A FLASH FLOOD PREDICTION MODEL FOR RURAL AND URBAN BASINS IN NEW MEXICO

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ABSTRACT

High intensity short duration (HISD) rainfall events cause extreme flash flood conditions throughout the state of New Mexico resulting in loss of life, property damage, and expensive emergency response. This research describes a distributed hydrological modeling system that estimates discharge from a watershed during HISD rainfall events. The modeling system calculates excess precipitation on impervious and pervious surfaces within the watershed and uses a modified kinematic wave approach to calculate overland flow rates. These overland flow rates are used to calculate travel times from the raster grid cells within the basin to the basin outlet. The model sums excess precipitation based on travel time to the basin outlet through an iterative process to calculate basin discharge. Although improvements are needed for the modeling system, it provides a substantial first step and framework from which to build an effective flash flood prediction tool.

Keywords: flash flooding, high intensity short duration precipitation, distributed GIS hydrological modeling, runoff

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INTRODUCTION

Problem Statement

High intensity short duration (HISD) rainfall events cause extreme flash flood conditions throughout the state of New Mexico resulting in loss of life, property damage, and expensive emergency response. It is not possible, given present forecasting methods, to issue flash flood warnings with sufficient lead time to avoid these tragic and costly outcomes. The reasons for this are numerous, but two of the most important are:

1) It is difficult to generate spatially explicit quantitative precipitation forecasts (QPFs) for HISD events.
2) The lumped hydrologic models[α] that have been used to predict flash floods are not spatially distributed models and thus generate biased estimates of runoff.

To improve the issuance of flash flood warnings and thus reduce the impact of such events, an approach to surface runoff modeling is needed to alleviate the above limitations. The system must be able to predict flash flood events with enough advance notice to evacuate vulnerable areas thereby reducing loss of life, property damage, and the need for emergency response. It is clear that there are other mechanisms in the emergency notification and response system necessary for a significant reduction in the impact of flash flood events, but prediction of the event is a crucial first link in that chain.

[α] Lumped hydrological models do not account for spatial variations in processes, input, boundary conditions, and watershed characteristics. Lumped models require only the assignment of single-valued parameters for the entire watershed. See Singh (1995) for a full discussion of lumped versus spatially distributed models.

Recent Approaches

Much of the prior flood modeling work has linked rainfall data with lumped parameter models. In this approach, hourly or daily rainfall data are averaged over a watershed of interest and excess precipitation is computed by the model (Cunge et al., 1992; Georgakakos 1989; Moore et al., 1990). Lumped parameter models do not account for the spatial variation of parameters within a watershed. Instead, watershed characteristics, such as soils, land cover, topography, and precipitation, are lumped together and spatial averages are computed for each model parameter (Beven 1985). Woodward (1995) described a flood forecast system that links a real-time rainfall database with the HEC-1 runoff model (Hydrologic Engineering Center 1981) to predict peak discharges and the time to the peaks. One severe limitation of this approach, and of lumped models in general, is that precipitation is assumed to be homogenous over the basin for the duration of the time step or for the entire rainfall event. Woodward (1995) found that an uneven distribution of rainfall produced skewed runoff results, thereby introducing error into the flood prediction.

In contrast to lumped models, distributed parameter models attempt to account for the spatial variability of basin parameters, as well as their hydrologic behavior, by discretizing the basin into many small, equally sized grid cells (Muzik 1996). Runoff is computed for each cell and then routed sequentially through the basin to its outlet. Derivation of the required watershed parameters necessary for computer simulation has been greatly aided by the use of geographical information systems (GIS) (Eash 1993; Martz and Garbrecht 1993; Cahill et al., 1993). A review of the use of GIS coupled with lumped and distributed parameter models for flood prediction is presented by Muzik (1996). Additionally, GIS has been used to aid in the parameterization of urban basins (Smith and Brilly 1992; Greene and Cruise 1996) and in the characterization of urban stormwater runoff in distributed models (Smith 1993).

Recently, the National Weather Service has employed its next-generation weather radar (NEXRAD) capable of producing relatively high spatial and temporal resolution precipitation data. This technology provides better precipitation estimates, which in turn, will enhance runoff prediction, particularly in areas where localized storm events are not captured by the existing rain gauge network (Shedd and Fulton 1993). Young and others (1998) presented an automated system for processing NEXRAD Stage III precipitation data for display and analysis within a GIS. Their system provided maps and contour rainfall estimates for hourly and daily precipitation. However, these data were not applied to a rainfall-runoff model. The coupling of high-resolution weather radar with a distributed rainfall-runoff model has the potential to improve rainfall-runoff modeling, thus improving flash flood prediction.

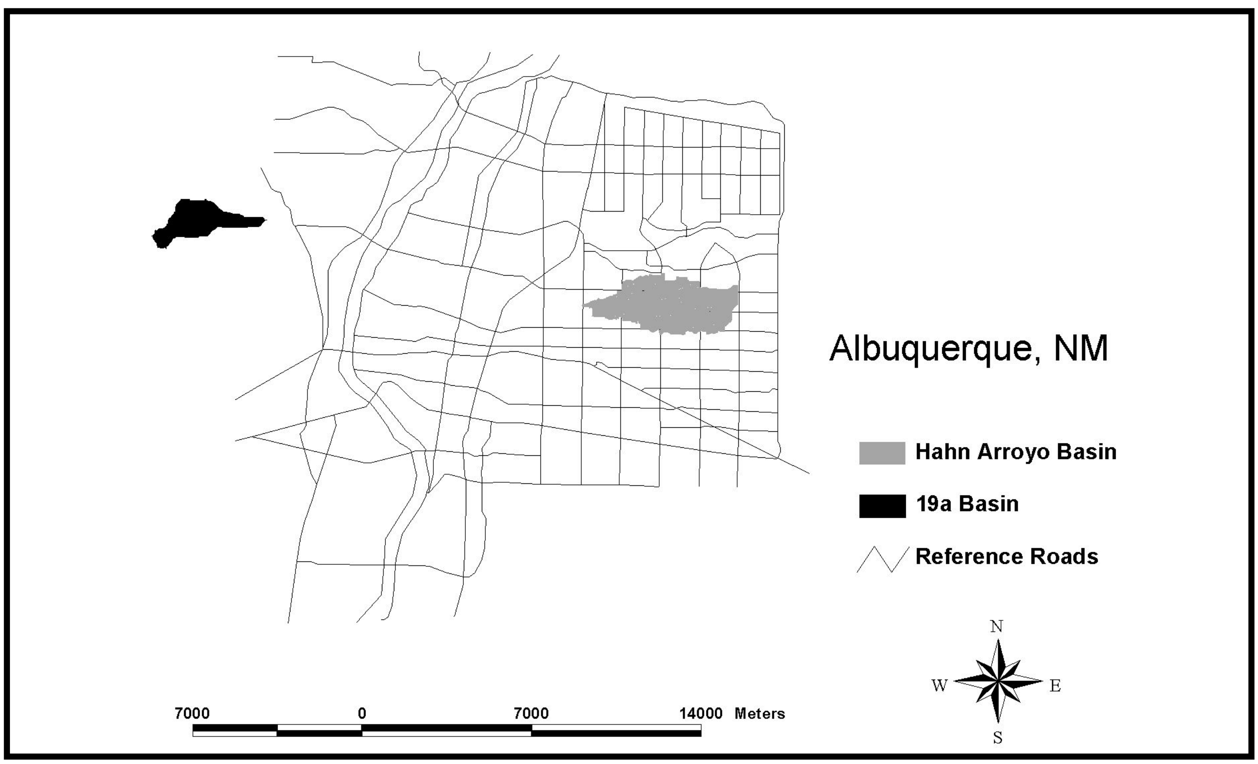
Scope of Research

In this research, we developed a spatially distributed hydrological model that can be used in either rural or urban watersheds to estimate discharge and flash floods accordingly. This research addresses the second issue described in the Problem Statement section above. Since the model operates within a spatially distributed framework, it circumvents problems inherent to lumped hydrological modeling. One of the criticisms of distributed modeling is the computational expense associated with modeling watersheds of even only moderate size. We discuss this issue in a separate section later in the report.

As mentioned earlier, the need for spatially explicit QPFs for HISD rainfall events is also an important factor in the successful prediction of flash flooding events. It is beyond the scope of the present research to deal with this issue. However, we discuss potential approaches to this aspect of the problem in the final section of this report.

This research focuses on an urban watershed in Albuquerque, NM, the Hahn Arroyo drainage basin (see Figure 1). We have also identified a rural basin on the west side of Albuquerque where discharge and precipitation data exist (see Figure 1). However, this basin, Arroyo 19A, has only two events over the past ten years that have generated measurable discharge. Other rural basins in the area have significant data shortcomings. As a result, we have not yet tested the model on a rural basin in New Mexico. In spite of this, we have been careful throughout the model building process to create a working model that can be parameterized to simulate either an urban or a rural watershed. We discuss this and other issues related to the scope of the research in the Conclusions and Future Directions section of this report.

Figure 1: Study Area Including Hahn Arroyo and Arroyo 19A Basins



DATA AND METHODS

Modeling System

The concept of a distributed unit hydrograph was proposed by Maidment (1993) and is based on the fact that the unit hydrograph ordinate at time *t* is given by the slope of the watershed time-area diagram over the interval [t-Δt, t]. The time-area diagram is a graph of cumulative drainage area contributing to discharge at the watershed outlet within a specified time of travel [δ]. Determination of the time-area diagram for the watershed was facilitated by a GIS. The GIS was used to describe the connectivity of the cells in the watershed flow network and to sum travel times to the watershed outlet for all locations within the watershed.

The process begins with the surface type present within each cell. In an urban setting there are, broadly speaking, pervious and impervious surfaces. Clearly there are hydrologic differences between the various land cover types *within* the categorization pervious vs. impervious. However, in terms of the first step in this model, calculating excess precipitation, the process is first-order separable into pervious and impervious surfaces.

