PARAMETERS FOR THE GREEN-AMPT LOSS-RATE FUNCTION FOR SELECT TEXAS WATERSHEDS.

by

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CHAPTER 1

INTRODUCTION

1.1. Background

Some portion of incoming rainfall gets intercepted by the vegetation cover and some portion gets infiltrated into the soil. The soil properties such as hydraulic conductivity and moisture content influence the rate of infiltration process. The remaining portion of the rainfall runs off into the watercourse and subsequently into a wash, creek or stream. This study includes the study of initial loss and infiltration loss parameters. The values for initial loss and infiltration parameters are obtained from an optimization process by the use historically recorded rainfall and runoff data.

For this study rainfall-runoff data recorded for selected watersheds in Texas were used. These watersheds were located primarily in Dallas, Fort Worth, Austin, San Antonio and in rural areas of central to north-central Texas. The watersheds were located for the period of 1957 to 1987.

1.2. The Rainfall-Runoff Loss Process

When it rains, the entire incoming rainfall does not contribute to the surface runoff. A portion of the incoming rainfall is lost to processes such as adhesion of the water on the foliage, storage of water in natural land depressions, and movement of water into the soil profile. These rainfall-runoff loss processes are explained below.

1.2.1 Interception

Interception is defined as "… the part of precipitation that moistens the different surface elements (mainly vegetation) and is temporarily stored in them" (Brutsaert, 2005). The incoming rainfall adheres to the surface of the vegetation by surface tension. When the vegetation cover cannot retain any more water, the incoming rainfall falls off the vegetation as throughfall. The precipitation that reaches the ground through this procedure is called the total depth of the rainfall. The term interception capacity is often used for the amount of water held by the vegetation canopy at the end of the storm.

The amount of abstraction attributable to interception loss depends on the vegetation cover, rainfall intensity, and storm duration. Interception losses are usually larger when the storm event has low to moderate rainfall intensity and long duration of rainfall compared to storm events that have high intensity of rainfall and are short in duration (Brutsaert, 2005). In tall, dense forest vegetation in temperate regions, interception loss has been observed to be of the order of 30−40 percent of the gross precipitation (Gash et al., 1980). In sparse forest, the interception loss is observed around 10−20 percent of the gross precipitation (Gash et al., 1995; Valente et al., 1997).

1.2.2 Depression Storage

Some of the precipitation that reaches the ground is stored in natural depressions such as a puddle or pond from which the water infiltrates or evaporates. Storage in these depressions is called depression storage, which generally is a small fraction of the precipitation depth. For modeling purposes, depression storage together with interception are sometimes referred to as the initial abstraction.

1.2.3 Infiltration

Infiltration is the vertical entry of the water into the soil surface and its subsequent vertical motion through the soil profile (Brutsaert, 2005). It is the most important loss process. The major factors that influence the infiltration rates are soil texture, vegetation cover, the soil surface condition, land use, soil porosity, soil hydraulic conductivity and soil moisture content. Some of the popular infiltration models are the model developed by Green and Ampt (1911), Horton (1933, 1939), and Philip (1957).

Green and Ampt (1911) developed an infiltration loss model based on the physical theory in which the wetting front moves vertically downward. The wetting front is a sharp boundary dividing the soil with saturated moisture content from the underlying soil with lesser moisture content. The water moves vertically downwards from saturated soil to unsaturated soil. Horton (1933, 1939) developed an empirical equation for infiltration capacity based on the observation that the infiltration rate begins at some rate f_o and then decreases exponentially until it reaches a constant saturated infiltration rate f_c. Philip (1957) solved Richard's equation and proposed an equation to estimate the infiltration capacity.

1.3. Objectives

The objectives of the research are as follows:

- To determine the Green-Ampt infiltration model loss parameters for selected Texas watersheds from measured rainfall-runoff data by the use of an optimization procedure in a mathematical model,
- To examine any relation between known infiltration model loss parameters and watershed characteristics such as drainage area, main channel length, basin slope, and main channel slope,
- To compare infiltration initial loss values obtained from the optimization procedure and initial-abstraction values obtained from using the curve numbers,
- To compare the saturated hydraulic conductivity values obtained optimization to the hydraulic conductivity values obtained from the soil survey for the same watersheds, and
- To determine whether the infiltration model loss parameters are sensitive to the development condition or to the geographical location of the watersheds.

The means for determining loss parameters is by the use of an optimization procedure in a mathematical model, the HEC-HMS model, version 3.1.0., developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (Scharffenberg, 2001). The infiltration model known as Green-Ampt infiltration model is used in this research. Some of the frequently used terminologies in this thesis are briefly elucidated in the paragraphs to follow.

1.4. Challenges in Modeling

The rainfall-runoff process is difficult to simulate precisely. The incoming precipitation is not distributed uniformly over the watershed. In addition, the runoff from all portions of the watersheds is not uniform. Betson et al. (1964) suggested that most runoff from a storm is contributed by a small portion of the watershed and that the location and the source of the contributing area is dependent on rainfall intensity, antecedent moisture, and depth of the soil layer. Therefore, the loss parameters may vary within the watershed area.

When optimizing loss parameters for a watershed, each storm event on the watershed may produce a different set of loss parameters. Unver and Mays (1984) discussed the difficulty of determining loss parameters and unit hydrographs from historical rainfall-runoff data because parameter values vary for every storm event on a particular watershed. Therefore, development of a representative mathematical model of rainfall-runoff process in a watershed is challenging.

1.5. Unit Hydrographs

A unit hydrograph is defined as the discharge, produced by a watershed when it receives a unit of excess rainfall distributed uniformly over the watershed at a constant rate for a specified duration of time. The unit hydrograph was originally conceived by Sherman (1932). The unit hydrograph approach can be used to mathematically model the rainfall- runoff process.

The following assumptions are made for the unit hydrograph procedure (Chow et al., 1988, p. 214).

1. The excess rainfall has a constant intensity within the effective duration.

2. The excess rainfall is uniformly distributed throughout the whole drainage area.
3. The base time of DRH (the duration of the direct runoff) resulting from an excess rainfall of given duration is constant.
4. The ordinates of all DRH's of a common base time are directly proportional to the amount if the direct runoff represented by each hydrograph.
5. For a given watershed, the hydrograph resulting from a given excess rainfall reflects the unchanging characteristics of the watershed.

Unit hydrographs can be derived for gaged watersheds from measured rainfall-runoff data. Unit hydrographs derived by this method are valid only for the particular watershed. For ungaged watersheds, synthetic unit hydrographs are used. Common synthetic unit hydrographs are Snyder's unit hydrograph (Snyder, 1938; Gray, 1961), Soil Conservation Service (SCS), dimensionless unit hydrograph (SCS, 1972) and Clark's unit hydrograph (Clark, 1943).

The SCS unit hydrograph method is used to simulate the rainfall-runoff process. "The SCS dimensionless unit hydrograph is a synthetic unit hydrograph in which the discharge is expressed by the ratio of discharge q to the peak discharge q_p and the time by the ratio of time t to the time of rise of the unit hydrograph T_p" (Chow et al., 1988, p. 228). A dimensionless SCS unit hydrograph is shown on Figure 1.1. A triangular unit hydrograph is used to estimate appropriate the values of T_p (in hours) and q_p (in cfs/inch of effective precipitation) used in the dimensionless unit hydrograph.

From research of numerous hydrographs the following relation has been suggested for SCS unitgraphs as

$$q_p = \frac{CA}{T_p} \tag{1.1}$$

where C= 483.4 in English system, and A is the drainage area square miles.

T_p is expressed as

$$T_p = \frac{t_r}{2} + t_{lag} \tag{1.2}$$

where t_r is the excess rainfall duration in hours and t_{lag} is the basin lag time in hours. The basin lag time is defined as the difference in time between the center of mass of rainfall excess and the peak discharge of the unit hydrograph.

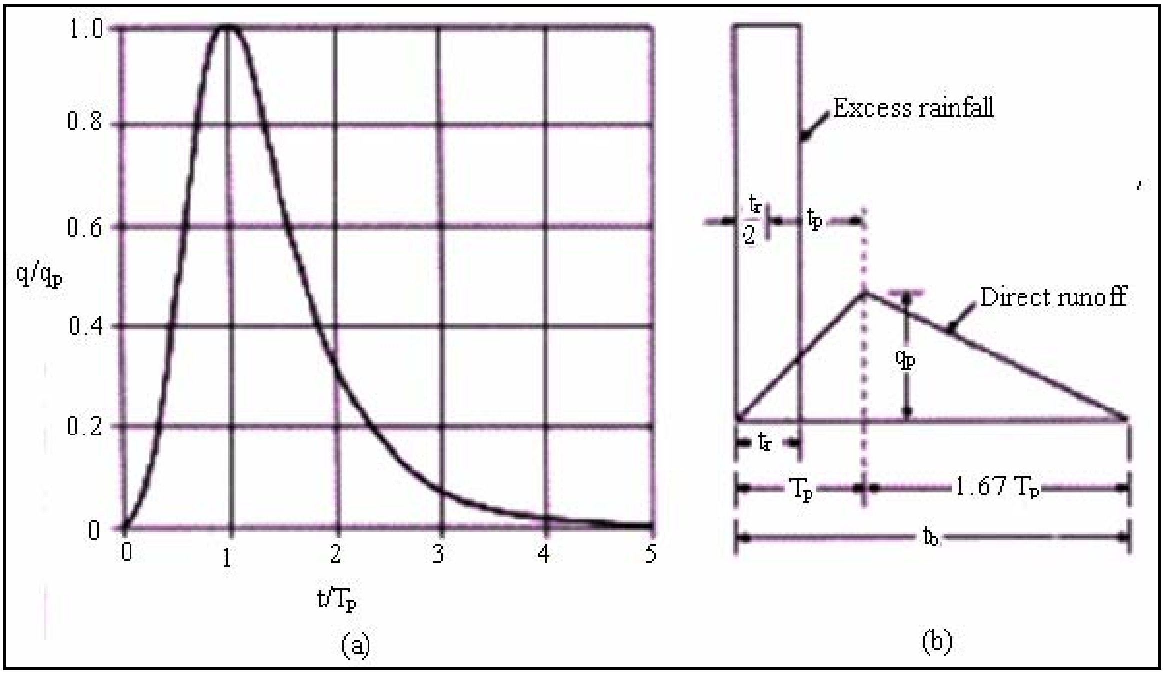

Figure 1.1. Soil Conservation Service synthetic unit hydrographs. (a) Dimensionless hydrograph and (b) Triangular unit hydrograph. (Source: Soil Conservation Service, 1972.).

1.6. Research Approach

Asquith et al. (2004) published a report documenting a database of more than 1,650 rainfall-runoff events from 91 selected Texas watersheds and this report was used as a source for all data used for this research. From the database in Asquith et al. (2004) report, 82 watersheds were selected for further study. A complete list of all the watersheds with United States Geological Survey (USGS) gage station numbers, location, and coordinates of watersheds in latitude and longitude are provided in

Appendix A. The known watershed characteristics for these selected watersheds are also provided in Appendix A.

The selected watersheds were divided into five "modules" based on geographic locations: Austin, San Antonio, Dallas, Fort Worth, and a group of small rural watersheds. The small rural watersheds module refers to the watersheds in areas of central and north-central Texas. The database was also divided into two groups based on the development criteria of the watersheds. The watersheds were grouped as developed watersheds and undeveloped watersheds on qualitative basis (Asquith et al., 2005).

The HEC-HMS software (Scharffenberg, 2001) was used to simulate the rainfall-runoff process. The initial loss, hydraulic conductivity, moisture deficit and wetting front suction parameters were optimized to create a synthesized runoff hydrograph similar to the observed runoff hydrograph. Among the data available for the storm events in the watersheds, the larger storm events from each watershed were chosen for analysis. From each watershed the median values for initial loss, hydraulic conductivity, moisture deficit, and wetting front suction are taken as representative values for the watershed. Further statistics were performed to examine correlations between model loss parameters and watershed characteristics.

CHAPTER 2

LITERATURE REVIEW

2.1. The HEC-HMS Software

The Hydrologic Modeling System, HEC-HMS was developed to simulate the rainfall-runoff processes in watershed systems that have multiple branches. The HEC-HMS software can be applied in solving a large range of problems such as large river basin water supply, flood hydrology, urban or natural watershed runoff, water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation. The HEC-HMS uses algorithms used in HEC-1 (HEC, 1998), HEC-1F (HEC, 1989), PRECIP (HEC, 1989), and HEC-IFH (HEC, 1992) in conjunction with new algorithms to form a comprehensive library of simulation routines.

When a mathematical model is used to optimize rainfall-runoff loss-rate parameters from observed rainfall-runoff data, it is important that the observed hydrograph and the hydrograph generated by using the optimization trial are as identical as possible. An objective function is a mathematical tool to measure the goodness of fit between the observed and generated hydrographs. The objective functions available in the HEC-HMS software are peak weighted root mean square, percentage of error in peak flow, percentage of error in volume, sum of absolute residuals, sum of squared residuals and time weighted errors. The HEC-HMS software contains two search algorithms, namely the univariate method and the Nelder and Mead (1965) method to find the lowest objective function value and optimum parameter values. The univariate gradient method computes and adjusts one parameter at a time while locking the other parameters. Alternatively, the Nelder and Mead method evaluates all parameters simultaneously and determines which parameter to adjust. The search algorithms are also known as optimization methods.

The search algorithms used to obtain the minimum value for an objective function can sometimes delude the modeler by providing a set of solution parameter values, but the objective function value may not be the least possible value. A solution set with a lesser objective function value could be available in the solution space. A global minimal solution may be defined as the solution with the lowest objective function value in the solution space while a local minimal solution may be defined as a solution with objective function values lower than those in the surrounding space. A local minimal solution can possibly occur if the seed values are in the close vicinity of the local minimum solution, or if the slope toward the local minimum is larger than that pointing toward the global minimum.

2.2. Infiltration Models

The mathematical models discussed so far are used to find the optimal unit hydrographs and values for infiltration model loss parameters. The infiltration process has been the prime focus for rainfall losses. Different equations for infiltration rates and mass infiltration, which is the time integral of infiltration rate, have been proposed by different researchers. The mass infiltration is also termed as cumulative infiltration.

The incoming rainfall gets intercepted by vegetation and natural depressions. Losses due to vegetation and depressions are referred to as initial losses. Mathematically they can be expressed as

$$P_e = P - IL$$

where P_e is the depth of precipitation (in) and P is the incoming precipitation (in), and IL in the initial- loss (in).

Some portion of the excess precipitation is lost to infiltration and the remaining water flows off the ground as sheet flow and joins the water course. Mathematically, the process can be expressed as

$$F(t) = P_e - R \qquad (2.1)$$

where *F(t)* is the total infiltration(in), P_e is the depth of precipitation, and *R* is the excess precipitation.

The flow in the river is the sum of the direct runoff contributed by the excess rainfall and the baseflow of the river. The baseflow is the flow in the river at the tie of rainless periods. Mathematically it can be expressed as,

$$D = BF + R \tag{2.2}$$

where *D* is the flow in the river expressed as depth (in), *BF* is the baseflow (in), and *R* is the excess precipitation (in).

Green and Ampt (1911) proposed an infiltration model based on a physical theory in which the infiltrated water moves vertically downwards through the soil profile as a wetting front. The amount of infiltration depends on the soil porosity, moisture content and wetting front suction head. The equation developed by Green and Ampt for infiltration capacity for plug flow is expressed as

$$f(t) = K\left(1 + \frac{\psi\Delta\theta}{F(t)}\right) \tag{2.3}$$

and the equation for mass infiltration, $F(t)$, is expressed as

$$F(t) = Kt + \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) \tag{2.4}$$

where *f(t)* is the infiltration rate in inches/hour, *F(t)* is the cumulative infiltration in inches, *K* is the saturated hydraulic conductivity in inches/hour, ψ is the wetting front soil suction head in inches, and $\Delta\theta$ is the moisture content deficit.

Horton (1940) developed an equation for infiltration capacity based on observations. Horton observed that infiltration begins at an initial rate, f_o, and decreases exponentially until it approaches a constant rate, f_c. Horton's equation for infiltration capacity is

$$f(t) = f_c + (f_o - f_c)e^{-kt} \tag{2.5}$$

from which the mass infiltration equation is given by

$$F(t) = f_c t + \frac{(f_o - f_c)}{k}(1 - e^{-kt}) \tag{2.6}$$

where, f_o is the initial infiltration capacity in inches/hour, f_c is the final infiltration capacity in inches/hour, F is cumulative infiltration in inches and k is the decay constant per hour.

