SUBDIVISION OF WATERSHEDS FOR MODELING

A Thesis

Presented to

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University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Civil Engineering

by

Thuy Luong

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SUBDIVISION OF WATERSHEDS FOR MODELING

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ABSTRACT

Rainfall-Runoff models such as Hydrologic Modeling System (HEC-HMS), Stormwater Management Model (SWMM), etc., are used for predicting the hydrologic response of watersheds. An important issue that must be addressed by all users of these models is the estimate of an appropriate level of watershed subdivision for simulating runoff. The size and number of subwatersheds can affect a watershed modeling process and subsequent results. The objective of this research herein, in response to TxDOT Problem Statement 0-5822, "Subdivision of Watershed for Modeling," is to evaluate the effect of various levels of watershed subdivision on simulated runoff hydrographs. HEC-HMS program was applied to five watersheds in Central Texas that varied from 12.3 to 166 square miles. They are divided into location modules: Austin, Dallas, Fort Worth, San Antonio, and Smallrural areas. In this study, the models were intentionally left uncalibrated, thus the subdivision specification is the result of application of engineering hydrologic modeling practice, as would occur when modeling ungaged watersheds. The results of the HEC-HMS analysis indicated that variation in the total number of subwatersheds had very little effect on runoff hydrographs. Also, there is no consistent pattern on whether lumped or multiple subbasins produce superior results; thus, the appropriate level of subdividing a watershed is difficult to determine.

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CHAPTER 1

PROBLEM STATEMENT

One routine task associated with hydraulic design is the delineation of the watersheds and subsequent computation of the watershed characteristics such as drainage area, main channel length, main channel slope, and etc. After this task is completed, the engineer must decide if the watershed should be further subdivided into smaller components, referred to as sub-watershed or sub-basins. The sub-basin parameters are then input into a hydrologic model to develop runoff hydrographs.

The ability of a model to simulate the watershed systems depends on how well the watershed system is described by model input parameters. In a lumped hydrologic model, the watershed is assumed homogeneous with representative parameters. However, the size of the watershed affects the homogeneity assumption, because larger watersheds are more likely to have variable conditions within the watershed. Subdividing a watershed into smaller sub-watersheds would certainly increase the input data preparation effort. In practice, subdividing watershed into smaller components might or might not produce more accurate model results compared to measured, that is observed, streamflow from the watershed. On the other hand, modeling a large watershed as a single lumped model might lead to poor simulation results. Thus, the art of watershed subdivision remains an unsolved problem facing many hydrologists and civil engineers inside and outside TxDOT.

The objective of this research, in response to TxDOT Problem Statement 0-5822, “Subdivision of Watershed for Modeling,” is to evaluate the effect of various levels of watershed subdivision on simulated runoff hydrographs.

This thesis presents one of several approaches to watershed subdivision: the iso-characteristic approach, where each sub-watershed has about the same physical characteristic (area, main channel length, etc.) as each other.

Five sets of watersheds in Central Texas with USGS streamflow-gaging stations were selected for this study. Drainage areas for these watersheds ranging from approximately 12.3 to 166 square miles, main channel lengths range from approximately 9 to 48 miles, dimensionless main channel slope are from approximately 0.002 to 0.02. A database of incremental cumulative rainfall values for storms that occurred during the period from 1961 to 1986 were used to input into the HEC-HMS program to construct cumulative rainfall hyetographs for runoff simulation.

There are two components for the hydrological modeling study in this research project. The first component is to estimate the hydrologic response of a watershed as a single basin with no subdivisions. The second component is to analyze the watershed by subdividing it into 2, 3, 5, and 7 sub-basins. These individual sub-basins responses can be combined to generate a composite response for an entire watershed. The model is then run and the results are reviewed and analyzed. The modeled hydrographs are compared with the observed hydrographs to see if the subdivision case can produce a response equivalent to observations any better than the single basin case or in other words, how the response changes as a function of watershed subdivision.

The remainder of this thesis is divided as follows. Chapter 2 is a review of relevant literature regarding to the impact of various levels of watershed subdivision on simulated runoff hydrographs. Chapter 3 describes the method used in this research. The procedure for developing each of the model parameters is also outlined. Model results and discussion are presented in Chapter 4. In Chapter 5, the findings of the study are summarized with the recommendations for further study.

CHAPTER 2

LITERATURE REVIEW

Researchers have been studying the effect of watershed subdivision on runoff for many decades. A variety of models have been applied for estimating surface runoff from watersheds, such as Soil and Water Analysis Tool (SWAT), Kinematic Runoff and Erosion Model (KINEROS), HEC-1, HEC-HMS, SWMM, NRCS TR20, and other codes written by researchers. Some of the studies used a synthetic approach, in which no data were used to evaluate model parameters, similar to the general use of models in a design setting. Other researchers used measurements of rainfall and runoff to evaluate some of the model parameters.

2.1. Literature Review

Hromadka (1986) developed an application manual for hydrologic design for San Bernardino County. In that manual, mechanics were developed based on the Los Angeles hydrograph method. In Hromadka's notes on application of the methods presented in the manual, it states "Arbitrary subdivision of the watershed into subareas should generally be avoided." The fact is that an increase in watershed subdivision does not necessarily increase the modelling "accuracy" but rather transfers the model's reliability from the valiated unit hydrograph and lag relationships to the unknown reliability of the subsequent flow routing submodels used to link together the divided subareas.

Wood et al. (1988) examined the relation between watershed scale and watershed runoff on the 6.5 mi^2 Coweeta River experimental watershed located in North Carolina.

Wood et al. divided the Coweeta River watershed into 3, 19, 39, and 87 subwatersheds. TOPMODEL (Beven and Kirkby, 1979) was used as the simulation engine, with watershed topography from a 30-meter digital elevation model and other model parameters and variables randomly sampled from distributions. Wood et al. (1988) reported that for a drainage area less than 0.4 mi^2, subwatershed response was highly variable. However, at scales greater than about 0.4 mi^2, further aggregation of subwatersheds had little impact of simulated results. It is important to observe, however, that the interest of Wood et al.'s (1988) study was to determine what they termed the representative elemental area (REA) for the Coweeta River watershed (if such a concept exists) but not to evaluate the impact of watershed subdivision on runoff hydrographs directly. Therefore, whereas the Wood et al.'s (1988) study is interesting, it does not directly apply to the current research problem.

Norris and Haan (1993) used a synthetic method to study the impact of watershed subdivision on hydrographs estimated using the Natural Resources Conservation Service (NRCS, then SCS) unit hydrograph procedure, as implemented in HEC-1. The Little Washita watershed near Chickasha, Oklahoma, which has a drainage area of about 59 mi^2, was used as the study watershed. The watershed was subdivided into 2, 5, 10, and 15 sub-watersheds, as well as treating the watershed as a whole. A balanced hyetograph was used to drive hydrograph computations, with duration of 24 hours and a return period of 50 years. Results from Norris and Haan (1993) were that watershed subdivision had a pronounced impact on the estimate of peak flow from the watershed. The change from a single watershed to 5 sub-basins resulted in a net increase in peak discharge of about 30 percent. Use of 15 sub-basins increased the difference from a single watershed to about

40 percent. However, the impact of subdivision diminished with further increase of sub-basins. Based on their synthetic study (no observed hydrographs were used to assess model performance), Norris and Haan (1993) concluded that the number of sub-basins for simulating watershed response should not vary through the course of a hydrologic study. If the watershed discretization scheme is changed during a hydrologic study, then the impact of changes in land-use (or other changes) may easily be masked by differences arising from the subdivision scheme. It was not clear from the report whether any assessment was made concerning which level of subdivision, if any, was most appropriate for reproduction of watershed hydrographs.

Sasowsky and Gardner (1991) applied the SPUR model to a 56 mi^2 sub-watershed of the Walnut Gulch experimental watershed in Arizona. The SPUR model operates on a daily time step and was designed for rangeland watersheds. A GIS procedure was used for watershed subdivision based on stream order, an approach not used by other researchers. The study watershed was divided into 3, 37, and 66 contributing sub-areas for modeling purposes. The model was calibrated against measured rainfall-runoff sequences. Sasowsky and Gardner (1991) used the "efficiency" statistic (Nash and Sutcliffe, 1970) to assess model performance on a monthly basis, that is, monthly runoff volumes were used to measure model accuracy. An efficiency greater than zero indicates that the model is a better predictor of observed runoff volumes than the mean runoff. In their study, Sasowsky and Gardner calibrated each "model" (instance of subdivision) to measured rainfall-runoff events, and then noticed that the curve number, in particular, decreased with increasing subdivision. Sasowsky and Gardner (1991) reported that simulations were sensitive to the degree of watershed subdivision. Lower curve numbers yield better results for coarser subdivision, and higher curves number yield better results for finer subdivision.

Michaud and Sorooshian (1994) applied three different model formulations to simulate the rainfall-runoff process for Walnut Creek Gulch in Arizona. The models used KINEROS-complex, KINEROS-simple, and the curve-number approaches to simulate the rainfall-runoff process. The authors reported that KINEROS was not able to produce reasonable solutions comparable to observations. In addition, the results from application of the curve number approach also did not compare well with observations.
An earlier study by Loague and Freeze (1985) also report mixed results from their hydrological simulations for a set of watersheds with three very different modeling approaches. In fact, their recommendation was that simpler models appear to perform better than more complex approaches.

Mamillapalli et al. (1996) conducted a study of the impact of watershed scale on hydrologic output. As other studies reported in the journal literature, the NRCS Soil and Water Analysis Tool (SWAT) model was used with a use of Geographic Information Systems procedure to develop the required input streams. Mamillapalli et al. (1996) concluded that, in general, increase of the level of discretization and the number of soil and land use combinations resulted in an increase of the level of accuracy. There is a level of discretization beyond which the accuracy cannot be further improved. It suggests that more detailed simulation may not always lead to better results.

Bingner et al. (1997) applied the SWAT to the Goodwin Creek watershed in northern Mississippi. SWAT uses the uniform soil-loss equation and its variants to predict sediment yield from the study watershed. Their objective was to determine the degree of watershed subdivision required to achieve reasonable results in predicting watershed runoff and sediment yield. Watershed drainage area of the Goodwin Creek Watershed was about 8.2 mi^2. A suite of subdivisions was generated with elemental areas that ranged from a maximum of 60 acres to a minimum of 4 acres was used to model runoff and sediment yield. The authors concluded that model predicted runoff volume was not heavily dependent on the degree of watershed subdivision, however, the model predicted sediment yield did depend on the degree of watershed subdivision.

FitzHugh and Mackay (2000) conducted a study similar to Bingner et al. (1997) for the Pheasant Branch watershed in Dane County, Wisconsin. FitzHugh and Mackay (2000) also reported that model predicted watershed runoff was not heavily dependent on the degree of subdivision (also using the SWAT model), but the predicted sediment yield dependened on the degree of subdivision.

Hernandez et al. (2002) presented results from use of the Automated Geospatial Watershed Assessment (AGWA) tool. The purpose of the software tool is to assist the development of input parameter sets for the KINEROS and SWAT watershed models. The authors did not specifically test the impact of watershed subdivision on model performance. However, the authors reported that results from the SWAT model differed substantially from observations for the two watersheds tested.

