TEXAS TECH UNIVERSITY
Multidisciplinary Research in Transportation™

Subdivision of Texas Watersheds for Hydrologic Modeling

David B. Thompson and Theodore G. Cleveland

Performed in Cooperation with the Texas Department of Transportation and the Federal Highway Administration

Research Project 0-5822
Research Report 0-5822-01-2
http://www.techmrt.ttu.edu/reports.php

NOTICE

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report

Technical Report Documentation Page

1. Report No.: FHWA/TX -0–5822–01–2	2. Government Accession No.:	3. Recipient's Catalog No.:
4. Title and Subtitle: Subdivision of Texas watersheds for hydrologic modeling		5. Report Date: June 2009 6. Performing Organization Code: TechMRT
7. Author(s): David B. Thompson, Theodore G. Cleveland		8. Performing Organization Report No. 0–5822–01–2
9. Performing Organization Name and Address: Texas Tech University College of Engineering Box 41023 Lubbock, Texas 79409-1023		10. Work Unit No. (TRAIS): 11. Contract or Grant No. : Project 0–5822–01–2
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology P. O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Cover: Final project report October 2006 – August 2008 14. Sponsoring Agency Code:

15. Supplementary Notes:
This study was conducted in cooperation with the Texas Department of Transportation

16. Abstract: The purpose of this report is to present a set of findings and examples for subdivision of watersheds for hydrologic modeling. Three approaches were used to examine the impact of watershed subdivision on modeled hydrologic response: (1) An equal-area approach, (2) an *ad-hoc* approach wherein subdivisions were created at locations based on engineering judgment, and (3) a distributed-modeling approach. The three methods were implemented by different individuals with varied hydrologic experience, using their professional judgment under the direction of project researchers. Technology included NRCS curve number method for runoff volume, a variety of runoff-transformation methods, and use of measured rainfall-runoff responses. In general, subdivision had little or no impact on runoff volume. Estimates of peak discharge from study watersheds showed modest improvement in accuracy, but none beyond about 5-7 subdivisions. Time to peak estimates tended to degrade with subdivision, most likely because hydrologic routing introduced additional parameters requiring estimates. The distributed-modeling approach was extremely difficult to apply. In general, subdivision of watersheds is beneficial primarily when flow rates at locations internal to the watershed are required. The improvement in implied accuracy does not generally justify the subdivision process.

17. Key Words Hydrology, watershed, drainage basin, catchment, hydrologic modeling, hydrologic prediction, hydrologic design	18. Distribution Statement No restrictions. Document available to public through TxDOT and TechMRT.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. Pages 97	22. Price

Form DOT F 1700.7 (8-72)

This page intentionally left blank.

Subdivision of Texas Watersheds for Hydrologic Modeling

by
David B. Thompson, R.O. Anderson Engineering, Inc.
Theodore G. Cleveland, Texas Tech University

with contributions by
William H. Asquith, U.S. Geological Survey

Research Report Number 0–5822–2
Project Number 0–5822
Project: *Subdivision of Watersheds for Modeling*

Sponsored by the Texas Department of Transportation
in Cooperation with the
U.S. Department of Transportation Federal Highway Administration

Center for Multidisciplinary Research in Transportation
Department of Civil and Environmental Engineering
Texas Tech University
P.O. Box 41023
Lubbock, Texas 79409–1023

June 2009

AUTHOR'S DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view of policies of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PATENT DISCLAIMER

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

ENGINEERING DISCLAIMER

Not intended for construction, bidding, or permit purposes.

TRADE NAMES AND MANUFACTURERS' NAMES

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

This page intentionally left blank.

Acknowledgements

Three graduate students played a large role in the accomplishment of the research reported herein. Ms. Thuy Luong earned her Master of Science degree under the Texas Department of Transportation (TxDOT) Master's Degree program at University of Houston working on the equal drainage-area problem. Mr. Matthew Wingfield completed his Master of Science degree under the Texas Department of Transportation Master's Degree program at Texas Tech University, working his way through the *ad-hoc* approach to watershed subdivision. Ms. Erika Nordstrom wrestled with distributed modeling under HEC-HMS while earning her Master of Science degree at Texas Tech University. Without the efforts of these students, the research reported in this report would not have been accomplished.

Dr. William Asquith, Ms. Meghan Roussel, and Ms. Sally Holl of the U.S. Geological Survey (USGS) in Austin, Texas provided much-needed help in two major areas. The first was in support of the distributed modeling problem. It cannot be sufficiently emphasized how difficult it is to create and use fully-distributed models under the current version of HEC-HMS (U.S. Army Corps of Engineers, 2008). USGS personnel were able to access U.S. Army Corps of Engineers personnel at the Hydrologic Engineering Center for assistance that would not have been available to university researchers. In addition, they provided substantial work on the stochastic approach reported herein.

The support and insight of the TxDOT Project Advisory Committee was invaluable in determining appropriate research directions. The authors thank the committee for their efforts.

Contents

List of Tables

List of Figures

1. Background

The purpose of this section of the report is to establish the historical importance of the watershed subdivision problem and to define project scope and objectives.

1.1. History of the Project

Texas Department of Transportation (TxDOT) engineers are tasked with design of drainage and other hydraulic structures. Such designs require development of estimates of a design discharge. A design discharge is the flow rate from the watershed draining to the design point for a given level of risk, termed either the exceedance probability[1] or the return interval[2].

One of the technologies used by TxDOT analysts is the hydrograph method. Application of the hydrograph method requires a risk level, estimation of the unit hydrograph, selection of a design hyetograph, and a loss method. Analysts sometimes subdivide the watershed into smaller units for analysis. It is this subdivision of watersheds that is the topic of this report.

Experienced analysts understand innately that watershed subdivision is sometimes required, but should be kept to some minimum degree. Why subdivision might be *a bad thing* is not articulated clearly either in education of the analyst or in the professional literature. This omission of guidance leads some analysts to believe that subdivision of a watershed leads to improved estimates[3]. However, as the number of sub-watersheds increases, so does the number of hydrologic parameters that must be estimated. Without substantial supporting data for use in estimating or calibrating the burgeoning parameter set, it is unclear whether anything is gained by the additional work required to subdivide the watershed.

Whereas the previous discussion obviously applies to lumped-parameter models, like the hydrograph method, it also applies to other modeling approaches, including the distributed-modeling approach and the traditional network rational method. In the former, the watershed is intentionally discretized into small components, each with a hydrograph-generation model and associated parameters. The connections between elements can be fairly simple or fairly complex. An example

[1] The *exceedance probability* is the probability the given event will be equaled or exceeded over a fixed period of time, usually one year.

[2] The terms *return interval* and *recurrence interval* are used interchangeably. These terms refer to the average time between events of similar magnitude over a relatively long period of time. The *long period of time must* be several times greater than the return interval. These terms are often misunderstood.

[3] It is tempting to use the term *accuracy*, but it is difficult to associate accuracy with hydrologic estimates.

of the former is a simple lag time between hydrographs from adjacent elements; an example of the latter is a hydrodynamic modeling scheme, such as used in the Storm Water Management Model (Rossman, 2008).

The problem with parameter identification and calibration remains, however, whenever a watershed is broken into small components. These issues were a major topic of research interest in the 1980s. Examples are Gupta and Sorooshian (1983), Gupta and Sorooshian (1985b), Gupta and Sorooshian (1985a), Hornberger and others (1985), Jakeman and Hornberger (1993), Loague and Freeze (1985), Sorooshian (1981), Sorooshian and Gupta (1983), and Sorooshian and Gupta (1985). A general conclusion from these research results is that *simplest is best*.

As a result of discussions between TxDOT analysts and the research community, a problem statement, TxDOT Research Project Number 0–5822 *Subdivision of Watersheds for Modeling*, was developed and proposals were solicited. The project began in fiscal year 2007. The objectives of the research were:

1. Determine justification and methodology for subdividing watersheds for use with lumped models, and
2. Assess the utility of distributed models, such as the gridded sub-model system of HEC-HMS.

1.2. Purpose

The purpose of this report is to present results of efforts by researchers at Texas Tech University, University of Houston, and U.S. Geological Survey.

1.3. Participants

Besides the principal investigators who were involved in this research, a number of graduate students contributed significant efforts. Ms. Thuy Luong worked on the equal watershed area problem. Mr. Matthew Wingfield conducted the lumped-parameter modeling. Ms. Erika Nordstrom fought her way through the distributed modeling problem. The work of these students is contained within the following text.

2. Procedure

2.1. Literature Review

A review of the professional literature was undertaken by members of the research team and the graduate students supporting those researchers. Results of the literature review were not presented as a separate report, but as a technical memorandum[1]. A review of the literature is included in this report as Chapter 3. A map of Texas with the study sites superimposed on it is shown as Figure 2.1.

2.2. Equal-Area Models

Luong (2008) presents one of several approaches to watershed subdivision: the iso-characteristic approach. In the iso-characteristic approach, watershed subdivision is implemented by creating subdivisions such that the characteristic of choice (area, main channel length, etc.) is approximately equal for each subdivision.

Luong's (2008) approach was to first estimate the hydrologic response of a watershed as a single basin with no subdivisions. This no-subdivision model formed the basis for comparison of results from the creation of additional sub-watersheds. The second part of Luong's (2008) approach was to analyze the watershed by subdividing it into 2, 3, 5, and 7 sub-basins. These individual sub-basins responses are combined to generate a composite response for an entire watershed at the watershed outlet. The modeled hydrographs are compared with the observed hydrographs to see if the use of watershed subdivisions results in hydrograph reponses equivalent to observations that are more accurate than use of a single, un-subdivided watershed. In other words, to determine how the hydrograph response changes as a function of the degree of watershed subdivision.

Five watersheds in Central Texas were selected for study: Onion Creek, South Mesquite, Little Fossil, Olmos Creek, and Trinity Basin-North. Drainage areas for these watersheds ranged from approximately 12.3–166 square miles, main channel lengths ranged from approximately 9–48 miles, and dimensionless main channel slopes ranged from approximately 0.002–0.02. Events selected from a database of incremental cumulative rainfall values for storms that occurred during the period 1961–1986 (Asquith and others, 2004) were used as input to the `HEC-HMS` program (U.S. Army Corps of Engineers, 2006) to test the iso-characteristic method.

[1]The technical memorandum documenting the results of the literature review was dated 31 August 2007.

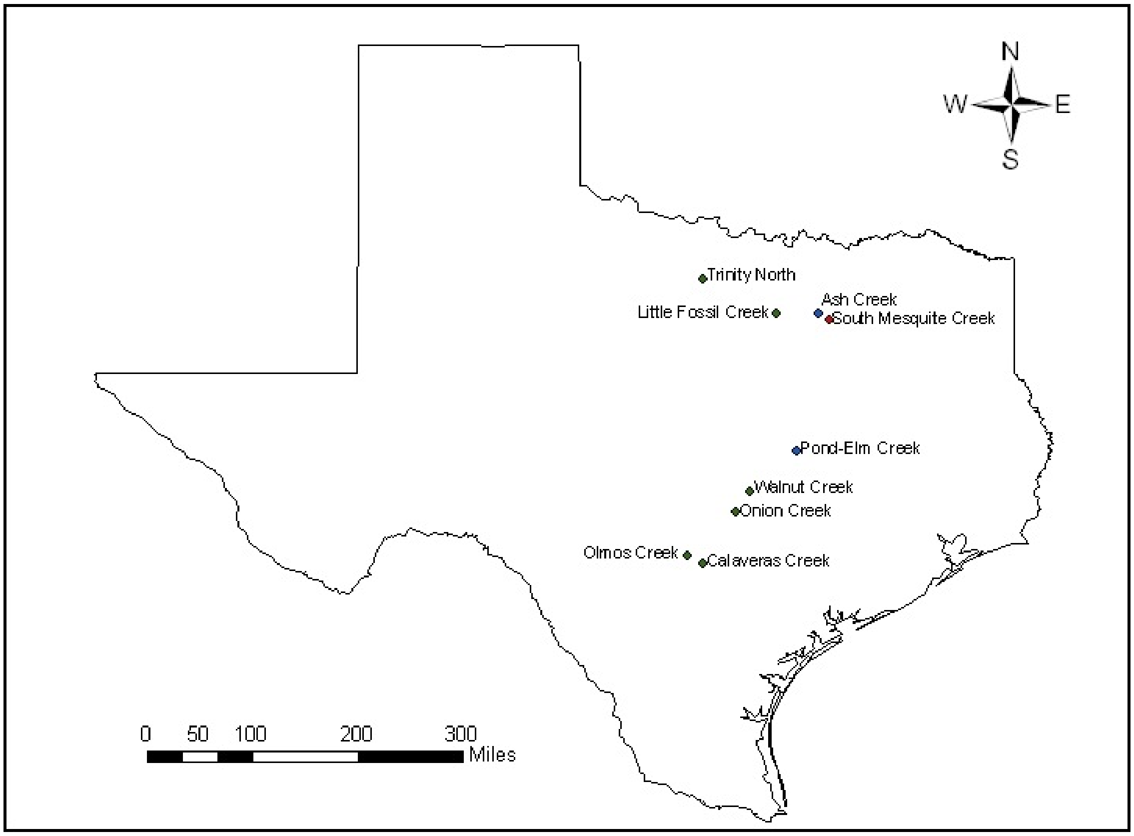


Figure 2.1: Approximate location of watersheds examined using `HEC-HMS` in the study. South Mesquite was modeled by all research teams as a consistency check (individual results were different, but the researchers desired at least one common watershed as an internal check). Other watersheds may have been uniquely modeled or modeled by two of the three research teams.

The supporting hydrologic data for each watershed are located within database[2] modules: **`austin`**, **`dallas`**, **`fortworth`**, **`sanantonio`**, and **`smallruralsheds`**, respectively. All database 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. Table 2.1 contains background information on each of the five watersheds.

USGS quadrangle maps (1:24,000 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

[2] Details of the database are presented by Asquith and others (2004). This database was developed as part of a suite of research projects executed for TxDOT treating loss-rate functions, unit hydrographs, and design hyetographs. The database represents the cumulative efforts of a dozen or more researchers located at Lamar University, University of Houston, U.S. Geological Survey, and Texas Tech University.

Table 2.1: Watershed characteristics for watersheds studied by Luong (2008).

Watershed	Module	Drainage area (mi^2)	Main channel slope
Onion Creek	Austin	166	0.026
South Mesquite Creek	Dallas	23	0.0022
Little Fossil Creek	Fort Worth	12.3	0.005
Olmos Creek	San Antonio	21.2	0.0038
Trinity Basin/North Creek	Smallrural	23.4	0.005

were adjusted until the individual sub-basin areas are about the same.

A discussion of "about the same" is appropriate. The study watersheds were subdivided manually using paper maps for watershed delineation and a mechanical planimeter for measurement of drainage area. Equal area subdivision is nontrivial and small movements of the subdivision outlet required re-delineation and re-measurement of the drainage area. A particular challenge was the treatment of main-channel tributaries. In many cases inclusion of a tributary channel in one sub-basin resulted in a substantial change to sub-basin drainage area with a small change to the location of the subdivision point on the main watershed channel. As a result, exact equal-area delineation was practically impossible. This experience alone suggests that prior studies by others that used stream bifurcation rules encountered similar issues and it is speculated that the subdivision challenge is in part why these bifurcation schemes exist.

Figure 2.2 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 the watershed (and sub-watersheds), such as area, main channel length, and main channel slope were measured. The watershed characteristics were used for estimation of model parameters.

The `HEC-HMS` models were assembled from the watershed and subdivisions of the watersheds. The Natural Resources Conservation Service[3] (NRCS) curve number procedure was used to represent the rainfall-runoff conversion process. Curve numbers for study watersheds (and their subdivisions) were developed using TR-55 (U.S. Department of Agriculture, Natural Resources Conservation Service, 1986) with Hydrologic Soil Group from the Web Soil Survey[4] and land-use/land-cover from Google Earth[5]. Impervious area was accounted for using a weighted curve number (McCuen and others, 2002),

$$CN = CN_p(1 - f) + 98f, \tag{2.1}$$

where CN_p is the table curve number, f is the fraction of impervious area, and the value 98 represents the curve number for impervious areas.

[3]The NRCS was the Soil Conservation Service (SCS) in a previous incarnation. The acronym, SCS, is retained in the current version of `HEC-HMS` (U.S. Army Corps of Engineers, 2006).
[4]The Web Soil Survey is the database service offered by NRCS through `http://websoilsurvey.nrcs.usda.gov` at the time of this writing.
[5]Google Earth is a freely-available application supported by Google and available from `http://earth.google.com/` at the time of this writing.

