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

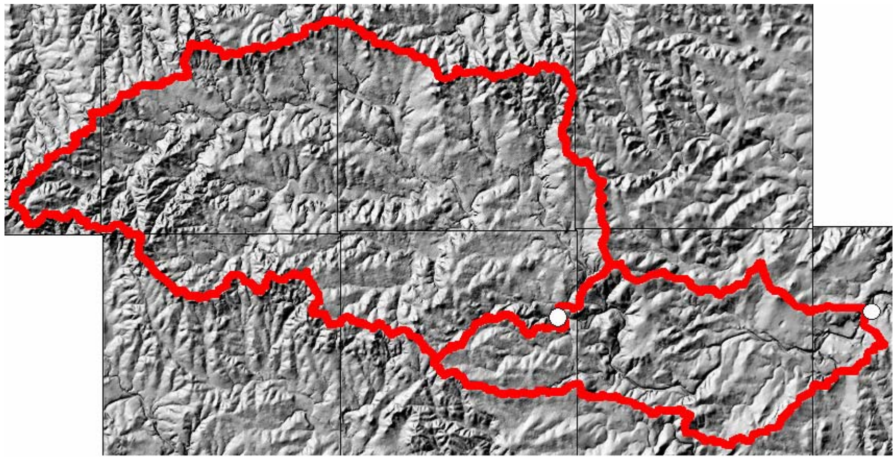


Figure 3.1. Onion Creek Watershed-Austin

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.

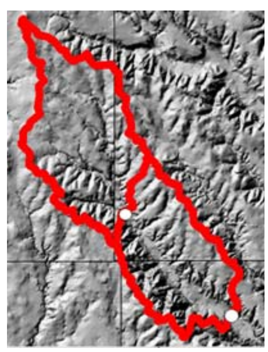


Figure 3.2. South Mesquite Watershed–Dallas

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.

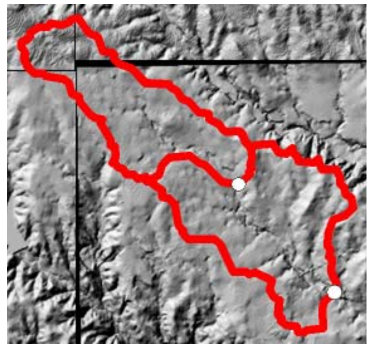


Figure 3.3. Little Fossil Watershed–Fort Worth

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.

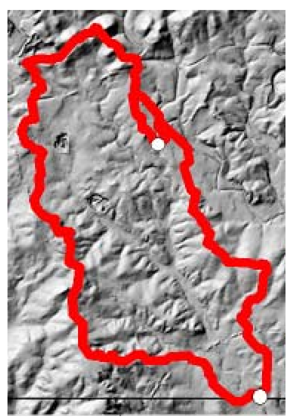


Figure 3.4. Olmos Creek Watershed–San Antonio

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.

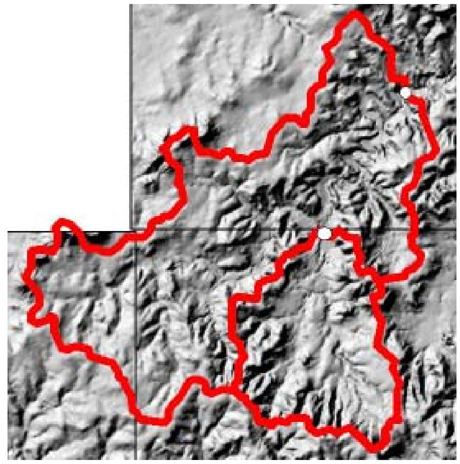


Figure 3.5. Trinity Basin/North–Small Rural

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.