Jha (2002) examined the relation between watershed subdivision and water-quality model results. He applied the SWAT model to four Iowa watersheds. Jha (2002) reported that streamflow was not significantly affected by a decrease in sub-watershed scale, where model predicted results stabilized with about ten subdivisions. However, model predicted sediment yields were more dependent on sub-watershed scale, requiring 40-50 divisions to stabilize model predicted sediment yield.

Tripathi et al. (2006) applied the SWAT model to the 35 mi^2 Nagwan watershed in eastern India. The watershed was subdivided into 12 and 22 sub-watersheds, as well as treating the entire watershed as a whole. Four years of record were used to carry out the model simulations. The model was calibrated to produce best estimates of model parameters. Tripathi et al. (2006) reported little difference in watershed runoff for different number of sub-watersheds used. However, they observed variations in other components of the hydrologic cycle. Estimates of evapotransipiration increased with increase of numbers of sub-watersheds.

2.2. Implications

The literature reviews described above have contributed to the understanding of how basin scale affects the hydrologic response of a watershed. An important note is that a number of papers referred to the insensitivity of runoff volume to the degree of watershed subdivision. It is important to realize that the principal input to the watershed, precipitation, is typically measured at point gages, which measure the rainfall field over an eight-inch diameter (if a standard rain gauge is used). In contrast, measurements from a stream gage reflect the integrated response of the watershed to the rainfall field and all of the processes that act as rainfall become runoff. The two phenomena and their measurements are inherently different.

Furthermore, it is not clear from the literatures how sets of parameters should be assigned to sub-watershed units. It seems reasonable to assume that each sub-watershed should have a unique parameter set, but even with data for calibration, it is nearly impossible to determine a unique parameter set for each sub-watershed as there is not enough information contained in a rainfall-runoff series. This was the message of Gupta and Sorooshian (1983) and others. It seems overly optimistic to believe that assigning a parameter set to a sub-watershed without specific data concerning watershed response characteristics will result in better estimates than using a lumped approach with fewer parameters. An important note is in all of the previous studies, the simulated runoff hydrograph of a single watershed (with no subdivision) was compared to that from modeling all sub-watersheds.

Synthesis of these and other references suggests the following approaches to model watershed subdivision (in the absence of obvious natural features and flow regulation structures):

1. An iso-characteristic approach, where each sub-basin has about the same physical characteristic (area, length, etc.). Drainage area ratios would fall into this approach. The characteristics may be subtle—one paper presented at the 2006 American Geophysical Union used contiguous areas of similar slope to define watershed subareas (McGuire, 2006). Although watershed subdivision was not the focus of the particular paper, nevertheless the idea appeared sound. The San Bernardino (1986) manual seems to imply a range of area ratios that are acceptable for preserving sufficient model believability, again a spatial characteristic based concept.

2. An iso-temporal approach, where each sub-watershed is selected to have about the same characteristic response time, that is, t_c. This particular approach may have great value in concurrent flooding (concurrent arrival times of flood waves). A challenge of

this conceptualization is that lumped systems will necessarily be replaced by routed systems and any gain in certainty by using smaller sub-basins may be more than offset by increased uncertainty caused by routing. Despite this important criticism, TxDOT researchers still feel this is a line of investigation that needs consideration. At some scales of high subdivision, the entire runoff process that is currently explained using unit hydrographs becomes entirely replaced by hydraulic elements; interestingly the hydrographs "look" like convolved unit hydrographs so the accepted connection between the physical processes in a distributed hydraulic model and the lumped hydrologic model are well manifest in this sense.

3. A scoring approach: Scoring is similar to the above concepts, except a set of characteristicsis assigned a score; similar scores that are geographically connected are selected as watersheds. The scoring approach could admit descriptors not easily quantified numerically. For example the use of binary variables in TXDOT Research Projects 0–4193 and 0–4696 to account for the effect of developed/undeveloped and rocky/non-rocky are arguably scoring approaches.

4. A gage-defined approach where the locations of existing gages are used to subdivide a watershed — not necessarily a modeling tool, but a good comparative tool. An extension would be to locate good gage locations based on measuring requirements and use these locations to divide a watershed.

5. Stream-order/bifurcation approach. Watersheds are subdivided based on branches in the dendritic drainage network. Several papers at 2006 American Geophysical Union used this approach to divide research watersheds for water quality and nutrient transport studies.

6. The ad hoc approach is a research-only approach where basins would be defined at random subareas, perhaps preserving some minimum measure. These random subareas would then be used to simulate runoff and these results compared to observations on the same watershed. Patterns that best agree with observations would be saved and analyzed to determine what physical features are common to “good” subdivisions (i.e. iso-temporal, iso-characteristic, etc.)

This research examines an iso-characteristic approach based on sub-basin areas. Area is the principal scale measure common in all hydrologic studies; it is usually available. The report by Rousel and others (2006) illustrated that different analysts, and diferrent methods (manual, automated) compute areas to within 10%; thus, area represents a reasonably consistent metric.

CHAPTER 3

METHOD OF ANALYSIS

3.1. Study area and data collection

Five sets of watersheds in Central Texas with USGS streamflow-gaging stations were selected for this study: Onion Creek, South Mesquite, Little Fossil, Olmos Creek, and Trinity Basin – North. The supporting data for each watershed are located within database modules: Austin, Dallas, Fort Worth, San Antonio, and Smallruralsheds, respectively. All modules with the exception of Smallruralsheds are named according to the city or area where the watershed is located. The Smallruralsheds module contains a cluster of intensive monitored small rural watershed study units within the Brazos River, Colorado River, San Antonio River, and Trinity River basins of Texas. The organization of the data and modular structure are described in Asquith and others (2004). Drainage areas for these watersheds range from approximately 12 to 160 square miles, main channel lengths range from approximately 9 to 48 miles, and dimensionless main channel slope are from approximately 0.002 to 0.02. Table 3.1 contains background information on each of the five watersheds. Figures 3.1 to 3.5 display the study watersheds on a shaded relief map. The map is constructed from a 30-meter resolution digital elevation model (DEM)

The source elevation data were downloaded from the Texas Natural Resources Information system (TNRIS) website. These data were not seamless and the dipping lines are distinctly displayed on the maps.

The display boundaries were computed by the Unites State Geological Survey (USGS), water resources center in Austin area 2005, using methodologies in Brown and others (2000), and Rousel and others (2006).

Also displayed on the figures are the location of USGS stream flow gages. On each watershed several rain gauges are known to exist, but their exact location is unknown. The data as described in Asquith and others (2006) contained individual gage readings and accumulated weighted precipitation. In some cases, Theissen weights were recorded, but the actual locations are not.

Table 3.1. Physical Characteristics of Study Watersheds

Modules	Watershed	Drainage area (mi^2)	Number of Applicable Rain Gauges	Number Storms Used in Study
Austin	Onion Creek	166	2	2
Dallas	South Mesquite	23	2	6
Fort Worth	Little Fossil	12.3	2	9
San Antonio	Olmos Creek	21.2	2	7
Smallrural	Trinity Basin North Creek	23.43	2	9

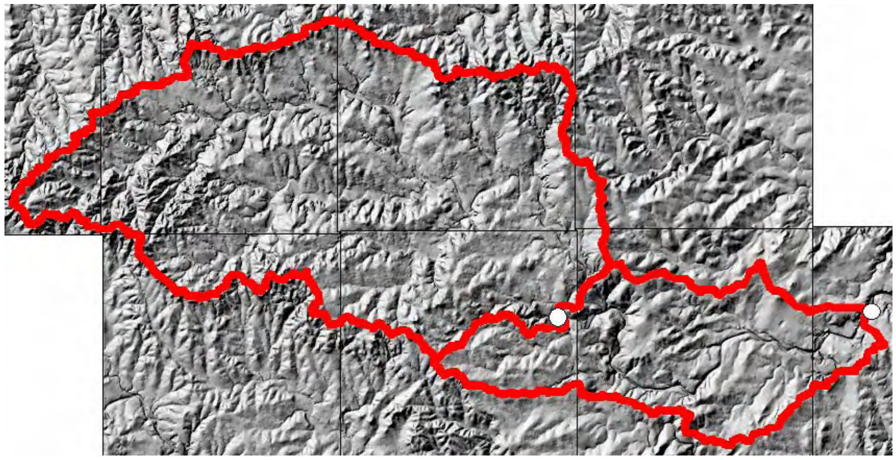

Figure 3.1. Onion Creek Watershed-Austin

Figure 3.1 is the Onion Creek watershed. The watershed contains two stream flow gages and has a total drainage area of 166 mi^2. The dimensionless slope along the main channel length is 0.0026. The map depicts distinct channel features in the lower reaches while in the upper portion (west) a distinct main channel is not visible.

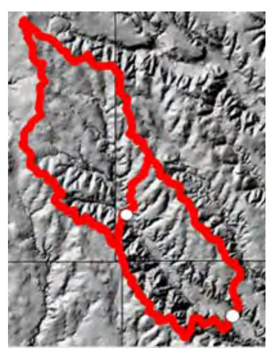

Figure 3.2. South Mesquite Watershed–Dallas

Figure 3.2 is the South Mesquite Creek watershed. The watershed also contains two stream flow gages. Total drainage area of this watershed is 23 mi^2. The dimensionless slope along the main channel length is 0.0022.

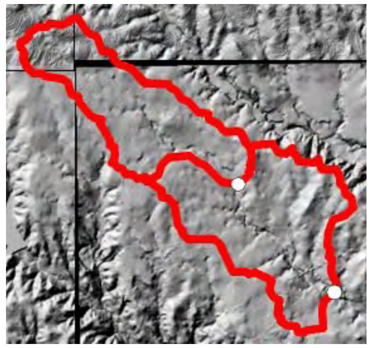

Figure 3.3. Little Fossil Watershed–Fort Worth

Figure 3.3 is the Little Fossil Creek watershed. The watershed also contains two stream flow gages. Total drainage area of this watershed is 12.32 mi^2. The dimensionless slope along the main channel length is 0.005.

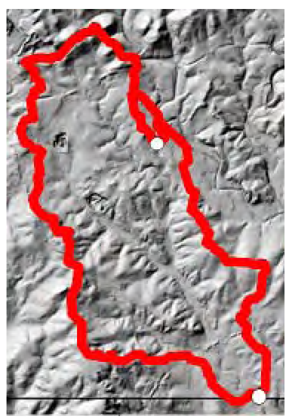

Figure 3.4. Olmos Creek Watershed–San Antonio

Figure 3.4 is the Olmos Creek watershed. The watershed also contains two stream flow gages. Total drainage area of this watershed is 21.29 mi^2. The dimensionless slope along the main channel length is 0.0038.

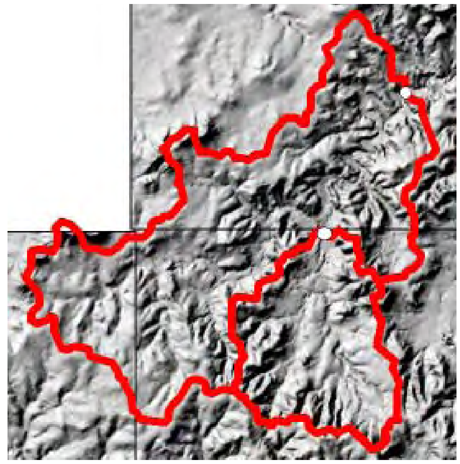

Figure 3.5. Trinity Basin/North–Small Rural

Figure 3.5 is the Trinity Basin/North Creek watershed. The watershed also contains two stream flow gages. Total drainage area of this watershed is 23.43 mi^2. The dimensionless slope along the main channel length is 0.005.