Philip (1957) developed with an equation for infiltration by solving the equation developed by Richard (1931).The equation developed by Philip (1957) for infiltration capacity is

$$f(t) = \frac{S}{2\sqrt{t}} + A \tag{2.7}$$

and the equation for mass infiltration equation is:

$$F(t) = S\sqrt{t} + Kt \tag{2.8}$$

where S is sorptivity in inches/hour$^{1/2}$, t is time in hours, $f(t)$ is infiltration time in inches/hour, and $F(t)$ is the cumulative infiltration in inches.

Kostiakov (1932) proposed an equation for calculating infiltration capacity as

$$f(t) = \frac{\alpha A}{t^{(1-\alpha)}} \tag{2.9}$$

and equation for cumulative infiltration as

$$F(t) = At^{\alpha} \tag{2.10}$$

where $f(t)$ is the infiltration capacity in inches/hr, $F(t)$ is the cumulative infiltration in inches and α and A are parameters.

The curve number method was developed by Natural Resource Conservation Service (NRCS), then called as Soil Conservation Service (SCS), in 1954 to estimate direct runoff from a watershed for a given precipitation event. NRCS curve numbers are based on land use description, hydrological soil group, land cover, percentage of impervious area, and soil moisture condition.

The curve number method provides relationships between initial abstractions, I_a, and curve numbers, CN, based on experiments carried out in small experimental watersheds. The equations are presented as

$$S = \frac{1000}{CN} - 10 \tag{2.11}$$

$$I_a = 0.2S \tag{2.12}$$

Also, a relationship for excess rainfall has been established as

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{2.13}$$

where S is potential maximum retention in inches, P is the total precipitation in inches and P_e is excess precipitation in inches.

2.3. Mathematical Models for Rainfall-Runoff Process

In the past most of the time researchers have focused their studies of infiltration processes to fit an equation to measure the infiltration capacity of soil. Only a few researchers have tried to use a mathematical model to optimize the rainfall loss parameters based on historical rainfall-runoff measurements.

Mays and Coles (1980) developed a linear programming model to fit the best unit hydrograph by minimizing the sum of differences between the observed and the calculated runoff hydrograph. The model was based on the principles of linearity and superposition of unit hydrographs. Mays and Taur (1982) developed two non-linear programs that determined both rainfall losses and the best unit hydrograph. Mays and Taur (1982) integrated the phi-index in their model procedure to determine the rainfall losses.

Unver and Mays (1984) extended the model developed by Mays and Taur (1982) and developed an optimization model based on non-linear programming by using observed rainfall-runoff data to find composite unit hydrographs and optimal values for loss parameters. Infiltration equations developed by Kostiakov (1932), Philip (1957) and Horton (1933, 1939), and the phi-index method were used to illustrate the performance of the model developed by Unver and Mays (1984). Unver and Mays (1984) suggested that it is difficult to determine infiltration model loss parameters and unit hydrographs from observed rainfall-runoff data because the values for loss parameters vary for every rainfall-runoff event in a particular watershed. In addition, there is no single combination of parameters that can be regarded as the best set of parameters values.

Unver and Mays (1984) model required initial seed values to initiate the optimization run, and the seed values would be optimized to achieve a minimum objective function value. Unver and Mays (1984) suggested that a good set of initial seed values will save computational time. The program developed by Unver and Mays (1984) provided different set of optimal solutions for loss parameter values when the supplied initial seed values were different. Unver and Mays (1984) suggested performing several trials of optimization runs with different set of initial seed values to avoid the presence of a local minimal solution.

Morel-Seytoux (1981) provided methodology for calculation of infiltration rates and the excess-rainfall rates based on observed rainfall-runoff data. The phi-index model, the ponding time approach model, the infiltration model developed by Horton (1933), and the infiltration model developed by Green and Ampt (1911) were used for infiltration calculations. Morel-Seytoux (1981) suggested that when the phi-index method is used, the generated excess rainfall hyetograph is different from the excess rainfall hyetographs generated by using the Horton model, the Green-Ampt model, and the ponding time approach model. The infiltration capacity of the soil is greater at the inception of a rainfall event and it decreases gradually with time. In the phi-index, the infiltration capacity is assumed to be constant throughout the event duration. This assumption of constant infiltration capacity is the reason that the phi-index model is inferior to the infiltration models developed by Horton, and Green and Ampt, and the ponding-time approach model.

Morel-Seytoux (1981) emphasized the importance of rainfall intensity when calculating infiltration capacity. Morel-Seytoux (1981) stated, “For low intensity rainfall, the totality of the rainfall infiltrates and it would infiltrate indefinitely unless either soil voids become completely filled with water to the (thin) upper layer was underlain by a (much) tighter layer. Only then would overland flow or interflow occur. On the other hand, with intense rainfall rates the infiltration capacity of the soil is quickly reached and either overland runoff occurs even though the soil below the drenched surface may be very dry or interflow occurs at the interface between the upper soil horizon and the lower tighter layer even though the soil below the interflow may be very dry” (p. 1012). Therefore rainfall intensity is an important factor to be considered when selecting the storm events and low intensity rainfall storms should not be selected.

Prasad et al. (1999) presented a model to determine optimal loss parameters values using historical rainfall-runoff data, infiltration theory, unit hydrograph theory, and a linear programming algorithm. Prasad et al. (1999) used infiltration equations developed by Kostiakov (1932), Philip (1957), and Green and Ampt (1911) in the model. The model developed by Prasad et al. (1999) does not require seed values unlike the Unver and Mays method (1984). Prasad et al. (1999) suggested that the solution generated by the Unver and Mays (1984) model, lead to a local minimum solution and the user ay not be aware of this. Prasad et al. (1999) suggested that when using the Unver and Mays (1984) model, numerous optimization trials each with different set of seed values should be performed, so that the algorithm is not tricked by the local minimal solution. However, the model developed by Prasad et al. (1999) examines all the possible solutions before selecting the optimal solution and is therefore advantageous than the Unver and Mays (1984) model.

Prasad et al. (1999) was critical about the method developed by Morel-Seytoux (1981). Prasad et al. (1999) stated, "...evaluation of any constant in any infiltration equation requires two or more boundary conditions" (p. 83). Prasad et al. (1999) further state "infiltration theory gives only one boundary condition; cumulative rainfall loss at the end of the rainfall is equal to the difference between total rainfall and the direct runoff volume" (p. 83). In the method developed by Morel-Seytoux (1981), typical values are assumed for some soil parameters values. For an example cited, Morel-Seytoux (1981) used typical value of 0.4 cm for storage suction factor for sandy soil. The storage suction factor is defined as the wetting front suction head times the moisture deficit.

Yu (1999) collected rainfall-runoff data recorded at one-minute intervals on 20–216 m^2 bare plots with no vegetation. Yu (1999) compared performance of the Green and Ampt (1911) infiltration model with the spatially variable infiltration model (SVIM) developed by Yu et al. (1997). Yu (1999) suggested that the infiltration equation developed by Green and Ampt cannot be readily applied to storm events with variable rainfall intensity. The Green-Ampt infiltration equation can only be applied if surface ponding occurs for each and every time interval. Yu (1999) stated , "Green-Ampt equation only describes a decrease of infiltration capacity with infiltration amount at a point in the landscape, and once rainfall intensity exceeds the infiltration capacity, actual infiltration is no longer dependent on the rainfall intensity" (p. 93). The rates of infiltration were measured as the difference between the rainfall and runoff. After analysis of field results, it was concluded that infiltration rate is related to the intensity of the rainfall and infiltration rate apparently does not decrease with time.

Sorooshian and Arfi (1982) and Kuczera (1990) referred to the importance of the structure of the objective function surface. The structure of the objective-function surface provides useful information to the modeler in evaluating the linearity and utility of the model. The objective function surface informs the modeler about the uncertainty of the estimated parameters obtained by using the model.

Gupta et al. (2003) referred that the performance of gradient-based methods is relatively poor with regard to determination of global minima. Use of gradient-based methods to minimize the objective function can lead to the determination of a parameter set that corresponds to a local objective function minimum rather than a global objective function minimum. The modeler is not provided with any information whether another location exists within the space of lower objective function value.

CHAPTER 3

METHODS AND PROCEDURE

3.1. Selection of Events

Asquith et al. (2004) documented the database of more than 1,650 measured rainfall-runoff data from 91 Texas watersheds. The Asquith et al. (2004) report was used as the source for all the data used for the research. The rainfall-runoff data were collected during the period 1957─1987. Among the 91 watersheds in the database, only 82 watersheds were selected for further study. Nine watersheds were left out because these watersheds contained less than two rainfall-runoff data sets suitable for further study. Rainfall-runoff data were deemed unsuitable if the discharges from watersheds were less than 300 cfs, the runoff hydrograph recorded in these watersheds had multiple peaks, errors were observed in recording rainfall-runoff data, or a combination of these reasons occurred. A few rainfall-runoff data sets were rejected after optimization trials were performed. These rainfall-runoff data produced a simulated hydrograph that is different from the observed runoff hydrograph even after a number of optimization trials. Decisions in rejecting watersheds or storm events in watersheds for further study were based on engineering judgment.

Among the events recorded in relatively larger storm events, the possibility of irregularities in rainfall intensity during precipitation and in the runoff volumes due to differences in soil type and land use in the watershed is diminished. The larger events within the watersheds were then considered for analysis for research purposes. The number of selected storm events in each watershed varied from 2─21. Parameter sets were optimized from a total of 455 sets of rainfall-runoff data. Storm durations varied from 50 minutes to 72 hours.

The watersheds in the database were divided into five “modules” based on their general location: Austin, San Antonio, Dallas, Fort Worth, and small rural watersheds. The small rural watersheds module referred to the watersheds that are located in areas of central to north-central Texas that were comparatively far from urban locale. These watersheds were relatively undeveloped. Among the geographical locations considered for study, all the watersheds in Dallas region were developed where as only one watershed in Fort Worth region was undeveloped and there was no developed watersheds in small rural watersheds. The locations of all the study watersheds are shown on Figure 3.1. The watersheds were divided into two groups based on their development condition, characterized as either developed or undeveloped watersheds on a qualitative basis (Asquith et al., 2004).

3.2. Refining of Data

The rainfall-runoff data in the database were recorded in break-point format. In break-point format, the values were recorded such that the analyst who records the data set could see a change in gradient in the data. This is obtained from chart-recorded data and is no longer in common use. Rainfall and runoff data for intermediate time intervals were missing. The HEC-DSS software was used to change the irregular time intervals into regular time intervals with a uniform time step of 10 minutes. The software linearly interpolated the rainfall and runoff values of the intermediate times.

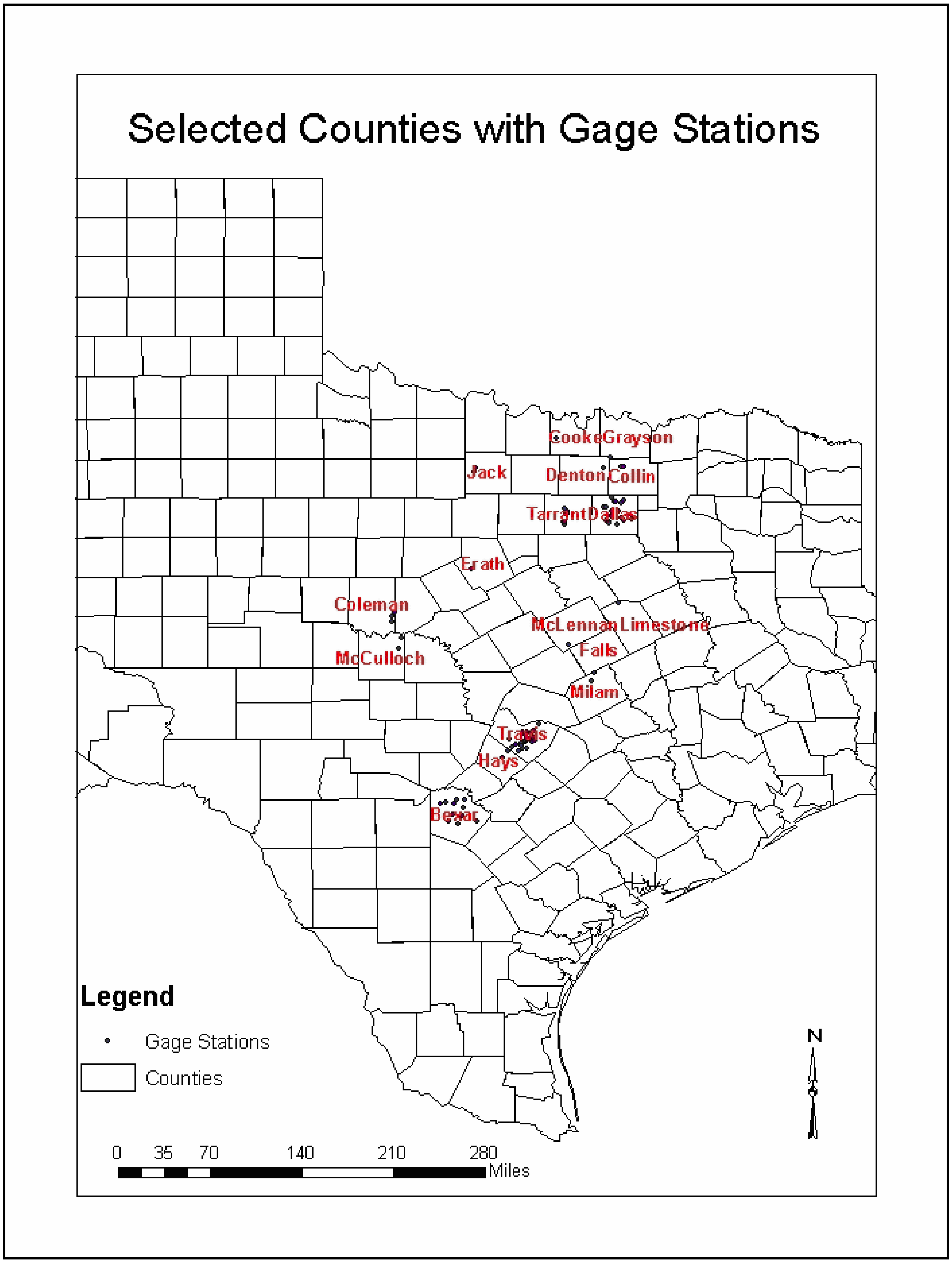

Figure 3.1. Gage locations on a Texas map.

3.3. Optimization Using the HEC-HMS

The rainfall-runoff data and the area of the watershed were input into the HEC-HMS software. The Green-Ampt model was selected as the infiltration model. The SCS unit hydrograph was chosen as the transform method. Recession curve model was selected for simulating base flow. The data for percentage of impervious area in the watersheds were not available. Therefore, impervious area was not taken into account for optimizing the rainfall-runoff loss rate parameters. Loss on account of evaporation and snowmelt were also neglected.

The sum of squared residuals was selected the objective function for the modeling purpose. Conservation of the volume of runoff in the observed hydrograph was preferred to conservation of the peak discharge in observed hydrograph for generating a simulated hydrograph. The univariate gradient algorithm was selected as the search algorithm to obtain the optimal parameters that generate the minimum objective function value.

Tolerance is a limiting value for the difference in objective function value for consecutive iterations to terminate a search. The tolerance for closure was selected as 0.001. When the difference between two iterations is less than the tolerance, the search terminates. The maximum number of iterations per run to find the objective function was 500. After 500 iterations the search terminates, regardless of whether the tolerance for closure has been achieved or not.

The Green-Ampt method as applied in the HEC-HMS has four parameters; hydraulic conductivity, initial loss, moisture deficit, and wetting front suction. In addition to the Green-Ampt parameters, recession constant, recession threshold ratio and SCS lag time parameters are also required to perform the optimization runs.

The recession constant is the rate at which baseflow recedes between storm events and is defined as the ratio of baseflow at the current time, to the baseflow one day earlier. The recession threshold ratio is the ratio of baseflow to the peak flow and is a useful parameter to reset the baseflow during a storm event. The SCS lag is the length of time between the centroid of precipitation mass and the peak flow of the runoff hydrograph.

Because of a large number of unknown parameters to be optimized, the values for recession constant, recession threshold ratio and SCS lag time were acquired from the values obtained from optimization runs that were performed using the same rainfall-runoff data for the same watersheds but a different loss model. The loss model that was used was initial and constant loss method (Lujan, in-press).