For impervious surfaces, excess precipitation is rainfall depth greater than depression storage (d_s). Depression storage is a value that is land cover/land use dependent and represents the total amount of water that can be stored in small surface depressions in a cell. The model

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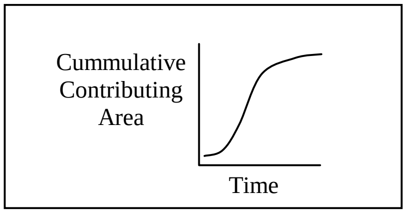
[δ] The time-area diagram for a typical watershed would be a positively increasing sigmoidal function such as the following:



accumulates precipitation up to the depth of storage assigned to each land use class (see Table 1). After the depression storage amount is met, runoff within a cell begins. The runoff amount is computed based on conservation of mass principles (continuity).

Table 1: Model Parameters by Land Cover

Land Cover	Cells	Percent of Basin Area	CN**	Depression Storage *
Road & Other Transportation	25,809	24.2%	98	0.098
Drainage (barren or surfaced)	1,713	1.6%	94	0.098
Chapparal	7	0.007%	63	0.25
Desert Grassland	133	0.1%	62	0.25
Sparse Grassland	706	0.7%	74	0.25
Residential Vegetation	20,373	19.1%	77	0.295
Irrigated Public Grounds	2,035	1.9%	62	0.295
Urban Development	11,574	10.9%	88	0.030
Residential Development	39,433	37.0%	84	0.047
Irrigated Agriculture	134	0.1%	83	0.394

* Depression storage values from Sheaffer et al., (1982).
** All soils in the Hahn Basin are codes EmB, Etc, WeB, or TgB. All are sandy loams and have a hydrologic soils classification of "B".

For pervious surfaces, excess precipitation is rainfall depth greater than infiltration *and* depression storage for a given cell for a given time interval. Infiltration losses and depression storage can be combined and may therefore be computed with the Soil Conservation Service (SCS – now the NRCS) curve number technique for unsteady rainfall (SCS 1985). In this method, runoff volume is given by a set of empirical relationships:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

where:

Q = the accumulated runoff volume or rainfall excess

P = the accumulated precipitation

S = a maximum soil water retention parameter given by:

$$S = \frac{1000}{CN} - 10 \tag{2}$$

where *CN* is known as the curve number. The curve number indicates the runoff potential of an area for the combination of land cover/land use characteristics *and* hydrologic soil groups. The SCS has classified more than 4,000 soils into four (4) hydrologic soil groups according to their minimum infiltration rate for bare soil after prolonged wetting. CNs differ within a land cover/land use class based on the hydrologic soil group of the underlying soil.

Equation [1] above indicates that P must exceed $0.2S$ before any runoff is generated. Consequently, a rainfall volume of $0.2S$ must fall before runoff is initiated. The model accumulates rainfall until the soil water retention is exceeded on a cell by cell basis. As with impervious surfaces, the runoff amount generated thereafter is governed by continuity conditions.

After excess precipitation is calculated for each pervious and impervious cell within the watershed, a modified kinematic wave approach (Chow et al., 1988) was used to compute overland flow rates for each cell. A kinematic wave is a wave caused by an accumulation of water due to lateral inflows. On a hillslope lateral inflow is the excess precipitation (i_e) which accumulates downslope. Overland flow per unit width (q_o) is given by the continuity equation:

$$q_o = VY = i_e L_o \cos\theta \qquad [3]$$

where:

L_o = length of overland flow

V = average velocity and is measured parallel to the surface

Y = average depth perpendicular to the surface.

Equations for laminar flow slightly underestimate flow depth since raindrop impacts increase the frictional resistance that in turn reduces water velocity (Chow et al., 1988). Thus, it was assumed that the equation for turbulent flow gives a better estimate of flow depth and therefore flow velocity. Assuming uniform turbulent flow, average velocity within a cell is computed using Manning's equation (Chow et al., 1988):

$$\overline{V} = \frac{uS^{0.5}\overline{Y}^{0.667}}{n} \qquad [4]$$

where:

n = Manning's roughness coefficient for overland flow

u = a constant = 1.49

S = slope

To use the equation above, the depth of flow must be known. Depth can be determined by combining the continuity equation for flow per unit width (equation [1]) with Manning's equation for turbulent flow (equation [2]) that yields:

$$Y = \left(\frac{(i - f) L_o Cos\theta n}{u S^{0.5}} \right)^{0.6} \quad [5]$$

For overland flow, travel time within the cell is computed as the time to steady flow(t_c) for overland flow given by the kinematic wave equation (Chow et al., 1988):

$$t_c = \frac{L^{0.6} n^{0.6}}{i^{0.4} S^{0.3}} \quad [6]$$

where

L = length of overland flow

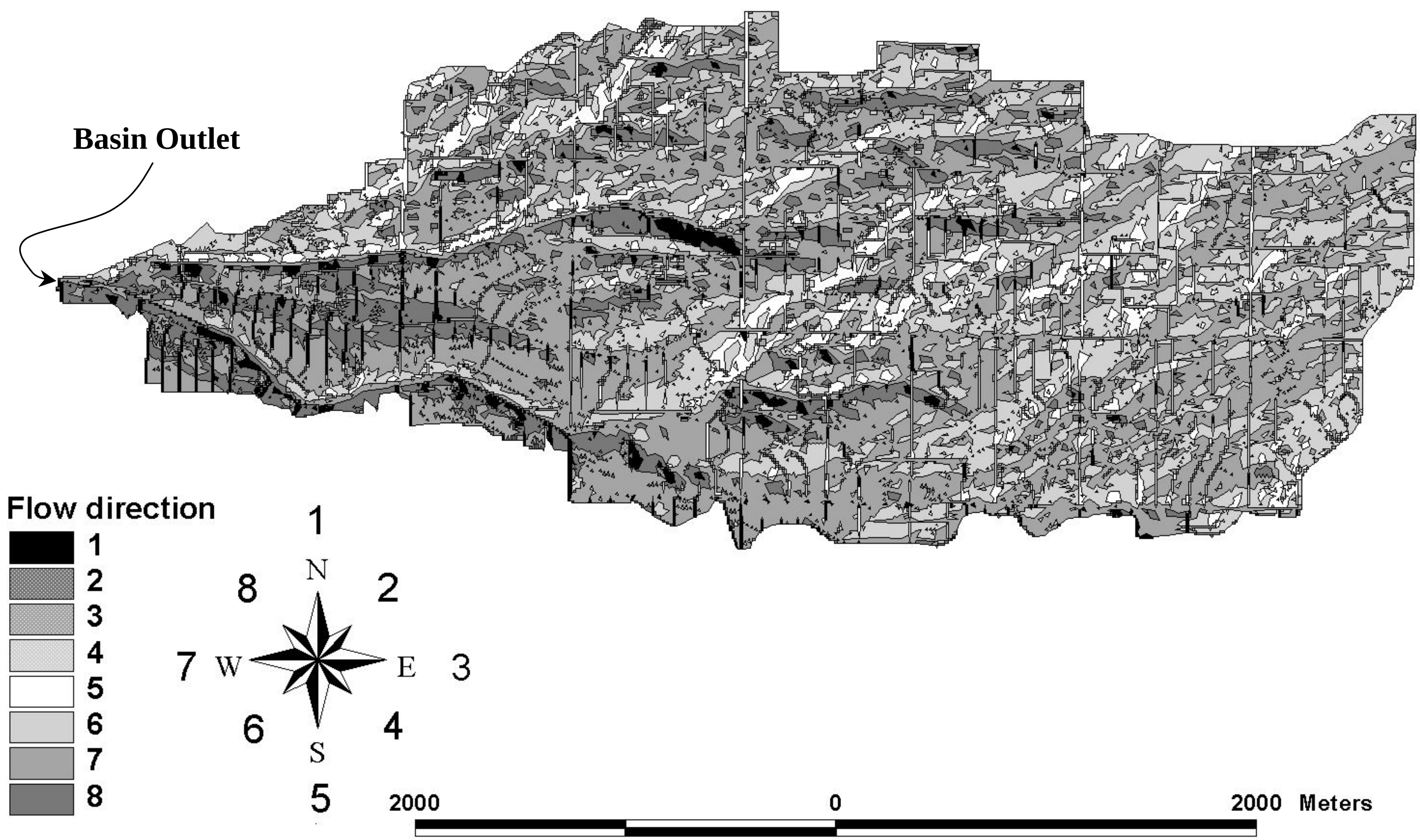
n = Manning's roughness coefficient for overland flow

i = excess precipitation

S = slope of the cell

Given this time of travel for each cell and the path water takes from each cell to the outlet of the basin, an overall time of travel to the outlet is calculated. The Arc/Info grid command `flowlength` is used to generate travel times from each cell to the gage location on the outlet of the Hahn basin. This `flowlength` command is weighted by the direction of flow within the basin that includes information about the slope of each cell and the modification of the direction of flow caused by the street network (see Figure 2). The process used to assess flow direction is described in the next section.

Figure 2: Flow Direction of the Hahn Arroyo Drainage Basin



Given these times of travel from each cell to the basin outlet *and* the runoff generated at each cell, one can sum the runoff from all cells with travel times of X minutes[Ω] to determine what the discharge will be at the outlet X minutes from now. The cells with travel times of Y > X minutes will constitute the discharge Y minutes from now, and so on. This process assumes that no water is lost either in storage or evaporation along its path to the outlet.

The model, in an iterative fashion (at a temporal resolution of five (5) minutes based on the availability of both precipitation and discharge data) sums and stores total runoff amounts (RO_{lag}) from cells with travel times at a range of 84 seconds around 5, 10, 15, …, n*5 minutes. n is basin and rainfall intensity specific and is determined separately for each time interval. In the first time step (t=0; and before precipitation starts in the basin), the discharge is zero and the runoff amounts are calculated and stored. In the second time step, discharge is equal to the 5 minute travel time runoff ($RO_{5min,1st\ period}$) from the first period and another set of runoff amounts are calculated and stored. In the third time step, discharge is equal to the first period 10 minute travel time runoff ($RO_{10min,1st\ period}$) plus the second period 5 minute travel time runoff ($RO_{5min,2nd\ period}$). This iterative process continues until discharge ceases.