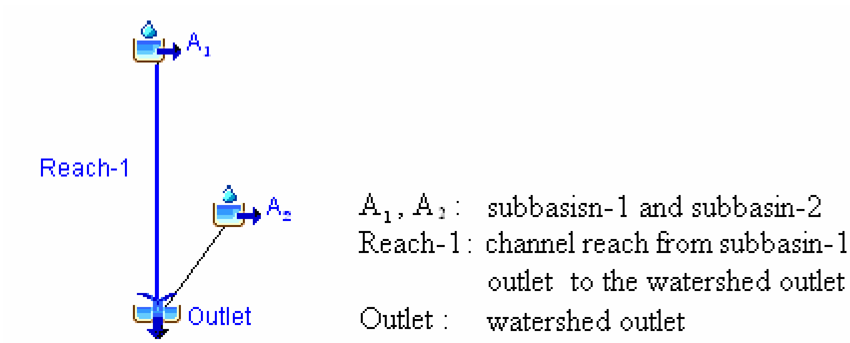


Figure 3.6. HEC-HMS Model

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.

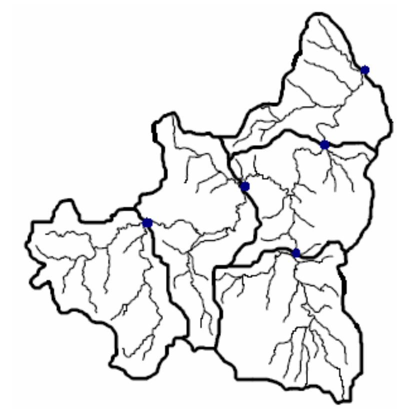
Figure 3.7 is an example of five subdivision configurations for one of the study watersheds, Trinity Basin-North Creek. Once the sub-basin was established, the physical properties of watersheds such as area, main channel length, main channel slope, etc. were measured. These are watershed properties that 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.

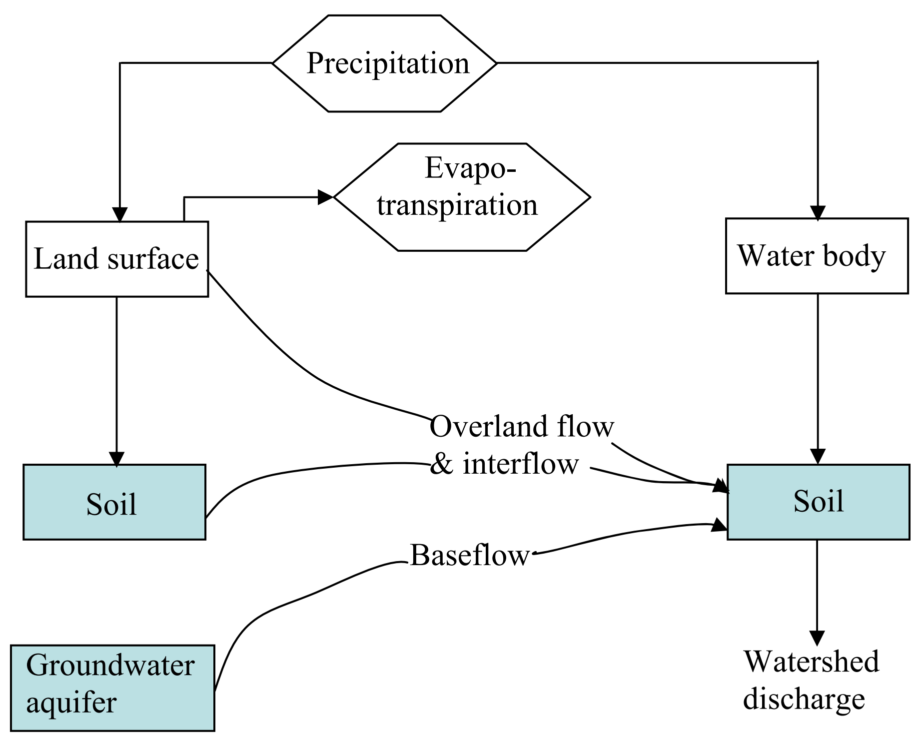


Figure 3.8. Typical HEC-HMS representation of watershed runoff

(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

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

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

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

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 $K = \Delta t$ 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.)