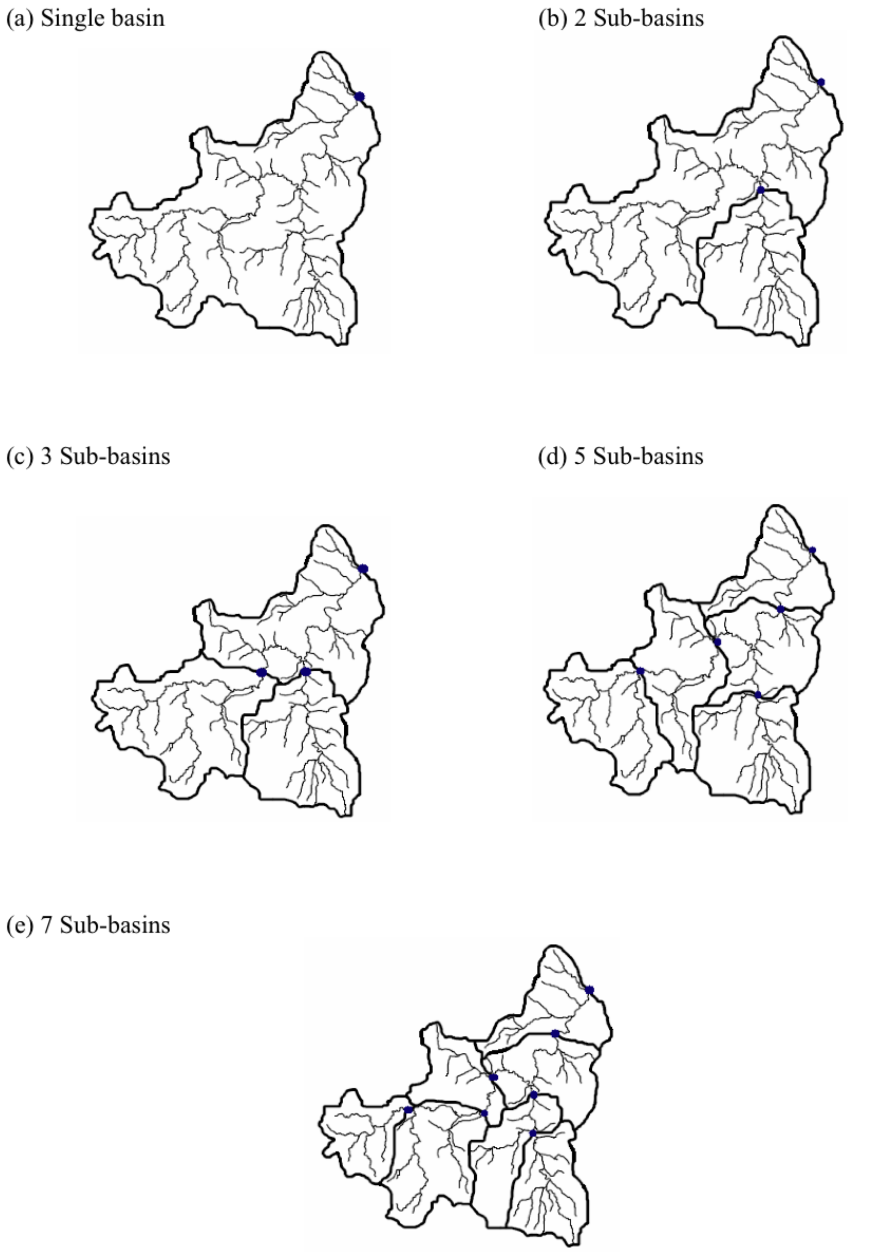


Figure 2.2: Subdivision scheme for the Trinity Basin-North Creek.

The NRCS dimensionless unit hydrograph was used as the transform function to compute watershed discharge from effective precipitation. The time of concentration for each watershed or watershed subdivision was estimated using a combination of overland flow travel time (Kerby, 1959) and channel flow time (Kirpich, 1940), based on research conducted under TxDOT project 0–4969 (Roussel and others, 2005). Kerby's (1959) overland flow travel time is

$$t_o = \left[\frac{0.67LN}{S^{0.5}}\right], \tag{2.2}$$

where t_o is the overland flow travel time (min, time of concentration), L is the length of overland flow (ft; L should be less than or equal to 600 ft), N is Kerby's roughness parameter[6], and S is the overland flow slope. Values for Kerby's retardance coefficient are listed on Table 2.2.

Table 2.2: Kerby's roughness parameter (Kerby, 1959).

Description	N
Pavement	0.02
Smooth, bare packed soil	0.10
Poor grass, cultivated row crops or moderately rough bare surfaces	0.20
Pasture, average grass	0.40
Deciduous forest	0.60
Dense grass, coniferous forest, or deciduous forest with deep litter	0.80

Kirpich's (1940) equation is

$$t_c = 0.0078L^{0.77}S^{-0.385}, \tag{2.3}$$

where t_c is the channel time of concentration (min), L is the main channel length (ft, the distance from the outlet to the distal end of the watershed), and S is the main channel slope (the change in elevation over the main channel divided by the main channel length). The time of concentration for the watershed is the sum of the overland flow and channel flow portions of the watershed response time. The NRCS dimensionless unit hydrograph lag time is

$$t_l = 0.6t_w, \tag{2.4}$$

where t_l is the lag time for the watershed (or subdivision) and t_w is the watershed (or subdivision) time of concentration.

When the study watershed was subdivided, routing was required to move the subwatershed hydrograph from the outlet of the subwatershed to the next junction downstream (or the watershed

[6]Kerby's N is not Manning's n, Values for N should be taken from tables of values for Kerby. See Kerby (1959) or Haan and others (1982) for details.

outlet). The simple lag routing method was chosen, with the lag time set to the channel time of concentration derived from the Kirpich equation. Reach lengths were relatively short so limited attenuation of routed hydrographs was expected, therefore lag routing was considered appropriate (Dooge, 1973).

The meteorologic model for `HEC-HMS` was defined using the measured hyetograph for each event modeled. In this research, the precipitation was observed rainfall from a historical event. These rainfall data were taken from a database assembled for previous projects and documented by Asquith and others (2004). Because the rainfall data tabulated with date and time and the accumulated rainfall were not uniformly spaced (break-point data), the data were converted by interpolation to have a 5-minute time interval. The arithmetic-mean method was used to determine areal average rainfall for all sub-watersheds because rainfall observations from only a few gages were available and the measurements from each gaging station did not differ greatly from the mean, and the precise location of the gages with respect to the watershed were unknown — therefore a complicated weighting scheme does not make sense[7].

Results from the `HEC-HMS` modeling were measured using three metrics, the mean relative deviation, the root mean square error, and a simple count of the number of times a given subdivision scheme provided the minimum error. These metrics were applied to peak discharge, Q, time to peak discharge, t_p, and runoff volume, V. The mean relative deviation is

$$\overline{X}_d = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_s - X_o}{X_o}\right), \tag{2.5}$$

where X_s is the model value, X_o is the observed value, and N is the number of events. The root mean square error is

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{X_s - X_o}{Xo}\right)^2}. \tag{2.6}$$

2.3. Lumped Models

Wingfield (2008) used automated tools to conduct watershed delineations and subdivision similar to the approach documented by Luong (2008), but using a different set of watersheds and a different subdivision approach. Wingfield's component of the study also addressed slightly different questions:

1. What fraction of a watershed must be different to justify a subdivision?
2. Where must the analyst expend effort to produce good estimates?

Wingfield's objectives were:

[7] Actual gage locations appear on watershed maps in the original sources used to construct the database.

1. To use `ArcGIS` and the extension tools `ArcHydro` (Maidment, 2002) and `HEC-GeoHMS` (U.S. Army Corps of Engineers, 2003) to delineate watersheds and sub-watersheds and to extract modeling parameters for each,

2. To evaluate the enhanced or diminished prediction value on watershed modeling as a function of subdivision, and

3. To determine if there is a certain percentage of a watershed that needs to be significantly different from the rest in order to justify subdividing.

The approach used to accomplish the objectives of this component of the project was:

1. Use the extension tools `ArcHydro` (Maidment, 2002) and `HEC-GeoHMS` (U.S. Army Corps of Engineers, 2003) within `ArcGIS`, to delineate the study watersheds and to extract model parameters for each watershed (drainage areas, curve numbers, channel slopes, etc.),

2. Use `HEC-HMS` (U.S. Army Corps of Engineers, 2008) to compute runoff hydrographs for the various subdivision schemes, and

3. Use the lumped and subdivided watershed models from the previous step and modify substantially one of three watershed parameters (curve number, basin transformation time, or routing time) for approximately 1/5, 1/3 and 1/2 of the total watershed area to assess sensitivity of model output to changes in model parameters. These modifications, in order, are anticipated to impact the runoff generation component (overall mass balance), time redistribution of rainfall excess at either the watershed outlet or routing inlet (peak discharge, peak arrival, and sub-basin hydrograph shape), and time redistribution of recombined hydrographs when routing is present in the model (peak discharge, peak arrival, and outlet hydrograph shape).

Five watersheds were selected for this research project: Walnut Creek, Ash Creek, South Mesquite Creek, Calaveras Creek, and Pond-Elm Creek. Watershed drainage areas ranged between 7.1–46.1 square miles. The watersheds were selected based on certain attributes unique to each one. The locations of the watersheds are shown on Figure 2.3.

Walnut Creek is located near Austin and is considered an urban watershed. The watershed is mostly developed, but does have areas that are undeveloped. Ash Creek and South Mesquite Creek are both located in Dallas and are urban watersheds. Ash Creek contains two distinct sections within the watershed. The northern 1/3 of the watershed is relatively flat and does not have distinct channel segments, while the southern 2/3 contains steeper sections and has distinct channel properties. South Mesquite Creek has a main channel running almost the entire length of the watershed with relatively short side branches. South Mesquite Creek is also a common watershed between completed and concurrent research projects.

Calaveras Creek is located in a rural part of Texas near San Antonio and is mostly undeveloped. It has a distinct main channel section with multiple branching side channels. Pond-Elm Creek is

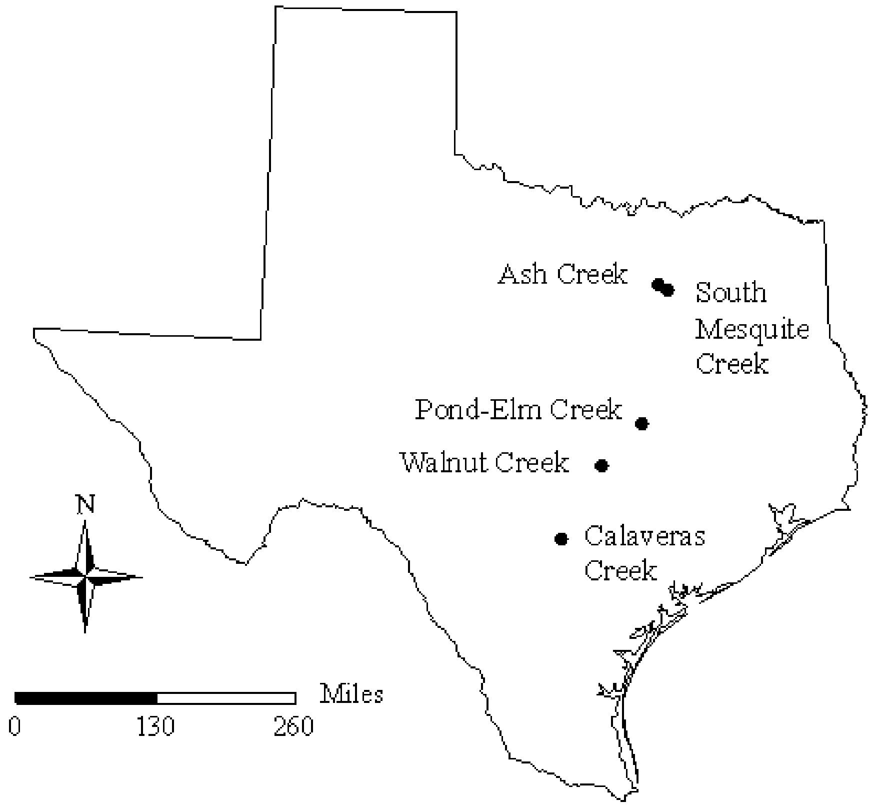


Figure 2.3: Location of lumped-parameter model study watersheds.

also an undeveloped watershed located in a rural section of Texas. This watershed contains a long slender channel along the western side of the watershed and has relatively flat areas at the upstream end. These five watersheds are summarized in Table 2.3 below. Maps showing each watershed are presented in Appendix B.

Table 2.3: Summary of lumped-model watershed characteristics.

Watershed	USGS station	North latitude	West longitude	Development class	Area mi^2
Walnut Creek	08158200	30°22'30"	97°39'37"	Urban	26.5
Ash Creek	08057320	32°48'18"	96°43'04"	Urban	7.7
South Mesquite Creek	08061950	32°04'32"	96°34'12"	Urban	23.3
Calaveras Creek	08182400	29°22'49"	98°17'33"	Rural	7.1
Pond-Elm Creek	08108200	30°55'52"	97°01'13"	Rural	46.1

For this research, a heuristic approach was chosen based on analyst expertise and judgment. A consequence is that a subdivision scheme applied to one watershed may not apply to another watershed. The criteria used for the location of the watershed subdivisions are:

1. Subdivide where there is a distinct change in land use or land cover,
2. Subdivide where there is a noticeable change in channel or watershed slope, and
3. Subdivide in areas where there are stream branches within the drainage network.

For example, if a mostly-urban watershed had a section that was undeveloped according to the National Land Cover Database (NLCD), then this undeveloped area would be separated from the total watershed. Next, areas which could no longer be subdivided according to differences in land use or land cover characteristics were subdivided based on changes in the watershed slope. As the number of subdivisions increased and the sub-watershed areas decreased, land use and slopes became relatively consistent across each sub-watershed. When this happened, stream branches within the drainage network determined subdivision locations.

Each of the five study watersheds was subdivided into 3, 5, 7, 10, 15, and 30 sub-watersheds using the method described above. The sub-watershed configurations for South Mesquite Creek are shown in Figure 2.4. Maps showing the location of the subdivisions for the remaining watersheds are presented in Appendix B.

Three metrics were used to evaluate differences between computed and observed runoff hydrographs. These metrics used the concept of relative error, as expressed in Equation 2.7,

$$R_e = \left(\frac{|X_c - X_o|}{X_o} \right), \tag{2.7}$$

where R_e is the relative error (dimensionless), X_c is the computed value, and X_o is the observed value. For each storm event and subdivision scheme, the relative error was computed for runoff volume, peak flow, and time to peak. In a "perfect" hydrologic model, the relative error is zero for all events. Two versions of the relative error were used to assess model results directly, and the impact of subdivision on computed values. The first is the arithmetic mean of the relative error,

$$\overline{R_e} = \frac{1}{N} \sum R_e, \tag{2.8}$$

where N is the number of observations. The second is the root mean square error,

$$RMSE = \sqrt{\frac{1}{N} \sum (R_e)^2}. \tag{2.9}$$

The third measure of error was the count of the number of storms for which a particular subdivision scheme presented the least error in comparison to the others.

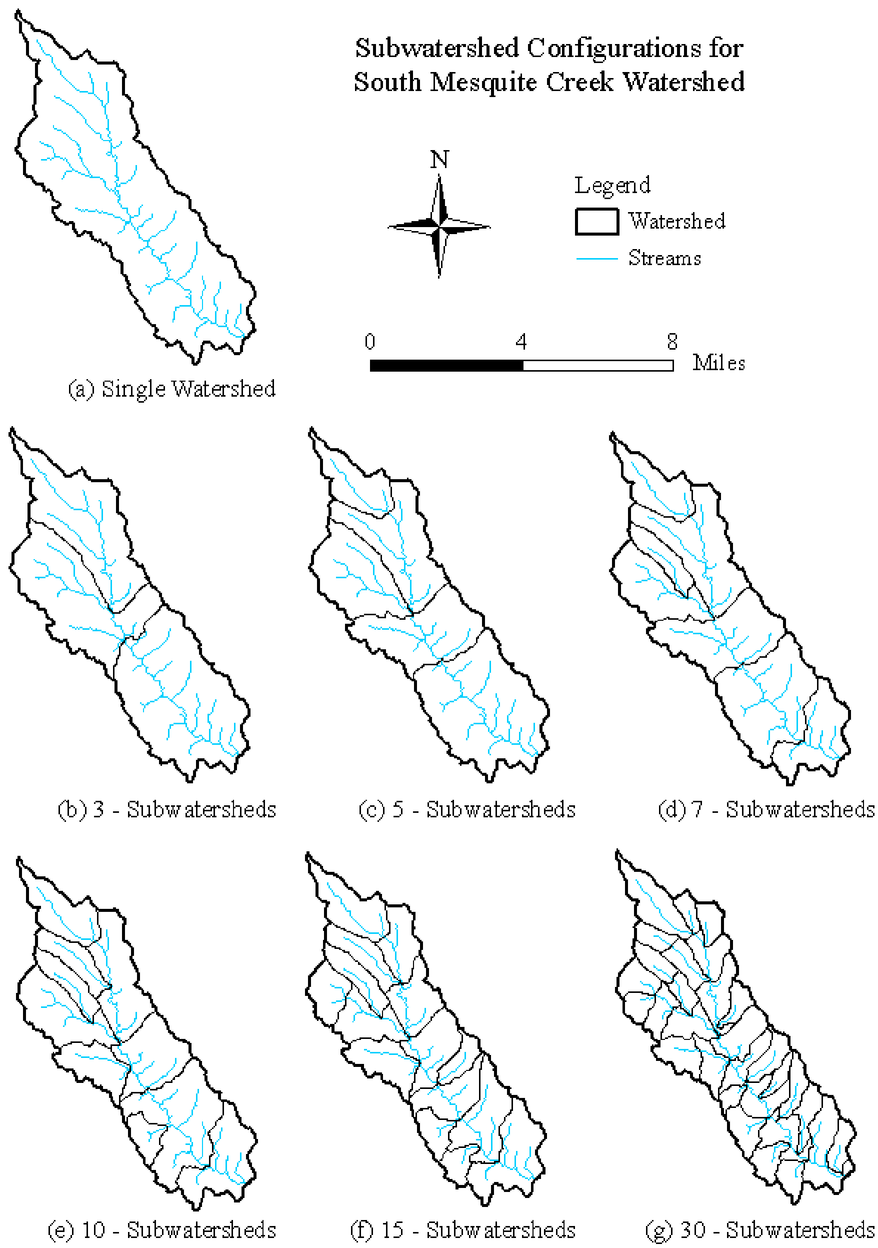


Figure 2.4: Watershed subdivision scheme for South Mesquite Creek.

2.4. Distributed Models

Application of distributed models[8] was examined using the U.S. Army Corps of Engineers (USACE) `HEC-HMS` (U.S. Army Corps of Engineers, 2008) model. Although most applications of `HEC-HMS` are in lumped-parameter mode, the USACE included a gridded hydrologic model in recent versions of the program. The Geographic Information Systems (GIS) tools, `ArcHydro` (Maidment, 2002) and `GeoHMS` (U.S. Army Corps of Engineers, 2003) were used as preprocessors to generate the distributed `HEC-HMS` models. Although the `GeoHMS` program used was the current version (for `ArcGIS` version 9.x, `GeoHMS` version z041708), the documentation was for Version 1.1 (supported under `ArgGIS` 3.x) and is several generations behind the distributed version of the program. At least, the software and the documentation were not compatible. This was an issue in development of the distributed models and is explained in Section 4.3.