Data Preparation

Several datasets were compiled for this research. All data were catalogued and processed in a GIS to insure data integrity and georeferencing of the necessary information. In this section we discuss the acquisition and preparation of the necessary data inputs to the model including: land

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[Ω] In practice, given that the travel times are real valued, a range around X minutes is used. In theory, since the discharge measurements are instantaneous measurments of flow, this range would be quite small. It is largely an empirical issue for our purposes in this research.

cover information, soil characteristics, elevation and slope information, natural and human made conveyances within the watershed, and precipitation information.

Land Cover

The land cover information for the Albuquerque, NM area was generated using a new expert classification routine available in the ERDAS Imagine image processing software. This expert classification technique made use of several data inputs both in raster and vector format to generate a 10-meter land cover classification for the entire Albuquerque, NM vicinity. The inputs to the expert classifier were:

1) two inputs derived directly from a Landsat 7 ETM+ image
    a) Normalized Difference Vegetation Index, and
    b) a supervised Maximum Likelihood classification of the image,
2) texture information derived from a USGS Digital Orthophoto Quarter Quad (DOQQ),
3) elevation information from the USGS 10-meter Digital Elevation Model (DEM),
4) an independently produced vegetation classification[Ψ], and
5) three additional vector data sources:
    a) street network for the Albuquerque area,
    b) a land use/land cover dataset, and
    c) a stream network available from the USGS.

These input data were used in the ERDAS Imagine with a set of detailed expert classification rules to derive the land cover of the Albuquerque area (see Figure 3). Given this land cover

[Ψ] This vegetation classification was completed in 1997 by the Earth Data Analysis Center at UNM. The 15-meter supervised classification made use of Landsat TM and IRS remotely sensed data.

information, essential model parameters were set for the different land covers within the Hahn basin as detailed in Table 1 above.

Soil Characteristics

Vector soil maps based on the SCS soil survey were obtained from Bernalillo County to characterize the underlying soil structure within the Hahn basin (Bernalillo 1978). Although the data were available in electronic format, attribute information needed to be added to describe the soil characteristics. It was found that the soils underlying the Hahn basin were either: EmB, Etc, WeB, or TgB types. All of these are sandy loams and have a hydrologic soils classification of "B" under the SCS approach.

Elevation and Slope Information

A 10-meter DEM was assembled for the Albuquerque, NM area, which was used in a number of areas of the project including a significant source of input data to the model. In addition to the fact that the DEM served as the basis for the delineation of the Hahn basin, it is also used to calculate the slope (see Figure 4) and aspect of cells within the basin. The aspect serves as a significant input to the procedure of determining the hydrologic connectivity within the basin. Slope is used in several of the fundamental equations that form the foundation of the model as described in the Modeling System section above.

In a natural drainage basin with very little or no human interaction, aspect information derived from a DEM alone is a very good indication of flow direction. This is especially true with a high resolution DEM like the one used in this research. However, in modified terrain, such as an urban watershed, barriers too small to be represented in the DEM govern surface flow much more strongly than derived aspect. In our case, the streets within the Hahn basin are the

Figure 3: Land Cover Within the Hahn Arroyo Drainage Basin

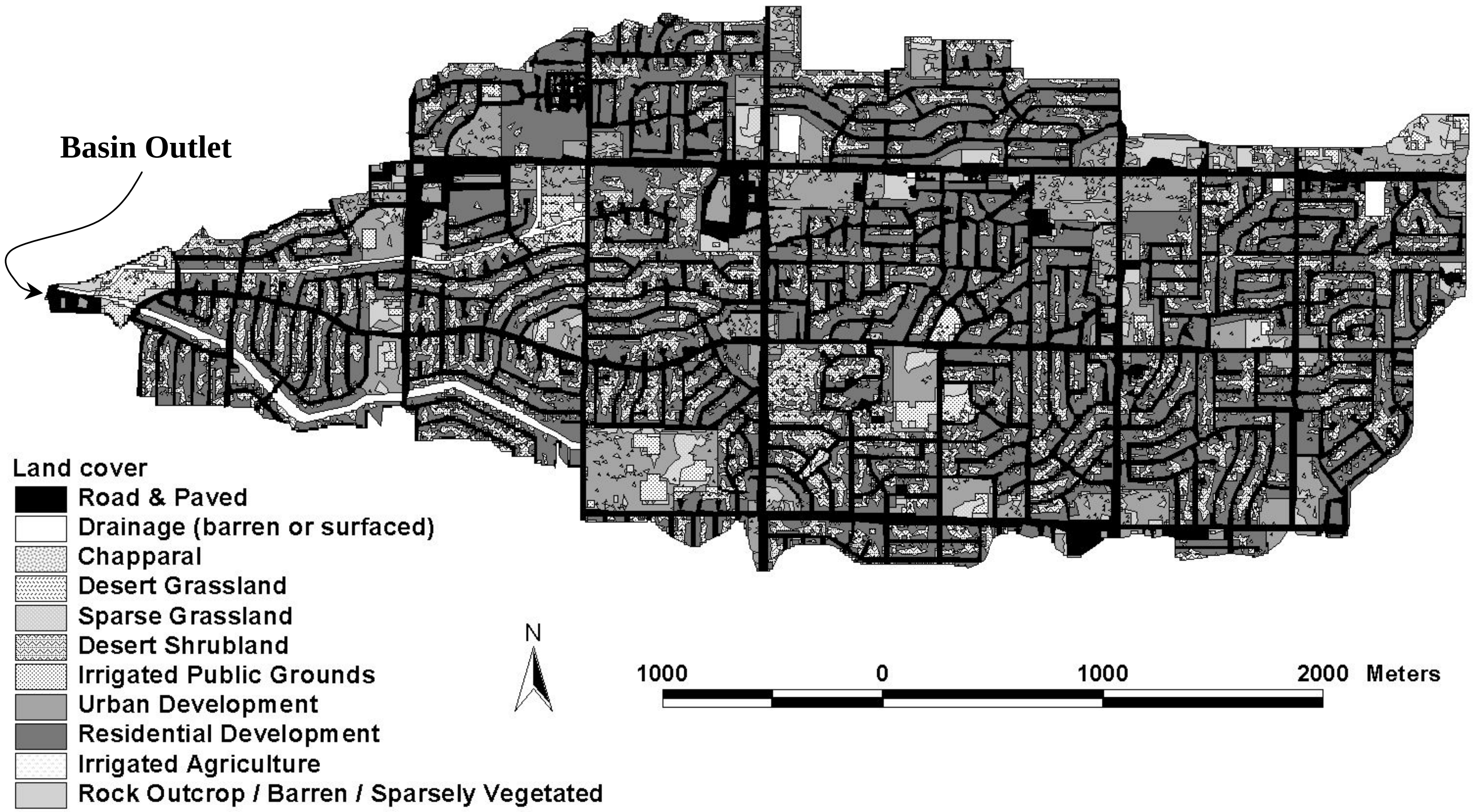
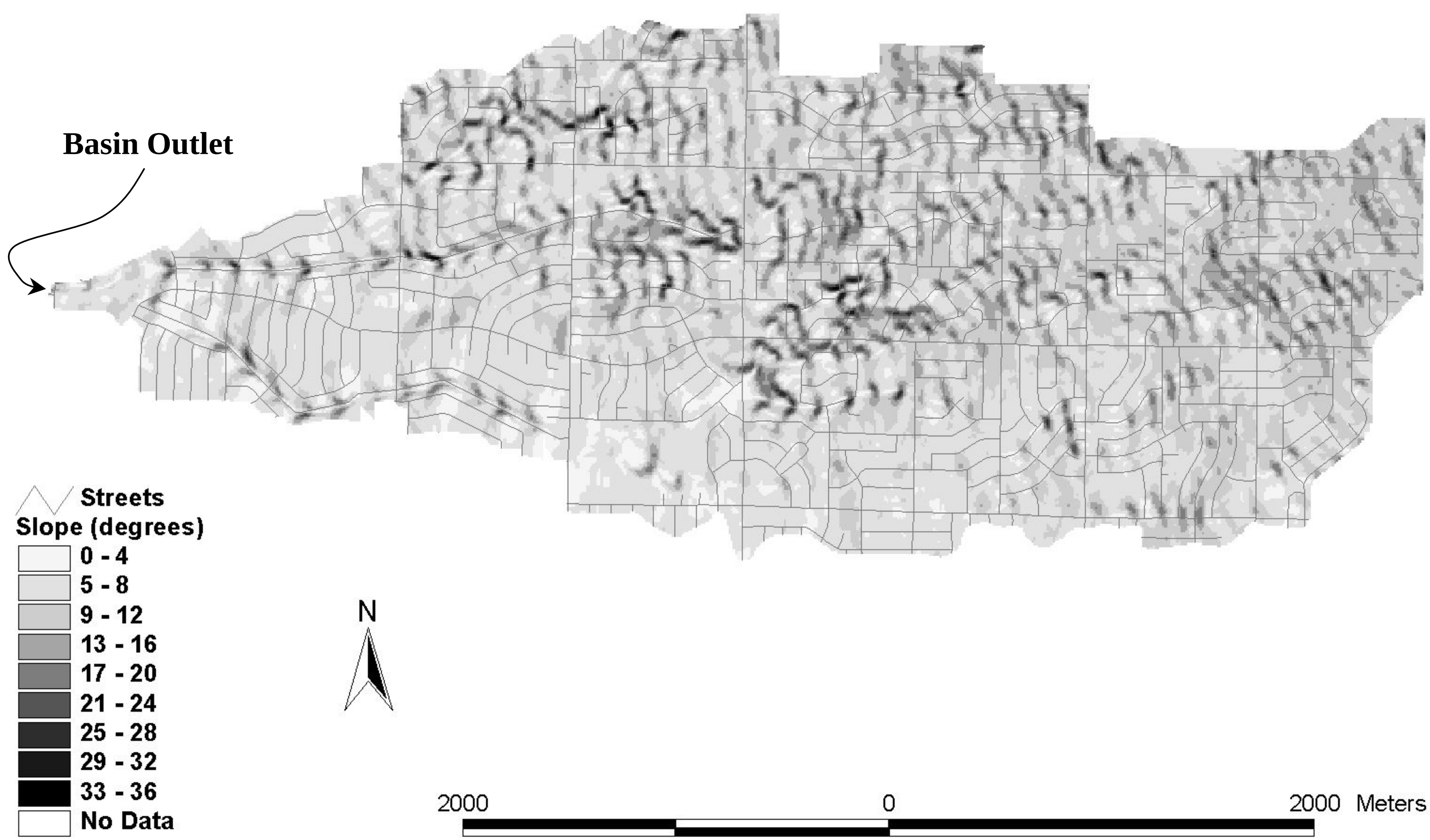