3.4. Determination of Infiltration Losses

Infiltration losses were calculated from the optimized loss parameter values that were obtained after optimization procedures were exercised in the HEC-HMS software. Initial loss, hydraulic conductivity, moisture deficit, wetting front suction, time to peak, time of center of mass, observed volume, simulated volume, observed peak discharge, simulate peak discharge, total precipitation, and total excess rainfall values were recorded after the optimization was performed for each storm event. The total loss of rainfall by infiltration was estimated from the following relationship

$$F(t) = P - IL - P_e - BF \qquad (3.1)$$

where $F(t)$ is total loss of infiltration in inches, P is precipitation in inches, IL is initial loss in inches, P_e is excess precipitation in inches and BF is base flow in inches.

The flow in most of the creeks before the storm was almost nil and the creeks can therefore be called ephemeral. The base flows for these creeks have been assumed to be zero cfs for modeling purposes. However, where base flow was observed before a storm event, the base flow was changed to the observed baseflow in the hydrograph instead of zero cfs flow.

The percentage of total rainfall loss was calculated for each rainfall event by using the following equation:

$$P = \frac{V}{T} \times 100\% \qquad (3.2)$$

where P is percentage of lost rainfall, V is rainfall losses in inches, and T is total rainfall in losses and

$$V = IL + F \qquad (3.3)$$

where V is volume of losses in inches, IL is initial loss in inches, and F is infiltration loss in inches.

Initial abstraction and potential maximum retention were also calculated using the NRCS curve number method. Predicted curve numbers refer to the estimate of curve numbers for a watershed for the average moisture condition in the particular watershed and were looked up in a table developed by the Natural Resources Conservation Services (NRCS). NRCS calculates the predicted curve number based on the hydrologic soil group and land use/land cover (LULC), antecedent moisture condition, and impervious area cover data. According to Thompson et al. (2003), observed curve numbers referred to the estimate of effective curve number for a watershed that is derived from paired observations of rainfall depth and runoff depth. The observed curve number were estimated by back calculation from the NRCS rainfall-runoff relation and computing the curve number for each event. A complete list of curve numbers for each watershed is presented in Appendix A. The initial abstraction and potential maximum retention parameters for each were calculated using the standard NRCS Curve Number procedure for both the observed and predicted curve numbers.

3.5 Obtaining Hydraulic Conductivity Data from Soil Survey

The coordinates of the gaging stations used for study in this research were provided by Asquith et al. (2004). An estimate of hydraulic conductivity parameter values of the soil around the gaging station of the watershed was obtained from soil survey map available in the NRCS website. These estimates of hydraulic conductivity from soil survey were compared to the hydraulic conductivity values obtained from optimization procedure.

3.6. Statistical Analysis

The objective of the statistical analysis is to find a correlation between the loss parameters, the basin characteristics and the curve numbers. Statistical analyses were carried out by grouping the watersheds based on the following factors:

1. Entire data set
2. Geographical location of the watersheds
3. Development condition of the watersheds (developed / undeveloped)
4. Geographical location and development condition of the watersheds

Loss parameters were calculated for every selected storm event in the watershed. The median is the central value of distribution when the values are arranged in order of magnitude. The median values of the Green-Ampt model loss parameters were chosen as representative parameter values for each watershed. The advantage of selecting a median was that the median value is least affected by outliners.

Scatterplots were generated to determine if correlations between simulated initial loss obtained using the HEC-HMS, and initial abstraction calculated from observed and predicted curves numbers existed. In addition, scatterplots were generated to explore if there was any correlation between the loss parameters and the watershed characteristics such as main channel length, main channel slope and drainage area. Regression equations were used to find correlations. Among linear, exponential, logarithmic and polynomial regression equations, the equation that had the maximim regression coefficient was chosen as the best fit regression equation.

A boxplot is a graphical representation of a dataset that shows the median, inter-quartile-range and the outliners. The whiskers of the boxplot show the 10 and 90 percentile values. It readily shows the skewness of the data. Boxplots were used to compare the magnitude of loss parameters. R software (Ihaka and Gentleman, 1996) was used for generating the boxplots.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Output from HEC-HMS

Using the procedures outlined in the previous sections, the HEC-HMS software was used to optimize the Green-Ampt model loss parameters values. Hydraulic conductivity, initial loss, moisture deficit and wetting front suction parameters were optimized. An example of the optimized hydrograph and the observed runoff hydrograph for the storm recorded on 26-03-1975 at USGS gaging station 08055580 are shown on Figure 4.1. The watershed draining to the gaging station is a developed watershed and is located at the Joes Creek at Royal Lane in Dallas, Texas.

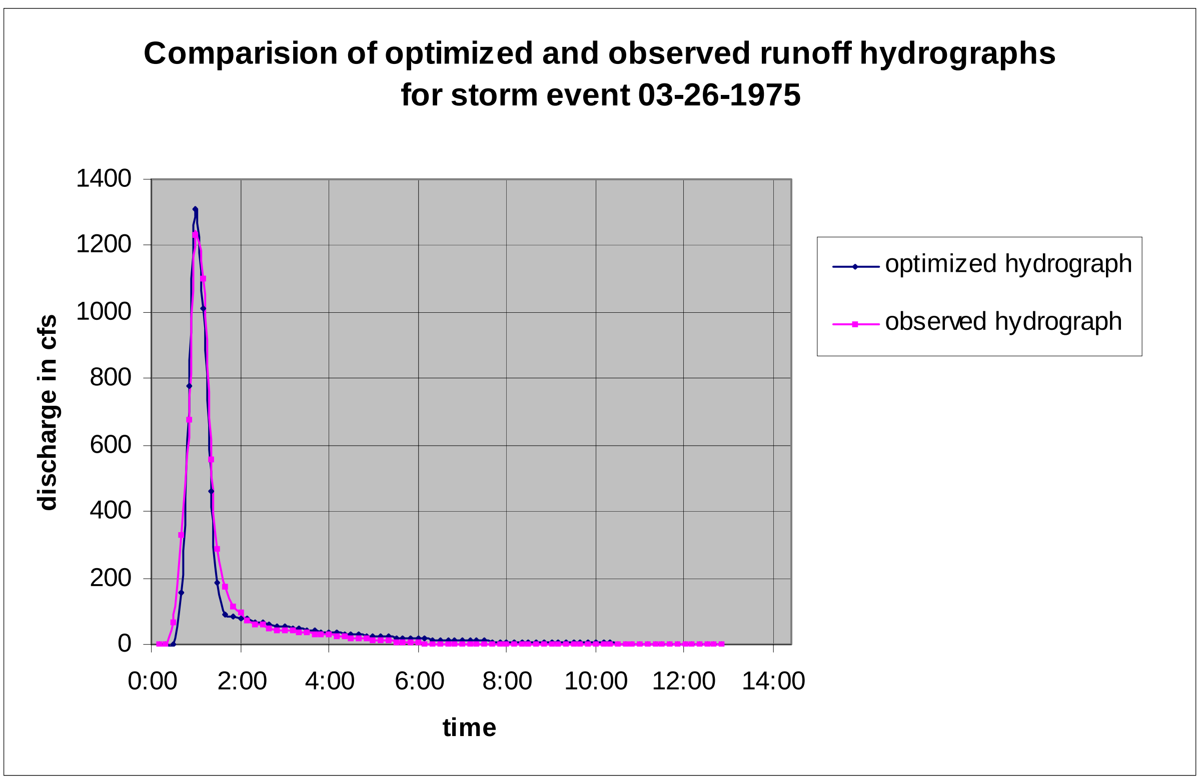

Figure 4.1. Comparison of optimized and observed runoff hydrographs for gaging station 08055580 for storm event 03-26-1975.

The loss parameter values were obtained for every selected storm event in the study watersheds by the use of the HEC-HMS software. The medians of the loss model parameters values were taken as the representative parameter values for that watershed. Optimized parameter values for watershed with USGS gage station 08156750 are listed in Table 4.1. The watershed for the gaging station 8156750 is an urban watershed which drains through Shoal Creek and the gaging station is located at Steck Avenue, Austin, Texas. The complete table of median parameter values for selected watersheds is given in Appendix A.

Table 4.1. Green-Ampt loss parameters obtained from optimizations for watershed number 08156750.

Date	**Hydraulic Conductivity (in/hr)**	**Initial Loss (inches)**	**Moisture Deficit**	**Wetting front suction (inches)**	**Recession threshold ratio**	**SCS lag (minute)**
12/31/1978	0.09	0.58	0.09	12	0.34	53
4/15/1977	0.29	0.20	0.10	18	0.18	41
5/11/1978	0.09	0.43	0.18	11	0.11	41
5/12/1980	0.10	1.16	0.05	10	0.2	40
5/21/1979	0.00	0.48	0.09	11	0.2	39
5/2/1978	0.19	0.67	0.10	12	0.06	43
7/19/1979	0.12	0.31	0.18	14	0.18	46
Median	0.10	0.48	0.10	12	0.18	41

When optimizing loss model parameters, some parameters were readily optimized compared to others. In the case of an insensitive parameter that did not optimize readily, the optimized values after optimization runs were very similar to the seed values. In other words, for insensitive parameters, optimized parameter values did not change significantly from the seed values. In addition, the model-generated hydrograph was not responsive to the changes in these insensitive parameter values. It was difficult to determine the representative value for insensitive parameters. When optimizing the Green-Ampt infiltration model loss parameters using the HEC-HMS software, the initial loss and hydraulic conductivity parameters were found to be more sensitive parameters compared to the moisture deficit and wetting front suction parameters. With the intention of minimizing the errors originated because of the parameter insensitivity, a wide range seed values for each parameter were used. For example, the initial values used for the initial loss parameter are ranged from 0.05 inches to 1.00 inches.

The moisture deficit and wetting front suction parameter values of the soil change with the moisture condition of the soil. The soil moisture content can varies on the rainfall conditions. The hydraulic conductivity of the soil does not change with the soil moisture content value. The initial loss parameter is dependent on vegetation condition and topography of the watershed. The hydraulic conductivity and soil moisture content are unchanging parameters where as the values of soil moisture deficit and wetting front suction change. Therefore hydraulic conductivity and initial loss parameters were only considered for further analysis.

4.2. Analysis of Initial Loss and Hydraulic Conductivity Parameters for Watershed Categories

The watersheds were grouped on the basis of their development conditions as developed or undeveloped. Loss parameters were studied to examine the sensitivity of the parameters to watershed development condition. Observation of the boxplots displayed as Figure 4.2 demonstrates that the initial loss parameter for undeveloped watersheds is greater than that for the developed watersheds. Table 4.2 lists the 25th, 50th and 75th percentile values for initial loss parameter for developed and undeveloped watersheds used to generate boxplots on Figure 4.2.

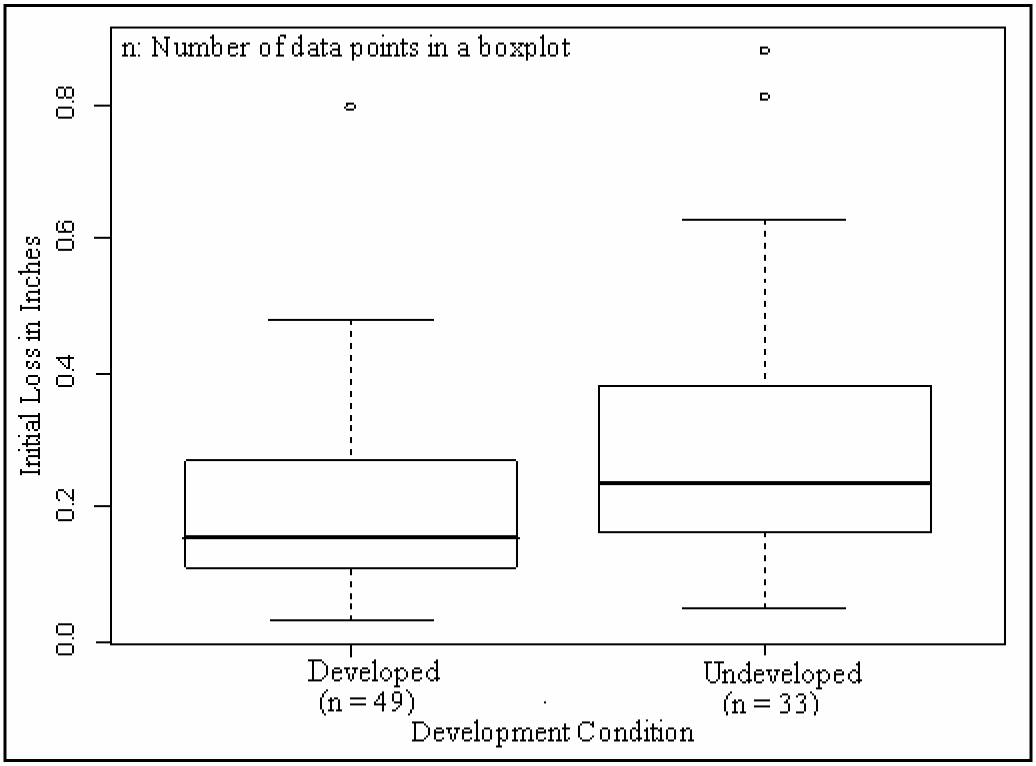

Figure 4.2. Comparison of initial loss values for developed and undeveloped watersheds.

Table 4.2. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.2.

Initial loss (in)		
Percentile	Developed	Undeveloped
25th percentile	0.11	0.18
50th percentile	0.16	0.24
75th percentile	0.27	0.42

Boxplots for the hydraulic conductivity parameter values for developed and undeveloped watersheds are displayed as Figure 4.3. The hydraulic conductivity parameter values in the undeveloped watersheds were higher compared to the developed watersheds. Listed on Table 4.3 are the 25th, 50th and 75th percentiles values for hydraulic conductivity parameter for developed and undeveloped watersheds, which were then used to generate boxplots on Figure 4.3.

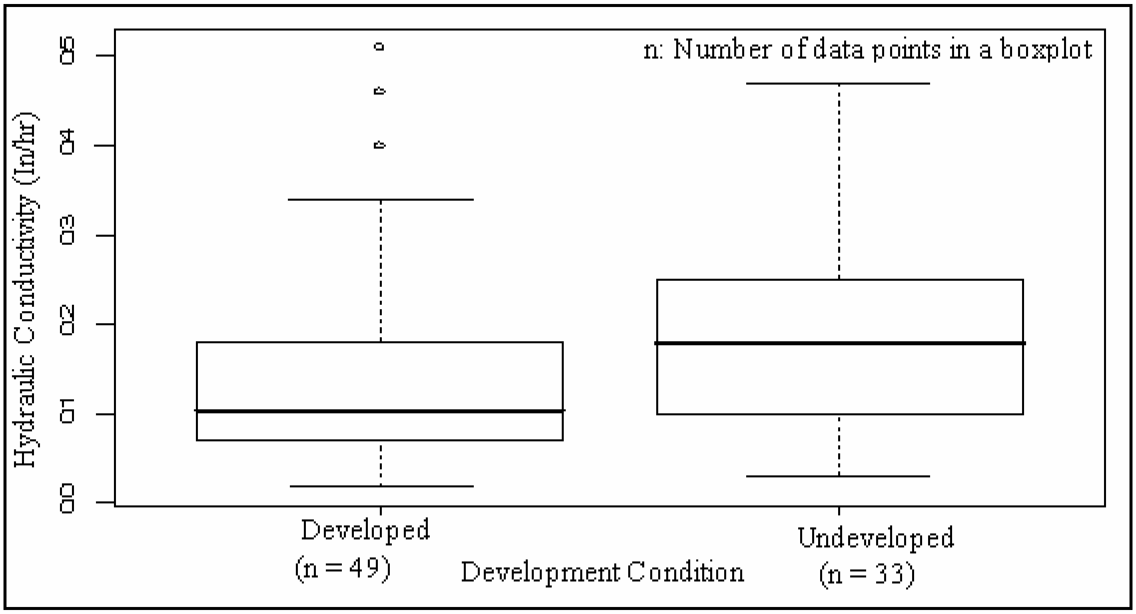

Figure 4.3. Comparison of hydraulic conductivity parameters for developed and undeveloped watersheds from data obtained from optimization.

Table 4.3. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.3.

Hydraulic conductivity (in/hr)		
Percentile	Developed	Undeveloped
25th percentile	0.07	0.24
50th percentile	0.1	0.18
75th percentile	0.26	0.42

The complete list of hydraulic conductivity values obtained from web soil survey for the study watersheds are listed in Appendix A. Hydraulic conductivity parameters values obtained from soil survey were grouped into two heads based on the development condition of the watersheds as developed or undeveloped. The boxplots of the hydraulic conductivity values from web soil survey are shown as Figure 4.4. Observations of boxplots on Figure 4.4 showed that the hydraulic conductivity parameter values were greater for undeveloped watersheds than developed watersheds. The difference in the hydraulic conductivity values is possibly caused because of the development of residential and commercial sites, and the construction of roads and parking spaces, which impede the infiltration process on the land.

