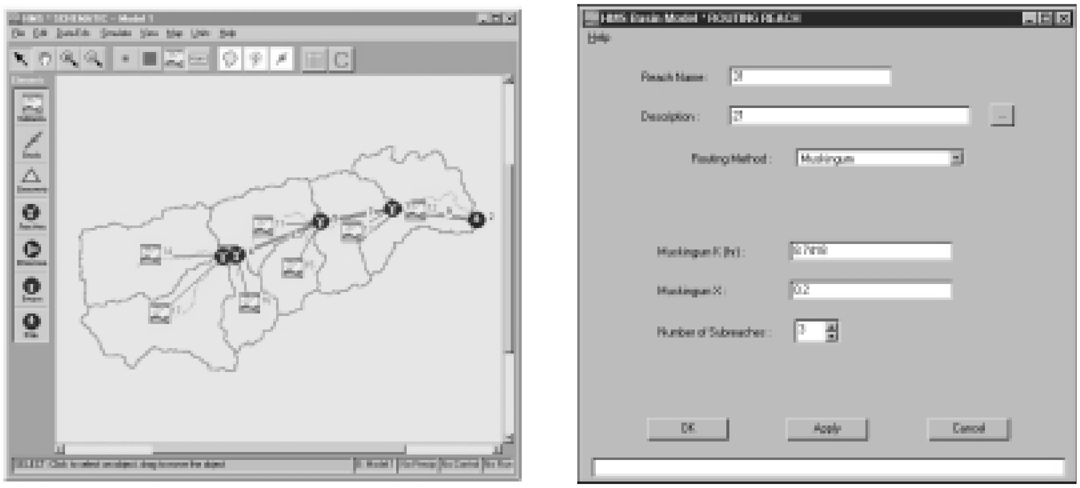


```
Subbasin: 155
     Description: 128
     Canvas X: 925772.488
     Canvas Y: 3073504.610
     Label X: 16
     Label Y: 0
     Area: 29.616
     Downstream: 33

     LossRate: Initial+Constant
     Percent Impervious Area: 0.0
     Initial Loss: 5
     Constant Loss Rate: 2

     Transform: SCS
     Lag: 485.182

     Baseflow: None
End:
```

```
Junction: 33
     Canvas X: 931548.120
     Canvas Y: 3072263.670
     Label X: 16
     Label Y: 0
     Downstream: 87
End:
```

```
Reach: 87
     Description: 126
     Canvas X: 939238.060
     Canvas Y: 3070333.320
     From Canvas X: 931548.120
     From Canvas Y: 3072263.670
     Label X: 16
     Label Y: 0
     Downstream: 39

     Route: Muskingum
     Muskingum K: 17.8082
     Muskingum X: 0.15
     Muskingum Steps: 36
End:
```

Figure 6: Connection between the text file prepared by CRWR-PrePro (based on the GIS data) and the basin schematic in HEC-HMS.



Reach Name :

Description :

Routing Method : Muskingum

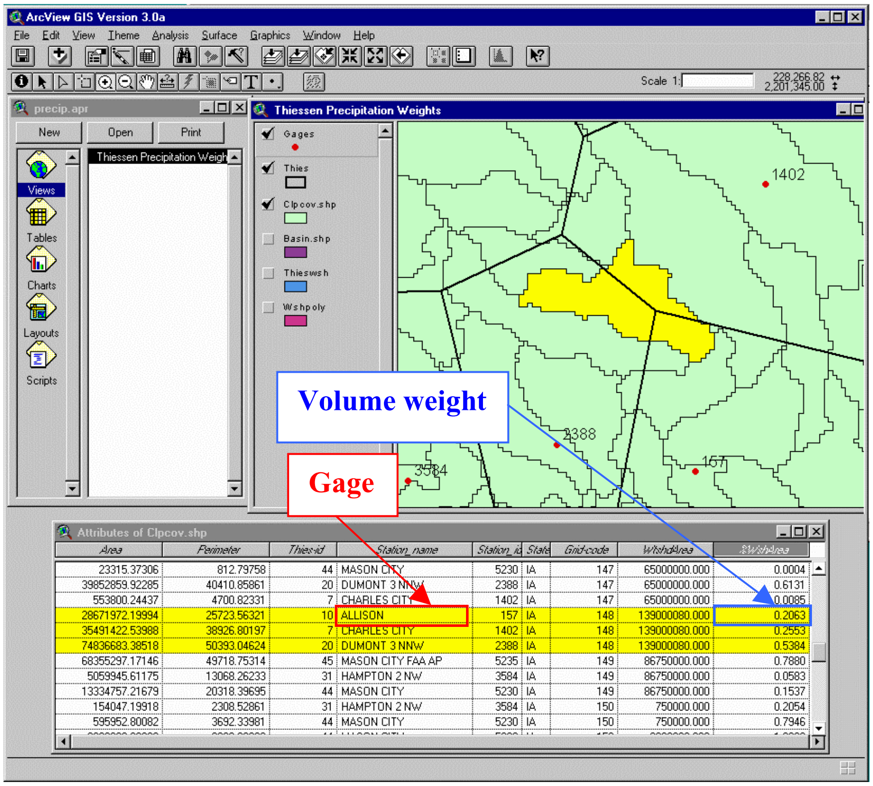
Muskingum K (hr) :