Figure 4: Slope Within the Hahn Arroyo Drainage Basin



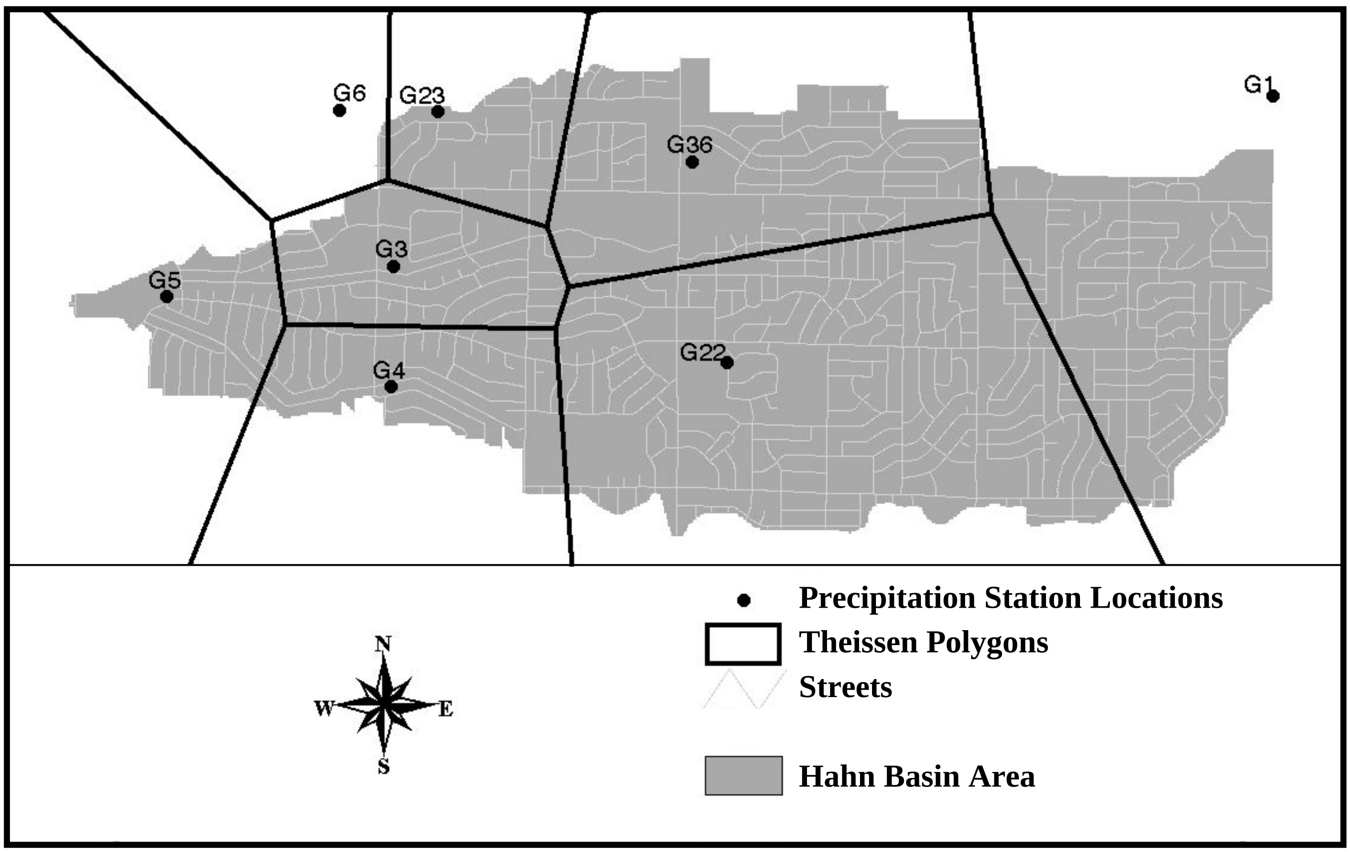
foremost barriers of this type to be considered. To alleviate this problem, we used the street network coverage along with detailed information from the City of Albuquerque (Zamora 1999) to identify the flow direction of each street in the basin. This information was then used to alter the flow direction map derived from aspect alone. The street network was overlain on a flow direction grid (derived from the 10-meter DEM). A visual inspection was performed to make sure the flow directions corresponded to the street network, since the streets serve as the major drainage conduits in the basin. Flow direction cells that did not correspond to the street drainage network were edited (flowdir corrected) to correspond to the drainage network.

Figure 2 above shows the final assessment of flow direction within the basin. The shades used in the map are arranged to show the similarity of direction associated with the dissimilar values of 1 and 8. The aspect direction throughout nearly all of the Hahn basin is toward the West as is not surprising given the layout of the basin. This is clear on the map from the high number of cells with 6, 7, or 8 as their flow direction. The alteration associated with the street network is most clearly seen by the North-South orientation within the basin. In most cases, the aspect of these street cells as derived by the DEM would have followed the majority of non-street cells (6, 7, or 8). Instead, it is clear that these street cells are more often than not coded 1 (north) or 5 (south). Once water enters a street cell within the Hahn basin, its normal flow is altered fundamentally by the presence of the barriers. This leads to very different flow directions and ultimately flow paths for water within the basin as will be discussed more fully in the Results section below.

Precipitation

As discussed in the Scope of Research section, a fundamental aspect of the problem of flash flood prediction is an accurate QPF with enough lead time to implement warnings and emergency measures. Since we are not able, within the scope of this research, to generate such forecasts, we take advantage of the fact that there are numerous high temporal resolution recording rain gages operated by the USGS in the area within and nearby the Hahn basin (see Figure 5). These rain gages (see Table 2 for details on each station) have been continuously operating for many years now and are a valuable source of information about precipitation in the area.

Figure 5: USGS Raingages Influencing the Hahn Arroyo Drainage Basin



In this research, we identify the Thiessen polygons derived from these rain gage locations (see "Theissen Polygons" in Figure5) and apply the rainfall amount recorded at each station in each 5-minute period uniformly to those cells within the Thiessen polygon surrounding each station. This method is only one of many different approaches that could be applied to this type of interpolation problem. However, since the Thiessen polygons identify the areas within the region that are closest to each station, they are appropriate for this predictive analysis.

Table 2: Details of USGS Raingages Influencing the Hahn Arroyo Drainage Basin

Station Name	Station Number	Gage Number	Lon(DD)	Lat(DD)
South Fork Hahn	000000008329838	G4	-106.56777778	35.12111111
North Fork Hahn	000000008329839	G3	-106.56777778	35.12694444
Hahn	000000008329840	G5	-106.58111111	35.12527778
Borland	350713106314230	G23	-106.56527778	35.13444444
Leonard	350722106325030	G22	-106.54805556	35.12250000
Thomas Pump	003507551063258	G36	-106.55027778	35.13222222
Firestation 16	350756106305430	G1	-106.51611111	35.13583333
Grant Line	000000008329860	G6	-106.57111111	35.13444444

Computational Resources

Given that flash flood prediction is a time sensitive issue, it is worth noting that the model is designed to run on a conventional Sun Ultra 60 Workstation with 512 MB of physical RAM utilizing the Arc/Info v.7.2.1 software. The model would work just as well under more recent releases of the software and could easily be adapted to run on other platforms (e.g., PC, SGI, DEC). For the model simulations completed on the Hahn basin (166,022 cells at 10m resolution), each 5-minute iteration took only 25 seconds of real time to compute. This is quite promising given the extensive calculations and data handling required to complete the task (see Appendix A for listing of Arc Macro Language (AML) routine and FORTRAN programs used in the project).

RESULTS

Time of Travel

A fundamental result and driving factor of the modeling system created in this research is the time of travel for water in various areas of the basin. Given that there is a degree of spatial heterogeneity to rainfall within the basin and that time of travel is dependent on rainfall intensity, the overall spatial distribution of travel times within the basin can become quite complicated. In the event on August 18, 2000 that was chosen to test the model for this research, the rain was first measured at Grant Line station (G6) in the northwestern tip of the Hahn basin (see Figure 5). For several time periods, no other areas of the basin receive rainfall and so the travel times for all other cells in the basin are irrelevant and therefore not calculated. As the storm progressed to other areas of the basin, many more cells became active and the distribution of travel time and runoff generated both became considerably more complicated.