A database of incremental cumulative rainfall values for storms that occurred during the period from 1961 to 1986 were used to input into the HEC-HMS program to construct cumulative rainfall hyetographs for runoff simulations. Figure 3.6 is an example of the HEC-HMS model topology for a 2-subbasin case.

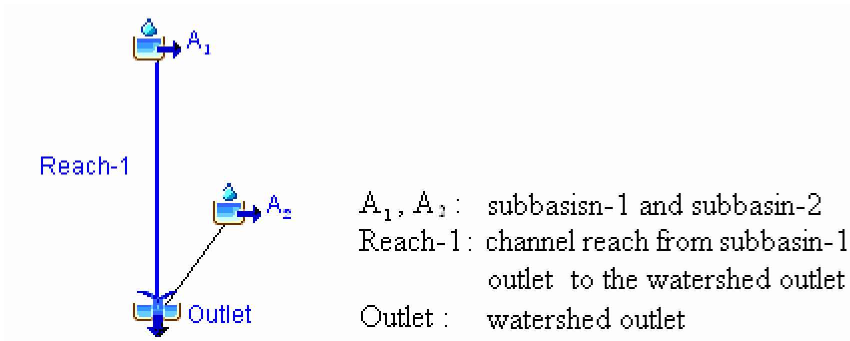

Figure 3.6. HEC-HMS Model

USGS quadrangle maps (1:24000 scale) containing the watershed were used for watershed delineation. To subdivide the selected watersheds into 3, 5, and 7 sub-basins, locations of the sub-basin outlets were chosen. The drainage area upstream of the outlet was measured. The outlet locations were adjusted until the individual sub-basin areas are about the same.

A discussion of “about the same” is in order. The subdivision process was manual, using paper maps and a mechanical planimeter. Iso-area subdivision is non-trivial and small movements of subdivision outlets on the map, required re-delineation. A particular challenge was the treatment of tributaries to main as layer channels. In many cases inclusion of a tributary in one sub-basin contributed too much area to that sub-basin and made exact equal area delineation practically impossible.

This experience alone suggests that prior works that used stream bifurcation rules encountered similar issues and the author speculates that this division challenge is in-part why these [bifurcation] schemes exist.

Figure 3.7 is an example of five subdivision configurations for one of the study watersheds, Trinity Basin-North Creek. Once the sub-basin was established, the physical properties of watersheds such as area, main channel length, main channel slope, etc. were measured. These are watershed properties that are used for estimation of the model parameters. These values are included in Table 3.2 to Table 3.6.

(a) Single basin

(b) 2 Sub-basins

(c) 3 Sub-basins

(d) 5 Sub-basins

(e) 7 Sub-basins

Figure 3.7. Sub-watershed configurations for Trinity Basin- North Creek when subdivided by (a) Single Basin, (b) 2 Sub-basins, (c) 3 Sub-basins, (d) 5 Sub-basins, and (e) 7 Sub-basins.

Table 3.2. Sub-basin Characteristics – Onion Creek (Austin, Texas)

Model Configuration	Sub-basin ID	Area (mi^2)	Main channel length (ft)	Concrete channel length (ft)	Channel slope (ft/ft)
Lumped	A	166	258,403	N/A	0.0026
2-Sub-watershed model (*)	A_1	124	176,018	N/A	0.0031
	A_2	42	82,826	N/A	0.0026
3-Sub-watershed model	A_1	65.42	102,607	N/A	0.0042
	A_2	49.77	85,153	N/A	0.0051
	A_3	50.81	115,829	N/A	0.0035
5-Sub-watershed model	A_1	34.92	87,269	N/A	0.0046
	A_2	33.19	77,748	N/A	0.0048
	A_3	37.81	74,046	N/A	0.0022
	A_4	32.38	61,352	N/A	0.0030
	A_5	27.71	53,948	N/A	0.0037
7-Sub-watershed model	A_1	23.31	54,477	N/A	0.0071
	A_2	23.45	47,072	N/A	0.0033
	A_3	22.86	63,997	N/A	0.0050
	A_4	26.37	51,832	N/A	0.0069
	A_5	20.65	48,923	N/A	0.0052
	A_6	24.72	67,170	N/A	0.0046
	A_7	24.64	48,130	N/A	0.0031

(*) Not iso-area; used stream gauge location for subdivision

Table 3.3. Sub-basin Characteristics – South Mesquite (Dallas, Texas)

Model Configuration	Sub-basin ID	Area (mi^2)	Main channel length (ft)	Concrete channel length (ft)	Channel slope (ft/ft)
Lumped	A	23.00	66,853	N/A	0.0022
2-Sub-watershed model (*)	A_1	13.40	40,408	N/A	0.0035
	A_2	9.60	26,445	N/A	0.0020
3-Sub-watershed model	A_1	7.20	28,296	N/A	0.0042
	A_2	7.90	25,387	N/A	0.0037
	A_3	7.90	20,627	N/A	0.0022
5-Sub-watershed model	A_1	5.59	20,363	N/A	0.0046
	A_2	3.64	15,074	N/A	0.0053
	A_3	4.17	14,280	N/A	0.0028
	A_4	5.00	12,958	N/A	0.0021
	A_5	4.60	13,487	N/A	0.0020
7-Sub-watershed model	A_1	3.02	17,454	N/A	0.0046
	A_2	3.16	11,636	N/A	0.0057
	A_3	3.29	19,411	N/A	0.0055
	A_4	3.93	9,785	N/A	0.0041
	A_5	3.16	9,838	N/A	0.0027
	A_6	3.14	9,626	N/A	0.0027
	A_7	3.30	9,785	N/A	0.0027

(*) Not iso-area; used stream gauge location for subdivision

Table 3.4. Sub-basin Characteristics – Little Fossil (Fort Worth, Texas)

Model Configuration	Sub-basin ID	Area (mi^2)	Main channel length (ft)	Concrete channel length (ft)	Channel slope (ft/ft)
Lumped	A	12.32	49,717	N/A	0.0050
2-Sub-watershed model (*)	A_1	5.50	31,893	N/A	0.0050
	A_2	6.82	17,824	N/A	0.0048
3-Sub-watershed model	A_1	3.93	26,075	N/A	0.0051
	A_2	4.27	23,007	N/A	0.0042
	A_3	4.12	18,035	N/A	0.0052
5-Sub-watershed model	A_1	2.57	18,617	N/A	0.0050
	A_2	2.47	10,948	N/A	0.0049
	A_3	2.40	12,429	N/A	0.0075
	A_4	2.55	13,064	N/A	0.0046
	A_5	2.33	14,016	N/A	0.0057
7-Sub-watershed model	A_1	1.78	13,593	N/A	0.0054
	A_2	1.85	9,626	N/A	0.0042
	A_3	1.87	14,175	N/A	0.0057
	A_4	1.83	12,429	N/A	0.0065
	A_5	1.64	12,165	N/A	0.0044
	A_6	1.62	7,510	N/A	0.0053
	A_7	1.73	14,016	N/A	0.0057

(*) Not iso-area; used stream gauge location for subdivision

Table 3.5. Sub-basin Characteristics – Olmos Creek (San Antonio, Texas)

Model Configuration	Sub-basin ID	Area (mi^2)	Main channel length (ft)	Concrete channel length (ft)	Channel slope (ft/ft)
Lumped	A	21.29	58,179	8,448	0.0038
2-Sub-watershed model (*)	A_1	0.33	6,876	N/A	0.0117
	A_2	20.96	58,179	8,448	0.0038
3-Sub-watershed model	A_1	7.10	37,552	N/A	0.0050
	A_2	6.69	29,354	N/A	0.0066
	A_3	7.50	29,090	8,448	0.0140
5-Sub-watershed model	A_1	4.29	20,680	N/A	0.0084
	A_2	4.14	18,088	N/A	0.0074
	A_3	5.00	18,935	N/A	0.0049
	A_4	3.14	11,900	2,112	0.0022
	A_5	4.72	25,916	15,840	0.0160
7-Sub-watershed model	A_1	3.10	14,439	N/A	0.0111
	A_2	2.98	14,280	N/A	0.0061
	A_3	3.12	17,877	N/A	0.0045
	A_4	2.62	14,545	N/A	0.0051
	A_5	3.05	17,718	N/A	0.0075
	A_6	3.21	16,555	4,752	0.0105
	A_7	3.30	16,660	10,560	0.0048

(*) Not iso-area; used stream gauge location for subdivision

Table 3.6. Sub-basin Characteristics – Trinity North (Small Rural, Texas)

Model Configuration	Sub-basin ID	Area (mi^2)	Main channel length (ft)	Concrete channel length (ft)	Channel slope (ft/ft)
Lumped	A	23.43	61,352	N/A	0.0050
2-Sub-watershed model (*)	A_1	6.82	24,329	N/A	0.0091
	A_2	16.61	61,352	N/A	0.0050
3-Sub-watershed model	A_1	6.82	24,329	N/A	0.0071
	A_2	7.90	28,825	N/A	0.0079
	A_3	8.71	40,990	N/A	0.0042
5-Sub-watershed model	A_1	5.45	18,776	N/A	0.0085
	A_2	5.14	19,040	N/A	0.0098
	A_3	4.76	15,867	N/A	0.0100
	A_4	4.38	14,280	N/A	0.0037
	A_5	3.69	15,074	N/A	0.0053
7-Sub-watershed model	A_1	3.45	18,247	N/A	0.0081
	A_2	3.37	22,478	N/A	0.0045
	A_3	4.35	26,974	N/A	0.0079
	A_4	2.69	16,396	N/A	0.0073
	A_5	3.48	16,396	N/A	0.0041
	A_6	2.64	11,371	N/A	0.0123
	A_7	3.45	15,074	N/A	0.0053

(*) Not iso-area; used stream gauge location for subdivision

3.2. The Hydrologic Modeling System (HEC-HMS)

HEC-HMS program is used to simulate precipitation-runoff processes of the watershed systems. In HEC-HMS, the response of a watershed is driven by precipitation that falls on the watershed, the evapotranspiration and infiltration losses from the watershed. Although HEC-HMS has served different loss models, all models are based on the Hortonian infiltration excess concept. Figure 3.8 is a schematic (block) diagram of the principal hydrologic processes available in HEC-HMS.

In this study, the evapotranspiration is not modeled. At the time scale of this study (event-based, several hours) evaporation data are simply not available, therefore, at this time scale, evaporation is irrelevant. Base flow is also ignored, principally for similar reasons (event-based, short duration.) He (2004) demonstrated for the same database that baseflow models had negligible effect on timing parameters related to storm runoff. This research is essentially concerned with storm runoff response; thus, a decision to ignore baseflow to be consistent with prior work, as well as simplify the study is justified.