Three watersheds were included in the study dataset: Ash Creek, Little Pond-Elm Creek, and South Mesquite Creek. Locations of these watersheds are displayed on Figure 2.3. A summary of study watershed characteristics is listed in Table 2.3.

The objectives of this component of the research project were to: (1) Assess the utility of distributed modeling in an uncalibrated mode that approximates the approach used in engineering practice and (2) Measure differences attributable to increased levels of watershed subdivision in an uncalibrated mode. The three study watersheds were subdivided into 1, 2, 3, 5, 7, and 9 sub-watersheds. Results from each group were extracted for comparison.

2.4.1. Datasets Used

Use of the distributed model represented by `HEC-HMS` requires a substantial amount of data and data processing. This is true of any distributed model. Furthermore, the more detailed the model, the greater the amount of data required. Freely-available datasets were used to develop the models. Spatial datasets used were:

Topography: Topographic data were extracted from the USGS seamless topographic National Elevation Dataset (NED) 30 m digital elevation model[9];

Land Cover: 2001 land cover was obtained from USGS NED (separate data layer);

Soils: the Soil Survey Geographic (SSURGO) database[10] was used for soil data; and

Hydrography: The National Hydrographic Database[11] was used to define stream locations.

[8] In this research, manual and automated tools were used to construct lumped and subdivided watersheds. The subdivided watersheds are in some sense distributed models, however in this project the term *fully-distributed* refers to models where gridded data were used to generate hydrographs (and routing) using automated tools with little operator intervention.

[9] The NED web site was `http://seamless.usgs.gov/` as of this writing.

[10] The SSURGO web site was `http://soils.usda.gov/survey/geography/ssurgo/` at the time of this writing.

[11] The NHD web site was `http://nhdgeo.usgs.gov/viewer.htm` at the time of this writing.

The project coordinate system was Universal Transverse Mercator (UTM) Zone 14N, National Datum of 1983. USGS rainfall-runoff data were taken from the dataset documented by Asquith and others (2004). Curve numbers were taken from TR-55 (U.S. Department of Agriculture, Natural Resources Conservation Service, 1986) and from Viessman and Lewis (2003).

2.4.2. Model Development

Development of distributed models using `HEC-HMS` requires a substantial amount of dataset preprocessing. The process involves integration of a variety of datasets from multiple sources and is not trivial. The steps required are:

1. Terrain preprocessing,
2. Watershed processing,
3. Curve-number generation,
4. `HEC-HMS` project setup,
5. Basin processing,
6. Basin characteristic development,
7. Hydrologic parameter development,
8. `HEC-HMS` file creation, and
9. Application of `HEC-HMS`.

Each of these high-level operations comprises a number (sometimes substantial) of sub-tasks. Furthermore, although the basic data were reused for each subdivision iteration, a significant number of the steps were repeated for each iteration.

Once the watershed grid was established, it was not changed. That is, a 30-meter grid was established when using the digital elevation model. This grid served as the basis for model development throughout the subdivision process. USGS personnel used the grid system established for watershed processing to produce a gridded precipitation dataset[12] for the hydrologic modeling. The precipitation dataset was developed using USACE tools that are generally unavailable to engineers outside the federal government (unreleased tools). The Asquith and others (2004) dataset provided the point measurements of rainfall used for the distributed modeling.

[12]The grids were created for 100-meter grid cells. The original DEM was a 30-meter DEM. However, there are processes to "convert" or create different sized grids. The 100-meter grid-cell size was used for compatibility with gridded precipitation data, which were created using 100-meter grid cells. The GIS-created grid was adjusted to "match" the precipitation grid.

2.4.3. Process Submodels

HEC-HMS requires three components for operation: a basin model, a meteorologic model, and a control specification. The bulk of the work presented in Section 2.4.2 is preparatory to building the basin model (or sub-basin models). The process sub-models chosen for this analysis are the gridded version (U.S. Army Corps of Engineers, 2000) of the Natural Resources Conservation Service (NRCS) curve number method (U.S. Department of Agriculture, Natural Resources Conservation Service, 1997). Flow is routed across each sub-basin using the modified-Clark[13] (U.S. Army Corps of Engineers, 2008). For the time of concentration, the Kirpich (1940) equation was used to represent travel time in channelized portions of the watershed[14].

2.4.4. Model Operation

After assembling the required datasets using HEC-GeoHMS and the watershed models using HEC-HMS, HEC-HMS was operated for each event in the study dataset and each subdivision scheme. Results were extracted from HEC-HMS and analyzed. The distributed-modeling results are presented in Section 4.3.

2.5. Stochastic Modeling

One of the approaches for modeling a watershed is the application of a set of single-purpose, custom-built programs developed by USGS personnel as part of the suite of research projects of which the project reported herein is one. These programs are in the R statistical system (R Development Core Team, 2006) and are based on the technology developed by USGS researchers and published in Asquith and Thompson (2003), Roussel and others (2005), and Asquith and Roussel (2007).

2.5.1. On The Computation of Celerity

Where a watershed is subdivided, the celerity V_{ck} in units of length per time is needed to parameterize a part of a hydraulic routing procedure. This requirement cannot be avoided — one or more estimates of V_{ck} are needed. It is well known that V_{ck} is a function of many hydraulic parameters, such as channel roughness; channel width, depth, localized slope; and other factors. These values are not well constrained for an arbitrary watershed when a hydrologic model of the rainfall-runoff process is to be used. Worse, as in the case of slope, the other hydraulic parameters often are highly localized — they can vary substantially at the reach scale.

[13]Sometimes referred to (in the USACE documentation, for instance) as the "modClark" algorithm.

[14]All distributed models were developed using only the Kirpich (1940) method. A second set of models were developed using Kirpich (1940) plus 30 minutes (to account for overland flow travel time). The 30-minute overland flow travel time was added to the time of concentration for each sub-basin in all models. Only the models using Kirpich (1940) are reported herein.

Further, direct computation of storm-to-storm or watershed-to-watershed V_{ck} in the context of analysis of the rainfall-runoff process is extremely problematic because the rainfall and runoff responses of whole watersheds typically are studied.[15] As an example, U.S. Geological survey streamflow-gaging stations are generally operated in comparatively isolated watersheds for those watersheds having drainage areas less than about 50 square miles. Hence the recorded streamflow data fundamentally represent the aggregation of subwatershed response and internal routing.

A special study of a value, c_k, that philosophically takes the place of V_{ck} was made as part of this research project. Hereafter, this value is referred to as a celerity c_k, but acknowledgment (no *emphasis*) is made that c_k does not result from *hydraulic analysis*, but results from *hydrologic analysis*.[16] An experimental approach is reported here that explores the nature of c_k using stochastic simulation of 3 inches of uniformly distributed rainfall over 1 hour in twelve 5-minute increments. This rainfall was uniformly distributed over a hypothetical 24 square mile watershed ($A_o = 24$). This hypothetical watershed is not rocky [$R = 0$ in the parlance of Asquith and Roussel (2007)], has a main-channel length of 6 miles ($L_o = 6$), has dimensionless main-channel slope S of 0.004, and curve number CN of 86.

2.5.2. The Experimental Approach

A primary assumption made for the experimental approach reported here is that the procedures of Asquith and Roussel (2007) represent state-of-the-practice. These procedures represent a fully lumped statistical method for computation of peak streamflow Q_p and time of peak streamflow T^{Q_p} for arbitrary watersheds. Specifically, the procedures produce the optimal value for $Q_p^{(\mathrm{AR})}$ given the watershed characteristics and input storm hyetograph. In summary, the Asquith and Roussel (2007) procedures outline methods to estimate the loss-rate parameters initial abstraction I_A in inches, constant loss C_L in inches per hour of a watershed-loss model and to estimate the unit hydrograph parameters T_p in hours, and q_p in inches per hour of a gamma unit hydrograph. These four values can be stochastically simulated by independent simulation using the t-distribution and the equations for prediction intervals outlined by Asquith and Roussel.

Given that $Q_p^{(\mathrm{AR})}$ can be simulated, in a watershed subdivision context, it follows to seek values for c_k that optimize the estimation of Q_p from routing of streamflow ($Q_p^{(\mathrm{route})}$). The optimization was made by minimization of $\epsilon(c_k) = |Q_p^{(\mathrm{route})} - Q_p^{(\mathrm{AR})}|$, which is the absolute value of the difference between discharge estimates. A stochastic approach was used, therefore the streamflow values were replaced by expectations or

$$\epsilon(c_k) = |E[Q_p^{i(\mathrm{route})}] - E[Q_p^{i(\mathrm{AR})}]| \tag{2.10}$$

where $E[\,]$ is the expectation operator, i represents the ith simulation run, and $Q_p^{i(\mathrm{AR})}$ represents individual realizations of the Asquith and Roussel procedures.

The values $Q_p^{i(\mathrm{route})}$ in Equation 2.10 are for a subdivided watershed and hence involve simultaneous

[15] Watersheds are remarkable signal integrators.

[16] It should be remarked however, that channel hydraulics in a regional context are silently represented in the hydrologic data available to the research team.

application of Asquith and Roussel procedures and a method of streamflow routing. The Muskingum method was used for routing downstream a distance H, and the method requires an estimate of celerity c_k and an X coefficient. The coefficient X is constrained on the interval $[0, 0.5]$ and typically has a value of about 0.2 in natural channels. Lacking of any other source of information for the purposes of the experimental approach, a triangular distribution of X $(X \mid 0 \leq X \leq 0.5)$ with the mode at 0.25 was used.

At this point values for c_k are the only remaining component for full-out simulation of watershed response to the input rainfall given watershed (and sub-watershed) characteristics, inter-connections (represented by an addressing and reach-length scheme) between sub-watersheds, and the Muskingum routing parameter X.

As a first-order approximation of flow velocity, the ratio of a length to a characteristic time was used. The selected values of length and time were (1) the main-channel length L and (2) time of concentration T_c. Asquith and Roussel (2007) used a time to peak T_p, but T_c seems more intuitively useful than T_p for velocity computations. (The length L is not the length for which the streamflow will be routed.) Using the conclusions of Roussel and others (2005, p. 15) concerning the relation between T_p and T_c the following approximation for c_k in feet per second was made

$$c_k \approx \begin{cases} \eta^{(D=0)} L^{[\text{feet}]} / T_c^{[\text{seconds}]} = \eta^{(D=0)} L^{[\text{feet}]} / (T_p^{[\text{seconds}]}/0.7) & \text{for } D = 0 \\ \eta^{(D=1)} L^{[\text{feet}]} / T_c^{[\text{seconds}]} = \eta^{(D=1)} L^{[\text{feet}]} / (T_p^{[\text{seconds}]}/0.4) & \text{for } D = 1. \end{cases} \tag{2.11}$$

where the units are shown for specificity and $\eta^{(D=0|1)}$ represents a celerity factor or *magic coefficient* that can be selected in such a fashion as to minimize Equation 2.10.

3. Literature Review

The purpose of this literature review is to examine some of the professional literature to determine what other researchers attempted and the results of their work in the context of watershed subdivision. Additional documents reviewed but not described in this chapter are discussed in Appendix C.

Hromadka II (1986) developed an application manual for hydrologic design for San Bernardino County. In that manual, mechanics were developed based on the Los Angeles hydrograph method. In application of the methods presented in the manual, Hromadka II and DeVries: *Arbitrary subdivision of the watershed into subareas should generally be avoided. It must be remembered that an increase in watershed subdivision does not necessarily increase the modelling [sic] "accuracy" but rather transfers the model's reliability from the calibrated unit hydrograph and lag relationships [sic] to the unknown reliability of the several flow routing submodels used to link together the several subareas.*

Wood and others (1988) examined the relation between watershed scale and watershed runoff on the 6.5 mi^2 Coweeta River experimental watershed located in North Carolina. Wood and others divided the Coweeta River watershed into 3, 19, 39, and 87 sub-watersheds. `TOPMODEL` (Beven and Kirkby, 1979) was used as the simulation engine, with watershed topography from a 30-meter digital elevation model, and other model parameters and variables randomly sampled from distributions. `TOPMODEL` was operated using five samples and results aggregated.

Wood and others reported that below a drainage area of about 0.4 mi^2, subwatershed response was highly variable. However, at scales greater than about 0.4 mi^2, further aggregation of subwatersheds had little impact of simulated results. Therefore, for the Coweeta River watershed, a scale of about 0.4 mi^2 seemed appropriate. It is important to observe, however, that the interest of Wood and others (1988) was in determining what they termed the *representative elemental area* for the Coweeta River watershed (if such a concept exists) and not in determining the impact of watershed subdivision on runoff hydrographs directly. Therefore, whereas the Wood and others (1988) study is interesting (and the sole application of `TOPMODEL` to this problem), the study does not directly apply to the current research problem[1].

Sasowsky and Gardner (1991) applied the `SPUR` model to a 56 mi^2 subwatershed of the Walnut Gulch experimental watershed in Arizona. The `SPUR` model operates on a daily time step and was designed for rangeland watersheds. A GIS procedure was used for watershed subdivision based on stream order, an approach not used by other researchers. The result was that the study watershed

[1]As an aside, no definition of representative elemental area was discovered.

was broken into 3, 37, and 66 contributing sub-watersheds. The model was then calibrated against measured rainfall-runoff sequences. The calibration of model parameters is another approach not common among the other papers reviewed for the TxDOT project.

Sasowsky and Gardner used the "efficiency" statistic (Nash and Sutcliffe, 1970) to asses model performance on a monthly basis, that is, monthly runoff volumes were used to measure model accuracy. An efficiency greater than one represents a model that performs better than using the mean runoff only. Sasowsky and Gardner (1991) reported that simulations were sensitive to the degree of watershed subdivision, with lower values of curve number for greater subdivision. This is consistent with the report of Norris and Haan (1993), who observed that increasing the degree of subdivision increased peak runoff for storm-event simulation. The Norris and Haan did not calibrate model parameters to adjust model-output to match observations; they used a synthetic approach. Sasowsky and Gardner calibrated each "model" (instance of subdivision) to measured rainfall-runoff events, and then noticed that the curve number, in particular, decreased with increasing subdivision. Although differing in approach to the problem, the results (either increasing discharge in the case of Norris and Haan or decreasing curve number in the case of Sasowsky and Gardner) reported by Sasowsky and Gardner are similar to the those reported by Norris and Haan.

Norris and Haan (1993) used a synthetic method to study the impact of watershed subdivision on hydrographs estimated using the Natural Resources Conservation Service (NRCS, then SCS) unit hydrograph procedure, as implemented in `HEC-1`. The Little Washita watershed near Chickasha, Oklahoma, which has a drainage area of about 59 mi^2, was used as the study watershed. The watershed was subdivided into 2, 5, 10, and 15 sub-watersheds, as well as treating the watershed as a whole. A balanced hyetograph was used to drive hydrograph computations, with a duration of 24 hours and a return period of 50 years. Results from Norris and Haan (1993) were that watershed subdivision had a pronounced impact on the estimate of peak flow from the watershed. The change from a single watershed to 5 sub-basins resulted in a net increase in peak discharge of about 30 percent. Use of 15 sub-basins increased the difference from a single watershed to about 40 percent. However, the impact of increased subdivision diminished with increasing sub-basin count.

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

Michaud and Sorooshian (1994) applied three different model formulations to Walnut Creek Gulch in Arizona: `KINEROS-complex`, `KINEROS-simple`, and the curve-number approaches were used to simulate the rainfall-runoff process. The authors reported that `KINEROS` (in either form) was not able to produce reasonable solutions comparable to observations. In addition, results from application of the curve number-approach did not compare well with observations.

As a note to the Michaud and Sorooshian report, Loague and Freeze (1985) report an attempt to apply three very different modeling approaches to a set of watersheds. Loague and Freeze also report mixed results from their modeling. In fact, their recommendation is that simpler models appear to perform better than more complex approaches.

Mamillapalli and others (1996) conducted a study of the impact of watershed scale on hydrologic output. As with many of the studies reported in the journal literature, the NRCS Soil and Water Analysis Tool (`SWAT`) model was used, with a Geographic Information Systems procedure used to develop the required input streams. Mamillapalli and others conclude: *The results indicate that in general, increasing level of discretization and increase in the number of soil and landuse combinations increases the level of accuracy. There is a level beyond which the accuracy cannot be improved, suggesting that more detailed simulation may not always lead to better results.*

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

FitzHugh and Mackay (2000) conducted a study similar to Bingner and others (1997) for the Pheasant Branch watershed in Dane County, Wisconsin. FitzHugh and Mackay also report that model-predicted watershed runoff is not heavily dependent on the degree of subdivision (also using the `SWAT` model), but that model-predicted sediment yield does depend on the degree of subdivision.

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

Jha (2002) and Jha and others (2004) examined the relation between watershed subdivision and water-quality model results. He applied the `SWAT` model to four Iowa watersheds. Jha and Jha and others reported that streamflow is not significantly affected by a decrease in sub-watershed scale, with model-predicted results stabilizing with about ten subdivisions. However, model-predicted sediment yields were more dependent on subwatershed scale, requiring 40–50 divisions to stabilize model-predicted sediment yield.

Tripathi and others (2006) applied the `SWAT` model to the 35 mi^2 Nagwan watershed in eastern India. The watershed was subdivided into 12 and 22 sub-watersheds, as well as treating the entire watershed as a whole. Four years of record were used to operate the model. The model was calibrated to produce best estimates of model parameters.

Tripathi and others report little difference in watershed runoff in response to the number of sub-watersheds. However, they observed variations in other components of the hydrologic cycle. Estimates of evapotranspiration increased with increasing numbers of sub-watersheds.

In conclusion, there is little guidance in the professional literature on when to subdivide. Furthermore, based on the literature review, arbitrary subdivision (without reason) was unrelated to accuracy. More important (than the lack of guidance) was that this seemingly obvious question was relatively unanswered in the hydrologic literature. It appears that subdivision of watersheds should result in more accurate modeling is more or less accepted dogma, unsupported by publications in the professional literature.