To get a sense of the travel times across the basin in a situation less dictated by the distribution of rainfall, we modeled a rainfall event of uniform depth across the entire basin and calculated the travel times from each cell (see Figure 6). The travel times for this uniform storm range from 0 to 38 minutes generally increasing from the outlet to the extreme eastern extent of the basin. Given the slope and aspect, as discussed before, this seems reasonable. However, it is quite evident that there are certain areas of the basin that do not adhere to this gradient even in a general sense. The most notable area of this deviation is the lighter area in the south-central portion of the basin. The travel times for the cells in this area are considerably longer than their neighboring counterparts to the north and west. In fact, cells in this region can experience travel times nearly twice as long as cells that are a similar distance from the watershed outlet. This is a result of an elongated flowlength imposed on these cells by the street arrangements in this area. It is important to recognize that these elongated flow lengths are a more accurate representation of reality than flow directions and flow lengths derived from the DEM aspect information alone. It is clear that there are other areas within the watershed where the barriers imposed by the street network affect the travel times as well (see Figure 6).

Simulation Results

The model was used to simulate the runoff generated by a storm that occurred on August 18, 2000 in the Albuquerque area. This storm generated significant discharge from the Hahn basin although it is not the largest discharge event recorded on the Hahn. The precipitation that fell over the basin is characterized by several periods of heavy rain starting shortly after midnight and continuing through the mid-morning hours leading to a break in the storm during the midday and afternoon and recommencing in the late evening hours (see average basin rainfall in Figure 7). This average basin rainfall is an areally weighted average of the eight rainfall amounts during each 5-minute period throughout most of the day. The discharge in the basin peaked at just over 200 cfs in the mid-morning hours (see discharge in Figure 7). One can see quite nicely in Figure 7 the time delay between precipitation and peak discharge in the Hahn basin. The delay seems to be on the order of twenty (20) to twenty-five (25) minutes.

Figure 6: Time of Travel for Uniform Precipitation Over the Hahn Basin

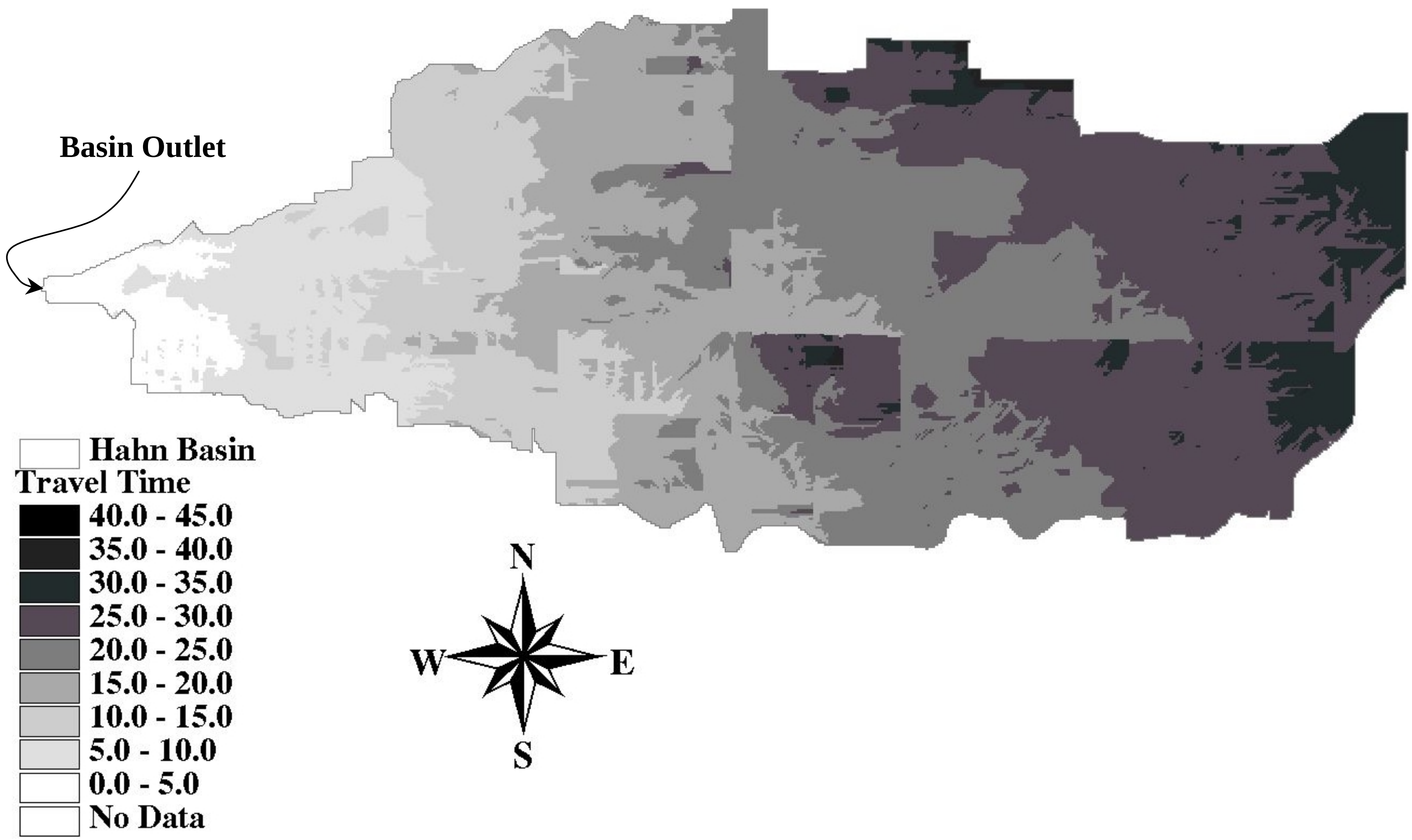


Figure 7: Precipitation and Discharge for August 18th, 2000 Event

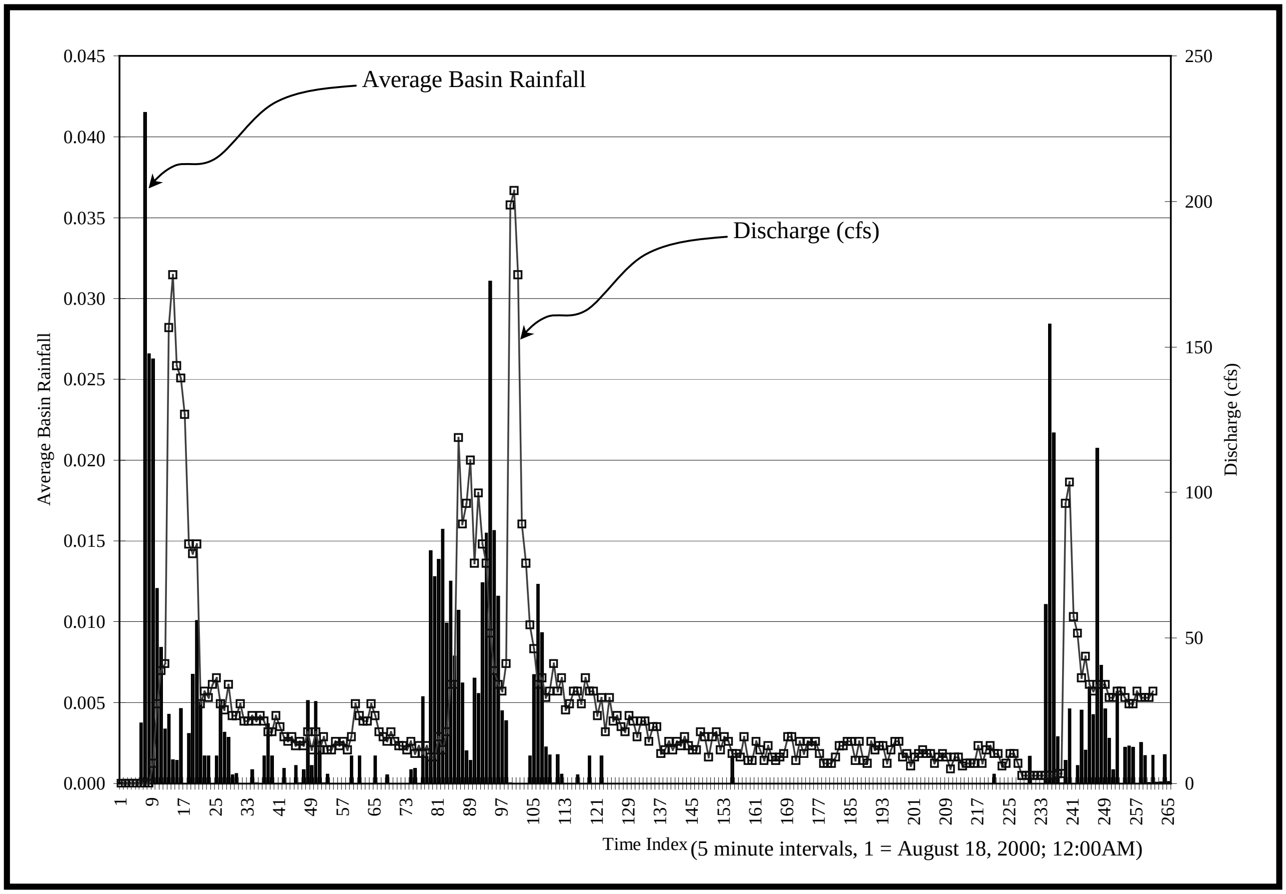
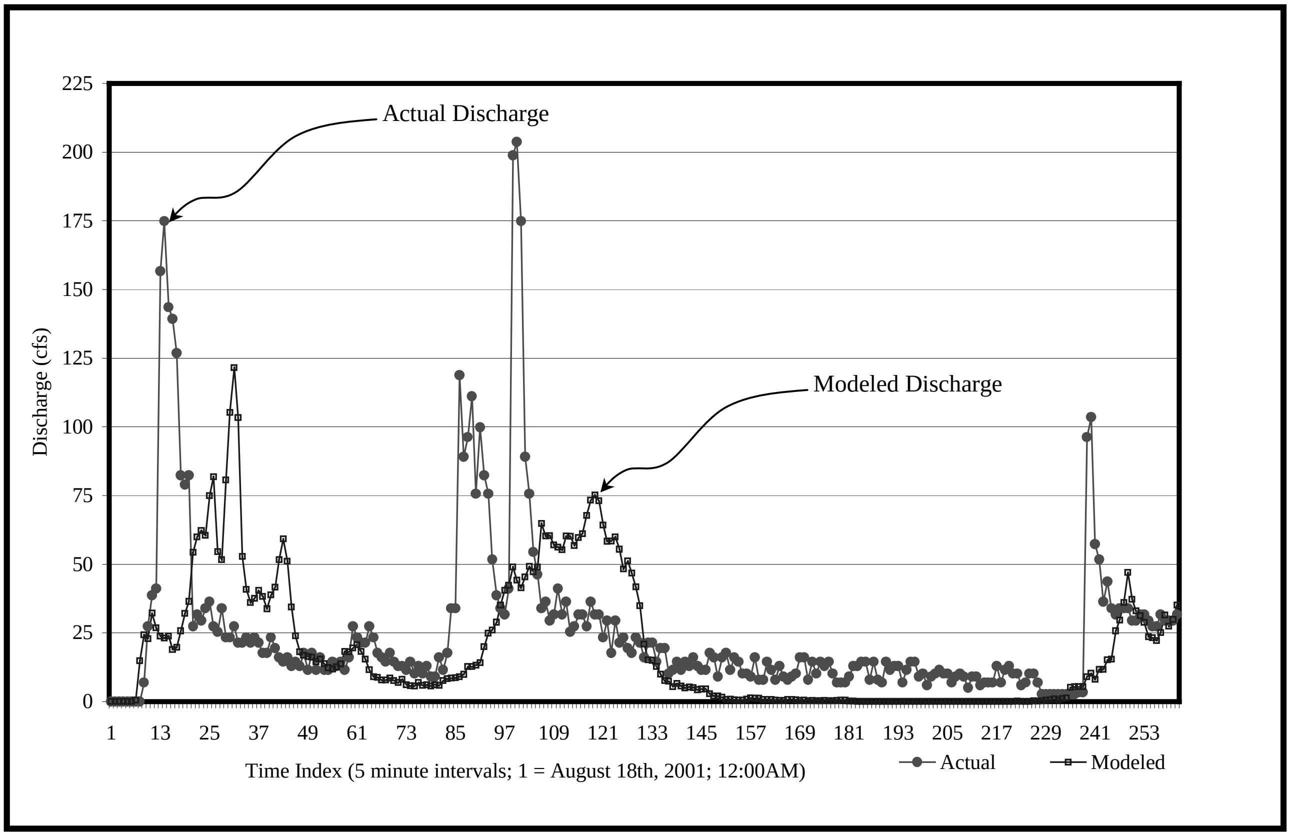