Muskingum X : 0.2

Number of Subreaches : 3

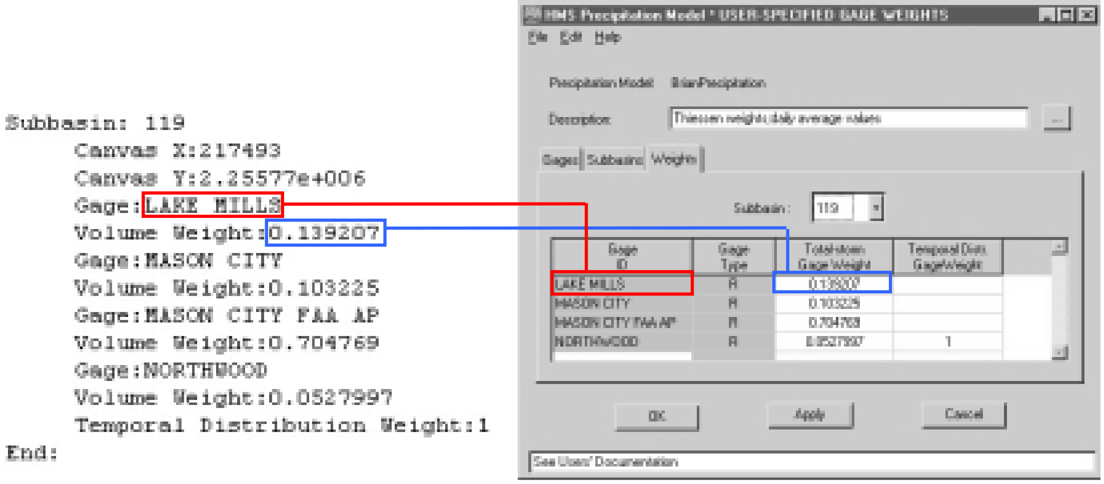
Figure 7: Left*: Basin schematic in HMS.* Right*: Reach attributes in HMS, after being calculated in GIS and transferred to HMS.*

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.



Area	Perimeter	Thies-id	Station_name	Station_id	State	Grid-code	WshdArea	%WshdArea
23315.37306	812.79758	44	MASON CITY	5230	IA	147	65000000.000	0.0004
39852859.92285	40410.85861	20	DUMONT 3 NNW	2388	IA	147	65000000.000	0.6131
553800.24437	4700.82331	7	CHARLES CITY	1402	IA	147	65000000.000	0.0085
28671972.19994	25723.56321	10	ALLISON	157	IA	148	139000080.000	0.2063
35491422.53988	38926.80197	7	CHARLES CITY	1402	IA	148	139000080.000	0.2553
74836683.38518	50393.04624	20	DUMONT 3 NNW	2388	IA	148	139000080.000	0.5384
68355297.17146	49718.75314	45	MASON CITY FAA AP	5235	IA	149	86750000.000	0.7880
5059945.61175	13068.26233	31	HAMPTON 2 NW	3584	IA	149	86750000.000	0.0583
13334757.21679	20318.39695	44	MASON CITY	5230	IA	149	86750000.000	0.1537
154047.19918	2308.52861	31	HAMPTON 2 NW	3584	IA	150	750000.000	0.2054
595952.80082	3692.33981	44	MASON CITY	5230	IA	150	750000.000	0.7946

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.



```
Subbasin: 119
     Canvas X:217493
     Canvas Y:2.25577e+006
     Gage:LAKE MILLS
     Volume Weight:0.139207
     Gage:MASON CITY
     Volume Weight:0.103225
     Gage:MASON CITY FAA AP
     Volume Weight:0.704769
     Gage:NORTHWOOD
     Volume Weight:0.0527997
     Temporal Distribution Weight:1
End:
```

HMS Precipitation Model * USER-SPECIFIED GAGE WEIGHTS

Precipitation Model: BrianPrecipitation

Description: Thiessen weights; daily average values

Subbasin: 119

Gage ID	Gage Type	Total-storm Gage Weight	Temporal Dist. Gage Weight
LAKE MILLS	R	0.139207	
MASON CITY	R	0.103225	
MASON CITY FAA AP	R	0.704769	
NORTHWOOD	R	0.0527997	1

See Users' Documentation

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.

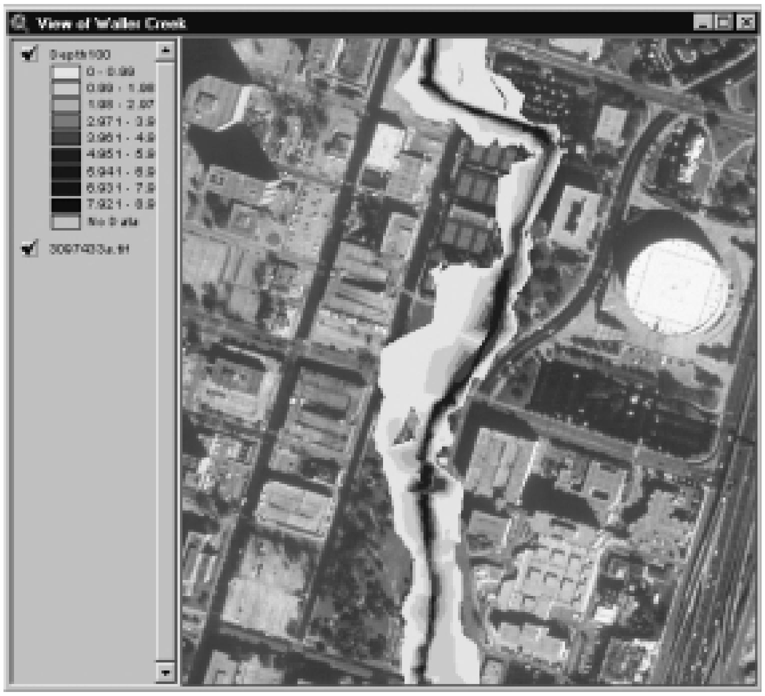


Figure 10: Floodplain (in blue) overlaid on the digital orthophoto of downtown Austin, Texas. Dark blue corresponds to deep areas.

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.

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