4. Results

The purpose of this chapter is to present results from each of the modeling approaches. After the results of individual researchers are presented, a synthesis of those results is presented to tie together the various components of the research. Suggestions for applying research results are also provided.

4.1. Equal-Area Models

Comparisons of peak discharges from the events selected by Luong (2008) for `HEC-HMS` modeling are presented in Table 4.1. Comparisons of times to peak discharge from the events selected by Luong (2008) are listed in Table 4.2. Finally, comparisons of runoff volumes from the events selected by Luong (2008) for `HEC-HMS` modeling are listed on Table 4.3.

Based on results presented in Tables 4.1–4.3, there is no single watershed discretization scheme that performs optimally of all observed storms on a particular watershed. In other words, there is no consistent pattern on whether lumped or multiple sub-watersheds produce superior results.

Examples of observed and model-predicted runoff hydrographs are presented in Figure 4.1. In cases where model-predicted runoff hydrographs approximate observed runoff hydrographs, there is no apparent substantial difference between the hydrographs. However, in many cases, the hydrographs generated by the model did not even approach observed results.

For example, the model hydrograph from South Mesquite Creek of January 1975 (Figure 4.1b) reasonably approximates the observed runoff hydrograph. However, the hydrographs from Little Fossil Creek of December 1971 (Figure 4.1a) are significantly different, particularly for the first hydrograph of the series. Moreover, there is little difference between the simulated runoff hydrographs for the subdivision and the single basin schemes and the observed hydrographs. The researchers speculate that the reason for this particular result is that the spatial variability of the watershed is insufficient for the simulation results to be sensitive to the selected subdivision scheme[1].

The use of soil type and land-use properties to determine spatial variability in the runoff generation component of a hydrologic model is plausible because they (soil type, land-use) are the major factors used to estimate runoff curve numbers, which were used in this application of `HEC-HMS` to estimate runoff volume. In this research, the NRCS runoff curve number approach was used as the runoff

[1]This finding was the motivation behind Wingfield's (2008) component in an attempt to test this hypothesis.

Table 4.1: Peak discharge analysis from equal-area subdivision approach (Luong, 2008). [*Metric* is the method used to measure the difference between modeled and observed peak discharge, *Number of Subdivisions* is the number of equal-area subdivisions for the study watershed, *Selected* is the number of equal-area subdivisions selected as providing the minimum error between modeled and observed peak discharge, and *Count* is the number of events for which a given subdivision scheme performs "better" than the other schemes tested. $\overline{X}_d$ and *RMSE* are expressed in percent.]

Watershed	Metric	Number of Subdivisions					Selected
		1	2	3	5	7	
Onion	$\overline{X}_d$	−200	−285	−325	−282	−331	1
	RMSE	233	294	367	313	368	1
	Count	2	0	0	0	0	1
South Mesquite	$\overline{X}_d$	10	−5	−16	−28	−9	2
	RMSE	16	12	21	33	15	2
	Count	2	3	1	0	0	2
Little Fossil	$\overline{X}_d$	−79	−99	−85	−123	−98	1
	RMSE	190	215	203	258	225	1
	Count	5	2	0	2	0	1
Olmos	$\overline{X}_d$	−244	−241	−247	−149	−262	5
	RMSE	334	331	368	240	382	5
	Count	0	0	1	6	0	5
Trinity North	$\overline{X}_d$	−14	−23	−18	−29	−10	7
	RMSE	72	73	68	74	63	7
	Count	2	0	0	3	4	7

generation model with `HEC-HMS` to compute runoff volumes. Alternative runoff-generation models are available (and implemented in `HEC-HMS`), but generally appeal to similar descriptive information.

In this study, the area-weighted mean curve number was almost identical across a watershed for all sub-watershed scenarios. As a result, there was little variation in the total runoff volumes between the sub-watershed configurations. The curve number for every unique soil and land-use combination in the study watersheds was estimated assuming good hydrologic condition; however, this condition might not be true for all watersheds. Until the appropriate runoff-generation process model for the sub-watershed is accurately determined and incorporated into models, the results may never be satisfactory.

In most cases, when hydrographs of subdivision are compared to the single basin, the pattern of peak discharge is similar to the finding in earlier studies. The peak discharge for a lumped watershed is less than the peak discharge from the subdivided watershed. However, the magnitude of the change in computed peak discharge changed little between the lumped and the subdivided scenarios in most cases, indicating that the peak flow component is relatively insensitive to changes in the number of sub-watersheds. This result implies that the model-predicted runoff is not heavily dependent on the degree of watershed subdivision. These findings are consistent with the results of Bingner and others (1997), FitzHugh and Mackay (2000), and Jha and others (2004).

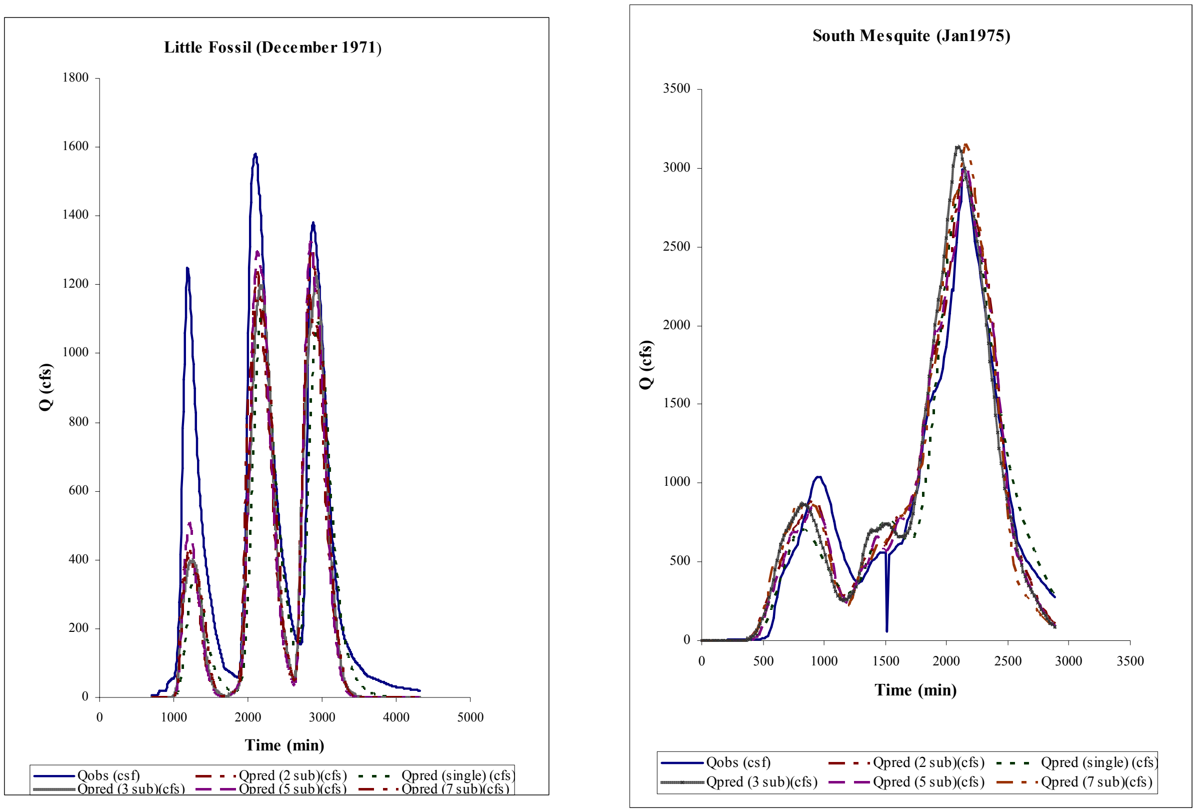
Also, regardless of subdivision, with the exception of few storms, the peak discharges in simulated

Table 4.2: Time to peak discharge analysis from equal-area subdivision approach (Luong, 2008). [*Metric* is the method used to measure the difference between modeled and observed peak discharge, *Number of Subdivisions* is the number of equal-area subdivisions for the study watershed, *Selected* is the number of equal-area subdivisions selected as providing the minimum error between modeled and observed peak discharge. $\overline{X}_d$ and *RMSE* are expressed in percent.]

Watershed	Metric	Number of Subdivisions					Selected
		1	2	3	5	7	
Onion	$\overline{X}_d$	−27	−23	−19	−30	−25	3
	RMSE	33	25	23	32	27	3
	Count	0	0	2	0	0	3
South Mesquite	$\overline{X}_d$	−3	−2	0	−3	−4	3
	RMSE	9	10	8	11	12	3
	Count	1	1	1	1	2	7
Little Fossil	$\overline{X}_d$	−7	−2	−12	−12	−10	2
	RMSE	11	14	35	26	23	1
	Count	1	5	1	0	2	2
Olmos	$\overline{X}_d$	−15	−16	−13	−8	−8	7
	RMSE	22	23	17	12	11	7
	Count	0	0	1	2	4	7
Trinity North	$\overline{X}_d$	−9	−9	−14	−14	−11	1
	RMSE	31	31	34	35	33	1
	Count	4	3	1	0	1	1

Table 4.3: Runoff volume analysis from equal-area subdivision approach (Luong, 2008). [*Metric* is the method used to measure the difference between modeled and observed peak discharge, *Number of Subdivisions* is the number of equal-area subdivisions for the study watershed, *Selected* is the number of equal-area subdivisions selected as providing the minimum error between modeled and observed peak discharge. $\overline{X}_d$ and *RMSE* are expressed in percent.]

Watershed	Metric	Number of Subdivisions					Selected
		1	2	3	5	7	
Onion	$\overline{X}_d$	−520	−432	−465	−467	−466	2
	RMSE	663	538	587	589	587	2
	Count	0	1	1	0	0	2, 3
South Mesquite	$\overline{X}_d$	−4	−6	−1	0	0	7
	RMSE	22	19	17	17	16	7
	Count	3	1	1	1	0	1
Little Fossil	$\overline{X}_d$	−107	−105	−100	−100	−106	3
	RMSE	218	223	223	224	230	1
	Count	4	1	2	0	2	1
Olmos	$\overline{X}_d$	−268	−264	−245	−244	−231	7
	RMSE	306	301	288	287	273	7
	Count	0	0	0	0	7	7
Trinity North	$\overline{X}_d$	−33	−20	−20	−18	−18	5
	RMSE	88	73	69	68	68	5
	Count	0	1	4	4	0	3, 5



(a) Little Fossil Creek.

(b) South Mesquite Creek.

Figure 4.1: Example observed and model-predicted runoff hydrographs from the equal-area approach.

and observed hydrographs occur almost simultaneously, which supports the utility the Kerby-Kirpich approach suggested by Roussel and others (2005).

As an important note, the models were intentionally left uncalibrated with respect to observed runoff behavior. In this sense the models represent engineering judgement as might be applied to ungaged watersheds with one important qualification — in an ungaged design setting the rainfall input would be a design storm and not measurements from an observed rainfall event. This approach introduces an imbedded assumption that the uncalibrated watershed model (as we use the concept) would produce peak discharges for a design storm that are comparable to statistically derived peak discharges[2]. The researchers anticipate that the response would indeed scale accordingly (mostly because these models are linear-response networks). This embedded assumption is not tested in this research.

As an evaluation of the effect of calibration as used in current practice, streamflow data for South

[2]These peaks could come from something as simple as 1–3 cfs/acre/in rainfall, to regression equation estimates, to scaled observations from nearby hydrologically-similar watersheds.

Mesquite Creek from January 1975 were used to calibrate the following parameters: curve number, sub-watershed lag, and routing lag time. The calibration procedure was automated using a systematic search strategy and an objective function based on squared error in peak flow, volume, and time to peak. The search converged to a parameter set that represented at least a local minimum for the selected objective function. Initial curve numbers for South Mesquite watershed were 91 (lumped) or 85–92 (distributed); calibrated values were 97 (lumped) or 82–97 (distributed). The calibrated sub-watershed lag and routing lag time for each subdivision scheme approximated the initial values. The calibrated values presented in Tables 4.4 and 4.5 were used to simulate runoff hydrographs for the January 1975 rainfall event of the South Mesquite watershed.

Table 4.4: Initial and calibrated curve numbers for South Mesquite Creek from the event of January 1975.

Scheme	Sub-watershed	Initial curve number	Calibrated curve number	Difference %
Lumped	A	91	90	−1.1
2-Sub-watershed	A_1	91	89	−2.2
	A_2	90	86	−4.44
3-Sub-watershed	A_1	92	96	4.35
	A_2	91	84	−7.69
	A_3	89	83	−6.74
5-Sub-watershed	A_1	92	91	−1.09
	A_2	91	90	−1.1
	A_3	92	91	−1.09
	A_4	91	84	−7.69
	A_5	85	82	−3.53
7-Sub-watershed	A_1	92	98	6.52
	A_2	92	86	−6.52
	A_3	92	87	−5.43
	A_4	91	86	−5.49
	A_5	91	86	−5.49
	A_6	91	87	−4.4
	A_7	85	82	−3.53

For the January 1975 event, the simulated time to peak for the single and 2-subbasin match observed exactly, the time to peak for 3-, 5-, and 7-subbasin are within 2% and 0.7% of observed, respectively. Additionally, the simulated runoff volume for the single basin is within 1.8% of the observed runoff while runoff volumes for other subdivision are 7% less than observed runoff. The simulated peak flow from the 7-subbasin model is approximately 2% less than observed runoff, whereas the single and other finer subdivisions are with in 5% of observed. The calibration and verification events are shown in Figure 4.2. In Figure 4.2b, the simulated flows from the 7-subbasin model compared well with the observed flow. However, the single basin model performed more poorly than the subdivision models. Although the calibrated version was more accurate than the uncalibrated version, the analyses were not be able to indicate which subdivision schemes perform

Table 4.5: Initial and calibrated timing parameters for South Mesquite Creek from the event of January 1975.

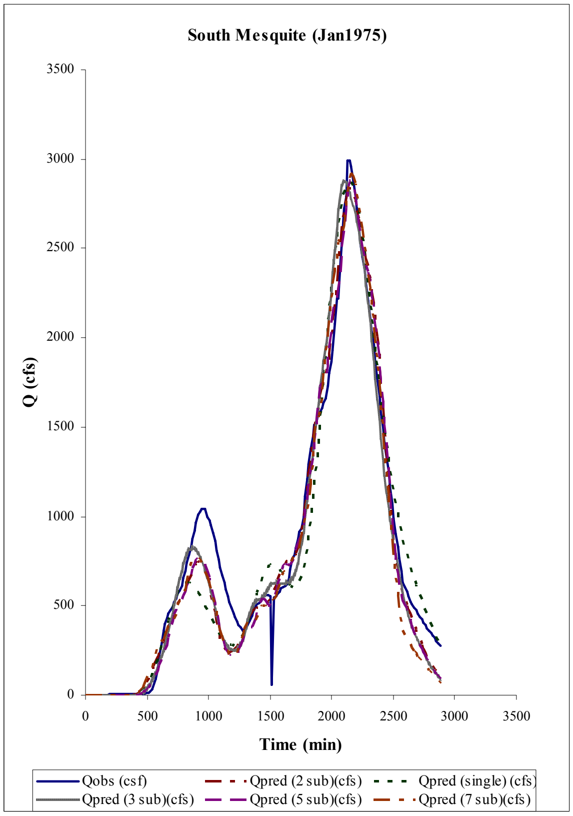
Scheme	Sub-watershed	Initial t_{reach}	Calibrated t_{reach}	Difference %
Lumped	A			
2-Sub-watershed	A_1			
	A_2	217	250	15.21
3-Sub-watershed	A_1			
	A_2	91	92	1.1
	A_3	173	174	0.58
5-Sub-watershed	A_1			
	A_2	72	73	1.39
	A_3	57	40	−29.82
	A_4	123	141	14.63
	A_5	129	125	−3.1
7-Sub-watershed	A_1			
	A_2	80	81	1.25
	A_3	68	69	1.47
	A_4	76	77	1.32
	A_5	90	91	1.11
	A_6	89	90	1.12
	A_7	90	91	1.11

best. Furthermore, the hydrographs generated using the uncalibrated and calibrated models are practically indistinguishable. Therefore, changes of a few percent in globally-applied values have little effect on the simulations. Finally, in many practical instances such calibration is unrealistic because the requisite data simply do not exist.

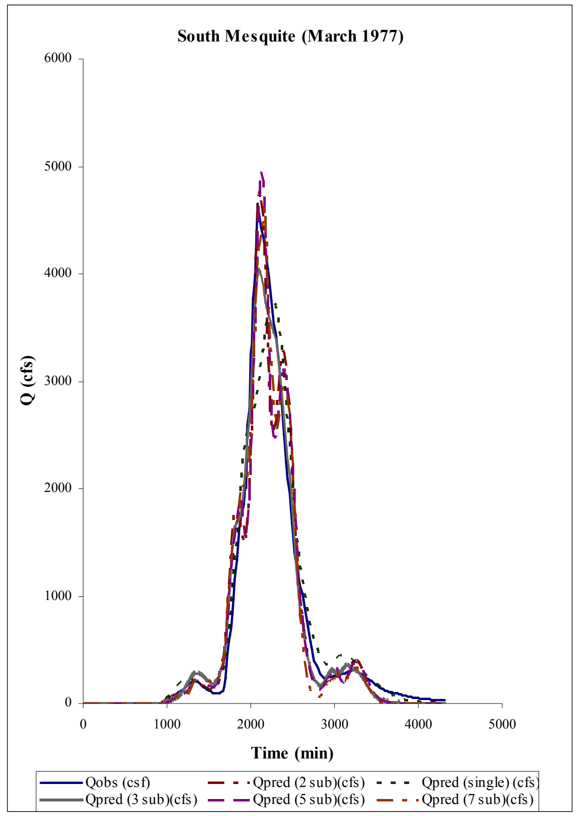
Runoff hydrographs that were developed for the Onion Creek, South Mesquite, Little Fossil, Olmos Creek, and Trinity Basin-North watersheds were used in similar analyses to determine the effects that sub-watershed count had on the runoff hydrographs. The increase in the sub-watershed count does not substantially affect the simulated runoff hydrograph.