Figure 8 shows the actual discharge and model predicted discharge for this August 18th, 2000 event. Although the model clearly generates discharge estimates on the correct order of magnitude for this event and basin, there are clearly some shortcomings. Two deficiencies are readily apparent from visual inspection. First, the model generates peak discharge that lags the actual peak flow. Secondly, the peak discharge predicted by the model is considerably lower than the actual peak discharge measured on the Hahn basin.

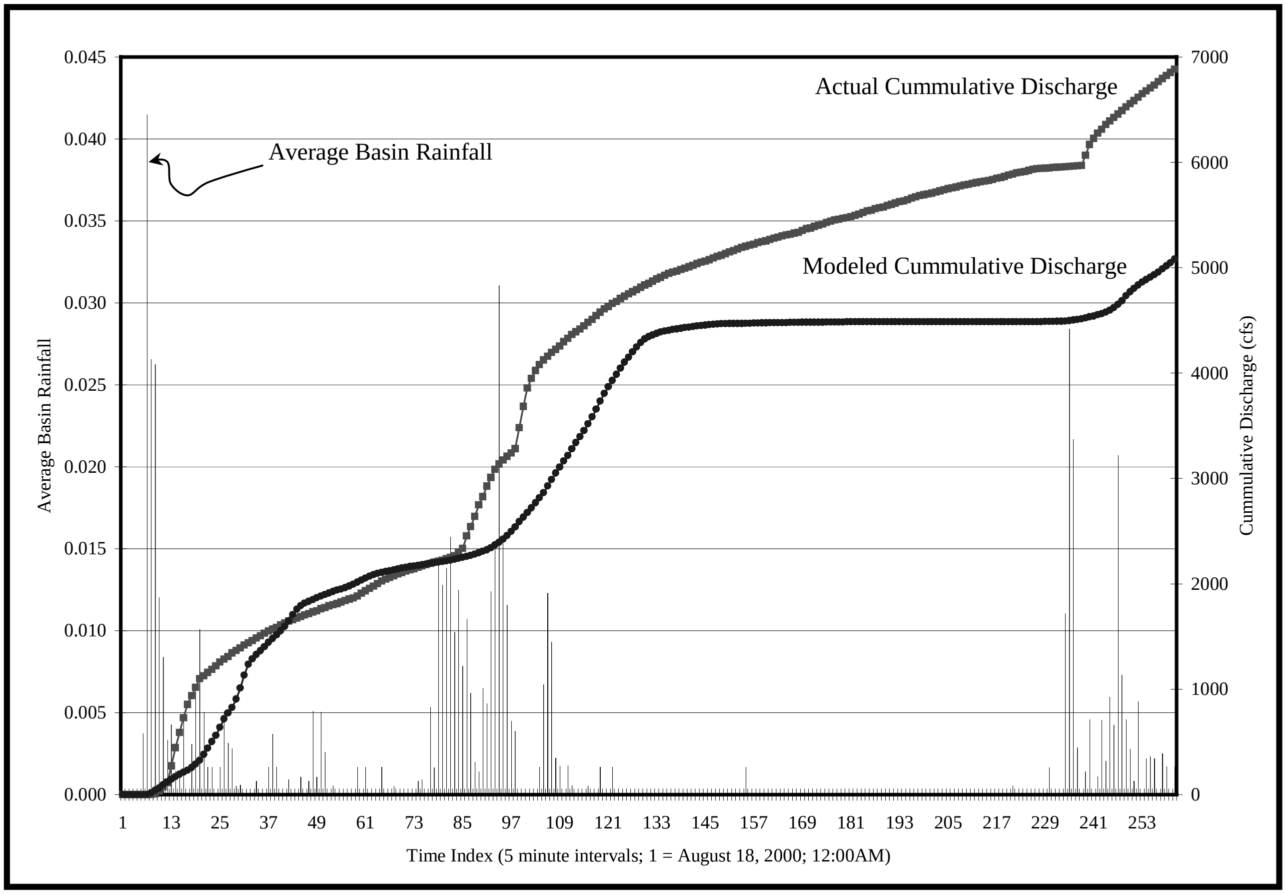
A third potential problem is less obvious from visual inspection, but is worth mentioning. The model predicted discharge increases and decreases to the peak flow less quickly than the actual

Figure 8: Hahn Basin Discharge and Model Estimated Discharge; August 18th, 2000



discharge. This leads to wider peaks for the modeled discharge and leaves open the question of how the cumulative discharge compares between model and actual. The ability of the model to explain cumulative discharge is mixed through the course of the storm (see Figure 9). The columns in the figure represent the average basin rainfall at each 5-minute interval. The lines in the figure are the actual and modeled cumulative discharge. By the end of the seventh hour of the storm, the cumulative discharges compare quite well, although, as mentioned before, the timing of the modeled discharge lags the actual. However, after that time, the actual cumulative discharge is consistently higher than the discharge accumulated by the model. By the end of the storm, the model underpredicts the accumulated discharge by just over 25%.

Figure 9: Modeled and Actual Cumulative Discharge



CONCLUSIONS AND FUTURE DIRECTIONS

This research lays the foundation for a distributed hydrological modeling system for the prediction of flash flooding. Although the simulation results from the model indicate that additional work is necessary to improve estimates of runoff and discharge, the existing model provides a substantial first step and framework from which to build.

The model results on time of travel of water within the basin are very encouraging for this method of handling overland flow routing for problems of this type. As discussed in the Data and Methods section, one of the primary assumptions of the method employed in this research is a zero loss of water to storage or evaporation during overland flow. Although this is not a trivial assumption, it is important to keep in mind the computational savings associated with it. Rather than calculating the inflow of water to and outflow of water from *each* cell in the basin and then routing the outflow from *each* cell based on its connectivity to its neighboring cells, this no-loss method cuts the calculations down to the assessment of inflow of water into a cell from precipitation and then travel time of the water to the outlet. Even if one only dealt with cells in the basin that have non-zero inflow in the calculations, the complete accounting and routing of water across a landscape is a computationally expensive undertaking. This new method may be able to generate defensible estimates at a fraction of the computational cost.

There are many future directions for this research. One of the most important is the development of a method to generate the needed precipitation forecasts. There are many methods for the generation of QPFs. We propose that one of the most fruitful for this kind of analysis would be coupling Artificial Neural Networks (ANNs) with output from the National Weather Service WSR 88-D radar system. ANNs are excellent tools for the estimation of output from highly non-linear systems both in the atmospheric sciences (Snell et al., 2000; Gardner and Dorling 1998; Cavazos 1997; Zhang and Scofield 1994) and elsewhere (Gopal and Scuderi 1995; Fischer and Gopal 1994). The goal of this future research will be to generate forecasts that are accurate and with enough lead-time to model flooding and issue warnings.

Another important area of future research is to complete a detailed sensitivity analysis for the inputs of the final calibrated model. In most new applications of this type of modeling system, there will be cost restraints on the collection and preparation of necessary input data. It will be essential to know which of the inputs are most important to the generation of accurate results, and therefore are cost justifiable.

Beyond these two areas of future research, there are a number of smaller but interesting avenues for investigation. For example, it would be interesting to quantify the benefit of the alteration of flow directions beyond those derived simply from aspect information. Geographers have seen in many applications, that scale matters. The model simulations completed for the Hahn Basin in this research were using cells with 10-meter spatial resolution. This is nearly as fine a resolution as can be handled without significantly altering the computational resources needed for the model runs. However, it would be interesting to know how model results would change as the spatial resolution is degraded to 15, 20, or 30 meters. If model results are not significantly harmed by such a change in resolution, it would have a marked effect on the computational time needed to complete model runs. This may be a significant benefit especially once the model is being used in real-life situations.