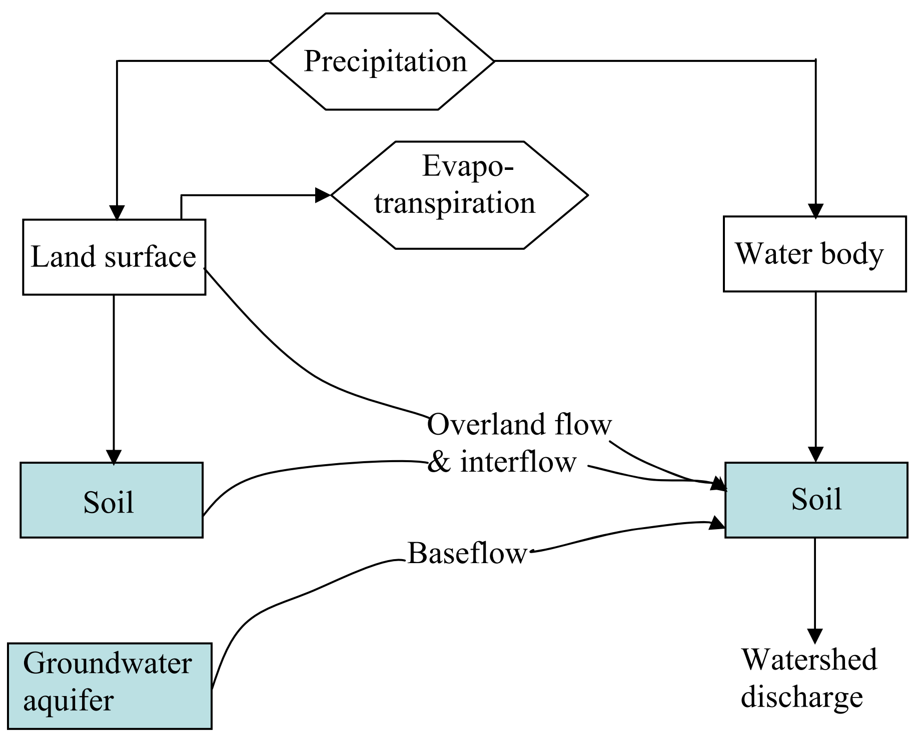

Figure 3.8. Typical HEC-HMS representation of watershed runoff

(Adapted from HEC-HMS Technical Reference Manual, March 2000)

A typical HMS model is made up of three components; a basin model, a meteorologic model, and a control specification model.

3.2.1. Basin model

The basin model contains information describing the hydrologic elements in the basin being modeled. It contains a list of the routing parameters and element connectivity as well as the methods for computing losses, transforming runoff and routing flow in each element. The volume of storm runoff depends on many factors. Volume of rainfall is one of the most important factors. For very large watersheds, the volume of runoff from one storm event may depend on rainfall that occurred during previous storm events. However, the assumption of storm independence is quite common in practice. In addition to rainfall, there are other factors that affect the volume of runoff. A common assumption in hydrologic modeling is that the rainfall available for runoff is partitioned into three compartments: initial abstraction, losses, and direct runoff. There are several methods available in HMS to compute the losses. The Soil Conservation Service (SCS) Curve Number (*CN*) loss model is selected in this research because of its simplicity, entrenchment in practice, and because the *CN* for the watersheds were studied in several prior research projects (TxDOT Report No. 0-2104-2, 0-4696.) and thus, these are established guidelines for the selected watersheds. The SCS *CN* model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad (3.1)$$

where,

P_e = accumulated precipitation excess at time t, mm (in).

P = accumulated rainfall depth at time t, mm (in).

I_a = the initial abstraction (initial loss), mm (in).

S = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation, mm (in).

Asquith and Roussel (2007) used an initial abstraction constant loss model for the same watersheds and CN was found to be a significant explanatory variable for estimate behavior on these watersheds. The initial abstraction, I_a, is typically set at 0.2S, and this relationship is the de-facto standard value for I_a.

Therefore, the cumulative excess at time t is

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (3.2)$$

Runoff will occur when $P > I_a$. The maximum retention, S, and watershed characteristics are related through an intermediate parameter, the curve number (commonly abbreviated CN) as

$$S = \begin{cases} \dfrac{1000 - 10CN}{CN} & (US\ \text{customary}) \\ \dfrac{25400 - 254CN}{CN} & (\text{SI}) \end{cases} \qquad (3.3)$$

CN is an index that represents the combination of a hydrologic soil group and a land use and a treatment class. CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates. Higher curve number reflects higher runoff potential. The CN for a watershed can be estimated as a function of land use, soil type, and antecedent watershed moisture, using tables published by the SCS in

Technical Report 55 (USDA-SCS, 1986). Soils are classified as A, B, C, and D hydrologic group as a group of soil having similar runoff potential. Type A soil has low runoff potential (high infiltration rate), type B soil has moderate infiltration rate, type C has slow infiltration rate, and type D soil has high runoff potential (very slow infiltration rate.) In this research, the hydrologic soil groups of the study watersheds were acquired online at the Natural Resources Conservation Services URL: http://websoilsurvey.nrcs.usda.gov/ and the land uses on the studied watershed were determined using Google Earth. The curve numbers are computed using a weighted *CN* approach, with *CN* of 98 used for the impervious area and the *CN* for other open spaces used for the pervious portion of the area (FHWA-NHI-02-001, 2002). The following equation is used to compute weighted *CN*

$$CN_w = CN_p(1 - f) + f(98) \tag{3.4}$$

in which f is the fraction (not percentage) of imperviousness, CN_w is the weighted curve number, CN_p is curve number for the pervious area. The weighted *CN* of the study watersheds are shown in Table 3.7.

Table 3.7. Estimated *CN* for the study watersheds

Model Configuration	Sub-basin ID	Onion Creek CN	South Mesquite CN	Little Fossil CN	Olmos Creek CN	Trinity North CN
Lumped	A	75	91	85	93	63
2-Sub-watershed model	A_1	75	91	84	83	63
	A_2	73	90	85	93	62
3-Sub-watershed model	A_1	75	92	84	92	63
	A_2	75	91	86	93	63
	A_3	73	89	83	93	62
5-Sub-watershed model	A_1	75	92	84	92	63
	A_2	75	91	86	92	63
	A_3	75	92	86	93	62
	A_4	74	91	85	93	62
	A_5	73	85	81	93	62
7-Sub-watershed model	A_1	75	92	86	87	63
	A_2	75	92	89	91	63
	A_3	75	92	85	92	63
	A_4	75	91	86	93	62
	A_5	75	91	84	93	62
	A_6	73	91	83	93	62
	A_7	73	85	81	93	62

The Soil Conservation Service (SCS) Unit Hydrograph (UH) is chosen in this study for simulating the process of direct runoff of excess precipitation on the study watersheds. The method is based upon average of UHs derived from gaged rainfall and runoff for a large number of small agricultural watersheds throughout the United States. After accounting for losses, the remaining excess precipitation is transformed to the sub-basin outlet where it enters the stream system. Runoff generated in a sub-basin is lumped together and routed to the basin outlet using the SCS Unit hydrograph method. In this method, the temporal distribution of flow at the sub-basin outlet is computed by transforming the SCS dimensionless hydrograph into a dimensional UH based on watershed characteristics times. The basin lag, t_{lag}, defined as the time difference between the center of mass of rainfall excess and the peak of the UH is computed as 0.6 times the time of concentration, t_c. Time of concentration is the time required for a particle of water to flow from the hydraulically most distant point in watershed to the outlet or design point. In unit hydrograph analysis, t_c, is defined as the time difference from the end of excess rainfall to the receding inflection point of the unit hydrograph.

However, in multiple peaked data, these values are difficult to locate. Time of concentration can be estimated as the sum of characteristics times in different flow regimes (McCuen and others, 1986). Equation 3.5 expresses t_c as the sum of characteristics times in sheet flow, shallow concentrated flow, and open channel flow

$$t_c = t_{sheet} + t_{shallow} + t_{channel} \tag{3.5}$$

where,

t_{sheet} = travel time in sheet flow segments over the watershed land surface (min).

$t_{shallow}$ = travel time in shallow flow segments (min).

$t_{channel}$ = travel time in channel segments (min).

TxDOT research project 0-4696-2 suggested that the preferable estimation approaches are the Kirpich-inclusive, specifically the Kerby-Kirpich approach for the study watersheds. Kerby (1959) provided a method to estimate the travel time for sheet flow using the following equation

$$t_s^i = \left[\frac{0.67(L \times N)}{S^{0.5}}\right]^{0.467} \tag{3.6}$$

where,

$t_s^i =$ travel time for sheet flow (overland flow), minutes.

L = length of overland flow, ft.

S = surface slope, ft/ft.

N = retardance coefficient, based on condition of the overland flow surface, given in Table 3.8.

Table 3.8. Average value of retardance coefficient "*N*" (from Kerby, 1959)

Surface cover type	*N*
Pavement (smooth impervious surface)	0.02
Smooth bare packed soil	0.10
Poor grass, cultivated row crops, moderately rough bare surface	0.20
Pasture or average grass	0.40
Deciduos timerland	0.60
Conifer timberland, decidous timeberland with deep forest litter or dense grass	0.80

The length used in equation 3.6 is the straight-line distance measured from the most distant point of the watershed in a direction parallel to the slope until a well-defined channel is reached (0-4696 PSR.) Kerby (1959) stated that overland flow becomes channel flow within 1,200 feet in most cases, thus, L, in equation 3.6 is not expected to exceed 1,200 feet, in fact, in this study, L, is upper bounded to this value. Kirpich (1940) estimated the travel time in shallow concentrated and open channel flow

using the equation

$$t_c^i = 0.0078 L^{0.77} S^{-0.385} \qquad (3.7)$$

where,

t_c^i = travel time for shallow concentrated flow and channel flow, minutes.

L = length of the longest channel from basin divide to outlet, ft.

S = dimensionless main channel slope, ft/ft.

The computed time of concentration should be multiplied by 0.4 and 0.2 for watersheds where the overland flow path is either concrete or asphalt and the channel is concrete lined, respectively (Kirpich, 1940.)

Basin lag (t_{lag}) is the time from the center of mass of the rainfall excess to the peak discharge rate on the runoff hydrograph t_{lag} = .6 t_c. Reach time (t_{reach}) is the time a water particle takes to travel from upstream of the river reach to downstream of the river reach of a watershed. Reach time was calculated using Equation 3.7, where L is the length of the channel reach and S is the dimensionless slope of the channel reach. The time of concentration, basin lag, and reach time used in this study for each watershed is listed in Table 3.9 to 3.13.