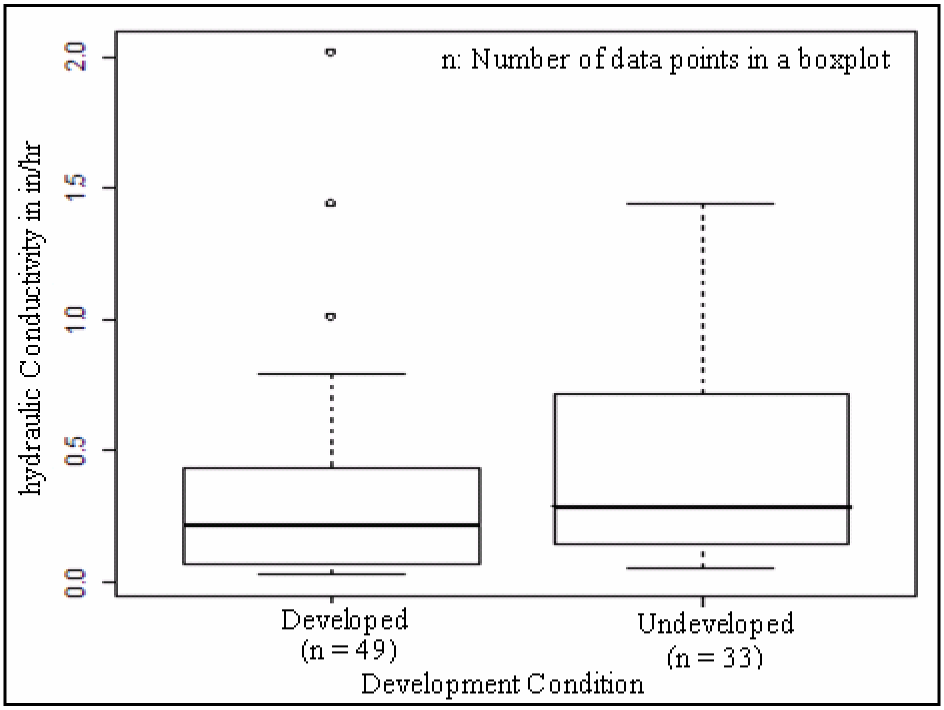

Figure 4.4. Comparison of hydraulic conductivity parameters for developed and undeveloped watersheds from data obtained from soil survey.

The watersheds were grouped based on their geographic locations and the loss model parameter values that were obtained from optimization runs were compared to determine the sensitivity hydraulic conductivity to the geographical locations of the watersheds. The watersheds were divided into five modules based on geographical locations : Austin, San Antonio, Dallas, Fort Worth, and small rural watersheds. Boxplots were prepared for the initial loss and the hydraulic conductivity parameter values as shown on Figure 4.5. Observations of the boxplots on Figure 4.5 demonstrate that the initial loss parameters in the San Antonio region are the greatest followed by rural small watersheds, Austin, Fort Worth, and Dallas.

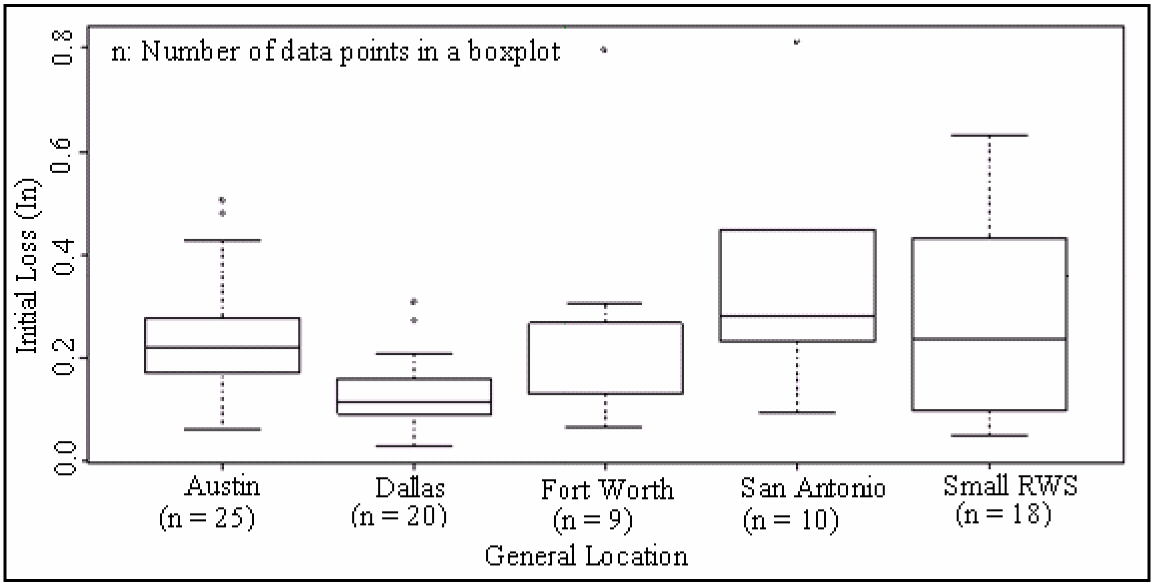

Figure 4.5. Comparison of initial loss parameters for different geographical locations.

Watersheds were grouped on the basis of general location and the boxplots of hydraulic conductivity values of these watersheds are shown as Figure 4.6. In the boxplot for Fort Worth data shown in Figure 4.5, the median coincides with the 25th percentile and the median is therefore not evident. Observation from the boxplots on Figure 4.6 demonstrates that the hydraulic conductivity parameter values are the greatest for the watersheds in the San Antonio area, followed by Austin, rural small watersheds, and Dallas-Fort Worth area. One of the reasons for San Antonio and Austin area to have higher hydraulic parameter values could be that the geographic location of San Antonio and Austin coincides with a portion of the Edwards Aquifer recharge zone. The recharge zone in the aquifer causes greater hydraulic conductivity. The areal extents of the Edwards aquifer region are shown on Figure 4.8. Conversely, Dallas-Fort Worth area has a clayey soil and the clayey soils possibly cause the low infiltration rates. The soil map for Dallas County is shown as Figure 4.9.

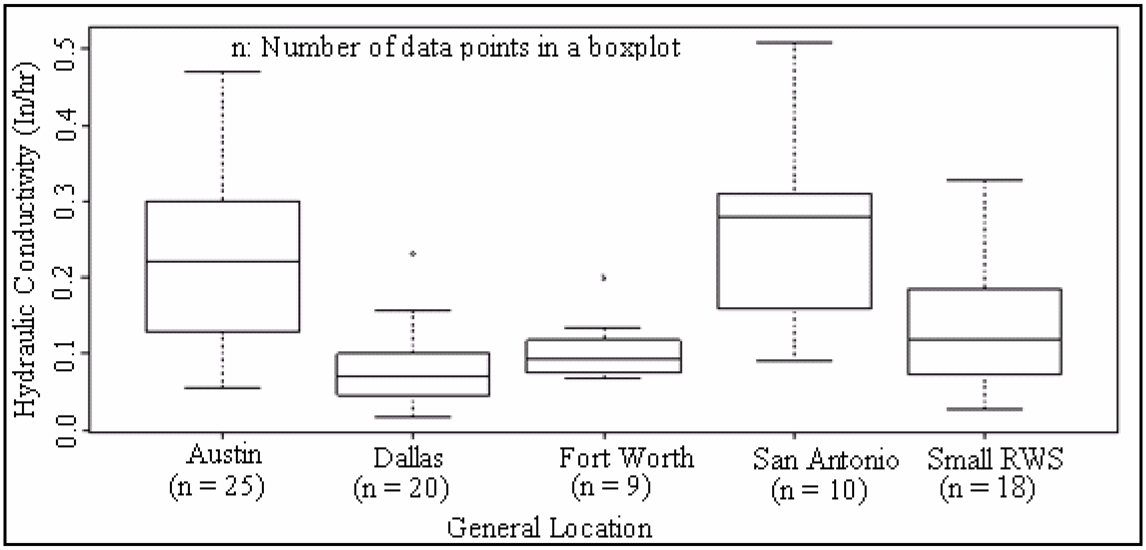

Figure 4.6. Comparison of hydraulic conductivity values obtained from optimization for different geographical locations.

The hydraulic conductivity parameter values were obtained from web soil survey through the NRCS website. Boxplots were plotted from hydraulic conductivity parameter values obtained from soil survey for different geographical regions and are shown as Figure 4.7. Observations of the boxplots indicated that hydraulic conductivity parameter values are only marginally greater for watersheds in San Antonio and Austin area than watersheds in Dallas-Fort Worth area. It was observed that the hydraulic conductivity values obtained from optimizations were about half the values obtained from the soil survey report.

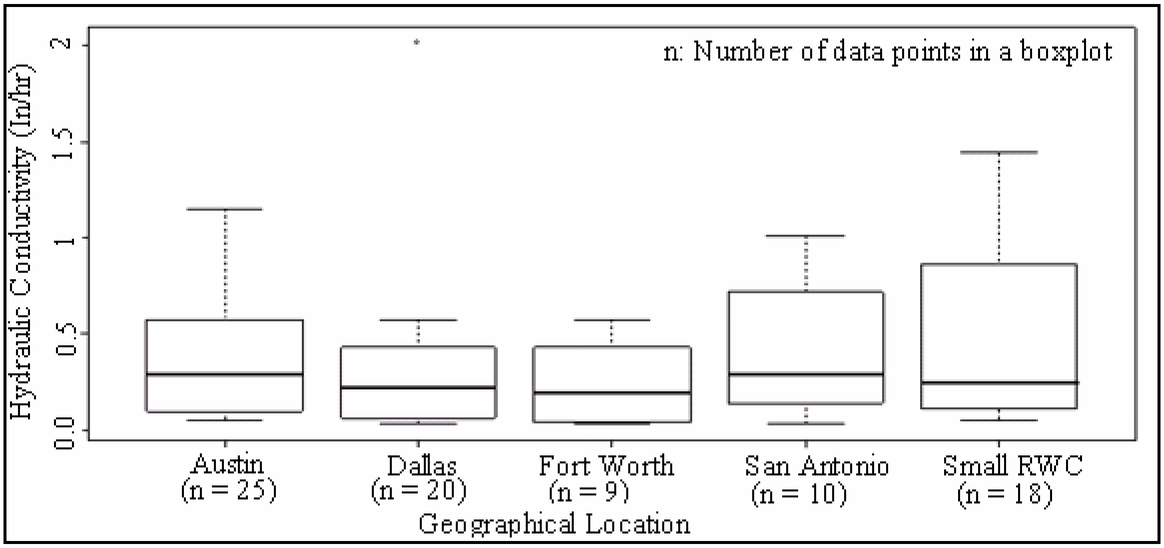

Figure 4.7. Boxplots for hydraulic conductivity values for different geographical regions, data obtained from soil survey report.
(Source:http://websoilsurvey.nrcs.usda.gov, last accessed 04-26-2007)

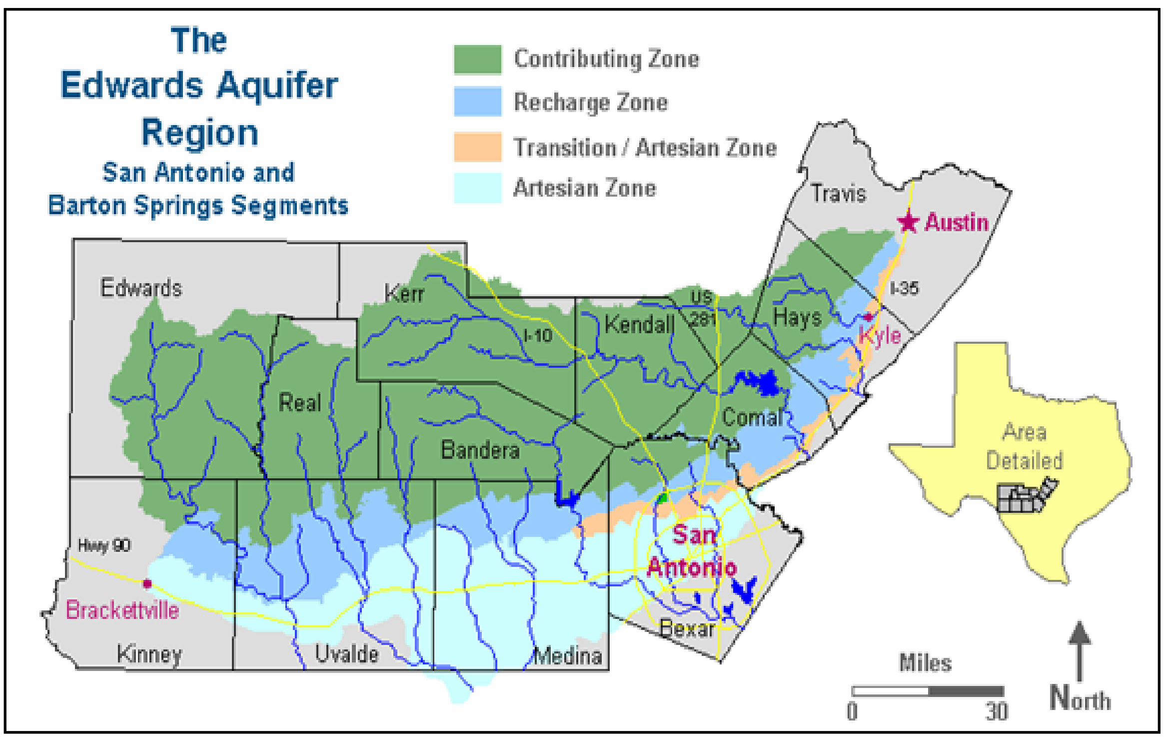

Figure 4.8. The Edwards aquifer region map (Source: www.edwardsaquifer.net, 1995-2006 by Greg Eckhardt, accessed 03-26-2007).

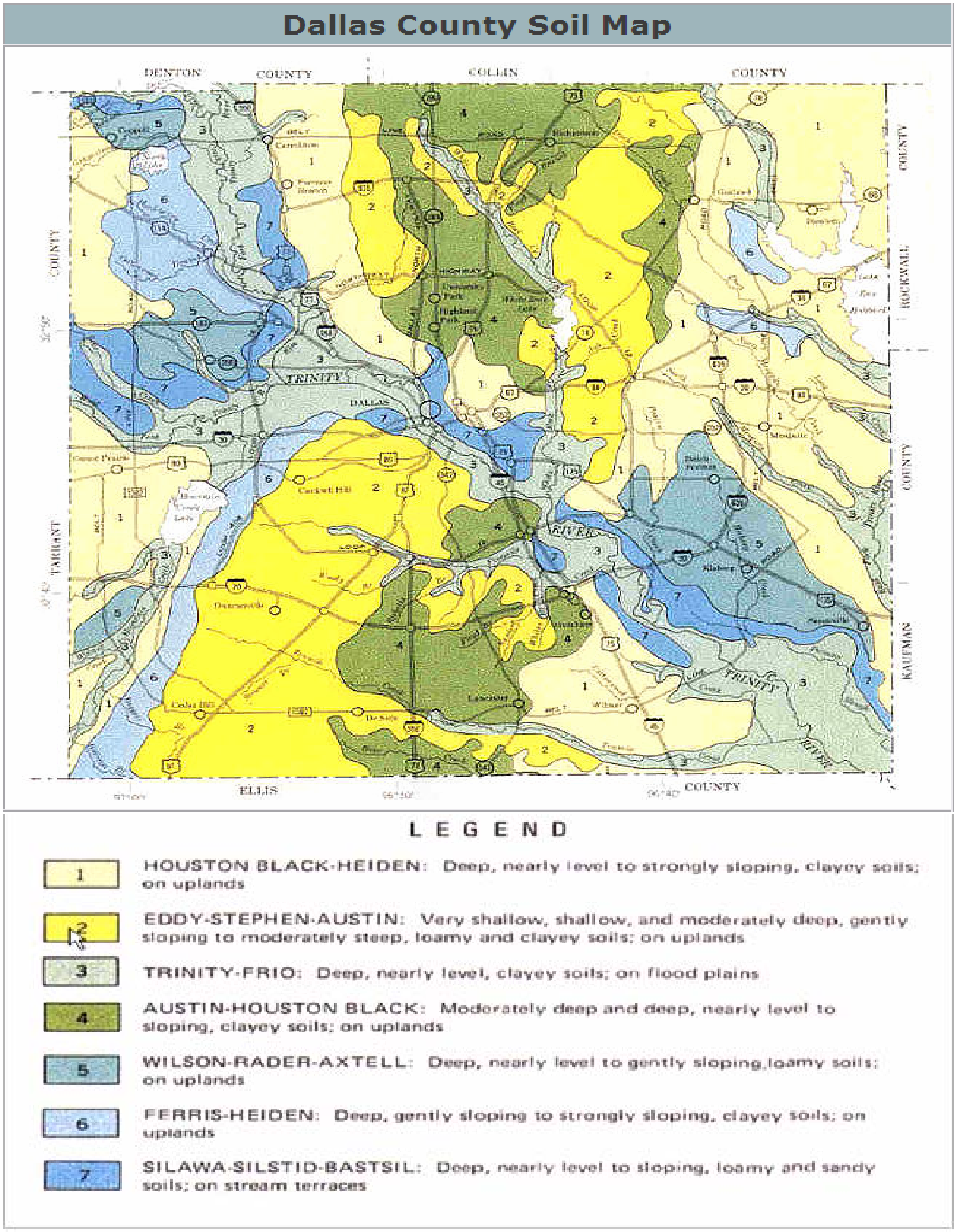

Figure 4.9. Dallas County soil map (Source: www.nhnct.org, last updated 03-06-2007).