This final point brings us full circle to the point where this research began: real-life flash flood prediction. Clearly, the other remaining area for future research is to see this kind of modeling system implemented in a real world situation in a NWS forecasting office. The model needs to be improved before this final step is an option, but it is the driving factor behind our efforts. We look forward to this modeling system making a real difference in the real world.

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APPENDIX A

Arc Macro Language Routine

```
   /* AML for Discharge Calculations */
/* Written by: Seth Snell and Kirk Gregory */
     /* Completion Date: June 2001 */

 &do i = 1 &to 265
   &ty Running pprep.out %i%
   &sv junk = [task pprep.out %i%]

&if [exists runoff -grid] &then; kill runoff all
&if [exists travel -grid] &then; kill travel all
&if [exists traveltime -grid] &then; kill traveltime all
&if [exists interval -grid] &then; kill interval all
&if [exists int_runoff -grid] &then; kill int_runoff all
&if [exists tmpgrid -grid] &then; kill tmpgrid all
&if [exists tmpgrid2 -grid] &then; kill tmpgrid2 all
date
grid

 runoff =  asciigrid (runoff.asc, float)
/* converts runoff (in cfs) to a grid. */

 travel = asciigrid (travel.asc, float)
/* converts travel time (in minutes) to a grid. */

 traveltime = flowlength(gridflowdir, travel)
/* use default of downstream to create travel time. */

 interval = slice(traveltime, TABLE,interval_84sec.rmp)
/* creates integer zones of travel times defined by  remap table. */

 int_runoff = zonalsum(interval, runoff)
/* creates sum of runoff in each defined zone. */

/* Grid Prep for DISCHARGE.OUT routine    */
/* Assumes the prior creation of interval */
/* and int_runoff grids                   */

 tmpgrid = int(int_runoff * 1000)
 tmpgrid2 = combine(tmpgrid, interval)

quit

tables
 sel interval.vat
 unload interval.txt value columnar junk init
 sel tmpgrid2.vat
 sort interval
 unload int_ro.txt interval tmpgrid columnar junk init
quit

&sv junk = [task discharge.out %i%]

&end
&return
```

FORTRAN Programs

Precipitation and Kinematic Wave Program (pprep.f)

```
************************************************************************
* This program generates precipitation intensities over a grid
* specified by an ascii text file output from Arc/Info GRID with
```

```
* zones corresponding to precipitation gage numbers. The routine then
* goes on to calculate times of travel for each cell within an basin
* utilzing the kinematic wave approach to overland flow.
*
* Note:
*     The maximum possible number of rows and columns are set as
*     parameters (maxrows, maxcols) in the routine. The maximum number
*     of precipitation stations within the basin.

************************************************************************
*      Programmed by: Seth E. Craigo-Snell (sethcs@unm.edu)        *
*                     and                                          *
*                     Kirk Gregory                                 *
*        Completion Date:  Jun 2001                                *
************************************************************************

*---+6---1----+----2----+----3----+----4----+----5----+----6----+----7--

      program pprep

        parameter (maxrows=1000, maxcols=1000, maxstations=10,
     1             maxintervals=1000, maxcell=167000)

      implicit none

        integer i, j, nrows, ncols, cellsize, row, col, nodata,
     1          prcpindex, loop, year, month, day, interval,
     2          resolution, nodata, intervals, curvenum, cn, fd, nr,
     3          nc, nn, n, f, lc, ii


      integer*2 thies, stations, stat

      character*14 cheader
      character*25 xllcorner, yllcorner
      character*121 header

        real*4  prcp, prcpthies, mannings, ofl, iph, xll, yll,
     1          depstore, sumrain, cumdr, rain, store, a, b, s, ds,
     2          deg, pslope, q, tof, tot, ri, dr, excess, ppt, iph,
     3          rc, slope

        dimension thies(maxrows,maxcols), cheader(6), stat(maxstations),
     1            prcp(maxstations), prcpthies(maxrows,maxcols),
     2            mannings(24), curvenum(24), depstore(24),
     3            sumrain(maxcell), cumdr(maxcell),
     4            rain(maxcell), q(maxcell), tof(maxcell),
     5            tot(maxcell)

      Data mannings/.012,.0,.01,.012,.8,.4,.4,.4,.4,.4,.4,.3,.25,.13,
     &              .15,.17,.15,.30,.41,.41,.01,.011,.17,.01/
      Data depstore/.098,.0,.25,.098,.5,.5,.4,.3,.4,.3,.4,.25,.25,.25,
     &              .25,.25,.25,.25,.295,.295,.030,.047,.394,.05/
      Data curvenum/98,100,72,94,57,64,60,60,60,60,60,60,60,63,62,60,
     &              74,60,77,62,88,94,83,75/
*       Data curvenum/98,100,72,94,57,64,60,60,60,60,60,60,60,63,62,60,
*      &              74,60,77,62,88,84,83,75/

      open(1,file='test2.dat',access='sequential',status='unknown')
      open(2,file='tempfile',access='sequential',status='unknown')
      open(3,file='pptaccum',access='sequential',status='unknown')
*       open(3,file='pptaccum',status='old')

      open(10,file='testppt.asc',access='sequential',status='unknown')
*       open(11,file='rain.dat',access='sequential',status='unknown')
4     format(/)

c    Variable List
c    ofl = overland flow length (dependent upon flowdirection)
c    fc = originating cell (or from cell)
c    tc = to cell (or receiving cell)
```

```
c    fd = flow direction (or originating cell aspect class)
c    lc = land cover type
c    rc = mannings n for overland flow
c    pslope = percent slope for cell
c    slope = degree of slope for cell
c       note - must employ a constant to convert from raidans
c              (fortran default) to a degree measure.
c    ppt(j)=rainfall in ft/sec
c    iph(j)=rainfall in inches/hour


*---+6---1----+----2----+----3----+----4----+----5----+----6----+----7--

      read(*,*) prcpindex

      open(12,file='hahnpthies.asc',status='old',err=102,
     1       action='read')

      read(12,1201) cheader(1), ncols
      read(12,1201) cheader(2), nrows
      read(12,1202) xllcorner
      read(12,1202) yllcorner
      read(12,1201) cheader(5), cellsize
      read(12,1201) cheader(6), nodata

 1201 format(a14,i)
 1202 format(a25)

*     write(*,1205) xllcorner, yllcorner
*     pause
* 1205 format(2a25)

      do 10 row = 1, nrows
         read(12,*) (thies(row,col) , col=1, ncols)
 10   continue
 1203 format(<ncols>i)


       open(13,file='AUG1820.txt',status='old')

       read(13,*) stations, intervals
       read(13,1300) header, (stat(i), i = 1, stations)

 1300  format(a15, <stations>i12)

       do 20 loop = 1, prcpindex
          read(13,1301) year, month, day, interval,
     1        (prcp(i) , i=1,stations)
 20    continue

 1301  format(i5, i2, i3, i5, <stations>f12.9)

      do 30 row = 1, nrows
         do 31 col = 1, ncols
            prcpthies(row,col) = 0.0
            if (thies(row,col) .eq. -9999) then
               prcpthies(row,col) = -.999
               goto 31
            else
               do 32 i = 1, stations
                  if (thies(row,col) .eq. stat(i)) then
                      prcpthies(row,col) = prcp(i)
                    goto 31
                 else
                 end if
 32            continue
            end if
 31      continue
 30   continue
```

```
*      open(14,file='hahnprcp.asc',status='old',err=102,
*     1         access='sequential')

*      write(14,1401) cheader(1), ncols
*      write(14,1401) cheader(2), nrows

* 1401 format(a14,1i)

*      do 40 row = 1, nrows
*         write(14,1403) (prcpthies(row,col) , col=1, ncols)
* 40   continue
* 1403 format(<ncols>f10.6)
*      close(14)

**********************************************************************
* Start of Kinematic Wave Runoff Code
**********************************************************************

       nr=257
       nc=646
       n=nr*nc
       nn=nr
       deg=57.29578
       f=0
       fd=1

* Re-arranging Prcp from prcpthies(row,col) to rain(nrows*ncols)

       i = 1
       do 50 row = 1, nrows
          do 51 col = 1, ncols
             rain(i) = prcpthies(row, col)
             i = i + 1
 51       continue
 50    continue

         if(prcpindex.eq.1) then
            do 60 i=1,n
*             read(11,34,end=500) rain(i)
             sumrain(i)=rain(i)
             cumdr(i)=0.
 60      continue
         else
            do 61 i=1,n
*             read(11,34,end=500) rain(i)
             read(3,6301) sumrain(i),cumdr(i)
 61      continue
         endif
 6301    format(2f12.7)


 64     rewind(unit=3)

        do 70 ii=1,n
           read(1,*,end=500) lc,pslope
800        format('  cover = ',i2,' rain = ',f12.7)

         if (lc.eq.-2) then
            q(ii)=-2.
            tof(ii)=-2.
            tot(ii)=-2.
           write(3,6301) sumrain(ii), cumdr(ii)
            go to 300   ! write null data to outfile
         end if

         ds=depstore(lc) ! Assign depression storage (in.) to
*                          land cover classes
         cn=curvenum(lc) ! Assign SCS CNs to land cover classes

         if(rain(ii).le.0.) then  ! be sure only to work on cells
*                                    with ppt.
```

```
             g(ii)=0.
             tot(ii)=0.
             tot(ii)=0.
            write(3,6301) sumrain(ii), cumdr(ii)
             go to 300   ! write zero flow to outfile
          end if


c   compute overland flow

c   pervious areas:

         if(lc.eq.1.or.lc.eq.4.or.lc.eq.19.or.lc.eq.21.or.lc.eq.22)
     &  go to 200   ! else work on pervious surfaces

c   accumulate rainfall up to storage capacity and estimate excess
c   with the SCS method for incremental rainfall

        s=(1000/cn)-10
        store=0.2*s
        if(sumrain(ii).le.store) then
           sumrain(ii)=sumrain(ii)+rain(ii)
           cumdr(ii)=0.
            ri=0.
            dr=0.
cc            rri(ii)=0.
            write(3,6301) sumrain(ii),cumdr(ii)
            go to 240
        end if

        a=(sumrain(ii)-(0.2*s))**2
        b=sumrain(ii)+(0.8*s)
        dr=a/b
        ri=dr-cumdr(ii)
cc        rri(ii)=ri
        cumdr(ii)=cumdr(ii)+dr


        write(3,6301) sumrain(ii),cumdr(ii)
        excess=ri  ! this may be a problem: renamed variable rain
        go to 230

200    continue

cccccccccccccccccccccccccccccccccccccccccccccccccccc
c    cumdr is dss in this part of the program
cccccccccccccccccccccccccccccccccccccccccccccccccccc

! work on impervious surfaces

        if(prcpindex.eq.1) cumdr(ii)=depstore(lc)
        if(rain(ii).gt.cumdr(ii)) then
           excess=rain(ii)-cumdr(ii)
           cumdr(ii)=0.
           write(3,6301) sumrain(ii),cumdr(ii)
           go to 230
        end if
        if(cumdr(ii).gt.0.) then
              excess=0.
ccc              sumrain(ii)=sumrain(ii)+rain(ii)
              cumdr(ii)=cumdr(ii)-rain(ii)
              write(3,6301) sumrain(ii),cumdr(ii)
          else
              excess=rain(ii)
              write(3,6301)sumrain(ii),cumdr(ii)

          end if


230    ppt=excess/3600.
       if(pslope.eq.0.) pslope=0.01
```

```
       slope=pslope/100.
       if(fd.eq.1.or.fd.eq.3.or.fd.eq.5.or.fd.eq.7) ofl=32.808
       if(fd.eq.2.or.fd.eq.4.or.fd.eq.6.or.fd.eq.8) ofl=46.398
       q(ii)=(ppt*ofl*cos(slope/deg))*ofl

240    continue

c   compute overland flow travel time

*       iph=rain(ii)*12.
       iph=excess*12
       rc=mannings(lc)    !Assign n values to land cover classes
       a=(1.49*sqrt(slope))/rc
       tof(ii)=(ofl/(a*iph**0.667))**0.6
       tot(ii)=tof(ii)/60.
cc       toc=((ofl**0.6)*(rc**0.6))/((iph**0.4)*(slope**0.3))


300       write(2,17)q(ii),tof(ii),tot(ii)


ccc      write(2,117)q,tot,tof,toc
c117   format(4f10.4)
17     format(3f10.4)
 70    continue


 500   continue
*      write(*,4)
*      write(*,*)'  Completed Hydrologic Computations...'
      close(unit=1)
      close(unit=3)
      close(unit=4)
      close(unit=11)
      rewind(unit=2)

ccc  Now, write to Esri's grid ASCII format:
*      write(*,4)
*      write(*,*)'  Now, Writing data to Esri grid ASCII format...'
*      write(*,4)
      open(7,file='runoff.asc',access='sequential',status='unknown')
      open(8,file='tot.asc',access='sequential',status='unknown')
      open(9,file='travel.asc',access='sequential',status='unknown')
ccc   these are grid header file parameters:
       xll=355419.014
       yll=3886802.986

      resolution=10
      nodata=-2

        write(7,9000) nc,nr
       write(7,9002) xllcorner
       write(7,9002) yllcorner
       write(7,9001) resolution,nodata

        write(9,9000) nc,nr
       write(9,9002) xllcorner
       write(9,9002) yllcorner
       write(9,9001) resolution,nodata

 9000  format('ncols',9x,i3/'nrows',9x,i3)
 9001  format('cellsize',6x,i2/'NODATA_value',2x,i2)
 9002  format(a25)
      do 80 ii=1,n,ncols
         write(7,8001)(q(j),j=ii,(ii+(ncols-1)))
         write(9,8001)(tot(j),j=ii,(ii+(ncols-1)))
 80    continue
 8001  format(<ncols>f10.6)
       close(7)
       close(9)
```

```
*********************************************************************
*********************************************************************
      goto 4000
 101  write(*,*) 'There was an error opening or reading prcpindexfile'
      goto 4000
 102  write(*,*) 'There was an error opening or reading:
     1  hahnpthiesgrid.asc'
      goto 4000

 4000 end
```