Table 3.9. Timing parameters for Onion Creek Watershed

Model Configuration	Sub-basin ID	t_c (min)	t_{lag} (min)	t_{reach} (min)	Routing Path
Lumped	A	1163	698		
2-Sub-watershed model	A_1	819	491		A_1 to A_2
	A_2	499	299	470	Outlet is at A_2
3-Sub-watershed model	A_1	491	295		A_1 to A_2
	A_2	401	240	248	A_2 to A_3
	A_3	574	344	421	Outlet is at A_3
5-Sub-watershed model	A_1	423	254		A_1 to A_2
	A_2	384	230	150	A_2 to A_3
	A_3	490	294	222	A_3 to A_4
	A_4	383	230	319	A_4 to A_5
	A_5	325	195	296	Outlet is at A_5
7-Sub-watershed model	A_1	261	156		A_1 to A_2
	A_2	307	184	279	A_2 to A_4
	A_3	329	198	41	A_3 to A_2
	A_4	254	153	93	A_4 to A_5
	A_5	270	162	214	A_5 to A_6
	A_6	351	211	221	A_6 to A_7
	A_7	319	191	290	Outlet is at A_7

Table 3.10. Timing parameters for South Mesquite Watershed

Model Configuration	Sub-basin ID	t_c (min)	t_{lag} (min)	t_{reach} (min)	Routing Path
Lumped	A	530	318		
2-Sub-watershed model	A_1	278	167		A_1 to A_2
	A_2	252	151	217	Outlet is at A_2
3-Sub-watershed model	A_1	208	125		A_1 to A_2
	A_2	202	121	91	A_2 to A_3
	A_3	208	125	173	Outlet is at A_3
5-Sub-watershed model	A_1	165	99		A_1 to A_3
	A_2	133	80	72	A_2 to A_3
	A_3	154	93	57	A_3 to A_4
	A_4	158	95	123	A_4 to A_5
	A_5	164	98	129	Outlet is at A_5
7-Sub-watershed model	A_1	150	90		A_1 to A_3
	A_2	113	68	80	A_2 to A_4
	A_3	152	91	68	A_3 to A_4
	A_4	112	67	76	A_4 to A_5
	A_5	125	75	90	A_5 to A_6
	A_6	124	74	89	A_6 to A_7
	A_7	125	75	90	Outlet is at A_7

Table 3.11. Timing parameters for Little Fossil Watershed

Model Configuration	Sub-basin ID	t_c (min)	t_{lag} (min)	t_{reach} (min)	Routing Path
Lumped	A	378	227		
2-Sub-watershed model	A_1	220	132		A_1 to A_2
	A_2	158	95	114	Outlet is at A_2
3-Sub-watershed model	A_1	193	116		A_1 to A_2
	A_2	190	114	99	A_2 to A_3
	A_3	152	91	78	Outlet is at A_3
5-Sub-watershed model	A_1	156	94		A_1 to A_2
	A_2	121	73	78	A_2 to A_3
	A_3	116	70	50	A_3 to A_4
	A_4	135	81	52	A_4 to A_5
	A_5	132	79	44	Outlet is at A_5
7-Sub-watershed model	A_1	132	79		A_1 to A_2
	A_2	118	71	75	A_2 to A_3
	A_3	133	80	90	A_3 to A_4
	A_4	121	72	41	A_4 to A_6
	A_5	132	79	61	A_5 to A_6
	A_6	100	60	29	A_6 to A_7
	A_7	132	79	30	Outlet is at A_7

Table 3.12. Timing parameters for Olmos Creek Watershed

Model Configuration	Sub-basin ID	t_c (min)	t_{lag} (min)	t_{reach} (min)	Routing Path
Lumped	A	321	193		
2-Sub-watershed model	A_1	74	45		A_1 to A_2
	A_2	321	193	223	Outlet is at A_2
3-Sub-watershed model	A_1	231	139		A_1 to A_2
	A_2	180	108	42	A_2 to A_3
	A_3	125	75	81	Outlet is at A_3
5-Sub-watershed model	A_1	135	81		A_1 to A_3
	A_2	129	78	119	A_2 to A_4
	A_3	150	90	67	A_3 to A_4
	A_4	135	81	166	A_4 to A_5
	A_5	91	55	53	Outlet is at A_5
7-Sub-watershed model	A_1	102	61		A_1 to A_3
	A_2	119	72	117	A_2 to A_4
	A_3	149	89	95	A_3 to A_5
	A_4	127	76	82	A_4 to A_5
	A_5	127	76	37	A_5 to A_6
	A_6	99	60	80	A_6 to A_7
	A_7	97	58	96	Outlet is at A_7

Table 3.13. Timing parameters for Trinity Basin – North Watershed

Model Configuration	Sub-basin ID	t_c (min)	t_{lag} (min)	t_{reach} (min)	Routing Path
Lumped	A	321	193		
2-Sub-watershed model	A_1	142	85	113	A_1 to A_2
	A_2	321	193		Outlet is at A_2
3-Sub-watershed model	A_1	154	92	120	A_1 to A_3
	A_2	165	99	189	A_2 to A_3
	A_3	255	153		Outlet is at A_3
5-Sub-watershed model	A_1	122	73	62	A_1 to A_4
	A_2	120	72	73	A_2 to A_3
	A_3	107	64	106	A_3 to A_4
	A_4	135	81	79	A_4 to A_5
	A_5	125	75		Outlet is at A_5
7-Sub-watershed model	A_1	124	74	39	A_1 to A_2
	A_2	169	101	72	A_2 to A_5
	A_3	158	95	40	A_3 to A_6
	A_4	120	72	65	A_4 to A_3
	A_5	142	85	114	A_5 to A_7
	A_6	85	51	53	A_6 to A_5
	A_7	125	75		Outlet is at A_7

When the runoff enters a river reach, it is routed to the next downstream element using a routing method. The routing models available in HEC-HMS include: Lag; Muskingum; Modified Puls (storage routing); Kinematic-wave; and Muskingum-Cunge. Each of these models computes a downstream hydrograph, given an upstream hydrograph as an input condition. Each does so by a variety of considerations for continuity and momentum. The Lag routing method is selected for this research. In HEC-HMS, each river reach is subdivided into multiple sub-reaches, and the Lag routing method is applied for each sub-reach. The subdivision of a routing reach into sub-reaches improves numerical stability. Because the length of the sub-reaches for the study sub-basins are relatively small, the routing tends towards pure translation, therefore, Lag routing is considered adequate (Dooge, 1973). Also, the Lag model is a special case of other models, as its results can be duplicated if parameters of those other models are carefully chosen. For example, if X = 0.50 and K = Δt in the Muskingum model, the computed outflow hydrograph will equal the inflow hydrograph lagged by K (HEC-HMS Technical Reference Manual, 2000.) Lag routing is widely used, especially in urban drainage channels, and is considered adequate for this study.

3.2.2. Meteorologic model

The meteorologic model (precipitation model) contains all information describing time varying input. In this research, the precipitation is observed rainfall from a historical event. These rainfall data were input and stored in the database by Asquith and others (2004). Because the rainfall data tabulated with date and time and the accumulated rainfall are not uniformly spaced, they were converted to a 5-minute interval for subsequent analysis. The arithmetic-mean method is used to determine areal average rainfall for all sub-watersheds because the rainfall observations from only two gages are available and the measurements from each gaging station do not differ greatly from the mean. The limit of the arithmetic-mean method is it only is satisfactory if the gages are relatively uniformly distributed over the area. If there are three or more gages then the Theissen method (nearest-neighbor weighting) can be used. The Theissen polygon method is inflexible because a new Theissen network must be constructed each time if there is a change in the gage network, such as when data are missing from one of the gages. Also, the Theissen method does not directly account for orographic influences in rainfall.

3.2.2. Control specification model

The control specification model is used to specify simulation start and end times, and routing intervals. The control model plays an important role in HMS modeling because in addition to defining simulation parameters it serves to tie the routing process to reality. Actual date and times are used in reporting simulation results. One minute routing interval (time step) could be used for the simulation; however, this may provide unnecessary resolution. If the program were used for longer duration events or continuous simulation, a large time step would prevent excess output and would reduce simulation time. To ensure that the peak of the hydrograph is captured, an appropriate time step is computed. There are several approaches to compute a time step. Harris County Design Manual recommends a time step of the time to peak, T_p, divided by 10. Herrmann (2007) recommends a practical way of computational time step size by T_p /5. A time step that yields between 5 to 10 points on the rising limb of the unit hydrograph for each sub-basin is usually adequate (HEC-HMS Technical Reference Manual, 2000.) In this study, the time step is calculated by dividing the minimum time of concentration of each sub-basin by 10. Because the minimum time of concentration of the smallest sub-basin is 51 minutes, this yields a minimum approximate time step of 5 minutes. For simplicity, the routing interval used for all sub-basin is 5 minutes. The 5 minutes time step is adequate for the definition of the ordinates on the rising limb of the SCS UH, which is less than 29% of t_{lag} (HEC-HMS Technical Reference Manual, 2000.)

CHAPTER 4

DISCUSSION OF RESULTS

Fundamental to the design of drainage facilities are analyses of peak rates of runoff, volumes of runoff, and time distribution of flows. Large errors in the estimations result in a structure that is either undersized, which could cause drainage problems, or oversized, which is more costly than necessary. Thus, three metrics are used in this study to evaluate the difference between the simulated and observed runoff hydrograph peak flows, runoff volumes, and times to peak. These metrics are used to compare different model structures to each other as well as to observed results.

Metrics

These metrics were used to evaluate the subdivision models. All of the metrics use the concept of error or relative error. The first metric is simply an arithmetic mean of relative errors (in percent)

$$AVG = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\left|X_S - X_O\right|}{X_O}\right)_i \qquad (4.1)$$

where X_S and X_O are simulated values (Q_P, T_P, or V) and observed values (Q_P, T_P, or V) and N is the total number of storm event used. Ideally this metric should be zero, and the sign of the metric helps convey a systematic bias. The second metric is a relative root-mean square error (in percent), again based on relative error

$$RRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_S - X_O}{X_O}\right)_i^2} \qquad (4.2)$$

Ideally this metric should also be zero, and does not convey a systematic bias. For time-series type comparison, these *RRMSE* metrics are sensitive to large deviations and relatively insensitive to small deviations. The last metric, unique to this research, is similar to the acceptance criteria approach of Cleveland and others (2006). A metric called minimum count, *MIN_COUNT*, is simply a count of the number of storms for which a particular subdivision performs best (better than the other configurations for that watershed). For example, suppose data for a given watershed represents five storms. Further suppose there are five different subdivision configurations. If, in this hypothetical case, the 3-subdivision configuration has smaller *AVG* and *RMSE* than all other configurations for 2 of the 5 storms, then *MIN_COUNT* for 3-subdivision configuration is assigned the value 2. These metrics are shown in Tables 4.1 to 4.3.