Initial loss values are physically difficult to measure. The curve number method provides an indirect technique for estimating the initial abstraction, I_a, by applying the standard NRCS procedure and using the equations 2.9 and 2.10, mentioned in the earlier section. Initial abstraction values calculated from the observed and the predicted curve numbers using equations 2.9 and 2.10 were compared to the initial loss values obtained from optimization procedure in the HEC-HMS software. Boxplots of the initial abstraction values calculated from the predicted curve numbers and observed curve numbers and the initial loss values obtained from optimization procedure for watersheds in each geographical location module are shown as Figures 4.10 to 4.14, respectively. The 25th, 50th and 75th percentile values used for the boxplots are shown in Tables 4.4 to 4.8 respectively. The initial loss values obtained from the optimization procedure were consistently lesser than the initial abstraction values from either observed or predicted curve numbers. The initial abstraction values obtained by using observed curve numbers were largest, followed by initial abstraction values calculated using the predicted curve numbers and initial loss values obtained from optimizations were the least.

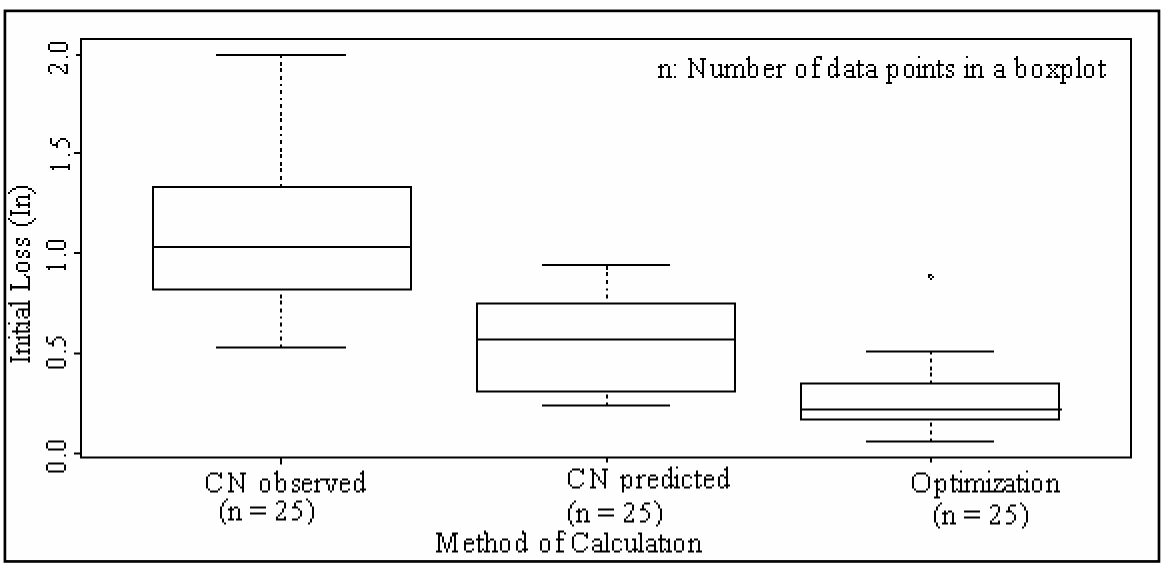

Figure 4.10. Comparison of boxplots of initial loss values obtained using three different methods for Austin watersheds.

Table 4.4. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.10.

Location : Austin			
Percentile	I_a from observed CN	I_a from predicted CN	IL from optimization
25th percentile	0.81	0.31	0.17
50th percentile	1.03	0.57	0.22
75th percentile	1.25	0.75	0.33

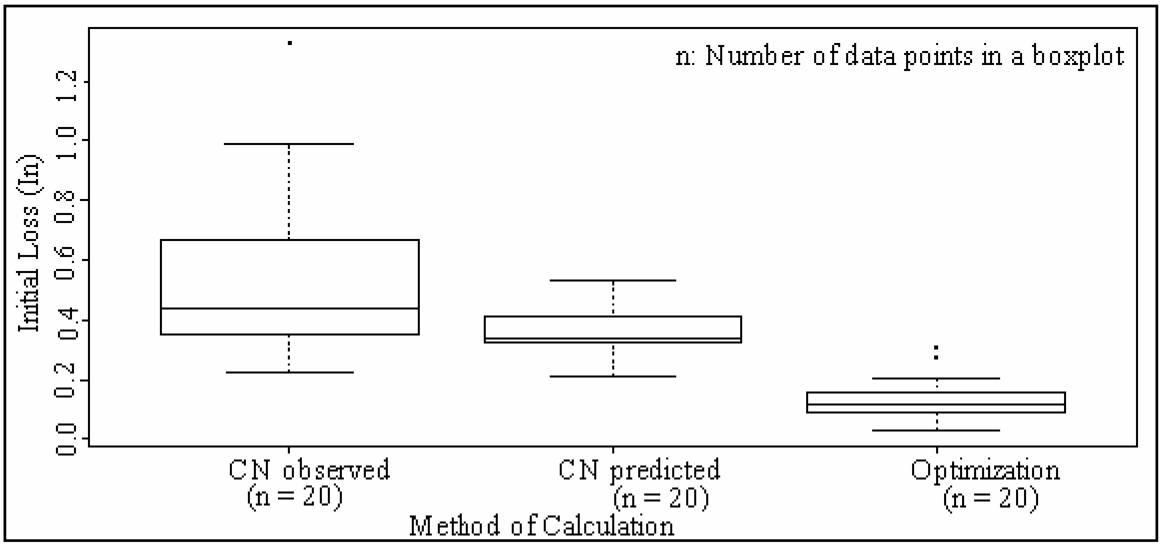

Figure 4.11. Comparison of boxplots of initial loss values obtained using three different methods for Dallas watersheds.

Table 4.5. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.11.

Location : Dallas			
Percentile	I_a from observed CN	I_a from predicted CN	IL from optimization
25th percentile	0.35	0.32	0.17
50th percentile	0.43	0.33	0.22
75th percentile	0.66	0.41	0.33

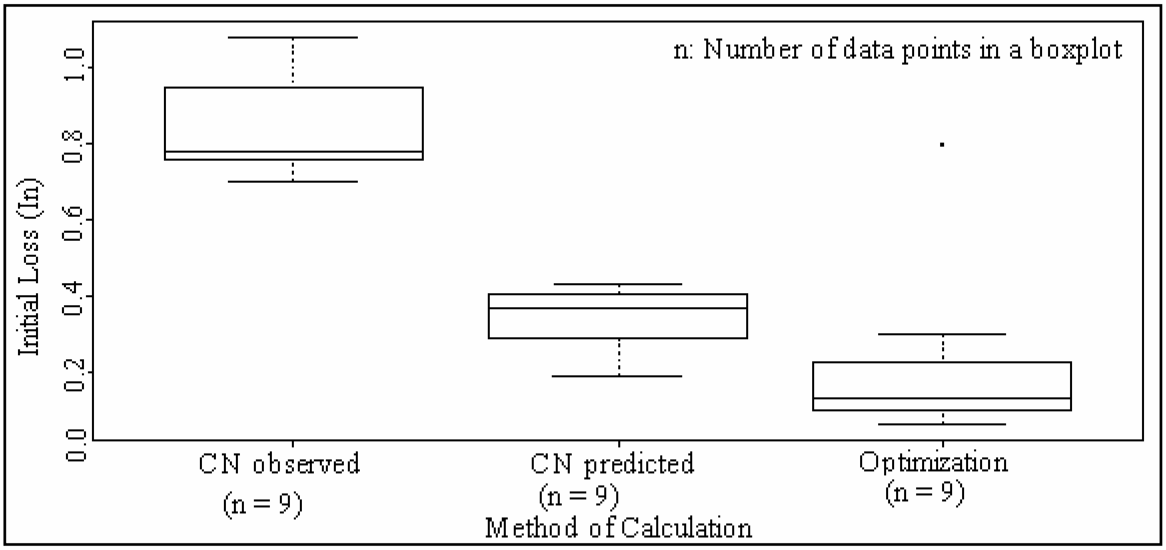

Figure 4.12. Comparison of boxplots of initial loss values obtained using three different methods for Fort Worth watersheds.

Table 4.6. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.12.

Location : Fort Worth			
Percentile	I_a from observed CN	I_a from predicted CN	IL from optimization
25th percentile	0.73	0.30	0.13
50th percentile	0.78	0.39	0.14
75th percentile	0.92	0.41	0.27

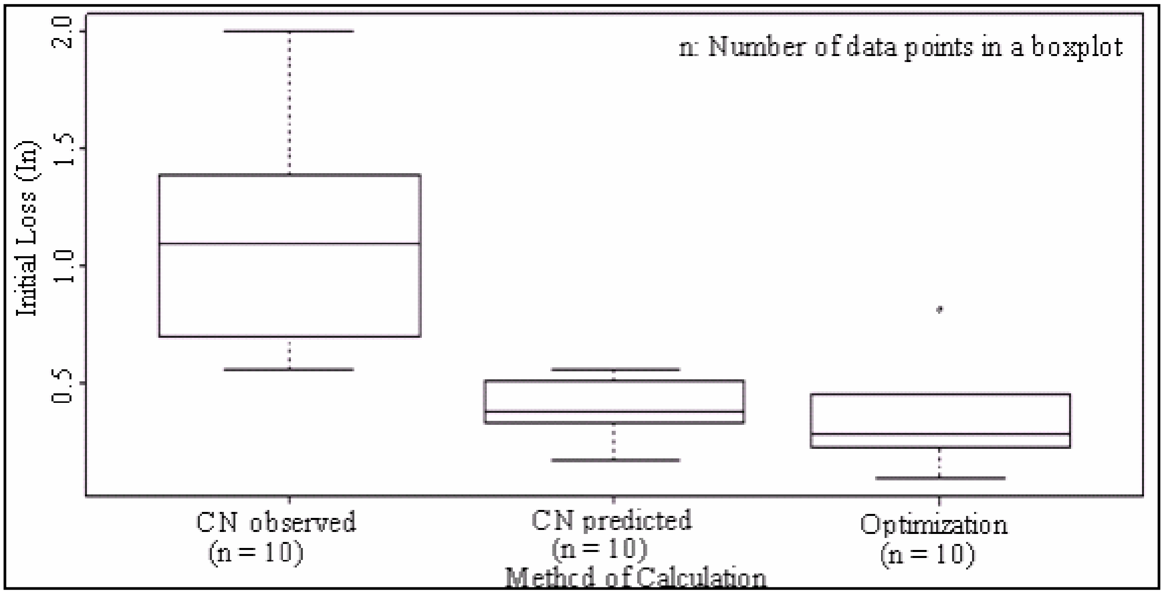

Figure 4.13. Comparison of boxplots of initial loss values obtained using three different methods for San Antonio watersheds.

Table 4.7**.** The 25th, 50th and 75th percentile values for box plots shown in Figure 4.13.

Location : San Antonio			
Percentile	I_a from observed CN	I_a from predicted CN	IL from optimization
25^{th} percentile	0.72	0.34	0.24
50^{th} percentile	1.09	0.37	0.28
75^{th} percentile	1.37	0.51	0.41

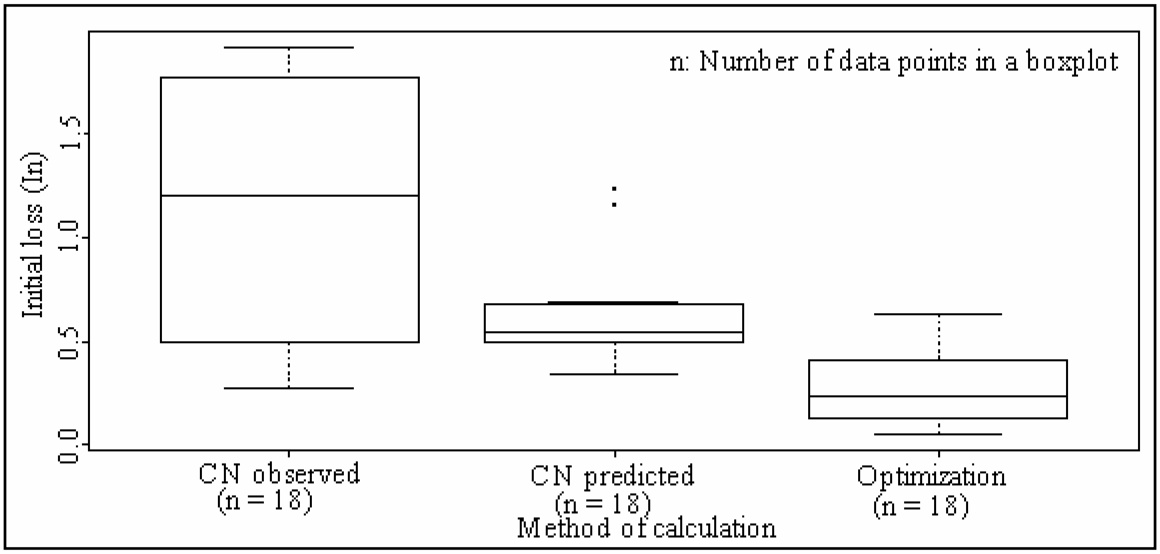

Figure 4.14. Comparison of boxplots of initial loss values obtained using three different methods for Small rural watersheds.

Table 4.8. The 25th, 50th and 75th percentile values for box plots shown in Figure 4.14.
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Location : Small Rural Watersheds			
Percentile	I_a from observed CN	I_a from predicted CN	IL from optimization
25th percentile	0.52	0.5	0.12
50th percentile	1.2	0.53	0.23
75th percentile	1.72	0.67	0.41

Boxplots of the initial loss and the hydraulic conductivity parameters were prepared, as shown in Figure 4.15 and Figure 4.16 respectively, to study the sensitivity of these parameters with respect to the combined effects of geographical locations and the development conditions of the watersheds. All the watersheds in Dallas region were developed, only one watershed in Fort Worth region was undeveloped and there were no developed watersheds in small rural watersheds. San Antonio and Austin areas had four or more watersheds in developed and undeveloped conditions, and hence the watersheds in San Antonio and Austin areas were selected to generate the boxplots and perform analysis on the boxplots.

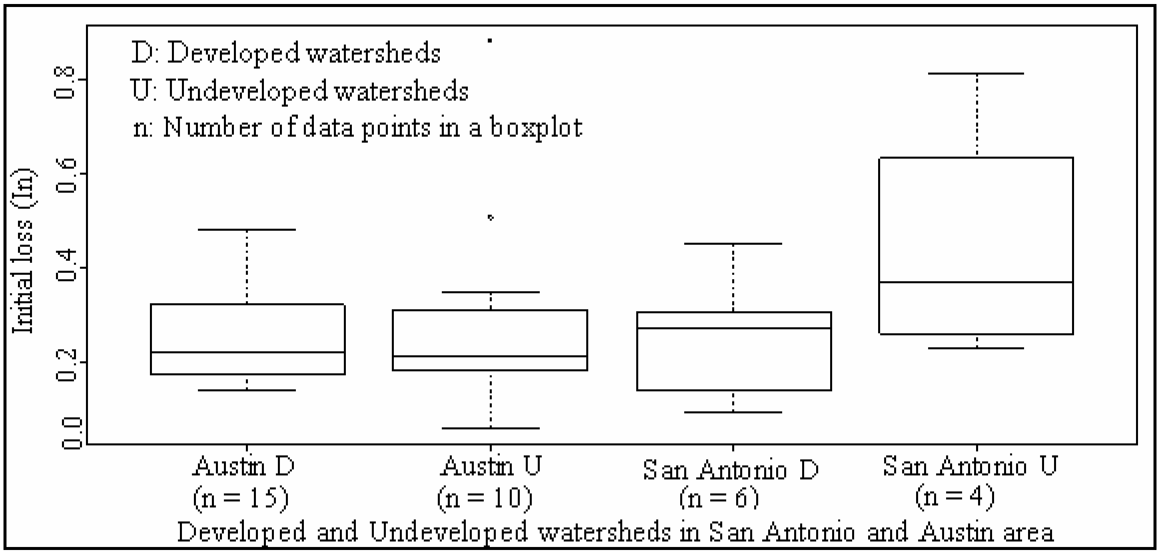

Figure 4.15. Comparison of initial loss values for developed and undeveloped watersheds in San Antonio and Austin area using a boxplot.