In Luong's study (2008), neither peak flows nor runoff volumes were simulated accurately from individual events, regardless of subdivision scheme. However, results of predicted time to peak were somewhat better.

Unless there is some compelling need to divide a watershed into smaller pieces, compute the discharge from those pieces, route those discharges to the outlet, and compute a total discharge, there is little if any gain in "accuracy." Compelling needs fall into only a few categories: (i) a huge change in watershed runoff generation is anticipated on a portion of the total watershed (both the change and the portion need to be substantial), (ii) a huge change in routing time is anticipated (perhaps by ditch building over considerable distances), (iii) a regulation effect is anticipated on a portion of



(a) Calibration event.



(b) Verification event.

Figure 4.2: Calibration and verification events for South Mesquite Creek from the events of January 1975 and March 1977.

the watershed (a reservoir being an extreme example), (iv) a huge change in on-watershed storage is anticipated (a subset of a reservoir case, or (v) there is a large change in slope (such as the watershed traversing across an escarpment — this is a special case of (ii)).

The general cases outlined in the previous paragraph are the compelling physical structures where subdivision would make sense — the cases are beyond what a lumped model could explain *a priori*[3].

These cases could justify subdivision in order to answer "what-if" questions. But improved "accuracy" in the absence of these demarkations is not justification for breaking a model into smaller parts.

The result of this component, and the conjectures in the above paragraph stimulated the Wingfield (2008) study to address "How big of a change is needed to impact the computed output hydrograph?"

[3]A lumped model could be forced to fit observations, but the researchers' opinion is that the various terms could not be explained beforehand.

4.2. Lumped Models

4.2.1. Watershed Subdivision

The first objective of the lumped-model component of this research was to apply `ArcHydro` and `HEC-GeoHMS` to delineate the five study watersheds and to extract modeling parameters for each one. Once this was completed, the five study watersheds were subdivided into 3, 5, 7, 10, 15, and 30 sub-watersheds. `ArcGIS` was used to develop modeling parameters for the sub-watersheds.

The relative error between computed and observed runoff volume for the Walnut Creek study watershed is displayed on Figure 4.3. The impact of watershed subdivision on computed runoff volume is minor. This result is attributable to the fact that the runoff potential, as represented by the NRCS curve number method, is not sensitive to watershed subdivision. Results for Walnut Creek are representative of relative errors in runoff volume for the remaining watersheds in the study dataset.

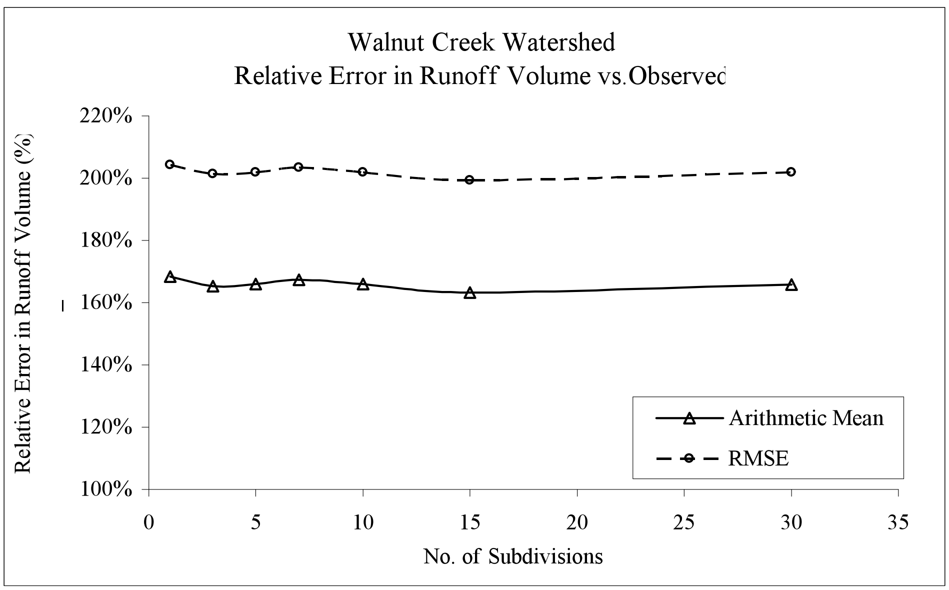
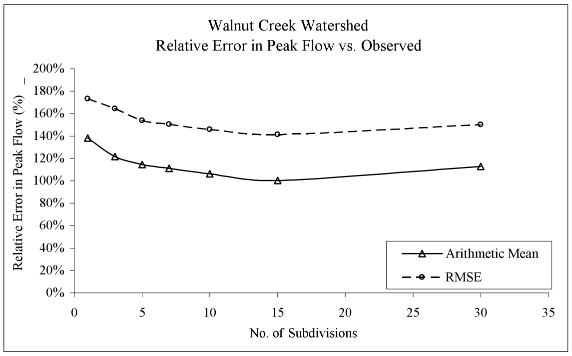


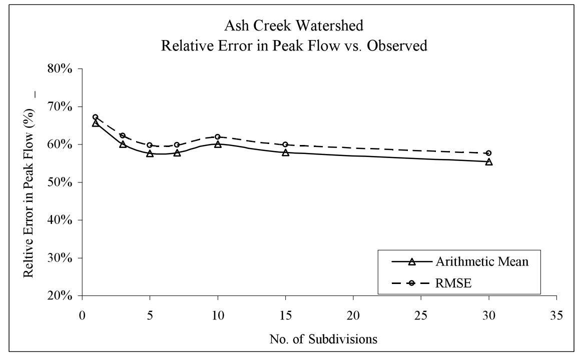
Figure 4.3: Runoff volume relative error for Walnut Creek study watershed.

The relative error for peak discharge is displayed on Figure 4.4. The tendency is for the relative error in peak discharge to decrease with the number of watershed subdivision. However, after between 5 and 10 subdivisions, no additional reduction in the relative error in peak discharge is obtained.

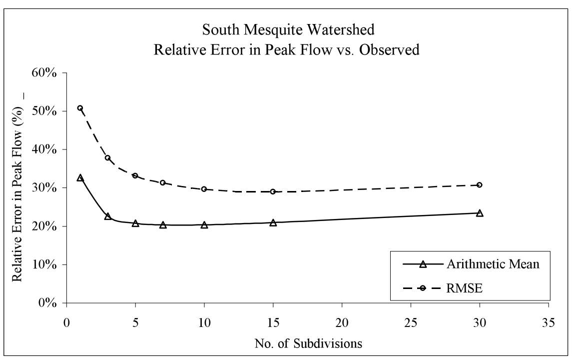
The time to peak discharge from the study events was extracted from both the modeled and observed hydrographs. Results from computation of the relative errors are displayed on Figure 4.5. With the exception of results from Pond-Elm Creek, the accuracy of time to peak estimates tend to decrease with increasing number of subdivisions.



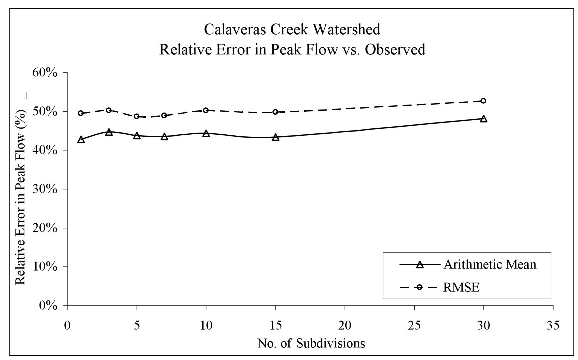
(a) Walnut Creek.



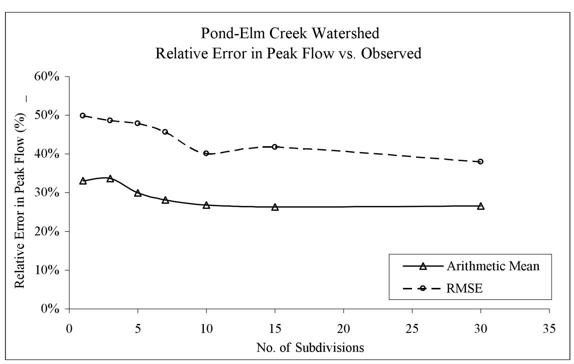
(b) Ash Creek.



(c) South Mesquite Creek.

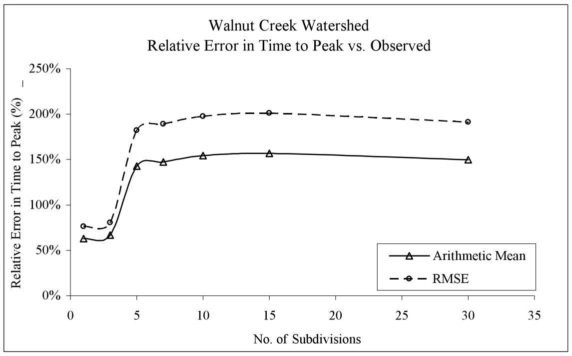


(d) Calaveras Creek.

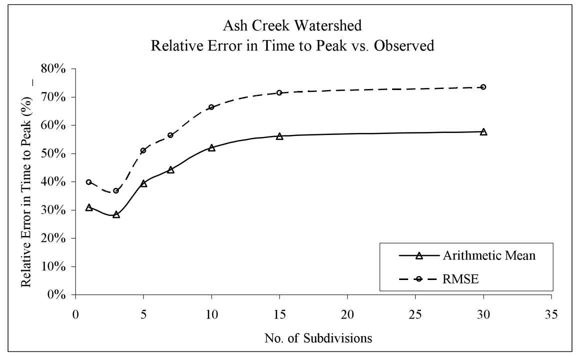


(e) Pond-Elm Creek.

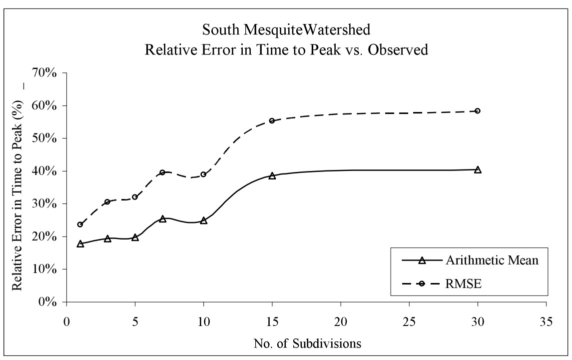
Figure 4.4: Relative error in peak discharge for study watersheds.



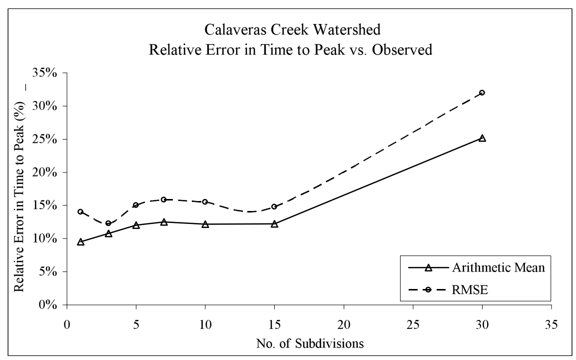
(a) Walnut Creek.



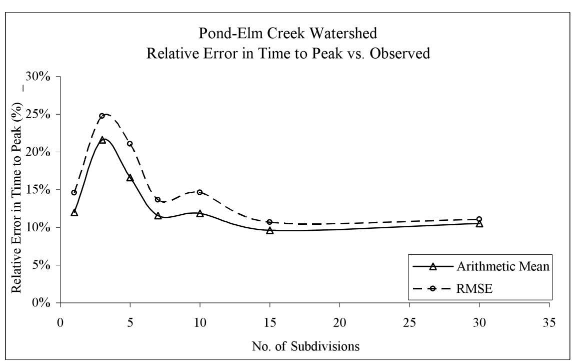
(b) Ash Creek.



(c) South Mesquite Creek.



(d) Calaveras Creek.



(e) Pond-Elm Creek.

Figure 4.5: Relative error in peak discharge for study watersheds.

As the number of watershed subdivisions increases, the complexity of the stream network used to connect the sub-watershed outlets increases. For each stream segment in the network, a number of parameters are required to route the sub-watershed hydrographs. That is, each stream segment has a set of routing parameters associated with it and each of these parameters must be estimated. For a relatively simple routing approach, such as simply lagging the input hydrograph in time, the number of required routing parameters increases roughly linearly with the number of sub-watersheds. However, errors in the routing-parameter estimates are reflected in the output hydrograph from the watershed.

For example, the observed and computed runoff hydrographs for the event of October 20, 1984 on Walnut Creek are presented on Figure 4.6. For three subdivisions, the computed runoff hydrograph becomes bimodal. Although there is some indication of the impact of a second pulse of effective rainfall evident in the observed hydrograph (the small "hump" on the recession limb), the pronounced bimodal computed hydrograph is indicative that the routing algorithm is either mis-specified or the routing parameters are not correct.

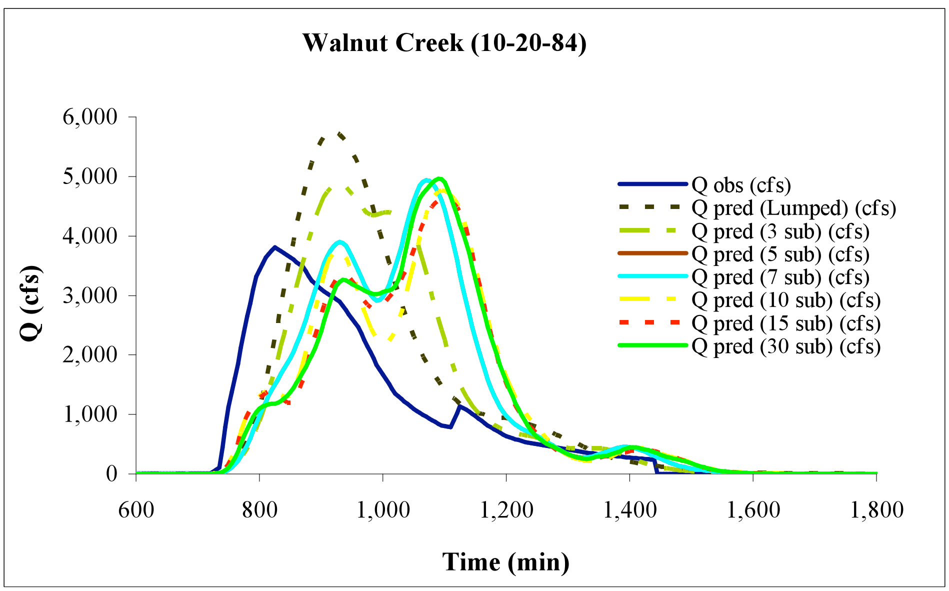


Figure 4.6: Runoff hydrographs from the event of October 20, 1984 on Walnut Creek.

Without an observed hydrograph for calibration, an analyst would have no idea whether the results depicted on Figure 4.6 are correct. The authors would suspect that a problem existed and any expert could "correct" the problem such that the computed hydrograph would be unimodal, as expected. However, without an observed hydrograph for calibration, it could not be known whether the routing sub-model was correctly specified or whether the parameters were reasonable, much less "correct."

The point is that when watershed are subdivided, the number of parameters increases more quickly than the number of sub-watersheds. The proliferation of parameters is a problem. Without measurements to use in calibrating the parameters, it is difficult to set those values to anything other than "average" or representative values, which results in the paradox. This issue was discussed at length by Hornberger and others (1985) and Jakeman and Hornberger (1993) and many other researchers who examined the complexity of watershed models during the 1980s.

For example, if a single watershed unit modeling using `HEC-HMS` requires three parameters[4], then a single subdivision (two sub-watersheds) would require estimates for six parameters for the rainfall-runoff model and at least two more for a routing sub-model. The required number of parameter estimates scales from that point. The problem is exacerbated if another runoff-generation process model (such as initial-abstraction/constant loss-rate or Green-Ampt) is used in place of the runoff curve number method.

4.2.2. Changes to Parameter Values

The second component of the lumped-model component of this research was to examine the impact that radical changes to parameter values for a subdivision (or subdivisions) of a watershed might have on the computed runoff hydrograph from the watershed. That is, the objective was to ask the question "What is the impact on the runoff hydrograph from the watershed if parameter x is changed by a ridiculous amount?", then adjust lumped-model parameters for various fractions of the total watershed drainage area and re-run the `HEC-HMS` models.

The runoff curve number was adjusted from the starting value to 100 for fractions of about 1/5, 1/3, and 1/2 of the total watershed area (denoted by 1/5CN, 1/3CN, and 1/2CN on the figures). The basin lag time was arbitrarily reduced by 20 percent for the same 1/5, 1/3, and 1/2 of the total watershed area (but in an independent set of `HEC-HMS` models; denoted by 1/5lag, 1/3lag, and 1/2lag on the figures). Finally, the routing lag time was decreased by 20 percent for about 1/5, 1/3, and 1/2 of the watershed drainage area (denoted by 1/5Rout, 1/3Rout, and 1/2Rout on the figures).

Results of the indicated changes to lumped-model parameter values are presented on Figures 4.7–4.11. With the exception of the models for Calaveras Creek, a change from the base parameter values to extreme parameter values (curve number of 100, 20 percent decrease in basin lag time or reach routing time) resulted in computed results that were within one-third log cycle of the base peak discharge from the watershed runoff hydrograph. Therefore, there must be a markedly different parameter value (or values) for a sub-watershed to justify subdivision on the basis of representing differences in parameter values by watershed subdivision.

The use of one-third log cycle as a discrimination range is a value that the researchers noticed is common in their recent work. The researchers believe that this range (one-third of a log cycle) represents current technological ability to discriminate differences[5], and that it would be difficult to discriminate using a statistical test with a reasonable level of significance between two models that produce responses within one-third of a log cycle. Therefore, any of the models for the Walnut

[4]Typical parameters used in a `HEC-HMS` model are lag time, runoff curve number, and percent impervious area.