Table 4.1. Summary of Peak Discharge Analysis

Watershed	Peak Discharge	No. Subdivisions					Selected No. Subdivisions
		1	2	3	5	7	
Onion	*AVG (%)*	200.06	285.30	324.68	281.96	331.20	1
	RRMSE (%)	233.08	294.30	366.57	313.13	367.94	1
	MIN_COUNT	2	0	0	0	0	1
South Mesquite	*AVG (%)*	9.67	5.00	16.04	27.63	9.13	2
	RRMSE (%)	16.47	12.09	20.78	32.53	14.50	2
	MIN_COUNT	2	3	1	0	0	2
Little Fossil	*AVG (%)*	78.52	98.97	85.48	123.41	97.63	1
	RRMSE (%)	189.92	214.92	203.43	258.12	224.63	1
	MIN_COUNT	5	2	0	2	0	1
Olmos	*AVG (%)*	244.10	240.92	246.95	149.12	261.98	5
	RRMSE (%)	333.61	331.35	367.80	239.54	382.17	5
	MIN_COUNT	0	0	1	6	0	5
Trinity North	*AVG (%)*	14.42	22.96	17.70	28.83	10.06	7
	RRMSE (%)	72.22	72.90	67.85	74.15	62.77	7
	MIN_COUNT	2	0	0	3	4	7

Table 4.2. Summary of Runoff Volume Analysis

Watershed	Runoff Volume	No. Subdivisions					Selected No. Subdivisions
		1	2	3	5	7	
Onion	*AVG (%)*	520.10	432.31	465.07	467.38	465.56	2
	RRMSE (%)	662.52	538.34	586.73	589.33	587.29	2
	MIN_COUNT	0	1	1	0	0	2, 3
South Mesquite	*AVG (%)*	3.72	5.63	0.51	0.45	0.43	7
	RRMSE (%)	21.82	18.90	16.52	17.24	16.44	7
	MIN_COUNT	3	1	1	1	0	1
Little Fossil	*AVG (%)*	107.48	104.54	99.59	100.50	105.56	3
	RRMSE (%)	218.30	223.19	223.15	224.10	229.74	1
	MIN_COUNT	4	1	2	0	2	1
Olmos	*AVG (%)*	267.83	263.85	244.71	243.75	231.39	7
	RRMSE (%)	305.66	301.46	288.12	287.03	273.06	7
	MIN_COUNT	0	0	0	0	7	7
Trinity North	*AVG (%)*	33.34	20.22	20.01	17.96	18.29	5
	RRMSE (%)	87.92	72.62	68.93	67.81	68.00	5
	MIN_COUNT	0	1	4	4	0	3, 5

Table 4.3. Summary of Time to Peak Analysis

Watershed	Time to Peak	No. Subdivisions					Selected No. Subdivisions
		1	2	3	5	7	
Onion	*AVG (%)*	26.80	22.98	18.74	29.77	25.01	3
	RRMSE (%)	33.45	25.20	23.32	32.40	27.11	3
	MIN_COUNT	0	0	2	0	0	3
South Mesquite	*AVG (%)*	2.76	2.30	0.12	2.77	3.87	3
	RRMSE (%)	9.10	10.09	8.49	11.05	11.96	3
	MIN_COUNT	1	1	1	1	2	7
Little Fossil	*AVG (%)*	6.79	2.03	11.56	12.15	10.18	2
	RRMSE (%)	10.64	13.55	34.91	25.62	23.02	1
	MIN_COUNT	1	5	1	0	2	2
Olmos	*AVG (%)*	15.15	15.87	13.34	8.30	8.49	7
	RRMSE (%)	21.61	23.13	17.27	11.84	10.68	7
	MIN_COUNT	0	0	1	2	4	7
Trinity North	*AVG (%)*	9.20	9.47	13.70	13.95	11.22	1
	RRMSE (%)	31.08	31.36	33.97	34.98	33.22	1
	MIN_COUNT	4	3	1	0	1	1

Evaluating the Results

It can be seen from the above tables that there is no single watershed discretization scheme that performs optimally of all observed storms on a particular watershed. In other words, there is no consistent pattern on whether lumped or multiple subbasins produce superior results.

Figures 4.1, to 4.4 are illustrations of the favorable and unfavorable results of the observed and simulated runoffs for two of the representative watersheds. In cases where runoff volume simulated and observed are close (favorable predictions,) there is no apparent significant difference among the hydrographs. In many storms, the runoff generated in the model did not reproduce runoff volume close to observed results (unfavorable predictions).

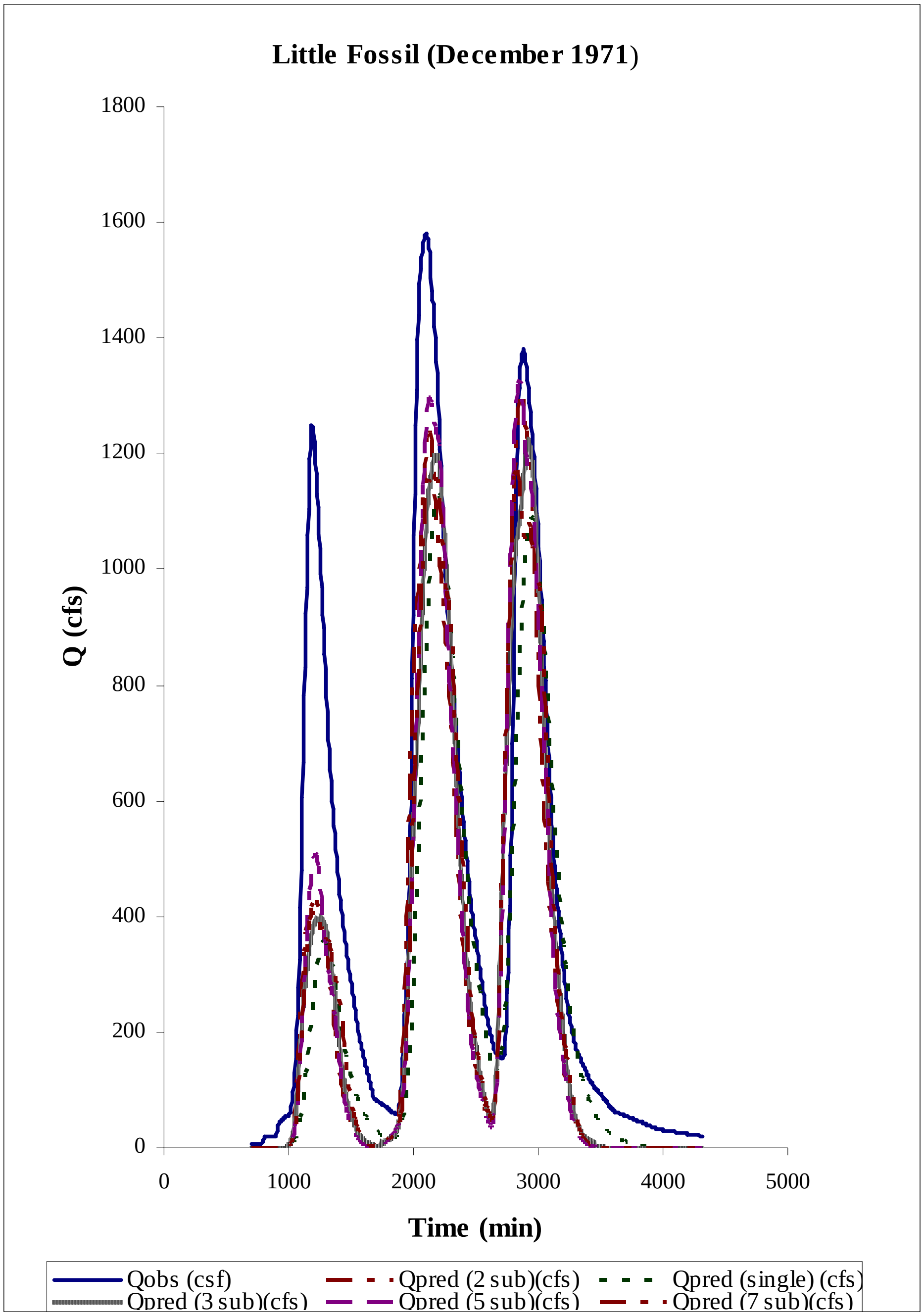

Figure 4.1. Simulated and observed hydrographs (Little Fossil 12/1971)

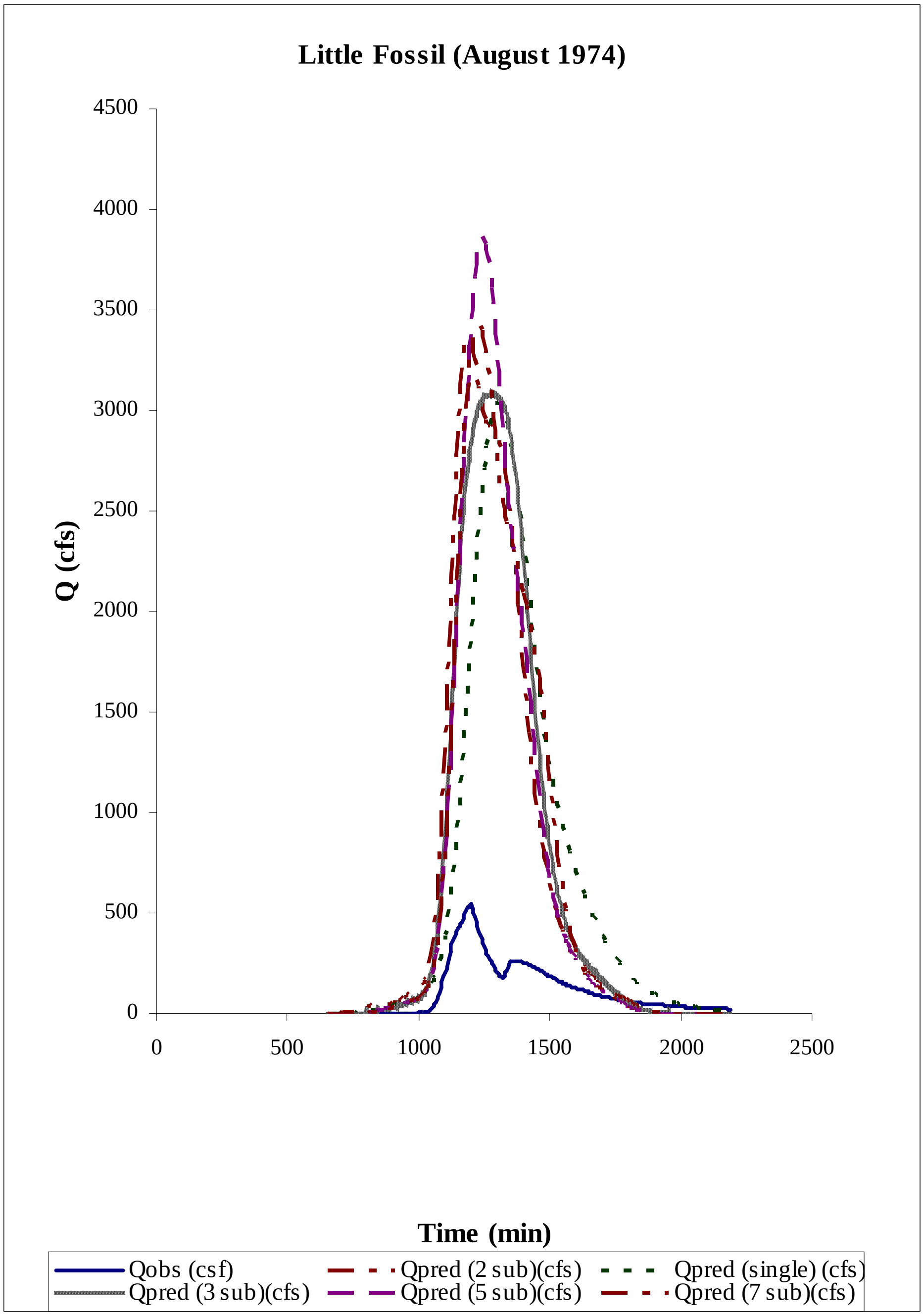

Figure 4.2. Simulated and observed hydrographs (Little Fossil 8/1974)