Observation of Figure 4.15 shows that the initial loss parameter values in the San Antonio area were greater for the undeveloped watersheds than the developed watersheds. However, for the Austin area, the initial loss parameter values in developed and undeveloped area were nearly the same.

Boxplots were generated to compare the hydraulic conductivity parameter values for developed and undeveloped watersheds in the Austin and San Antonio area. The boxplots are shown as Figure 4.16. Observation of Figure 4.16 shows that the hydraulic conductivity for the undeveloped watersheds were greater than hydraulic conductivity values for developed watersheds in Austin and San Antonio area.

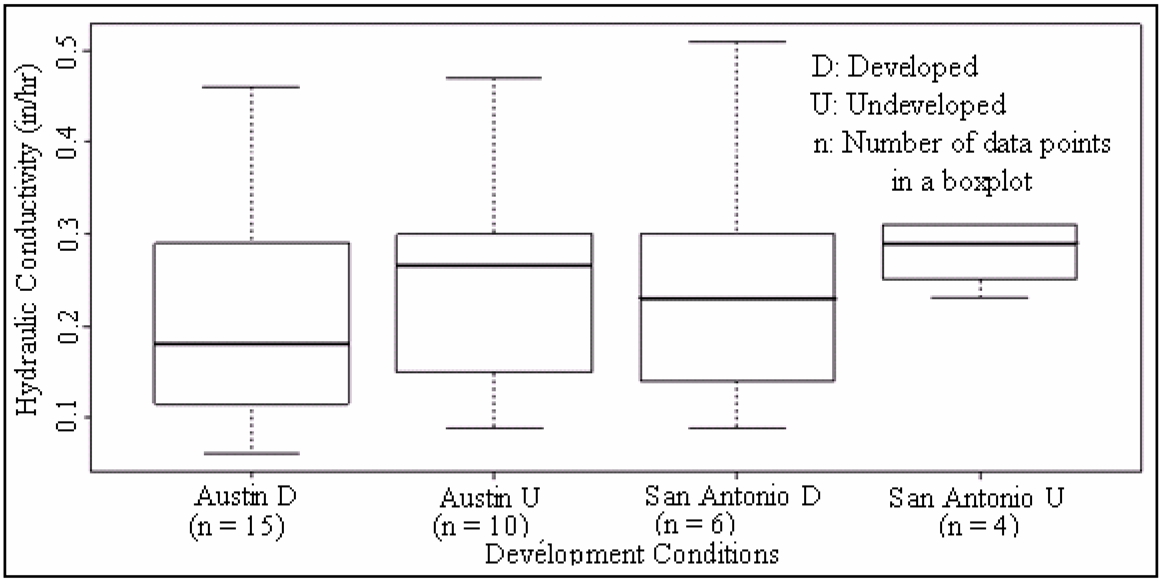

Figure 4.16. Boxplots for hydraulic conductivity parameter values for developed and undeveloped watersheds in Austin and San Antonio areas.

The amount of incoming rainfall lost to infiltration in the selected watersheds was calculated as the total rainfall minus the rainfall excess. The percentage of total loss was calculated for all selected events in the watersheds. The median of percentage of loss was calculated for every watershed and the median value was considered the representative value for percentage of incoming rainfall lost for each watershed. It was observed that more than 60 percent of the incoming rainfall was lost to interception, depression storage and infiltration processes. Boxplots of percentage of rainfall losses for developed and undeveloped watersheds are shown on Figure 4.17. It was observed from Figure 4.17 that the rainfall losses were greater for the undeveloped watersheds compared to developed watersheds.

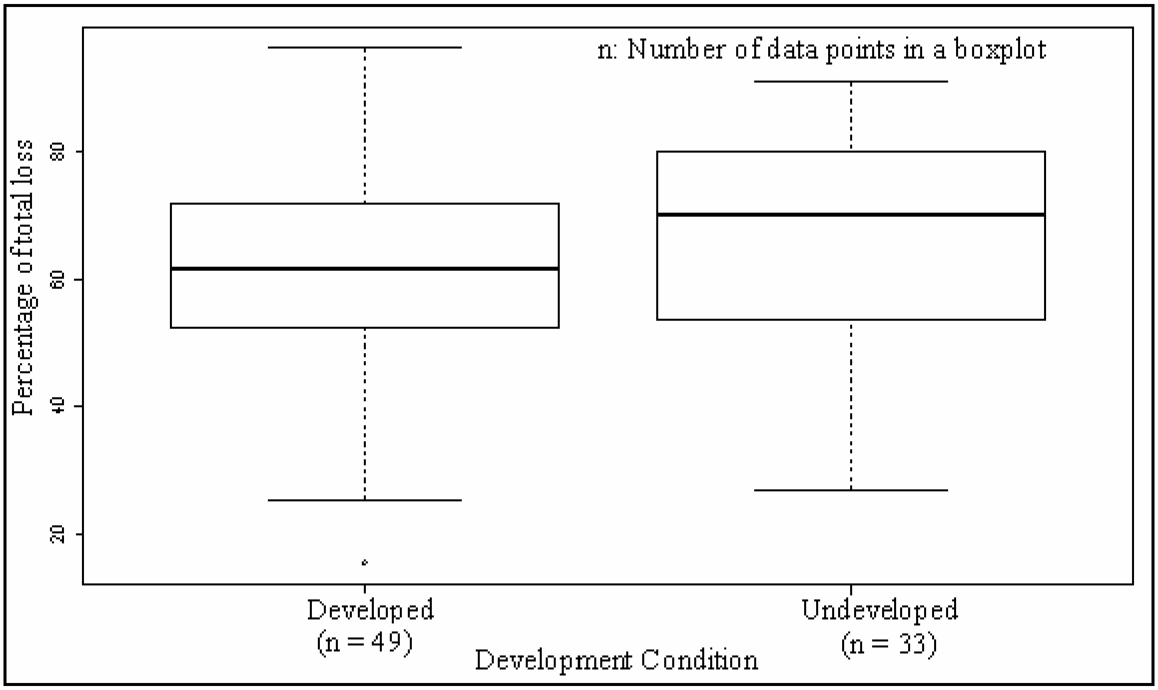

Figure 4.17. Boxplots of percentage of total loss in a rainfall event for developed and undeveloped watershed.

4.3. Relationships Between Loss Parameters and Watershed Characteristics

One of the main objectives of the research was to examine relations between the loss parameters and the known watershed parameters. The loss parameters were compared to the known watershed parameters such as drainage area, main channel length, and the main channel slope. Scatterplots were prepared to test the covariation among the following parameter sets

1. Initial loss versus drainage area
2. Hydraulic conductivity versus drainage area
3. Total depth of infiltration versus drainage area
4. Initial loss versus main channel length
5. Hydraulic conductivity versus main channel length
6. Total depth of infiltration versus main channel length

7. Initial loss from optimization versus initial loss from observed curve number
8. Initial loss from optimization versus initial loss from predicted curve number
9. Initial loss versus hydraulic conductivity
10. Total depth of infiltration from optimization versus maximum potential storativity (observed)
11. Total depth of infiltration from optimization versus maximum potential storativity (predicted)
12. Hydraulic conductivity versus observed curve number
13. Hydraulic conductivity versus predicted curve number
14. SCS lag time versus main channel length

The scatterplots were prepared by grouping the watersheds in four criteria

1. Entire watershed sets
2. Watersheds grouped based on development condition (developed/undeveloped)
3. Watersheds grouped under general location
4. Watersheds grouped under general locations and also development conditions.

Simple regression analyses were performed to understand the covariation between two parameter sets of interest. From the analysis of R-square, which is a measure of fit of the regression line, relations between parameters could not be established. The R-square values were less than 0.5 for all the parameter sets listed above, except for the relationship between SCS lagtime and main channel length. The relationship of SCS lagtime and main channel length is discussed later in this chapter. Visual inspection of some scatterplots showed that correlations could possibly exist. The parameters of these scatterplots were tested for correlation. Kendall’s Tau was used to determine the correlation. For example relationship between SCS lagtime and hydraulic conductivity (obtained from optimization) is discussed here. Scatterplot was generated for the parameter set and linear regression line was fitted. The R-square value was 0.23. Kendall's tau was calculated to be -0.4 and two-sided probability, *p*, equaled 2.33×10^{-7}. Tau value of 0.7 or greater and Pearson's r of 0.9 or greater are considered as good correlations (Helsel and Hirsch, 1993). In the most cases, correlation or trend between the parameters were found. However, in some cases, some trends were seen but the correlation between the parameters was not significant. For example, scatter plot between observed curve number and hydraulic conductivity is shown as Figure 4.18.

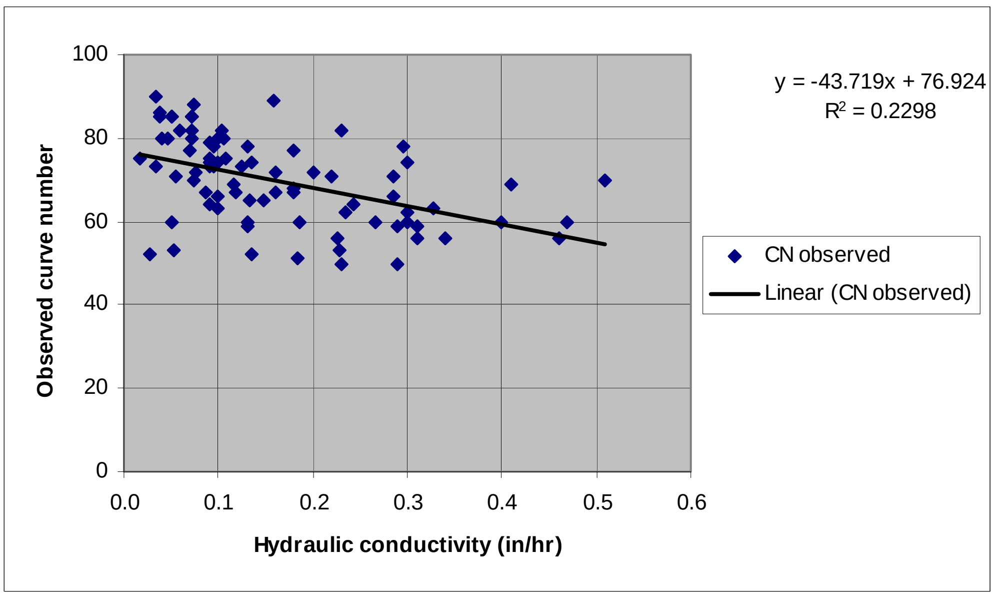

Figure 4.18. Scatterplot hydraulic conductivity and observed curve number.

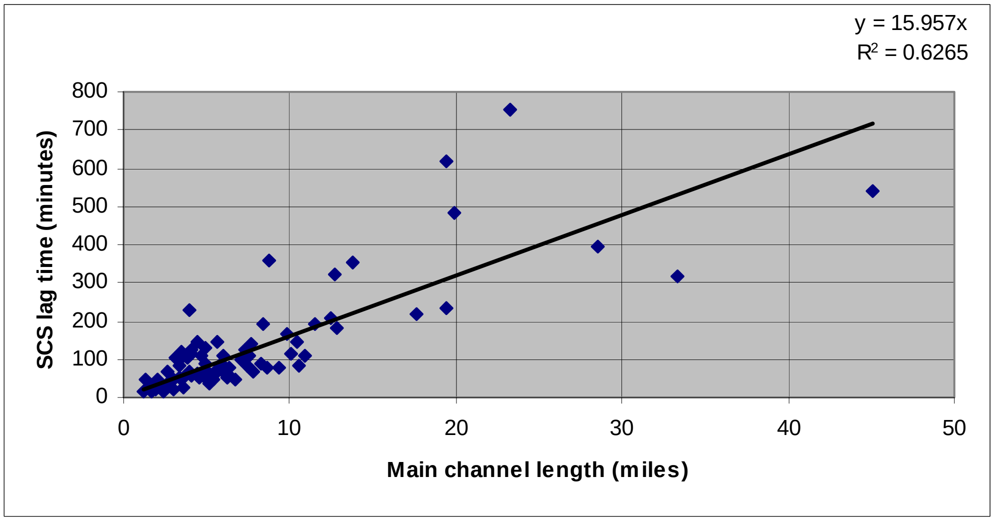

Figure 4.19. Scatterplot of SCS lag time versus main channel length.

The scatterplot of SCS lag time and the main channel length is as Figure 4.20.The r-square value was observed to be 0.62. Lag time is defined as the difference in time between the center of mass of rainfall excess and the peak discharge of the unit hydrograph. The main channel length is defined as the length of the longest watercourse in the watershed. Linear correlation was tested using Perason's *r*, and Pearson's r was found to be 0.79. Kendall's tau was calculated to be 0.56 and *p* equaled to zero. This is not a very strong correlation. It is concluded that a statistically strong relations between the parameters could not be established.

CHAPTER 5

CONCLUSIONS

The purpose of this research was to determine the Green-Ampt infiltration model loss parameters for selected Texas watersheds from measured rainfall-runoff data by the use of the HEC-HMS model. It was examined whether the infiltration model loss parameters were sensitive to the development condition or to the geographical location of the watersheds. In addition, any relation between watershed characteristics and infiltration model loss parameters were also examined.

The HEC-HMS software was used to mathematically model the measured rainfall-runoff process and the Green-Ampt infiltration model loss parameters were then optimized. Representative values of hydraulic conductivity, initial loss, soil moisture deficit and soil wetting front suction were also determined for each watershed. Moisture deficit and wetting front suction values depend on the moisture content of the soil and are variable for the same soil type. Hydraulic conductivity is a relatively constant parameter for a particular soil type for all moisture content values. So hydraulic conductivity and initial loss were only consider for further statistical analysis.

Statistically significant correlation coefficient between the infiltration parameters and the watershed characteristics could not be established. However, some trends of relationship between the parameter values were observed but the correlations were not statistically significant.

Results obtained from this research confirmed that the initial loss and the hydraulic conductivity were greater for undeveloped watersheds compared to that of developed watersheds. The median value for the initial loss in developed watersheds was 0.16 inches while that for undeveloped watersheds was 0.24 inches. Similarly, the median value for hydraulic conductivity in developed watersheds was 0.1 inches/hr while that for undeveloped watersheds was 0.18 inches/hr.

Initial loss and hydraulic conductivity were greater for watersheds in Austin and San Antonio area compared to rural watersheds or watersheds in Dallas-Fort Worth area. Initial loss values obtained from the optimization procedure were lesser compared to initial abstraction values calculated using the observed or predicted curve number. Hydraulic conductivity values obtained from the soil survey were about two times higher than that obtained from optimizations.

To sum, initial loss and hydraulic conductivity parameters were modeled based on historical rainfall-runoff data. These parameters were analyzed to determine if the parameter values changed depending on the development or geographical location of the watersheds. In addition, optimized initial loss values were compared to initial abstraction values obtained from curve numbers. Optimized hydraulic conductivity values were compared to hydraulic conductivity values obtained from the web soil survey.

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APPENDIX A

Table A.1 General location and cordinates of the study watersheds.
Source: Asquith et al. (2004).