[5]For example, the standard error of estimate for the regional regression equations for Texas, Asquith and Thompson (2005, 2008), and Asquith and others (in press), is about 40 percent, which approximates one-third of a log cycle.

Creek, South Mesquite Creek, or Pond Elm Creek watersheds would perform about the same (barely escape the range). More diagnostic is which changes matter more — in runoff volume the generation model is important, and that importance is indeed reflected by results presented in the graphs. Lesser sensitivity occurs with the other important responses, peak discharge and time to peak. The relative insensitivity (change in response related to change in parameter) in these limited studies supports the contention that arbitrary subdivision with only subtle variation in watershed parameters is not useful.

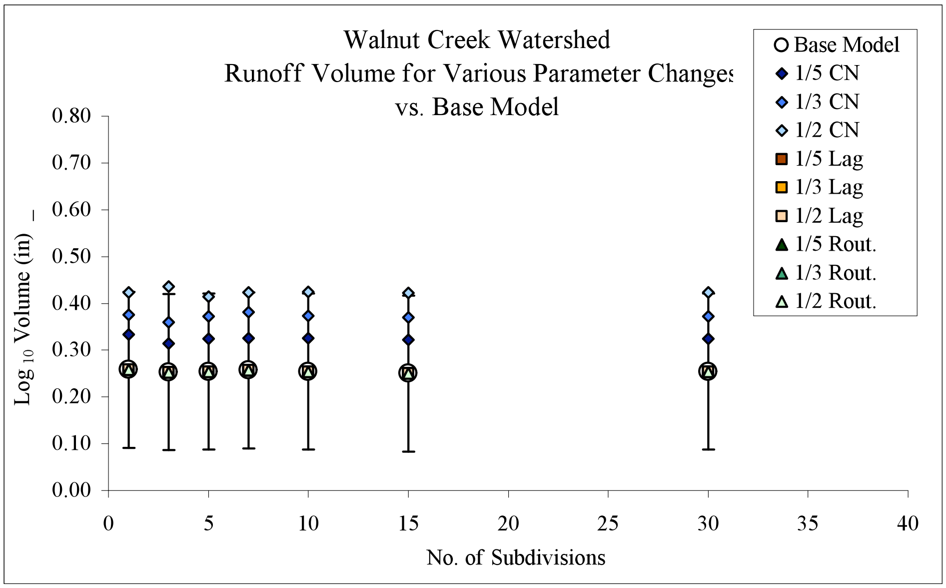


Figure 4.7: The impact of extreme parameter changes on the runoff hydrograph from Walnut Creek. Marks denote changes to hydrograph runoff volume resulting from the indicated change in parameter value. Error bars denote range corresponding to one-third of a log cycle.

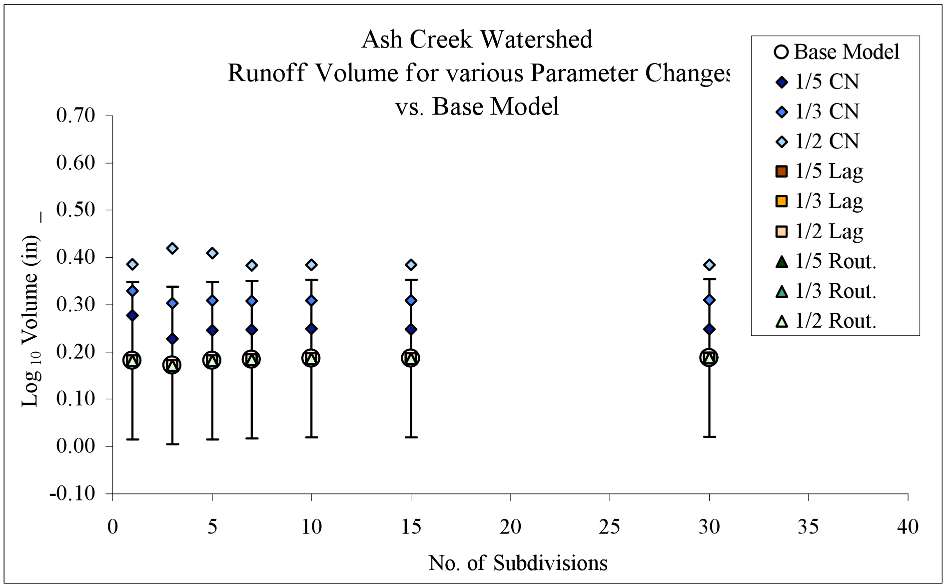


Figure 4.8: The impact of extreme parameter changes on the runoff hydrograph from Ash Creek. Marks denote changes to hydrograph runoff volume resulting from the indicated change in parameter value. Error bars denote range corresponding to one-third of a log cycle.

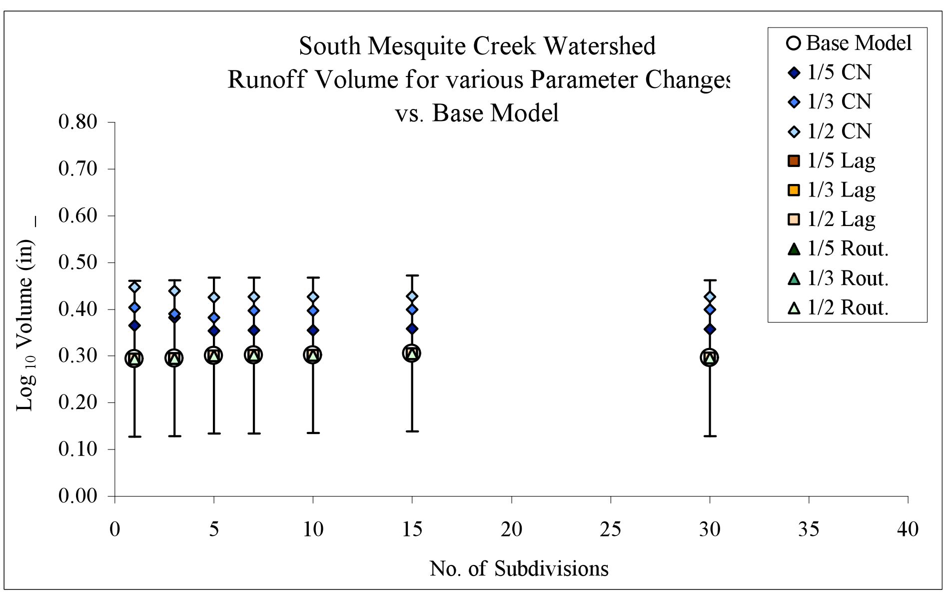


Figure 4.9: The impact of extreme parameter changes on the runoff hydrograph from South Mesquite Creek. Marks denote changes to hydrograph runoff volume resulting from the indicated change in parameter value. Error bars denote range corresponding to one-third of a log cycle.

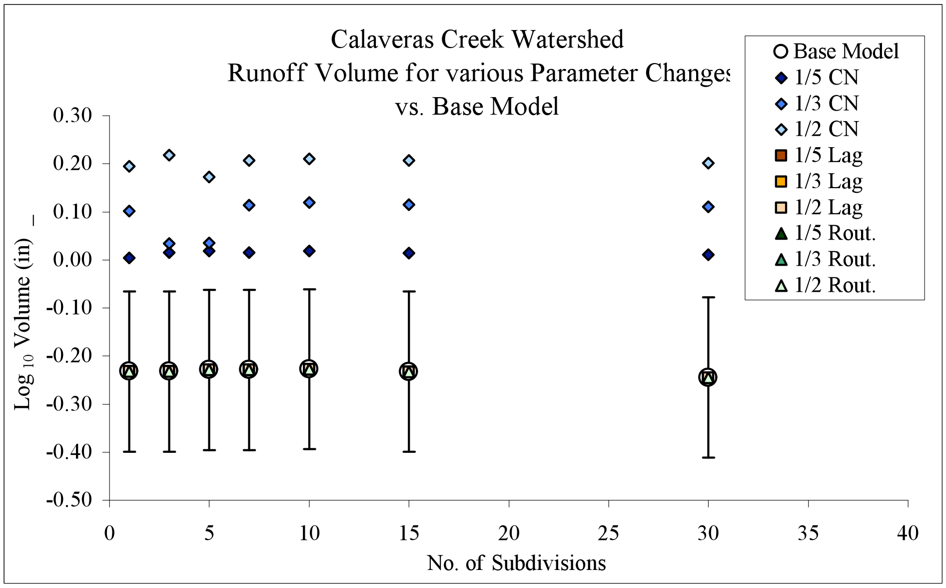


Figure 4.10: The impact of extreme parameter changes on the runoff hydrograph from Calaveras Creek. Marks denote changes to hydrograph runoff volume resulting from the indicated change in parameter value. Error bars denote range corresponding to one-third of a log cycle.

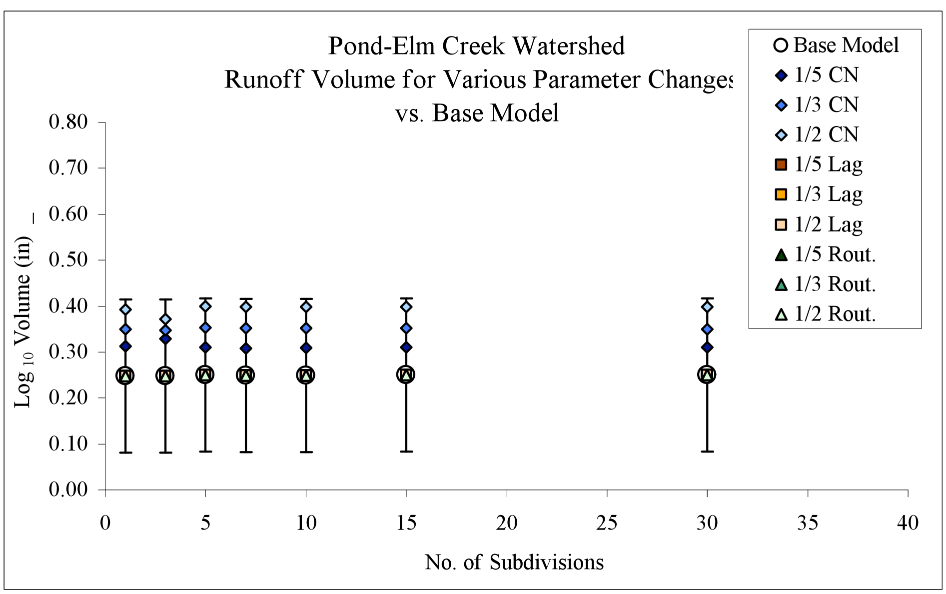


Figure 4.11: The impact of extreme parameter changes on the runoff hydrograph from Pond-Elm Creek. Marks denote changes to hydrograph runoff volume resulting from the indicated change in parameter value. Error bars denote range corresponding to one-third of a log cycle.

4.3. Distributed Models

ArcHydro and GeoHMS were used to develop distributed hydrologic models using the gridded model feature of HEC-HMS (U.S. Army Corps of Engineers, 2008). The three study watersheds (Ash Creek, Pond-Elm Creek, and South Mesquite Creek) were subdivided into 1 (no subdivision), 2, 3, 5, 7, and 9 sub-watersheds using an approach where the watershed was subdivided at locations that provided sub-watersheds of approximately equal drainage area. However, sub-watershed drainage areas could not be forced to be strictly equal; a tolerance of about ten percent was used.

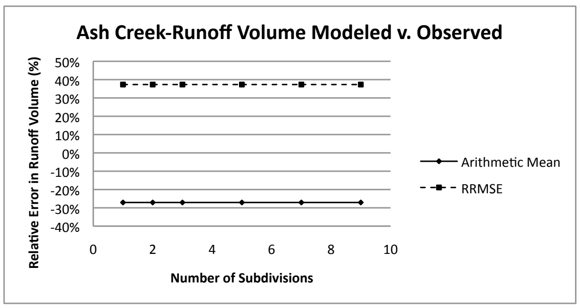
The resulting suite of watershed models[6] were operated and results extracted. Relative errors (arithmetic mean and root mean squared errors) were computed using Equations 2.8 and 2.9. A plot of the relative errors of runoff volume as a function of the number is subdivisions is presented in Figure 4.12. A pattern similar to that observed using the lumped-modeling approach (Figure 4.3) is evident. Little change in runoff volume occurs based on the number of watershed subdivisions. This occurs because the runoff curve number is not sensitive to watershed subdivision.

Estimates of peak discharge were extracted from the model results and the relative errors were computed. The relative errors are displayed on Figure 4.13. A moderate change in the relative errors occurred with an increasing number of subdivisions. When the mean relative error is used as a metric, predicted peak discharge was less accurate with increasing subdivision of the study watersheds. Furthermore, the RMSE for only South Mesquite Creek improved with increasing subdivision.

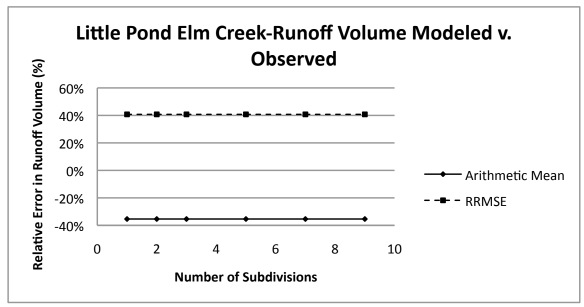
The modeled time to peak discharge was extracted from the model output and relative errors were computed. The relative errors are presented on Figure 4.14. Estimates of time to peak from the subdivided model worsened with increasing subdivision of the study watersheds.

An example hydrograph from the March 27, 1977 runoff event from Ash Creek is displayed on Figure 4.15. A significant error in the uncalibrated modeled time to peak discharge is evident. The secondary watershed response is amplified in the model-predicted runoff hydrograph, which probably indicates that the measured rainfall hyetograph does not represent the actual spatial distribution of event rainfall. Furthermore, the impact of subdivision on routing through the watershed drainage network is evident from the changes in hydrograph timing that occur with increasing watershed subdivision. This finding is similar to that observed with the lumped-modeling approach and reinforces observations about the increasing importance of hydrologic routing as the level of watershed subdivision increases.

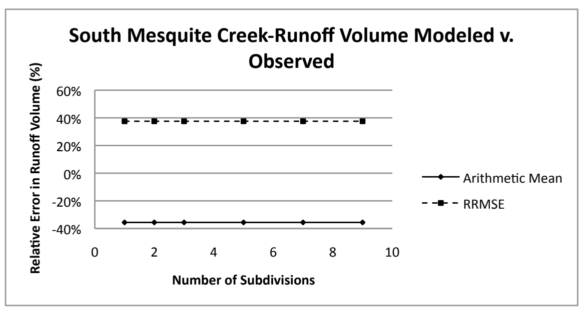
[6] It must be emphasized that a tremendous amount of work was required to develop the basin models using ArcHydro and GeoHMS.



(a) Ash Creek.

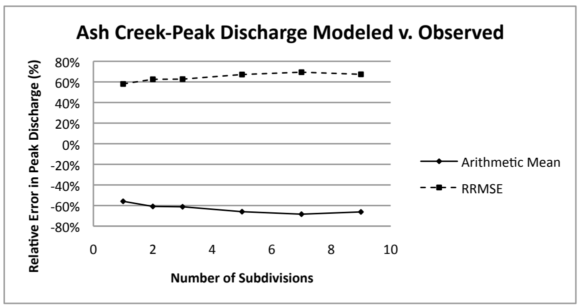


(b) Little PondElm Creek.

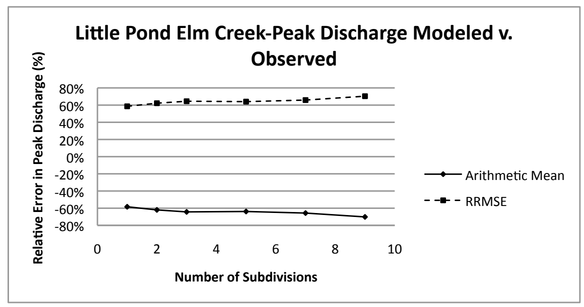


(c) South Mesquite Creek.

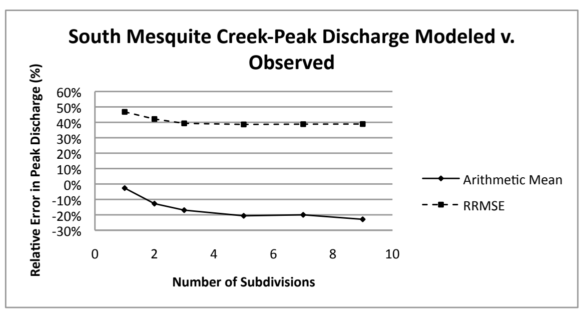
Figure 4.12: Relative errors of runoff volume as a function of the number of subdivisions from distributed modeling.



(a) Ash Creek.

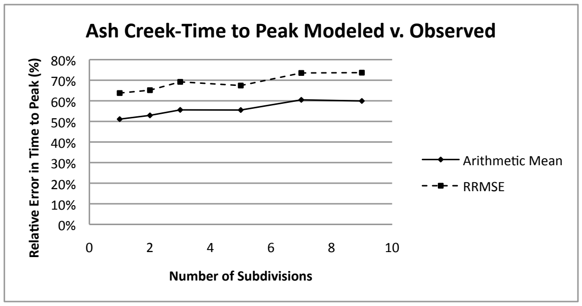


(b) Little Pond Elm Creek.

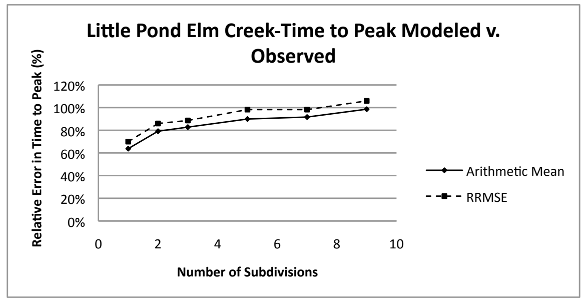


(c) South Mesquite Creek.