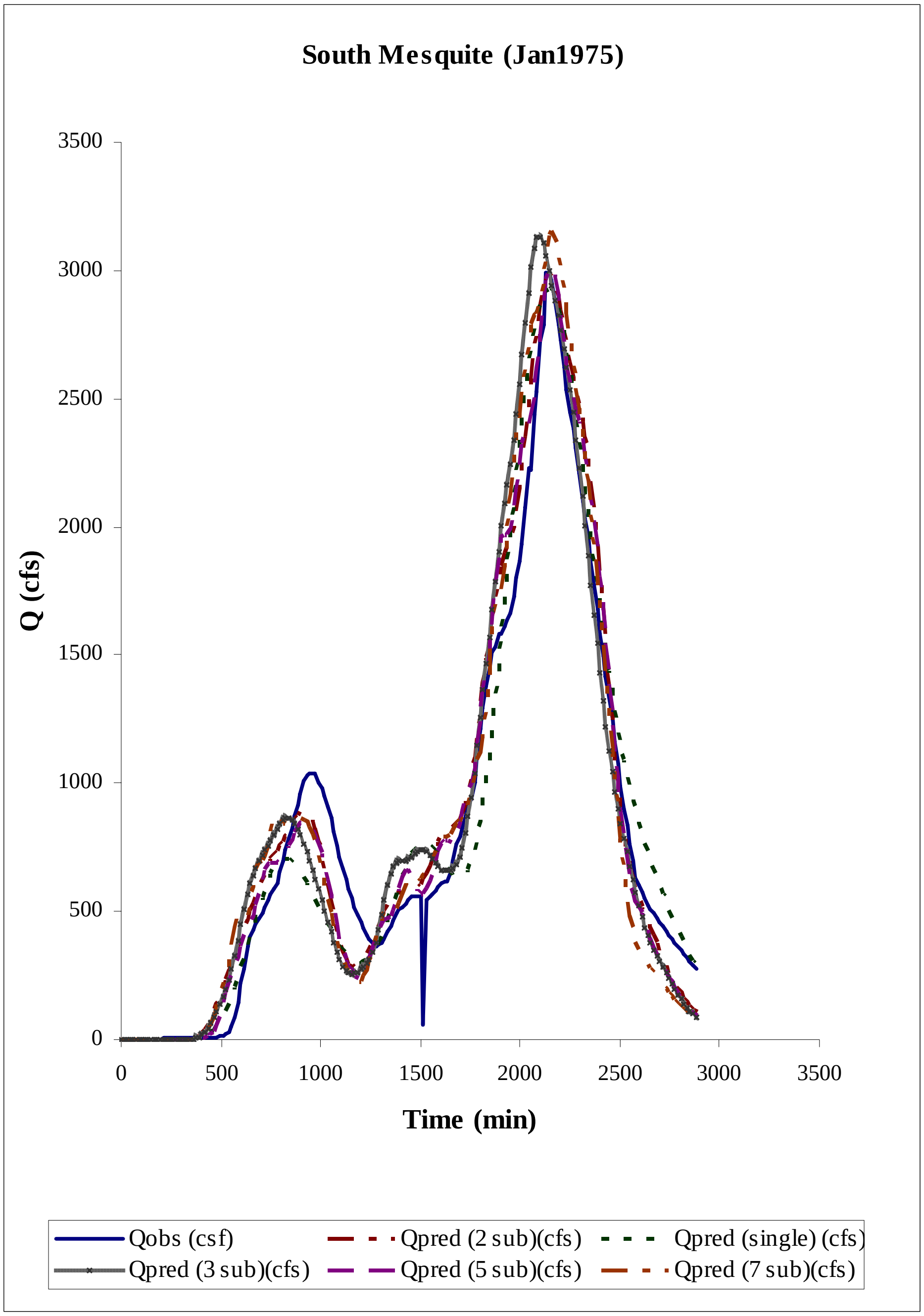

Figure 4.3. Simulated and observed hydrographs (South Mesquite 1/1975)

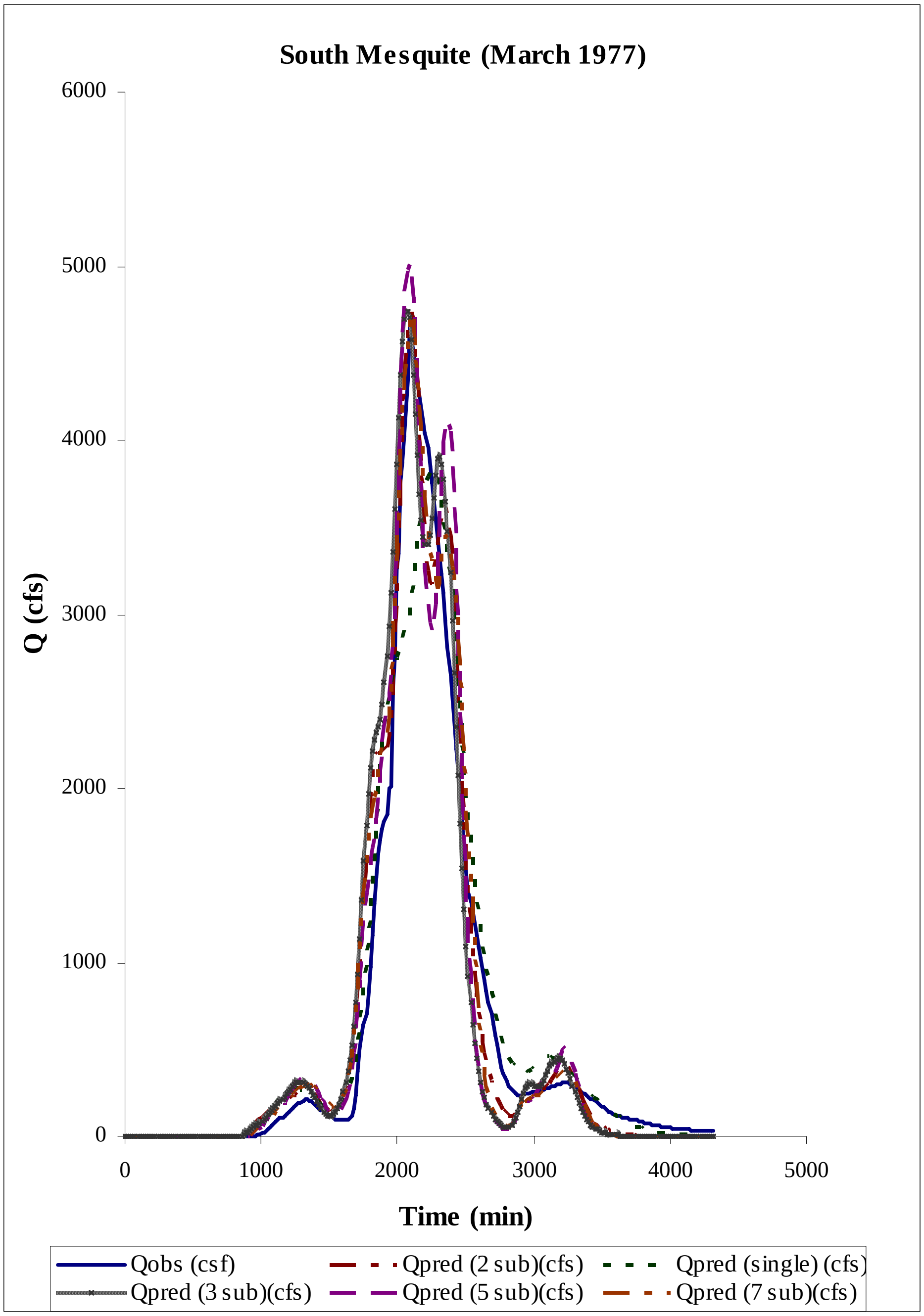

Figure 4.4. Simulated and observed hydrographs (South Mesquite 3/1977)

It can be seen from Figures 4.1, 4.3, and 4.4 that there is no significant difference between the simulated runoff hydrographs for the subdivision and the single basin schemes and the observed hydrographs. The reason is the spatial variability of the watershed is not large enough for the simulation results to be sensitive to the selected subdivision scheme. The use of soil type and land use properties to determine spatial variability is plausible because they are the major factors considered when estimating runoff curve numbers which HEC-HMS uses to estimate the volume of runoff. In this study, the area weighted mean curve number was almost identical across a watershed for all subwatershed scenarios. This finding results in little variation in the total runoff volumes between the subwatershed configurations. The curve number for every unique soil and land use combination in the study watersheds was estimated assuming good hydrologic condition; however, this condition might not be true for all watersheds. Until the appropriate CN of the subbasin is accurately determined and incorporated into models, the results may never be satisfactory.

Figure 4.2 is an example of an unfavorable prediction. Similar results were found on the Onion Creek (Austin) and the Trinity Basin – North (rural area). The quantity of simulated runoff hydrograph is not equal to the observed flow as shown in this figure. It is likely explained by incomplete or missing raingage data. These data were hand-entered from written reports and therefore, data might have been lost during the entry phase or lost in the original data collections (Williams-Sether and others 2004). Also, the assumption that these rainfall amounts were representative of rainfall across the drainage area might not be valid. The actual rainfall amounts might not be distributed over the entire watershed. The geographic location of the watershed is also a significant factor which affects the runoff generation. The presence of site-specific water impoundments as reservoirs or ponds is inclusive.

The South Mesquite January 1975 hydrographs (Figure 4.3) are much more uniform.

They fit the assumptions of unit hydrographs better than the March 1977 hydrographs (Figure 4.4). This is evident by the failure of the March 1977 lumped model to maintain the shape of the observed hydrograph. In most cases, when hydrographs of subdivision are compared to the single basin, the pattern of peak discharge is similar to the finding in earlier studies. The peak discharge of a single basin is less than the subdivision peak. The peak discharge increased very little between the single and the subdivision scenarios in most cases indicating that the peak flow component is relatively insensitive to changes in the number of subwatersheds. This result implies that the model-predicted runoff is not heavily dependent on the degree of watershed subdivision. These findings are consistent with the results of Bingner et al. (1997), FitzHugh and MacKay (2000), and Jha (2002).

Also, regardless of subdivision, with the exception of few storms, the peak discharges in simulated and observed occur almost at the same times which supports the utility the Kerby-Kirpich approach suggested in TxDOT research project 0-4696-2.

As an important note, the models were intentionally left uncalibrated with respect to observed runoff behavior. In this sense the models represent engineering analyst judgment as would be applied in ungaged conditions. This comparison structure was chosen because the scope of the research was to evaluate the enhanced or diminished prediction value on watershed modeling as a function of subdivision. The author acknowledges that if each subdivision model were calibrated on a storm-by-storm basis, the models with greater subdivision count would likely outperform the lumped (single basin) models in nearly every case. The reason for this enhanced performance is because the increased subdivision count adds degrees of freedom to the calibration procedure; as in regression, such additional explainatory variables, regardless of how insignificant, always improve the model "fit" to the data better than a more parsimonious case.

As an example, South Mesquite watershed’s January 1975 stream flow data was used to calibrate the following parameters: *CN*, subbasin lag, and routing lag time. The calibration procedure was automated using a systematic search strategy and an objective function based on squared error in peak flow, volume, and time to peak. The search converged to a parameter set that represents at least a local minimum for the selected objective function. Initial curve numbers for South Mesquite watershed were 91 (lumped) or 85-92 (distributed); calibrated values were 97 (lumped) or 82-97 (distributed). The calibrated subbasin lag and routing lag time for each subdivision scheme are close to the initial values. The calibrated values presented in Table 4.4 and Table 4.5 were used to simulate runoff hydrographs for the January 1975 rainfall event of the South Mesquite watershed.