Gage ID	Location	Latitude °N in decimals	Longitude °E in decimals
08042650	North Creek sub. 28A near Jermyn, Texas (Rural Fort Worth Dallas)	33.2478	-98.3219
08042700	North Creek near Jacksboro, Texas (Rural Fort Worth Dallas)	33.2825	-98.2981
08048520	Sycamore Creek at IH 35W, Fort Worth, Texas	32.6653	-97.3211
08048530	Sycamore Creek tributary above Seminary South Shopping Center, Fort Worth, Texas	32.6856	-97.3289
08048540	Sycamore Creek tributary at IH 35W, Fort Worth, Texas	32.6883	-97.3197
08048550	Dry Branch at Blandin Street, Fort Worth, Texas	32.7886	-97.3061
08048600	Dry Branch at Fain Street, Fort Worth, Texas	32.7761	-97.2883
08048820	Little Fossil Creek at IH 820, Fort Worth, Texas	32.8394	-97.3222
08048850	Little Fossil Creek at Mesquite Street, Fort Worth, Texas	32.8092	-97.2911
08050200	Elm Fork Trinity River sub. 6 near Muenster, Texas (Rural Fort Worth Dallas)	33.6203	-97.4042
08052630	Little Elm Creek sub. 10 near Gunter, Texas (Rural Fort Worth Dallas)	33.4092	-96.8114
08052700	Little Elm Creek near Aubrey, Texas (Rural Fort Worth Dallas)	33.2833	-96.8925
08055580	Joes Creek at Royal Lane, Dallas, Texas	32.8953	-96.6933
08055600	Joes Creek at Dallas, Texas	32.8592	-96.8833
08055700	Bachman Branch at Dallas, Texas	32.8603	-96.8536
08056500	Turtle Creek at Dallas, Texas	32.8072	-96.8022
08057020	Coombs Creek at Sylvan Ave, Dallas, Texas	32.7669	-96.8353
08057050	Cedar Creek at Bonnieview Road, Dallas, Texas	32.7472	-96.7956
08057120	McKamey Creek at Preston Road, Dallas, Texas(Rural Fort Worth Dallas)	32.9661	-96.8031
08057130	Rush Branch at Arapaho Road, Dallas, Texas	32.9625	-96.7956
08057140	Cottonwood Creek at Forest Lane, Dallas, Texas	32.9092	-96.7650
08057160	Floyd Branch at Forest Lane, Dallas, Texas	32.9092	-96.7594
08057320	Ash Creek at Highland Road, Dallas, Texas	32.8050	-96.7178
08057415	Elam Creek at Seco Boulevard, Dallas, Texas	32.7372	-96.6933
08057418	Fivemile Creek at Kiest Boulevard, Dallas, Texas	32.7053	-96.8589
08057420	Fivemile Creek at US Highway 77W, Dallas, Texas	32.6875	-96.8228
08057425	Woody Branch at IH 625, Dallas, Texas	32.6828	-96.8228
08057435	Newton Creek at IH 635, Dallas, Texas	32.6553	-96.7447
08057440	Whites Branch at IH 625, Dallas, Texas	32.6572	-96.7403
08057445	Prarie Creek at US Highway 175, Dallas, Texas	32.7047	-96.6697

Table A.1 (continued).

Gage ID	Location	Latitude °N in decimals	Longitude °E in decimals
08057500	Honey Creek sub. 11 near McKinney, Texas (Rural Fort Worth Dallas)	33.3033	-96.6894
08058000	Honey Creek sub.12 near McKinney, Texas (Rural Fort Worth Dallas)	33.3056	-96.6700
08061620	Duck Creek at Buckingham Road, Garland, Texas	32.9314	-96.6653
08061920	South Mesquite Creek at SH 352, Mesquite, Texas	32.7692	-96.6217
08061950	South Mesquite Creek at Mercury Road, Mesquite, Texas	32.7256	-96.5700
08063200	Pin Oak Creek near Hubbard, Texas (Rural Central)	31.8003	-96.7172
08094000	Green Creek sub. 1 near Dublin, Texas (Rural Central)	32.1658	-98.3411
08096800	Cow Bayou sub. 4 near Bruceville, Texas (Rural Central)	31.3331	-97.2672
08098300	Little Pond Creek near Burlington, Texas (Rural Central)	31.0264	-96.9881
08108200	North Elm Creek near Cameron, Texas (Rural Central)	30.9311	-97.0203
08136900	Mukewater Creek sub. 10A near Trickham, Texas (Rural Central)	31.6503	-99.2250
08137000	Mukewater Creek sub. 9 near Trickham, Texas (Rural Central)	31.6944	-99.2050
08137500	Mukewater Creek at Trickham, Texas (Rural Central)	31.5900	-99.2267
08139000	Deep Creek sub. 3 near Placid,Texas (Rural Central)	31.2903	-99.1561
08140000	Deep Creek sub. 8 near Mercury, Texas (Rural Central)	31.4022	-99.1214
08154700	Bull Creek at Loop 360, Austin, Texas	30.3719	-97.7844
08155200	Barton Creek at SH 71, Oak Hill, Texas	30.2961	-97.9253
08155300	Barton Creek at Loop 360, Austin, Texas	30.2444	-97.8019
08155550	West Bouldin Creek at Riverside Drive, Austin, Texas	30.2636	-97.7547
08156650	Shoal Creek at Steck Avenue, Austin, Texas	30.3653	-97.7364
08156700	Shoal Creek at Northwest Park, Austin, Texas	30.3472	-97.7447
08156750	Shoal Creek at White Rock Drive, Austin, Texas	30.3392	-97.7472
08156800	Shoal Creek at 12th Street, Austin, Texas	30.2764	-97.7500
08157000	Waller Creek at 38th Street, Austin, Texas	30.2969	-97.7267
08157500	Waller Creek at 23rd Street, Austin, Texas	30.2856	-97.7336
08158050	Boggy Creek at US 183, Austin, Texas	30.2631	-97.6722
08158200	Walnut Creek at Dessau Road, Austin, Texas	30.3750	-97.6603
08158380	Little Walnut Creek at Georgian Drive Austin, Texas	30.3542	-97.6978
08158400	Little Walnut Creek at IH 35, Austin, Texas	30.3492	-97.6928
08158500	Little Walnut Creek at Manor Road, Austin, Texas	30.3094	-97.6678

Table A.1 (continued).

Gage ID	Location	Latitude °N in decimals	Longitude °E in decimals
08158600	Walnut Creek at Webberville Road, Austin, Texas	30.2831	-97.6547
08158700	Onion Creek near Driftwood, Texas	30.0831	-98.0081
08158810	Bear Creek below FM 1826, Driftwood, Texas	30.1553	-97.9397
08158840	Slaughter Creek at FM 1826, Austin, Texas	30.2089	-97.9031
08158860	Slaughter Creek at FM 2304, Austin, Texas	30.1619	-97.8319
08158880	Boggy Creek (south) at Circle S Road, Austin, Texas	30.1806	-97.7819
08158920	Williamson Creek at Oak Hill, Texas	30.2350	-97.8600
08158930	Williamson Creek at Manchaca Road, Austin, Texas	30.2211	-97.7933
08158970	Williamson Creek at Jimmy Clay Road, Austin, Texas	30.1892	-97.7322
08159150	Wilbarger Creek near Pflugerville, Texas	30.4544	-97.6006
08177600	Olmos Creek tributary at FM 1535, Shavano Park, Texas	29.5764	-98.5458
08178300	Alazan Creek at St. Cloud Street, San Antonio, Texas	29.4581	-98.5497
08178555	Harlendale Creek at West Harding Street, San Antonio, Texas	29.3514	-98.4922
08178600	Panther Springs Creek at FM 2696 near San Antonio, Texas	29.6253	-98.5183
08178645	East Elm Creek at San Antonio, Texas	29.6178	-98.4281
08178690	Salado Creek tributary at Bitters Road, San Antonio, Texas	29.5267	-98.4403
08178736	Salado Creek tributary at Bee Street, San Antonio, Texas	29.4439	-98.4536
08181000	Leon Creek tributary at FM 1604, San Antonio, Texas	29.5872	-98.6278
08181400	Helotes Creek at Helotes, Texas	29.5783	-98.6914
08181450	Leon Creek tributary at Kelly Air Force Base, Texas	29.3867	-98.6000
08182400	Calaveras Creek sub. 6 near Elmendorf, Texas	29.3803	-98.2925

Table A.2 Median values of rainfall loss-rate parameters for Green-Ampt equation obtained from optimizations trials for study watersheds

Abbreviations: K, hydraulic conductivity in in/hr; IL, initial loss in inches; MD, moisture deficit in percentage; WFS, wetting front suction in inches; SCS lag,lagtime in minutes; SCS, Soil conservation Service; RTR, recession threshold ratio;RC, recession constant;RF,runoff in inches.

Gage ID	K (in/hr)	IL (in)	MD	WFS (in)	RTR	SCS lag (minutes)	RC	Total RF (in)	Total Excess (in)	total loss(in)	Percentage of total loss	Infiltration loss (in)
08042650	0.13	0.09	0.20	16.00	0.20	108.00	0.0001	2.87	0.93	1.94	67.60	1.85
08042700	0.23	0.44	0.18	13.55	0.15	190.50	0.0400	3.29	0.54	2.64	78.06	2.16
08048520	0.20	0.13	0.09	16.00	0.38	111.00	0.0001	1.71	0.40	1.29	75.74	1.08
08048530	0.12	0.07	0.17	15.61	0.09	17.00	0.0001	1.33	0.36	0.97	70.68	0.71
08048540	0.09	0.13	0.12	16.23	0.05	18.00	0.0001	1.20	0.42	0.69	62.73	0.54
08048550	0.09	0.13	0.12	16.34	0.13	35.00	0.0001	1.79	0.62	0.97	62.28	0.84
08048600	0.13	0.15	0.13	16.13	0.16	104.00	0.0001	2.30	0.84	1.53	67.78	1.44
08048820	0.12	0.30	0.07	13.25	0.59	107.50	0.0001	2.79	0.55	1.25	64.15	0.75
08048850	0.08	0.80	0.08	8.00	0.27	77.50	0.0001	2.27	0.08	2.16	96.11	1.72
08050200	0.10	0.63	0.07	8.00	0.20	68.00	0.0001	3.30	2.41	1.05	26.97	0.91
08052630	0.11	0.26	0.11	15.06	0.27	53.00	0.0001	3.57	2.34	1.58	42.06	1.29
08052700	0.10	0.10	0.04	15.06	0.30	755.00	0.1000	3.02	1.26	1.71	57.07	1.56
08055580	0.05	0.09	0.06	17.00	0.07	23.00	0.0001	2.00	1.67	0.74	34.80	0.65
08055600	0.23	0.09	0.10	15.00	0.11	48.00	0.0001	3.05	1.32	1.54	52.35	1.49
08055700	0.12	0.11	0.13	17.04	0.17	69.00	0.0001	3.04	1.24	1.28	59.68	1.17
08056500	0.07	0.06	0.10	17.19	0.20	76.00	0.0001	1.20	0.84	0.73	59.09	0.70
08057020	0.11	0.06	0.18	12.92	0.21	45.00	0.0001	2.49	0.96	1.53	61.45	1.47
08057050	0.02	0.03	0.01	15.68	0.09	54.00	0.0001	0.91	0.77	0.14	15.38	0.11
08057120	0.07	0.27	0.14	14.26	0.75	61.50	0.0001	1.61	0.51	1.10	68.27	0.83
08057130	0.16	0.14	0.14	13.42	0.33	37.00	0.0001	3.89	2.41	1.48	46.96	1.34
08057140	0.10	0.16	0.12	14.67	0.30	82.00	0.0001	1.53	0.60	0.93	58.49	0.76
08057160	0.07	0.15	0.14	15.39	0.15	60.00	0.0001	1.71	0.78	1.12	58.80	1.02
08057320	0.04	0.09	0.09	13.23	0.15	45.00	0.0001	1.91	1.45	1.14	38.38	0.87
08057415	0.03	0.12	0.06	14.94	0.04	19.00	0.0001	2.19	1.95	0.85	25.45	0.73
08057418	0.07	0.10	0.09	17.10	0.20	67.00	0.0001	3.19	1.36	1.24	56.91	1.14
08057420	0.04	0.15	0.16	14.02	0.11	88.00	0.0001	2.51	1.21	1.36	49.16	1.19
08057425	0.03	0.16	0.11	15.87	0.14	62.00	0.0001	2.54	1.20	1.24	50.58	1.15
08057435	0.06	0.18	0.17	15.20	0.07	116.00	0.0001	2.94	1.54	1.40	47.62	1.22
08057440	0.09	0.21	0.09	17.04	0.14	121.50	0.0001	3.30	1.54	1.77	54.13	1.56
08057445	0.05	0.09	0.11	14.83	0.31	192.00	0.0001	2.53	1.25	1.28	52.38	1.19

Table A.2 (continued)

Gage ID	K (in/hr)	IL (in)	MD	WFS (in)	RTR	SCS lag (minutes)	RC	Total RF (in)	Total Excess (in)	total loss(in)	Percentage of total loss	Infiltration loss (in)
08057500	0.05	0.20	0.10	14.04	0.20	38.10	0.0001	1.67	0.76	0.71	42.51	0.64
08058000	0.04	0.07	0.11	13.40	0.14	47.51	0.0001	2.33	1.51	0.83	36.37	0.75
08061620	0.07	0.30	0.12	16.28	0.24	67.61	0.0001	2.98	2.22	1.29	44.55	0.83
08061920	0.05	0.07	0.04	18.00	0.30	141.56	0.0001	2.93	1.83	0.95	37.54	0.88
08061950	0.10	0.27	0.04	15.00	0.20	321.89	0.0001	5.04	2.43	2.65	52.17	2.26
08063200	0.07	0.45	0.09	13.88	0.20	358.16	0.0001	3.47	1.40	1.52	53.60	1.47
08094000	0.19	0.50	0.16	15.42	0.15	96.40	0.0001	4.98	1.42	3.52	70.16	2.96
08096800	0.23	0.43	0.19	15.01	0.21	60.02	0.0001	2.66	0.47	2.33	83.04	1.92
08098300	0.07	0.24	0.09	18.52	0.20	352.84	0.0001	4.05	2.51	1.55	46.53	1.31
08108200	0.18	0.05	0.08	20.00	0.20	484.00	0.0001	2.94	1.61	1.15	45.24	1.06
08136900	0.18	0.38	0.15	15.58	0.08	209.00	0.0001	2.59	0.46	2.13	82.24	1.75
08137000	0.13	0.23	0.06	14.29	0.10	147.99	0.0001	1.76	0.81	0.96	54.63	0.72
08137500	0.05	0.06	0.03	15.08	0.10	620.00	0.0001	1.38	0.17	1.21	87.68	1.15
08139000	0.23	0.16	0.19	14.66	0.08	82.21	0.0001	3.18	1.29	1.97	62.98	1.73
08140000	0.33	0.27	0.14	15.02	0.17	89.81	0.0001	2.00	0.44	1.34	78.00	1.19
08154700	0.29	0.51	0.20	15.02	0.21	116.47	0.0001	3.82	1.00	2.82	79.83	2.53
08155200	0.15	0.20	0.17	15.50	0.25	393.95	0.0001	2.35	0.40	2.01	84.01	1.70
08155300	0.24	0.20	0.17	15.00	0.20	541.73	0.0001	2.62	0.64	1.94	75.00	1.55
08155550	0.29	0.43	0.20	15.42	0.23	58.49	0.0001	2.01	0.58	1.81	86.97	1.30
08156650	0.40	0.22	0.18	14.00	0.16	49.00	0.0001	2.50	0.56	1.94	77.72	1.79
08156700	0.13	0.15	0.10	17.00	0.30	54.00	0.0001	5.46	1.38	2.13	74.73	1.93
08156750	0.10	0.48	0.10	12.00	0.18	41.00	0.0001	2.43	0.25	2.15	86.29	1.57
08156800	0.29	0.19	0.10	15.00	0.18	82.00	0.0001	3.13	0.57	2.23	71.20	2.37
08157000	0.18	0.28	0.17	14.00	0.11	57.50	0.0001	3.90	1.03	2.25	65.55	1.98
08157500	0.16	0.17	0.12	14.00	0.18	37.00	0.0001	2.16	0.45	1.77	76.44	1.64
08158050	0.06	0.40	0.07	14.50	0.19	122.50	0.0001	3.67	1.17	2.51	69.00	2.06
08158200	0.30	0.35	0.20	15.00	0.15	111.00	0.0001	2.55	0.23	2.33	88.29	1.86
08158380	0.15	0.18	0.21	18.50	0.11	66.50	0.0001	2.62	0.97	1.66	59.64	1.48
08158400	0.09	0.15	0.06	14.00	0.10	55.00	0.0001	3.00	1.11	1.78	56.39	1.61
08158500	0.22	0.27	0.18	13.00	0.10	80.00	0.0001	3.18	0.74	2.06	76.73	1.91
08158600	0.09	0.14	0.12	14.00	0.20	236.00	0.0001	3.84	0.92	2.40	76.04	2.29

Table A.2 (continued)