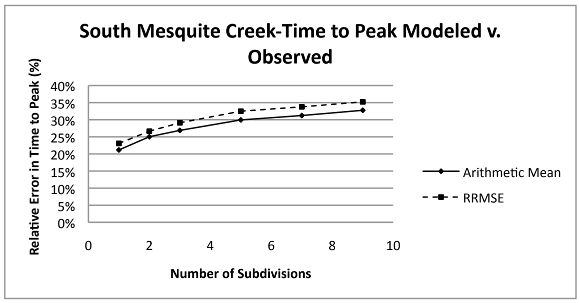
Figure 4.13: Relative errors of peak discharge as a function of the number of subdivisions from distributed modeling.



(a) Ash Creek.



(b) Little Pond Elm Creek.



(c) South Mesquite Creek.

Figure 4.14: Relative errors in time to peak discharge as a function of the number of subdivisions from distributed modeling.

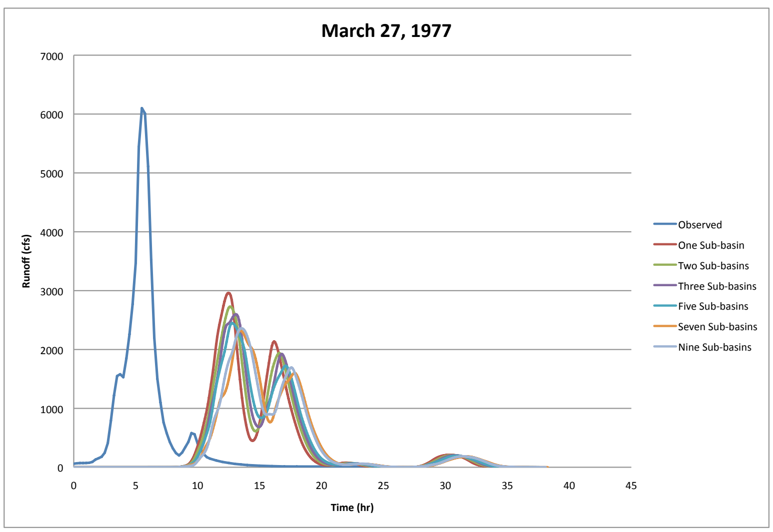


Figure 4.15: Observed and modeled runoff hydrograph from Ash Creek for the event of March 27, 1977.

4.4. Stochastic Modeling

Two numerical experiments were conducted using a highly-complex, single-purpose suite of programming tools written in the `R` language (R Development Core Team, 2006). These tools are collectively referred to as `GUHtools` and are anticipated to be available for download from the home page of Asquith and Roussel (2007). These tools allow simulation of I_A, C_L, T_p, Q_p, and X, and combine various intermediate computations to yield a simulated hydrograph given the input precipitation identified previously. These tools also accommodate vector summation to superimpose hydrographs and routed hydrographs using route length H as necessary to mimic a watershed subdivision scenario.

The two numerical experiments, that is, the configuration and properties of the sub-watersheds, are as follows:

1. Two undeveloped ($D = 0$) sub-watersheds with $A = 12 = A_o/2$ and $L = 3 = L_o/2$ were simulated in which one watershed cascades into the second and therefore the length of routing for the upstream watershed through the downstream watershed is 3 miles or $H = 3$.

2. Two developed ($D = 1$) sub-watersheds with $A = 12 = A_o/2$ and $L = 3 = L_o/2$ were simulated in which one watershed cascades into the second and therefore the length of routing for the upstream watershed through the downstream watershed is 3 miles or $H = 3$.

For both simulation experiments, all other watershed characteristics matched those of the whole watershed. In order to compute $Q_p^{i(\mathrm{AR})}$ the whole watershed was simulated for $D = 0$ or $D = 1$ depending on which experiment was conducted.

In an unsophisticated fashion, values of c_k ($c_k \mid 1 \rightarrow 2 : \Delta c_k = 0.05$) were systematically incremented (each value used) and 2,000 simulations per loop made. The resulting values for ϵ for each c_k by experiment were retained. The results are depicted on Figures 4.16 and 4.17. From the figures, the values for η are determined by inspection of the generalized location of the minimum of the $\epsilon(c_k)$ values and are approximately 1.05 and 1.6 for the undeveloped and developed watersheds, respectively.

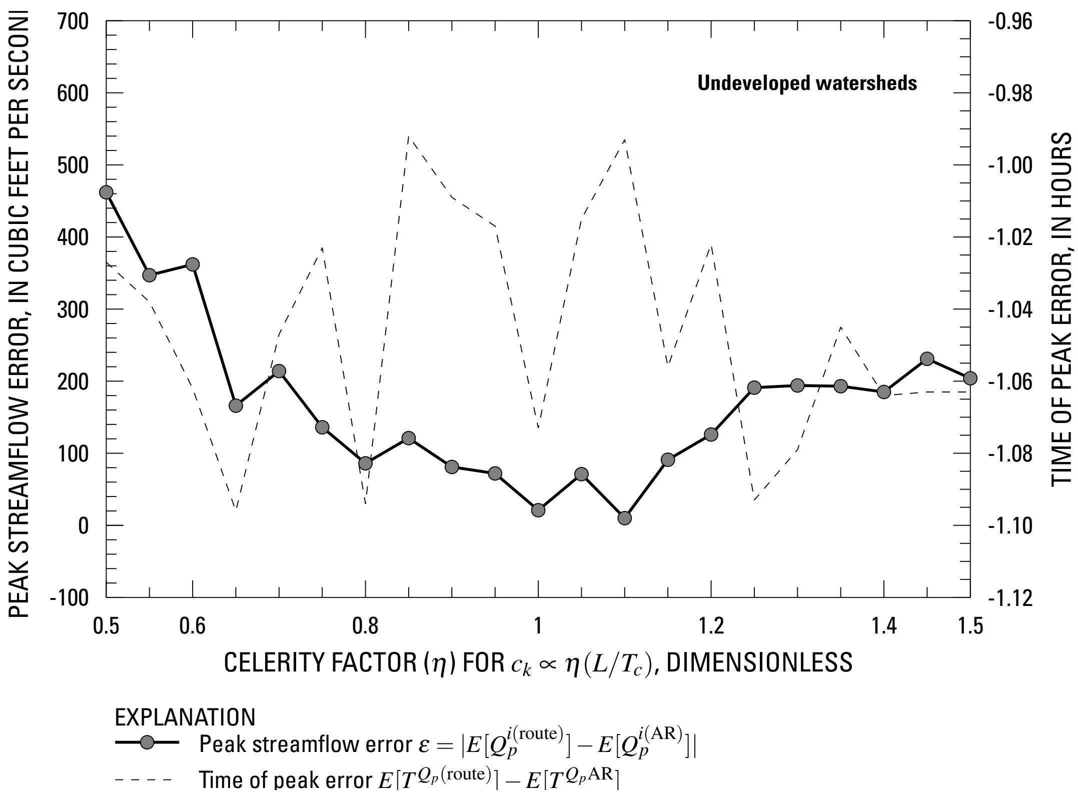


Figure 4.16: Relation between absolute value of peak streamflow error and celerity factor for two cascading undeveloped sub-watersheds.

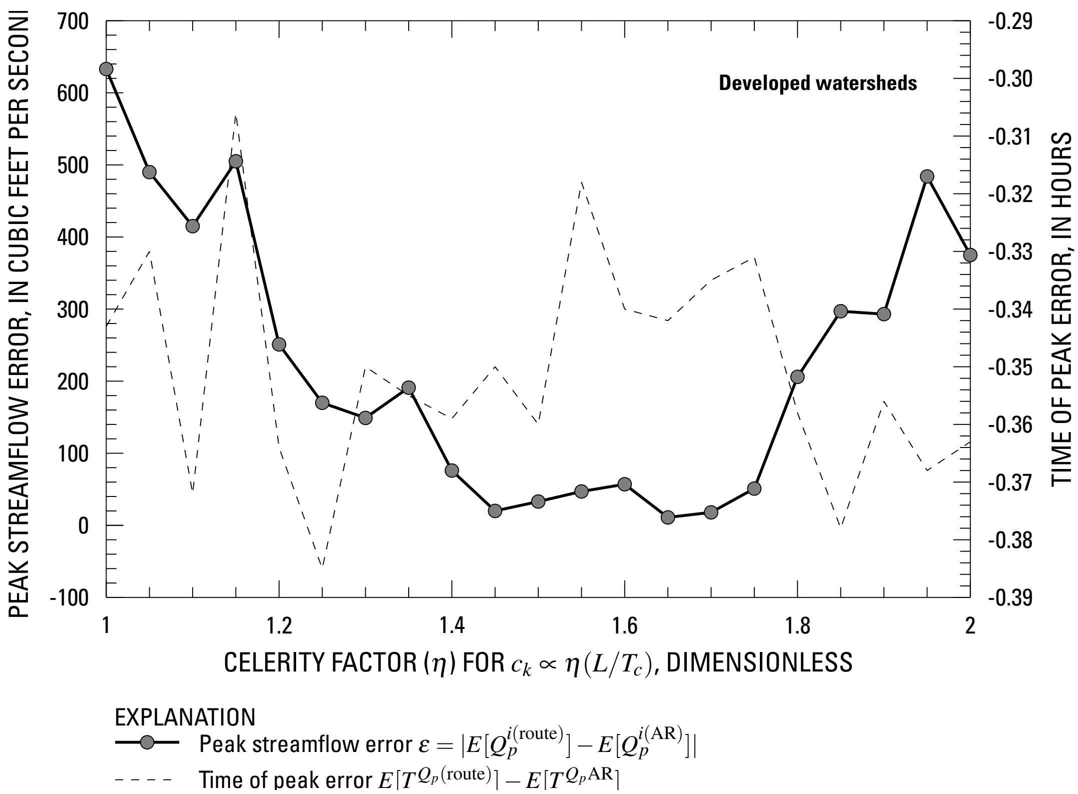


Figure 4.17: Relation between absolute value of peak streamflow error and celerity factor for two cascading developed sub-watersheds.

The results of the numerical experimentation described in Section 2.5 suggest that $\eta^{(D=0)} \approx 1.05$ and that $\eta^{(D=0)} \approx 1.6$. From which, following Equation 2.11 we can express c_k as

$$c_k \approx \begin{cases} 1.05L^{[\mathrm{feet}]}/(T_p^{[\mathrm{seconds}]}/0.7) & \text{for } D = 0 \\ 1.6L^{[\mathrm{feet}]}/(T_p^{[\mathrm{seconds}]}/0.4) & \text{for } D = 1, \end{cases} \tag{4.1}$$

or after simplification

$$c_k \approx \begin{cases} 0.74L^{[\mathrm{feet}]}/T_p^{[\mathrm{seconds}]} & \text{for } D = 0 \\ 0.64L^{[\mathrm{feet}]}/T_p^{[\mathrm{seconds}]} & \text{for } D = 1. \end{cases} \tag{4.2}$$

Combining the two η values by averaging through justification that η represents something innate to hydraulics, we get a generalized $\eta = 0.69$, which following the structure of Equation 4.2, yields

$$c_k \approx 0.69 \frac{(L^{[\mathrm{miles}]} \times 5280)}{(T_p^{[\mathrm{hours}]} \times 3600)}, \tag{4.3}$$

where unit conversion factors have been introduced, c_k is celerity in feet per second, L is main-channel length in miles, and T_p is time to peak in hours. Emphasis again is needed that L is not a routing length H, but is the main-channel length of the sub-watershed from which streamflow will be routed R distance downstream. Upon further simplification units, we get

$$c_k \approx 1.01 \frac{L}{T_p} \rightarrow c_k \equiv \frac{L}{T_p}, \tag{4.4}$$

which is an appropriate generalization given substantial fraction of $\log_{10}$-cycle errors seen in estimation of I_A, C_L, T_p, q_p, and X.

Asquith and Roussel (2007) established that

$$T_p = 10^{-1.49-0.354D} L^{0.602} S^{-0.672}. \tag{4.5}$$

Therefore, with substitution, c_k can be directly computed by observing that the equivalency $c_k \equiv L/T_p$, which is established in Equation 4.4, yields

$$c_k = 10^{1.49+0.354D} L^{0.398} S^{0.672}, \tag{4.6}$$

where the variables are previously defined. The equation is interpreted as follows:

- Developed $D = 1$ watersheds have higher c_k than undeveloped $D = 0$ watersheds,
- As S increases c_k increases, and
- As L increases c_k increases.

The response of c_k to S is obviously consistent with expectation of fundamental open-channel hydraulics. The response of c_k to D could be indicative of the more "urban" nature of the channels (stabilized, lined, sewer, other utility co-location...) intrinsically represented in the $D = 1$ watersheds of available to the research team. Finally, the fact that Equation 4.6 shows c_k increasing with increasing L is more difficult to interpret other than acknowledging that as L increases the S for a watershed generally decreases. Perhaps some compensation between the two characteristics occurs.

Based on these results, c_k can be estimated through Equation 4.6 for an arbitrary watershed in such a fashion as to constrain an important parameter in hydraulic routing to produce Q_p values that are generally consistent with values that would be produced by treating the watershed as a lumped system through the Asquith and Roussel (2007) procedures. This is an important finding as either some constraint on values for c_k or some estimate of c_k can be made from purely hydrologic analysis. Another contribution of the experimental approach is that the relation between T_p and T_c as shown in Roussel and others (2005, p. 15) define a situation in which the η could be treated as a constant for undeveloped and developed watersheds.

4.4.1. Example Computation

Suppose that a hydrograph is to be routed a distance H downstream from a 6-square mile, undeveloped, and rock-dominated $R = 1$ watershed with a main-channel length of 4 miles, a dimensionless channel slope of 0.009, and a curve number of $CN = 65$. What Muskingum routing parameters should be used? Given that no other information is provided, it is suggested that $X \approx 0.2$ be used as this value seems representative from discussion in engineering textbooks. The values for R and CN are not part of the solution to the question. The celerity $c_k = 10^{1.49+0.354(0)} 4^{0.398} (0.009)^{0.672}$ or about 2.3 feet per second.

If the watershed were to become developed, what is the estimate for c_k? Substitution yields $c_k = 10^{1.49+0.354(1)} 4^{0.398} (0.009)^{0.672}$ or about 5.1 feet per second

4.4.2. Caveats

Final caveats are needed. Although providing potentially valuable insight in to the problem of parameterizing a component of the Muskingum routing for a subdivided watershed, the experiments reported here constitute an elementary example of watershed subdivision. The authors experimented with multiple levels of cascading subdivisions and similar behavior for η value and the minimization of ϵ were seen.

The authors attempted, through stochastic simulation, to retain uncertainty and mitigate for potential nonlinearities caused by the discontinuous nature of the initial-abstraction, constant-loss model of watershed losses. It is difficult to assess the full reliability of the numerical computations; although various intermediate visualizations of hydrographs were used in development of the algorithms. The authors used mutually independent simulations of all characteristics; this is likely not an appropriate method but further assessment is well beyond the scope of this research project. Also the authors do not address the question of how large a reach length for routing should be.

The authors recognize that it is entirely possible that the generalized $\eta = 0.67$ in Equation 4.3 is in fact not generalizable and therefore not a constant. If such a situation could be shown by other configurations of stochastic experiments as described here or by real-world data, then the watershed subdivision problem is exceptionally difficult to simplify[7] and preference to lumped-parameter models, such as that described in Asquith and Roussel (2007), should be made lacking specific information about the hydraulics of a channel system.

[7] In the absence of sufficient geometric, topographic, and topologic information to specify channel hydraulics (including underground engineered drainage networks) generalizations or just plain engineering guesses are a logical step to configure uncalibrated subdivided models. Such generalizations could be interpreted as a style of lumped-parameter modeling, much in the same vein that modeling itself is really a sophisticated from of regression. The intellectual controversy of this point of view notwithstanding, the authors lean to lumped-parameter models when channel system hydraulics are poorly characterized and when the subdivision is a relatively arbitrary choice.

5. Summary and Conclusions

The purpose of this chapter is to provide a summary of research work accomplished and a synopsis of the research findings. In addition, suggestions for further research into issues associated with watershed modeling, in general, and subdivision of watersheds for modeling are provided.

TxDOT engineers and consultants to TxDOT are tasked with hydrologic modeling of watersheds to provide estimates of design discharges. The resulting design discharge estimates are then used to size hydraulic structures for Texas highways. Inevitably, working with watersheds is a required component of this modeling. The objectives for TxDOT Research Project 0–5822, *Subdivision of watersheds for hydrologic modeling* were:

1. Determine justification and methodology for subdividing watersheds for use with lumped models, and
2. Assess the utility of distributed models, such as the gridded sub-model system of `HEC-HMS`.

Based on the literature review, the general consensus of the researchers is that *simpler is better.* That is, the principle of parsimony[1] is wise. In this context, parsimony refers to an conceptualization of watershed behavior that depends on the least complex assembly of model components. That is, watershed models should generally not be subdivided any more than necessary to obtain a conceptual representation that reflects the physical reality of the system. Subdivision does not result in improved "accuracy" and should not be used with the assumption that results from subdivided watershed models are somehow superior to topologically-simpler models.

Watersheds should not be arbitrarily subdivided; additional subdivision does not result in improved "accuracy." Subdivision to accommodate (i) a huge change in watershed runoff generation on a substantial portion (1/3) of the total watershed, (ii) a huge change in routing time (perhaps by ditch building over considerable distances), (iii) a regulation effect on a portion of the watershed (a reservoir being an extreme example), (iv) a huge change in on-watershed storage, or (v) a large change in slope (such as the watershed traversing across an escarpment), makes sense and these physical situations demand such consideration. The analyst will need to be aware that such subdivision increases the parameter count. Furthermore, if subdivision is applied the model has to route flows — the selection of routing parameters becomes exceedingly important and the uncertainty in the timing parameters in a runoff hydrograph is transferred (and probably multiplied) to the uncertainty in the routing parameters.