Discharge Calculation FORTRAN Program (discharge.f)

```
**********************************************************************
* This program generates the discharge at the outlet of a defined basin
* given the *.vat from a grid of 5 minute travel time intervals
* and the *.vat from a grid of accumulated runoff over those same
* travel time intervals.
*
* Note:
*     The maximum possible number of zone intervals is basin and storm
*     dependent and is thus set as a parameter (maxzones) in the
*     routine.

**********************************************************************
*   Programmed by: Seth E. Craigo-Snell (sethcs@unm.edu)      *
*      Completion Date: Jun 2001                              *
**********************************************************************

*---+6---1----+----2----+----3----+----4----+----5----+----6----+----7--

      program discharge

        parameter (maxzones = 80)

      implicit none

        integer i, j, zones, value_i, value_ro,
     1   interval, numlag, rows, count, prcpindex

        real RO, lag, discharge

*        logical lagexist

        dimension value_i(maxzones), value_ro(maxzones),
     1   lag(maxzones,maxzones), interval(maxzones),
     2   ro(maxzones), count(maxzones)

*---+6---1----+----2----+----3----+----4----+----5----+----6----+----7--

      read(*,*) prcpindex

* Read intervals from interval.txt file to obtain the number
* of zones in this time interval.

        open(12,file='interval.txt',status='old',err=102)
        i = 0
 10     i = i + 1
        read(12,1200,end=101,err=102)
     1    value_i(i)
        goto 10
 1200   format(i10)
 101    close(12)
*        zones = value_i(i-1)
      zones = i-1


* Read interval and runoff values from int_ro.txt file.
* int_ro.txt stores output from UNLOAD operation with final
* interval runoff grid. The values are scaled by 1000 to be
* stored as integer values.

        open(13,file='int_ro.txt',status='old',err=103)
        do 20 i=1,zones
           read(13,1300,err=103)
     1       interval(i), value_ro(i)

*         write(*,*) interval(i), value_ro(i)
          ro(i) = value_ro(i)/1000.
 20     continue
 1300   format(2i16)
```

```
        close(13)

* Rearrange runoff values for sequentially ordered vat output
*        do 21 i=1,zones
*           do 22 j=1,zones
*              if (interval(j) .eq. i) ro(i) = value_ro(j)/1000.
*            write(*,*) i,j, interval(j), ro(i)
* 22        continue
*         write(*,*) '        ',i, j, interval(i), ro(i)
* 21     continue

* Get rid of zone 0 if it exists.
      if (interval(1) .eq. 0) then
         do 23 i = 1, (zones-1)
            interval(i) = interval(i+1)
            ro(i) = ro(i+1)
 23      continue
         zones = zones-1
      else
      end if
*        write(*,*) 'Number of zones for interval.out:', zones

* Read lagged runoff values from lagfile into variable: lag.
        do 30 i=1,maxzones
           do 31 j=1,maxzones
              lag(i,j) = 0.0
            count(i) = 0
 31        continue
 30     continue

*        inquire(file='lagfile.txt',exist=lagexist)
*      write(*,*) 'lagfile.txt exists?', lagexist

        if (prcpindex .ne. 1) then
           open(14,file='lagfile.txt',status='old',err=104)
           read(14,*,err=104) numlag
*         write(*,*) 'number of lags:', numlag
           do 40 i=1,numlag
              read(14,*,err=104) count(i)
              read(14,1400,err=104) (lag(i,j) , j=1,count(i))
*            write(*,*) 'count: ',count(i)
*            write(*,*) 'lags: ', (lag(i,j) , j=1,count(i))
 40        continue
        else
          discharge = 0.0
          numlag = 0
          do 41 i=1,(zones+1)
             count(i) = 0
 41       continue
          goto 45
      end if
 1400   format(<count(i)>f10.3)
        close(14)

* Calculate discharge from lag = 1 values
        discharge = 0.0
        do 50 j=1, count(1)
           discharge = discharge + lag(1,j)
 50     continue

* Write discharge values to a file.
 45    open(15,file='discharge.txt',access='append')
        write(15,1500) discharge
 1500   format(f15.3)
        close(15)

* Reindex and save lagged runoff information.

*      write(*,*) 'Reindexing ....'
*      pause
```

```
       open(16,file='lagfile.txt',access='sequential',err=106)
       do 60 i = 1, zones
          lag((i+1),(count(i+1)+1)) = ro(i)
          count(i+1) = count(i+1) + 1
60     continue

      write(*,*) 'zones: ',zones,'Numlag: ', numlag

       if (zones .gt. (numlag-1)) rows = zones + 1
       if (zones .le. (numlag-1)) rows = numlag
       write(16,*,err=106) (rows-1)
         do 61 i = 2, rows
            write(16,*,err=106) count(i)
            write(16,1600,err=106) (lag(i,j), j=1,count(i))
61       continue

1600  format(<count(i)>f10.3)
       close(16)

      goto 4000

102    write(*,*) 'An error ocurred while reading file: interval.out'
      goto 4000
103    write(*,*) 'An error ocurred while reading file: int_ro.out'
      goto 4000
104    write(*,*) 'An error ocurred while reading file: lagfile.txt'
      goto 4000
105    write(*,*) 'An error ocurred while reading file:
    1   firstlagfile.txt'
      goto 4000
106    write(*,*) 'An error ocurred while trying to write to
    1   file: lagfile.txt'

4000  end
```