Gage ID	K (in/hr)	IL (in)	MD	WFS (in)	RTR	SCS lag (minutes)	RC	Total RF (in)	Total Excess (in)	total loss(in)	Percentage of total loss	Infiltration loss (in)
08158700	0.41	0.27	0.10	20.00	0.10	316.00	0.0001	2.70	0.57	2.13	78.89	1.86
08158810	0.09	0.06	0.05	22.00	0.10	62.00	0.0001	4.63	2.18	1.76	41.63	1.70
08158840	0.30	0.25	0.19	15.00	0.10	86.00	0.0001	3.15	0.71	2.44	73.83	2.15
08158860	0.47	0.14	0.10	21.50	0.18	182.00	0.0001	7.76	3.89	3.87	60.22	3.73
08158880	0.18	0.17	0.12	15.00	0.18	60.86	0.0001	2.71	1.24	1.47	58.37	1.35
08158920	0.29	0.37	0.16	14.50	0.19	62.65	0.0001	3.71	1.01	3.12	78.17	2.59
08158930	0.34	0.27	0.18	15.00	0.18	144.65	0.0001	4.12	1.18	2.90	70.39	2.73
08158970	0.46	0.22	0.09	14.00	0.08	217.70	0.0001	4.50	1.16	3.34	74.22	2.46
08159150	0.10	0.21	0.10	18.00	0.18	108.60	0.0001	2.46	0.81	1.87	70.00	1.65
08177600	0.51	0.14	0.10	19.00	0.10	47.00	0.0001	4.07	1.77	2.30	59.08	2.16
08178300	0.16	0.27	0.18	15.03	0.08	23.49	0.0001	2.06	0.44	1.39	71.90	1.07
08178555	0.09	0.27	0.10	13.86	0.02	122.82	0.0001	2.51	0.81	1.91	69.72	1.45
08178600	0.27	0.45	0.17	14.28	0.06	100.29	0.0001	2.83	0.51	2.26	84.66	2.20
08178645	0.31	0.29	0.16	12.40	0.10	229.00	0.0001	2.72	0.57	2.15	79.04	1.86
08178690	0.30	0.10	0.19	15.20	0.18	15.96	0.0001	2.78	0.80	1.59	71.27	1.51
08178736	0.14	0.30	0.20	14.99	0.10	31.50	0.0001	2.60	1.21	1.54	55.71	1.34
08181000	0.23	0.23	0.18	14.26	0.10	57.88	0.0001	1.80	0.25	1.55	86.11	1.28
08181400	0.31	0.81	0.15	14.00	0.10	168.00	0.0001	4.52	0.45	3.02	90.76	1.86
08181450	0.30	0.45	0.15	14.00	0.10	103.00	0.0001	2.80	0.63	2.22	78.00	1.87
08182400	0.03	0.22	0.12	10.48	0.10	129.00	0.0001	3.09	1.92	1.18	37.56	0.96
OSSSC	0.07	0.06	0.06	12.03	0.04	17.00	0.0001	1.50	1.12	0.50	26.98	0.47

Table A.3. Watershed characteristics for study watersheds.

Sources: (Asquith et al. 2004), drainage area,mainchannel length,mainchannel slope,basin shape factor and elongation ratio from 30-meter DEM,web soil survey. Abbreviations: DEM, Digital Elevation Model,sub., subwatershed; IH, Interstate Highway; US, United States; SH, State Highway; FM, Farm to Market; D, developed watershed; U, undeveloped watershed,CN(obs),observed curve number;CN(pre),predicted curve number;S(obs), maximum potential storage caluclated using CN(obs) in inches;S(pre), maximum potential storage caluclated using CN(pre) in inches;I_a(obs), initial abstraction caluclated using CN(obs) in inches;Ia(pre), initial abstraction caluclated using CN(pre)in inches; mi.,miles.

Gage ID	USGS Area in mi^2	Location	Development Condition	CN(obs)	CN(pred)	S (obs)	S (pred)	Ia (obs)	Ia (pred)	Average Basin Slope	Main Channel Length in mi.	Main Channel Slope	Basin Shape Factor	Elongation Ratio	Hydraulic Conductivity (in/hr)
08042650	6.82	Small RWS	U	59	63.4	6.95	5.77	1.39	1.15	0.06	4.63	0.01	2.25	0.75	0.11
08042700	21.60	Small RWS	U	56	62	7.86	6.13	1.57	1.23	0.05	11.57	0.01	2.46	0.72	0.10
08048520	17.70	Fort Worth D	D	72	82.3	3.89	2.15	0.78	0.43	0.02	7.53	0.00	2.01	0.80	0.11
08048530	0.97	Fort Worth D	D	69	86.7	4.49	1.53	0.90	0.31	0.02	1.70	0.01	1.79	0.84	0.12
08048540	1.35	Fort Worth D	D	73	88	3.70	1.36	0.74	0.27	0.02	2.37	0.01	2.86	0.67	0.10
08048550	1.08	Fort Worth D	D	74	91.2	3.51	0.96	0.70	0.19	0.01	2.02	0.00	3.10	0.65	0.09
08048600	2.15	Fort Worth D	D	65	84.3	5.38	1.86	1.08	0.37	0.01	3.85	0.00	5.23	0.49	0.07
08048820	5.64	Fort Worth D	D	67	83.4	4.93	1.99	0.99	0.40	0.01	6.03	0.01	5.14	0.50	0.07
08048850	12.30	Fort Worth D	D	72	83	3.89	2.05	0.78	0.41	0.01	9.40	0.00	5.16	0.50	0.07
08050200	0.77	Small RWS	U	80	79.6	2.50	2.56	0.50	0.51	0.04	2.64	0.01	7.50	0.41	0.06
08052630	2.10	Small RWS	U	80	85.4	2.50	1.71	0.50	0.34	0.03	3.30	0.01	4.75	0.52	0.07
08052700	75.50	Small RWS	U	74	84.1	3.51	1.89	0.70	0.38	0.02	23.23	0.00	4.81	0.51	0.07
08055580	1.94	Dallas D	D	85	85.2	1.76	1.74	0.35	0.35	0.02	3.00	0.01	3.43	0.61	0.09
08055600	7.51	Dallas D	D	82	86.1	2.20	1.61	0.44	0.32	0.02	6.74	0.01	6.29	0.45	0.06
08055700	10.00	Dallas D	D	73	85.5	3.70	1.70	0.74	0.34	0.02	7.77	0.01	3.98	0.57	0.08
08056500	7.98	Dallas D	D	85	85.8	1.76	1.66	0.35	0.33	0.02	6.37	0.01	4.82	0.51	0.07
08057020	4.75	Dallas D	D	75	85.5	3.33	1.70	0.67	0.34	0.04	5.09	0.01	4.30	0.54	0.08
08057050	9.42	Dallas D	D	75	85.7	3.33	1.67	0.67	0.33	0.03	6.21	0.01	3.08	0.64	0.09
08057120	6.77	Fort Worth U	U	77	80.2	2.99	2.47	0.60	0.49	0.02	5.19	0.01	3.33	0.62	0.09
08057130	1.22	Dallas D	D	89	82.9	1.24	2.06	0.25	0.41	0.02	2.63	0.01	4.41	0.54	0.08
08057140	8.50	Dallas D	D	78	86.8	2.82	1.52	0.56	0.30	0.02	7.47	0.01	4.31	0.54	0.08
08057160	4.17	Dallas D	D	80	90.3	2.50	1.07	0.50	0.21	0.02	5.34	0.01	5.30	0.49	0.07
08057320	6.92	Dallas D	D	85	85.7	1.76	1.67	0.35	0.33	0.02	5.42	0.01	4.12	0.56	0.08
08057415	1.25	Dallas D	D	73	87.8	3.70	1.39	0.74	0.28	0.01	1.88	0.01	2.89	0.66	0.10
08057418	7.65	Dallas D	D	85	79.1	1.76	2.64	0.35	0.53	0.03	5.65	0.01	3.43	0.61	0.09
08057420	13.20	Dallas D	D	80	81	2.50	2.35	0.50	0.47	0.04	8.33	0.01	3.56	0.60	0.09

Table A.3. (continued)

Gage ID	USGS Area in mi^2	Location	Development Condition	CN(obs)	CN(pred)	S (obs)	S (pred)	Ia (obs)	Ia (pred)	Average Basin Slope	Main Channel Length in mi.	Main Channel Slope	Basin Shape Factor	Elongation Ratio	Hydraulic Conductivity (in/hr)
08057425	11.50	Dallas D	D	90	82.9	1.11	2.06	0.22	0.41	0.04	6.16	0.01	2.47	0.72	0.10
08057435	5.91	Dallas D	D	82	81.1	2.20	2.33	0.44	0.47	0.03	4.12	0.01	2.20	0.76	0.11
08057440	2.53	Dallas D	D	67	79.1	4.93	2.64	0.99	0.53	0.03	3.52	0.01	4.03	0.56	0.08
08057445	9.03	Dallas D	D	60	86.5	6.67	1.56	1.33	0.31	0.02	8.42	0.00	5.98	0.46	0.07
08057500	2.14	Small RWS	U	80	78.2	2.50	2.79	0.50	0.56	0.05	2.07	0.01	2.56	0.71	0.10
08058000	1.26	Small RWS	U	86	80.1	1.63	2.48	0.33	0.50	0.03	2.09	0.01	3.16	0.63	0.09
08061620	8.05	Dallas D	D	82	85	2.20	1.76	0.44	0.35	0.01	5.52	0.00	2.49	0.71	0.10
08061920	13.40	Dallas D	D	85	86	1.76	1.63	0.35	0.33	0.02	7.64	0.00	3.62	0.59	0.09
08061950	23.00	Dallas D	D	82	85.3	2.20	1.72	0.44	0.34	0.03	12.65	0.00	5.40	0.49	0.07
08063200	17.60	Small RWS	U	70	79.4	4.29	2.59	0.86	0.52	0.02	8.73	0.00	3.00	0.65	0.09
08094000	3.34	Small RWS	U	60	78.4	6.67	2.76	1.33	0.55	0.04	3.35	0.01	3.70	0.59	0.08
08096800	5.25	Small RWS	U	62	80	6.13	2.50	1.23	0.50	0.06	4.49	0.01	2.59	0.70	0.10
08098300	22.20	Small RWS	U	88	80.5	1.36	2.42	0.27	0.48	0.02	13.73	0.00	5.94	0.46	0.07
08108200	48.60	Small RWS	U	77	79.9	2.99	2.52	0.60	0.50	0.02	19.96	0.00	6.67	0.44	0.06
08136900	21.80	Small RWS	U	51	75.8	9.61	3.19	1.92	0.64	0.02	12.42	0.00	4.78	0.52	0.07
08137000	4.02	Small RWS	U	52	74.5	9.23	3.42	1.85	0.68	0.02	4.40	0.00	3.94	0.57	0.08
08137500	70.40	Small RWS	U	53	76.5	8.87	3.07	1.77	0.61	0.02	19.38	0.00	4.13	0.56	0.08
08139000	3.42	Small RWS	U	53	74.6	8.87	3.40	1.77	0.68	0.05	3.36	0.02	2.80	0.67	0.10
08140000	5.41	Small RWS	U	63	74.4	5.87	3.44	1.17	0.69	0.04	5.91	0.01	3.96	0.57	0.08
08154700	22.30	Austin U	U	59	68.9	6.95	4.51	1.39	0.90	0.11	10.04	0.01	3.15	0.64	0.09
08155200	89.70	Austin U	U	65	70.7	5.38	4.14	1.08	0.83	0.07	28.50	0.00	3.70	0.59	0.08
08155300	116.00	Austin U	U	64	69.8	5.63	4.33	1.13	0.87	0.08	45.07	0.00	5.98	0.46	0.07
08155550	3.12	Austin D	D	50	87.3	10.00	1.45	2.00	0.29	0.04	3.66	0.01	3.32	0.62	0.09
08156650	3.19	Austin D	D	60	83.6	6.67	1.96	1.33	0.39	0.03	3.00	0.01	1.64	0.88	0.13
08156700	7.03	Austin D	D	78	86.6	2.82	1.55	0.56	0.31	0.03	4.53	0.01	2.22	0.76	0.11
08156750	7.56	Austin D	D	66	86.8	5.15	1.52	1.03	0.30	0.03	5.13	0.01	2.60	0.70	0.10
08156800	12.80	Austin D	D	66	87	5.15	1.49	1.03	0.30	0.03	10.58	0.01	6.07	0.46	0.07
08157000	2.31	Austin D	D	68	88.3	4.71	1.33	0.94	0.27	0.02	4.12	0.01	6.54	0.44	0.06
08157500	4.13	Austin D	D	67	89.1	4.93	1.22	0.99	0.24	0.03	5.16	0.01	5.37	0.49	0.07

Table A.3. (continued)

Gage ID	USGS Area in mi^2	Location	Development Condition	CN(obs)	CN(pred)	S (obs)	S (pred)	Ia (obs)	Ia (pred)	Average Basin Slope	Main Channel Length in mi.	Main Channel Slope	Basin Shape Factor	Elongation Ratio	Hydraulic Conductivity (in/hr)
08158050	13.10	Austin D	D	71	83.9	4.08	1.92	0.82	0.38	0.03	7.36	0.01	2.86	0.67	0.10
08158200	26.20	Austin U	U	62	75.6	6.13	3.23	1.23	0.65	0.04	10.92	0.01	2.42	0.73	0.10
08158380	5.22	Austin D	D							0.02	4.01	0.01	2.24	0.75	0.11
08158400	5.57	Austin D	D	79	88.9	2.66	1.25	0.53	0.25	0.02	4.48	0.01	2.87	0.67	0.10
08158500	12.10	Austin D	D	71	85.6	4.08	1.68	0.82	0.34	0.03	8.59	0.01	4.32	0.54	0.08
08158600	51.30	Austin D	D	73	76.7	3.70	3.04	0.74	0.61	0.04	19.47	0.00	3.87	0.57	0.08
08158700	124.00	Austin U	U	69	74.5	4.49	3.42	0.90	0.68	0.06	33.28	0.00	3.48	0.60	0.09
08158810	12.20	Austin U	U	64	69.8	5.63	4.33	1.13	0.87	0.06	6.29	0.01	2.00	0.80	0.11
08158840	8.24	Austin U	U	74	69.8	3.51	4.33	0.70	0.87	0.05	4.96	0.01	2.65	0.69	0.10
08158860	23.10	Austin U	U	60	68	6.67	4.71	1.33	0.94	0.04	12.79	0.01	4.80	0.51	0.07
08158880	3.58	Austin U	U	67	79.4	4.93	2.59	0.99	0.52	0.04	4.40	0.01	4.08	0.56	0.08
08158920	6.30	Austin D	D	71	77.5	4.08	2.90	0.82	0.58	0.06	4.97	0.01	3.02	0.65	0.09
08158930	19.00	Austin D	D	56	75.2	7.86	3.30	1.57	0.66	0.04	10.40	0.01	4.81	0.51	0.07
08158970	27.60	Austin D	D	56	77.7	7.86	2.87	1.57	0.57	0.04	17.61	0.01	6.96	0.43	0.06
08159150	4.61	Austin U	U	63	78.8	5.87	2.69	1.17	0.54	0.02	3.74	0.01	1.93	0.81	0.12
08177600	0.33	San Antonio D	D	70	84.8	4.29	1.79	0.86	0.36	0.02	1.30	0.01	4.81	0.51	0.07
08178300	3.26	San Antonio D	D	72	85.7	3.89	1.67	0.78	0.33	0.05	3.58	0.02	3.03	0.65	0.09
08178555	2.43	San Antonio D	D	75	84.2	3.33	1.88	0.67	0.38	0.00	4.05	0.00	6.34	0.45	0.06
08178600	9.54	San Antonio U	U	60	79.7	6.67	2.55	1.33	0.51	0.07	7.05	0.01	4.65	0.52	0.08
08178645	2.33	San Antonio U	U	59	78.2	6.95	2.79	1.39	0.56	0.05	3.96	0.01	4.60	0.53	0.08
08178690	0.26	San Antonio D	D	78	84.4	2.82	1.85	0.56	0.37	0.01	1.17	0.00			0.00
08178736	0.45	San Antonio D	D	74	92.3	3.51	0.83	0.70	0.17	0.01	1.67	0.01	3.18	0.63	0.09
08181000	5.57	San Antonio U	U	50	79.2	10.00	2.63	2.00	0.53	0.13	5.42	0.01	3.17	0.63	0.09
08181400	15.00	San Antonio U	U	56	79.8	7.86	2.53	1.57	0.51	0.13	9.82	0.01	4.80	0.52	0.07
08181450	1.19	San Antonio D	D	60	87.3	6.67	1.45	1.33	0.29	0.01	3.13	0.00	6.45	0.44	0.06
08182400	7.01	Small RWS	U	52	80	9.23	2.50	1.85	0.50	0.03	4.87	0.01	2.87	0.67	0.10
OSSSC	0.38	Fort Worth D	D												

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