Table 4.4. Initial and calibrated CN (South Mesquite)

Model Configuration	Sub-basin ID	Initial CN	Calibrated CN	Percent Change (%)
Lumped	A	91	90	-1.10
2-Sub-watershed model	A_1	91	89	-2.20
	A_2	90	86	-4.44
3-Sub-watershed model	A_1	92	96	4.35
	A_2	91	84	-7.69
	A_3	89	83	-6.74
5-Sub-watershed model	A_1	92	91	-1.09
	A_2	91	90	-1.10
	A_3	92	91	-1.09
	A_4	91	84	-7.69
	A_5	85	82	-3.53
7-Sub-watershed model	A_1	92	98	6.52
	A_2	92	86	-6.52
	A_3	92	87	-5.43
	A_4	91	86	-5.49
	A_5	91	86	-5.49
	A_6	91	87	-4.40
	A_7	85	82	-3.53

Table 4.5. Initial and calibrated t_{reach} (South Mesquite)

Model Configuration	Sub-basin ID	Initial t_{reach} (min)	Calibrated t_{reach} (min)	Percent Change (%)
Lumped	A	N/A	N/A	N/A
2-Sub-watershed model	A_1			
	A_2	217	250	15.21
3-Sub-watershed model	A_1			
	A_2	91	92	1.10
	A_3	173	174	0.58
5-Sub-watershed model	A_1			
	A_2	72	73	1.39
	A_3	57	40	-29.82
	A_4	123	141	14.63
	A_5	129	125	-3.10
7-Sub-watershed model	A_1			
	A_2	80	81	1.25
	A_3	68	69	1.47
	A_4	76	77	1.32
	A_5	90	91	1.11
	A_6	89	90	1.12
	A_7	90	91	1.11

For the January 1975 event, the simulated time to peak for the single and 2-subbasin match observed exactly, the time to peak for 3-subbasin, 5-, and 7-subbasin are within 2% and 0.7% of observed, respectively. Additionally, the simulated runoff volume for the single basin is within 1.8% of the observed runoff while runoff volumes for other subdivision are 7% less than observed runoff. The simulated peak flow of the 7-subbasin model is approximately 2% less than observed flow while the single and other finer subdivisions are with in 5% of observed. Figure 4.5 illustrates the calibrated result of the observed and simulated runoffs for the January 1975 event. Additionally, a validation test was performed for the March 1977 event using the “optimal” parameters obtained from the January 1975’s calibration. As shown is Figure 4.6, the simulated flows of the 7-subbasin model compared well with the observed flow. However, the single basin model performed more poorly than the subdivision models. It can be concluded that although the calibrated version was more accurate than the uncalibrated version, the analyses were not be able to indicate which subdivision schemes perform best.

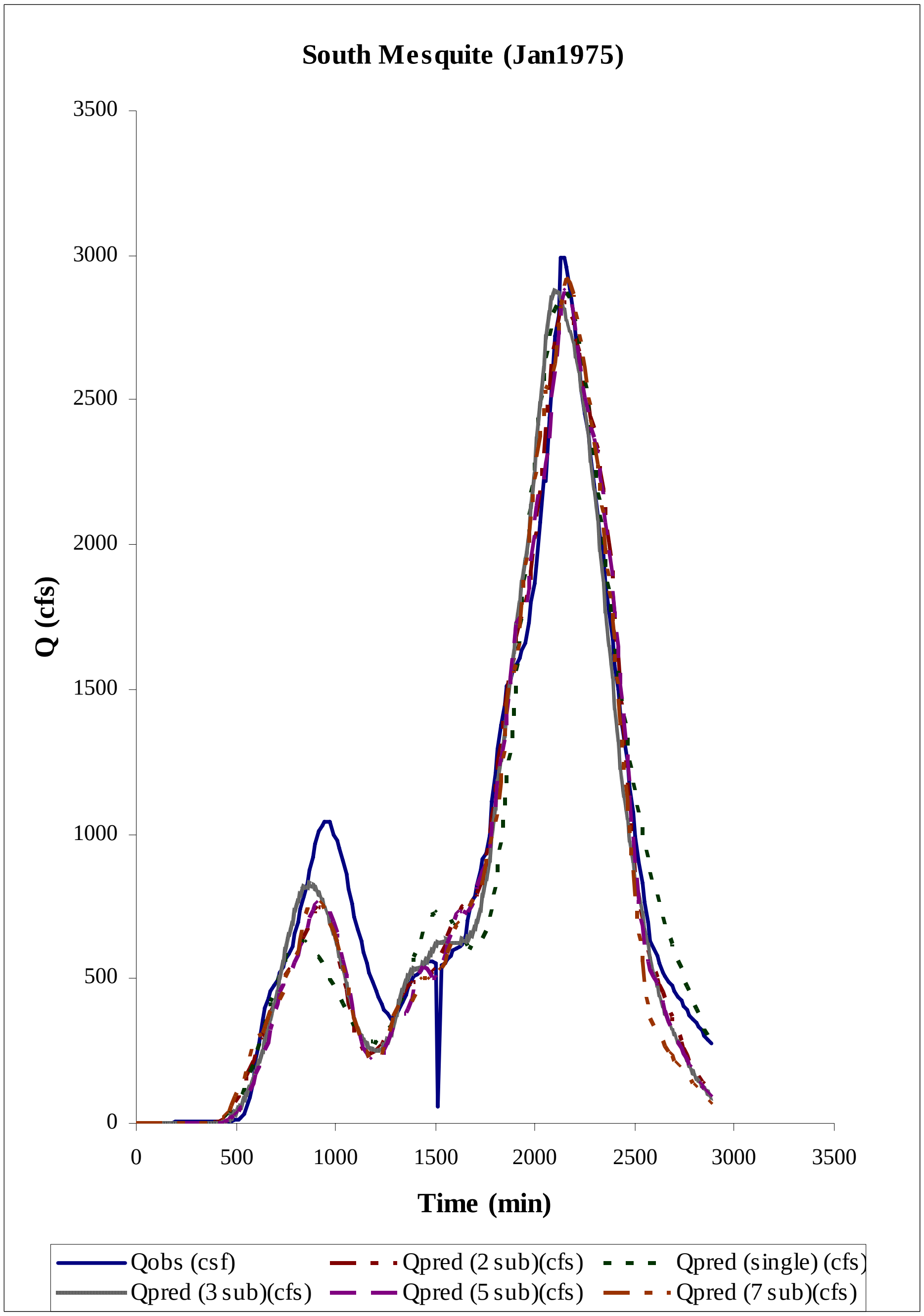

Figure 4.5. Simulated and observed hydrographs (South Mesquite 1/1975-Calibrated)

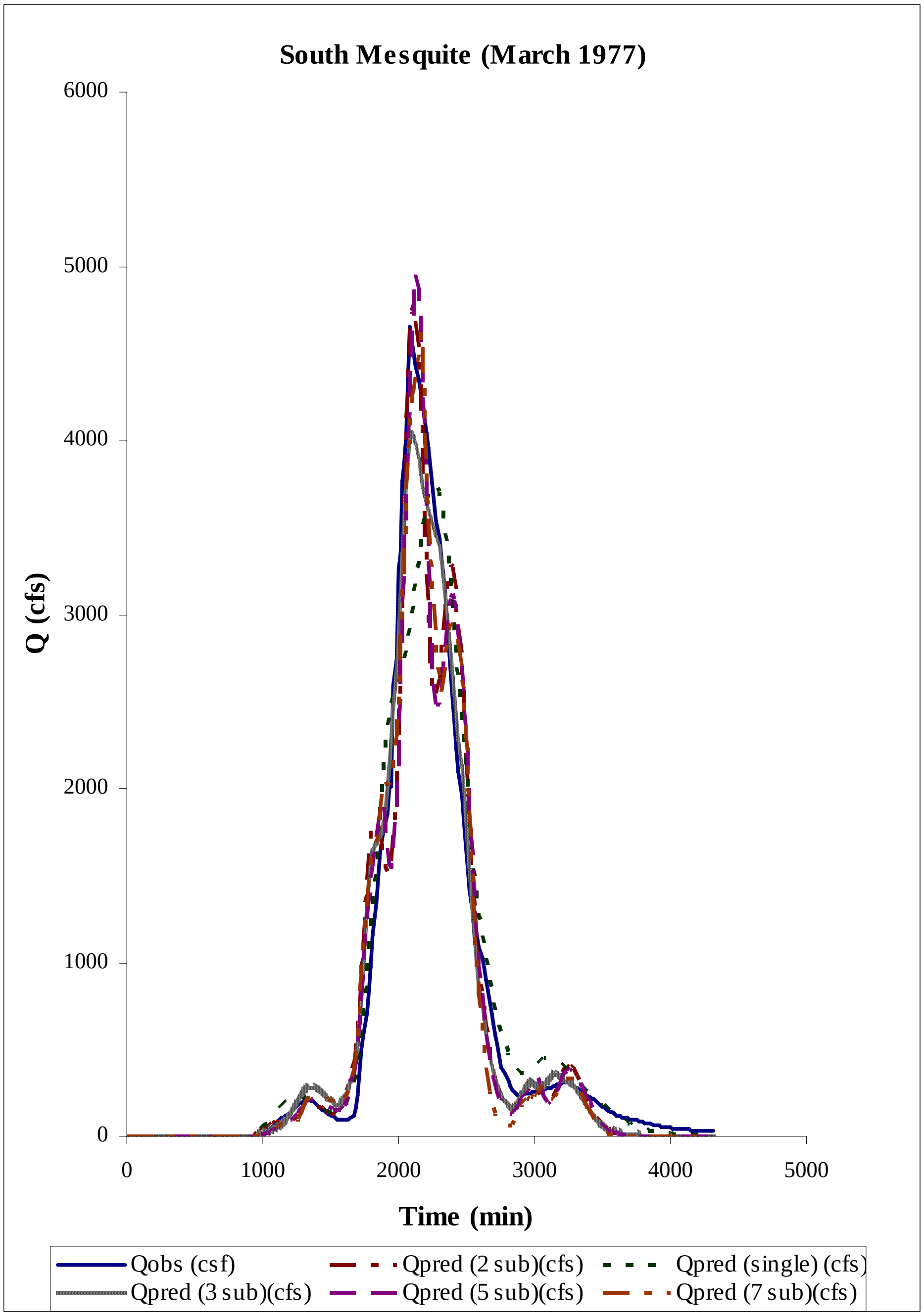

Figure 4.6. Simulated and observed hydrographs (South Mesquite 3/1977-Calibrated)

CHAPTER 5

CONCLUSIONS

Runoff hydrographs that were developed for the Onion Creek, South Mesquite, Little Fossil, Olmos Creek, and Trinity Basin-North watersheds were used to determine the affects that number of sub-watersheds had on the runoff hydrographs. It was found that the increase in the number of sub-watersheds does not significantly affect the simulated runoff hydrograph. The surface runoff is directly related to the curve number which is one of the most important characteristics of the watershed. The appropriate CN of the sub-basin should be accurately determined and incorporated into the hydrological model, or else, the results may never be satisfactory.

This study also shows that none of the subdivision schemes were able to accurately simulate peak flows or runoff volumes from individual events. However, the study shows somewhat better in predicting the time to peak. In general, this study, as performed, indicates that unless the engineer needs internal flows, subdivision simply to gain accuracy does not justify the additional modeling effort. Future research is needed to ascertain if the results obtained in this study will change if using initial abstraction/constant loss model or some runoff generation model that is less sensitive to hyetograph behavior than the *CN* loss model.

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