[1] Also known as *Occam's Razor.*

A few words about the concept of model calibration are required. When modelers use the term *calibration*, the general intent is optimization of watershed-model parameter sets such that the measured hydrograph response of a watershed is reproduced (in some objective sense) by the calibrated model[2]. The process is similar in concept to application of least squares curve fitting in that an objective function (for example, the sum of the squared residuals) is minimized by adjusting model parameters. In the context of a watershed model, the resulting parameter sets must pass the "reasonableness" test. That is, it is inappropriate to choose parameters that are beyond physical justification simply to improve the fit of the model to the observations[3]. A substantial degree of professional judgment is required to choose appropriate parameter values, even when using tools such as `HEC-HMS` to provide "best" parameter estimates. Finally, measured rainfall-runoff observations generally contain sufficient information to calibrate no more than about ten parameters (Hornberger and others, 1985).

Another approach is that watershed models (all models for that matter) should be compared to observations if excitation-response data are available. In some instances, these observations can be used to adjust some of the model parameters with the caveat that the adjusted values should remain physically realistic and appropriate for the system being modeled, an equally acceptable alternative is to scale the response for the comparison. The first kind of "calibration" becomes thorny when the observation set is partitioned into a calibration component and a validation component — if the validation fails, then it (the validation set) has just become part of the calibration set and is no longer an independent partition.

Regardless of the end-user's opinion about calibration, measured rainfall-runoff responses should be used to confirm model operation is such observation are available. Whether that approach takes the form of a parameter-optimization method or a scaling method is a matter of professional judgment and remains in the purview of the analyst. The expectation, however, is that (1) it is impossible to find a parameter set that reproduces the observed hydrograph for all rainfall-runoff events in the database and such expectation on the part of the analyst is unreasonable, and (2) parameter sets (whether estimated or calibrated) must be within the realm of physical reasonability.

The research project was pursued through four avenues of study: (1) An *iso-characteristic* approach, implemented as equal drainage area[4]; (2) an *ad-hoc* subdivision approach implemented as a professional would choose to subdivide a watershed based on professional experience; (3) a distributed-modeling approach, using `HEC-HMS` (U.S. Army Corps of Engineers, 2008) as the modeling tool; and (4) a stochastic-simulation approach to examine the channel travel-time for Muskingum routing. A variety of Texas watersheds for which measured rainfall-runoff responses (Asquith and others, 2004) were used to conduct the study. The degree of subdivision depended on the method used to examine the impact of watershed subdivision. A maximum of 30 subdivisions was used.

[2] This is in direct opposition to the notion that a desired computational result can be obtained by "tweaking" model parameters. The latter approach is, at best, intellectually dishonest. The comedic consultant's response "What would you like the answer to be?" is a parody thereof.

[3] This is one of the reasons that the optimizer in `HEC-HMS` provides the capability to limit the search space for parameter values.

[4] Other iso-characteristic subdivision schemes include equal time of concentration, equal main channel slope, and equal overland flow slope. Basically, any physical watershed characteristic could be used.

Uncalibrated HEC-HMS models[5] were developed for each of the watersheds in the study database. A no-subdivision model was included in each method tested. This model represented the simplest case (no subdivision) in which all parameters are averaged (or lumped) for the watershed. Selected rainfall-runoff events were used for each watershed model, the model was operated, and estimates of runoff volume (watershed units), peak estimated discharge, and time to peak discharge were extracted from model output. Relative errors between predicted and observed values were computed and are reported in Chapter 4.

In general, no change was observed in the estimation of runoff volume. This result is directly attributable to use of the NRCS curve number method. However, unless the distribution of rainfall-runoff sub-process model parameters at sub-watershed scale is justified (and sufficient supporting data actually exist or can be obtained), this result will hold true regardless of the rainfall-runoff sub-process model used.

The number of parameters requiring estimates increased as the number of subdivisions increased. The issue was exacerbated by introduction of required hydrologic routing to move computed hydrographs from internal sub-watershed outlets to the main watershed outlet. The number of routing parameters required depended on the choice of the hydrologic routing sub-process model and the number of elements chosen. In the simplest case, one "channel" was required to convey flows from the sub-watershed outlet to the next downstream confluence of sub-watersheds.

Examination of the travel-time parameter for Muskingum routing using a stochastic-modeling approach was undertaken. Two simple watersheds were assumed, each comprising a cascade of two sub-watersheds — an upper sub-watershed and a lower sub-watershed. One set was assumed to be undeveloped and the second set was assumed to be developed. Estimates of peak discharge were extracted using methods defined by Asquith and Roussel (2007) for the upstream and downstream sub-watersheds, and for the watershed as a whole. The travel time (or wave celerity) required to minimize the deviation between the routed and summed sub-watershed discharges and the watershed discharges was computed. The implied travel time (wave celerity) was related to time to peak and channel length from the relation presented by Asquith and Roussel (2007).

Although the approach taken in the stochastic experiments was not generalized, it appears that wave celerity (reach travel time) might be estimated using the results presented herein. That result could prove useful for those circumstances where design flow rates are required at points inside a study watershed and the introduction of hydrologic routing is therefore required for modeling of the entire watershed. Additional research and testing of this approach is needed.

[5]Uncalibrated models are those with parameter sets that are not adjusted to force a match between observed and modeled runoff hydrographs. It is rare that data exist for use in calibrating watershed models in applied settings. Therefore, this situation (uncalibrated) represents the most-likely mode for watershed model application. Watershed models (all models for that matter) should be calibrated if excitation-response data are available.

5.1. Project Findings

Based on the results of the research reported in previous sections, the conclusions for this project are:

1. In general, subdivision of watersheds for modeling results in no more than modest improvements in prediction of peak discharge. Improvements generally are not observed with more than about five to seven subdivisions;
2. Watershed subdivision multiplies the number of sub-process model parameters required to model watershed response and introduces the requirement to route flows through the watershed drainage network. Discrimination of parameters between sub-watersheds is difficult to justify from a technical perspective;
3. The introduction of watershed subdivisions requires hydrologic (or hydraulic) routing for movement of sub-watershed discharges toward to watershed outlet. The routing sub-process model requires estimates of additional parameters that are subject to uncertainty;
4. Regardless of the subdivision scheme used, little or no change in runoff volume was observed in model output;
5. Little or no change in predicted peak discharge was observed from the watershed models constructed as part of the research reported herein;
6. The dependence of computed hydrographs on internal routing became more apparent as the number of subdivisions increased[6]; and
7. Application of distributed modeling[7], as currently implemented in `HEC-HMS`, was difficult and time-consuming. It is unclear what technical advantage is gained by application of this modeling approach in an uncalibrated mode, given the level of effort required to develop the models.

There are settings in which watershed subdivision is appropriate. If one of the sub-watersheds is distinctly different than other components of the watershed, and if the drainage of that sub-watershed is a significant fraction of the whole[8], then a subdivision might be appropriate. Specific examples of an appropriate application of watershed subdivision would be the presence of a reservoir on a tributary stream, a significant difference in the level of urbanization of one component of a

[6] Even in cases where relatively large differences in watershed properties were forced to emulate a motivating reason to subdivide, the effect was different than expected, and the dependence on routing was crucial — in fact the researchers believe that if one has to route hydrographs, that the time/attenuation property is the most crucial component of "getting it right."

[7] In this research, the attempt was to use `HEC-HMS` in its fully-distributed mode. The use of gridded curve numbers only is a different problem and was not investigated. The gridded curve number approach might be useful for determining estimates of areally-averaged runoff curve number. This was not investigated as part of this research project.

[8] Although this was not specifically investigated, a reasonable value would seem to be in the 20–50 percent range.

watershed, or a substantial difference in physical characteristics (main channel slope, overland flow slope, loss characteristics, and so forth).

There is little justification for subdividing a watershed for the purpose of improving model accuracy. Watershed subdivision increases the number of parameters that must be estimated by the analyst. Furthermore, watershed subdivision introduces the requirement to route internal flows to the watershed outlet, adding additional parameters that must be estimated. Unless flow rates are needed at locations internal to the watershed being modeled, there is little to be gained for the purpose of infrastructure design by subdividing a watershed[9].

[9] In this research the considerations are strictly hydrologic — the subdivision schemes examined were applied on watersheds where there was little obvious "structure" with regards to parts of the greater watershed being different from one another.

Bibliography

Asquith, W. H. and M. C. Roussel (2007). An initial abstraction, constant-loss model for unit hydrograph modeling for applicable watersheds in Texas. Scientific Investigations Report 2007–5243, U.S. Geological Survey, Austin, Texas 78754.

Asquith, W. H. and D. B. Thompson (2003). Modeling of runoff-producing rainfall hyetographs in Texas using L-moments. In *Proceedings Texas Section American Society of Civil Engineers Spring Meeting, Corpus Christi, Texas, April 2–5, 2003*, pp. 29. In PDF.

Asquith, W. H. and D. B. Thompson (2005). Alternative regression equations for estimation of annual peak-streamflow frequency for undeveloped watersheds in Texas using PRESS minimization. Project Report 0–4405–2, TechMRT, Texas Tech University, Lubbock, Texas 79409.

Asquith, W. H. and D. B. Thompson (2008). Alternative regression equations based on drainage area and mean annual precipitation for estimation of annual peak-streamflow frequency for undeveloped watersheds in Texas using PRESS minimization. Scientific Investigations Report 2008–5084, U.S. Geological Survey, Austin, Texas 78754. Republication of TxDOT Research Report 0–4405–2.

Asquith, W. H., D. B. Thompson, T. G. Cleveland, and X. Fang (2004). Synthesis of rainfall and runoff data used for Texas Department of Transportation research projects 0–4193 and 0–4194. Open-File Report 2004–1035 (TxDOT Reports 0–4193–2 and 0–4194–2), U.S. Geological Survey, Austin, Texas.

Beven, K. J. and M. J. Kirkby (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 43–69.

Bingner, R. L., J. G. J. G. Arnold, and R. Srinivasan (1997). Effect of watershed subdivision on simulation runoff and fine sediment yield. *Transaction of the ASAE 40*(5), 1329–1335.

Dooge, J. (1973). Linear theory of hydrologic systems. Technical Bulletin 1468, U.S. Department of Agriculture, Washington, D.C.

FitzHugh, T. W. and D. S. Mackay (2000). Impacts of input parameter spatial aggregation on an agricultural nonpoint source pollution model. *Journal of Hydrology 236*, 35–53.

Gupta, V. K. and S. Sorooshian (1983). Uniqueness and observability of conceptual rainfall-runoff model parameters: The percolation process examined. *Water Resources Research 19*(1), 269–276.

Gupta, V. K. and S. Sorooshian (1985a). The automatic calibration of conceptual catchment models using derivative-based optimization algorithms. *Water Resources Research 21*(4), 473–485.

Gupta, V. K. and S. Sorooshian (1985b). The relationship between data and the precision of parameter estimates of hydrologic models. *Journal of Hydrology 81*, 57–77.

Haan, C. T., H. P. Johnson, and D. L. Brakensiek (Eds.) (1982). *Hydrologic modeling of small watersheds*. Number 5 in ASAE Monograph. St. Joseph, Michigan 49085: American Society of Agricultural Engineers. A review of modeling small watershed hydrology in the late 1970s and early 1980s.

Hernandez, M., S. Miller, D. Semmens, D. C. Goodrich, W. P. Miller, and W. G. Kepner (2002). Quality assurance and quality control in the development and application of the automated geospatial watershed assessment (AGWA) tool. Technical Report EPA/600/R-02/046, U.S. Environment Protection Agency, Las Vegas, Nevada.

Hornberger, G., K. Beven, B. Cosby, and D. Sappington (1985, December). Shenandoah watershed study: Calibration of a topography-based, variable contributing area hydrological model to a small forested catchment. *Water Resources Research 21*(12), 1841–1850.

Hromadka II, T. V. (1986). County of San Bernardino hydrology manual. Engineer's report, Williamson and Schmid, Civil Engineers, Irvine, California.

Hromadka II, T. V. and J. J. DeVries (1986). Kinematic wave routing and computational error. Technical report.

Jakeman, A. and G. Hornberger (1993). How much complexity is warranted in a rainfall-runoff model. *Water Resources Research 29*(8), 2637–2649.

Jha, M., P. W. Gassman, S. Secchi, R. Gu, and J. Arnold (2004). Effect of watershed subdivision on SWAT flow, sediment, and nutrient predictions. *Journal of the American Water Resources Association 40*(3), 811–825.

Jha, M. K. (2002). Level of watershed subdivision for water quality modeling. Master's thesis, Iowa State University.

Kerby, W. S. (1959). Time of concentration for overland flow. *Civil Engineering 29*(3), 60.

Kirpich, Z. P. (1940). Time of concentration of small agricultural watersheds. *Civil Engineering 10*(6), 362. The original source for the Kirpich equation. (In PDF).

Loague, K. M. and R. A. Freeze (1985). A comparison of rainfall-runoff modeling techniques on small upland catchments. *Water Resources Research 21*(2), 229–248.

Luong, T. (2008). Subdivision of watersheds for modeling. Master's thesis, University of Houston, Houston, Texas.

Maidment, D. R. (2002). *Arc Hydro*. ESRI, Inc.

Mamillapalli, S., R. Srinivasan, J. G. Arnold, and B. A. Engel (1996). Effect of spatial variability on basin scale modeling. In *Third International Conference/Workshop on Integrated Remote Sensing Resource Center, established with support from NASA (NAG5-6535). Third International Conference/Workshop on Integrating GIS and Environmental Modeling, Santa Fe, New Mexico, January 21 – 26, 1996.* National Center for Geographic Information and Analysis, Santa Barbara, CA, USA.

McCuen, R. H., P. A. Johnson, and R. M. Ragan (2002). Highway hydrology: Hydraulic design series number 2, second edition. FHWA National Hydraulics Institute Report FHWA–NHI–02–001, Federal Highway Administration, Room 3203, 400 Seventh Street, SW, Washington D.C., 20590.

Michaud, J. and S. Sorooshian (1994). Comparison of simple versus complex distributed runoff models on a midsized semiarid watershed. *Water resources research 30*(3), 593–605.

Nash, J. E. and J. V. Sutcliffe (1970). River flow forecasting through conceptual models. *Journal of Hydrology X*(3), 282–290.

Norris, G. and C. T. Haan (1993). Impact of subdividing watersheds on estimated hydrographs. *Soil and Water Division American Society of Agricultural Engineers 9*(5), 443–445.

R Development Core Team (2006). *R: A Language and Environment for Statistical Computing.* Vienna, Austria: R Foundation for Statistical Computing. ISBN 3–900051–07–0.

Rossman, L. A. (2008). Storm water management model: User's manual. Technical Report EPA/600/R–05/040, U.S. Environment Protection Agency, Cincinnati, Ohio 45268.

Roussel, M. C., D. B. Thompson, X. Fang, T. G. Cleveland, and A. C. Garcia (2005). Timing parameter estimation for applicable Texas watersheds. Final Project Report 0–4696–2, TxDOT, Lubbock, Texas 79409.

Sasowsky, K. C. and T. W. Gardner (1991). Watershed configuration and geographic information system parameterization for spur model hydrologic simulations. *Water resources bulletin 27*(1), 7–18.

Sorooshian, S. (1981). Parameter estimation of rainfall-runoff models with heteroscedastic streamflow errors - the noninformative data case. *Journal of Hydrology 52*, 127–138.

Sorooshian, S. and V. K. Gupta (1983, February). Automatic calibration of conceptual rainfall-runoff models: the question of parameter observability and uniqueness. *Water Resources Research 19*(1), 260–268.

Sorooshian, S. and V. K. Gupta (1985, April). The analysis of structural identifiability: theory and application to conceptual rainfall-runoff models. *Water Resources Research 21*(4), 487–495.

Tripathi, M. P., N. S. Raghuwanshi, and G. P. Rao (2006). Effect of watershed subdivision on simulation of water balance components. *Hydrological processes 20*, 1137–1156.

U.S. Army Corps of Engineers (2000). Hydrologic modeling system HEC-HMS: Technical reference manual. Technical reference manual CPD–74B, Hydrologic Engineering Center, Davis, California.

U.S. Army Corps of Engineers (2003). Geospatial hydrologic modeling extension HEC-GeoHMS – version 1.1. User's manual CPD–77, Hydrologic Engineering Center, Davis, California.

U.S. Army Corps of Engineers (2006). Hydrologic modeling system HEC-HMS — version 3.1.0. User's manual CPD–74A, Hydrologic Engineering Center, Davis, California.

U.S. Army Corps of Engineers (2008). Hydrologic modeling system HEC-HMS — version 3.2.0. User's manual CPD–74A, Hydrologic Engineering Center, Davis, California.

U.S. Department of Agriculture, Natural Resources Conservation Service (1986). Urban hydrology for small watersheds. Technical Release 55, U.S. Department of Agriculture.

U.S. Department of Agriculture, Natural Resources Conservation Service (1997, September). Part 630 hydrology, national engineering handbook. Downloaded from NRCS web site. (In PDF).

Viessman, W. and G. L. Lewis (2003). *Introduction to hydrology* (Fifth ed.). Prentice-Hall.

Wingfield, M. T. (2008). Evaluating the effect that watershed subdivision and watershed parameters have on modeling results. Master's thesis, Texas Tech University, Lubbock, Texas 79409.

Wood, E. F., M. Sivapalan, K. Beven, and L. Band (1988). Effects of spatial variability and scale with implications to hydrologic modeling. *Journal of Hydrology 102*, 29–47.

A. Equal-Area Modeling Results

The purpose of this appendix is to present results from Luong (2008) that, while pertinent to the research results, are not appropriate for the main body of the text.

Table A.1: Curve number for equal-area watersheds and subdivisions from Luong (2008)

Subwatershed	Onion Creek	South Mesquite	Little Fossil	Olmos Creek	Trinity North
A	75	91	85	93	63
A_1	75	91	84	83	63
A_2	73	90	85	93	62
A_1	75	92	84	92	63
A_2	75	91	86	93	63
A_3	73	89	83	93	62
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
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

B. Lumped-Parameter Models

Tabular material presented in Wingfield (2008) was an important part of the research presented in this report. Although that material is preserved in Mr. Wingfield's thesis, a portion of it is presented here as part of the research reported herein.

Table B.1: Basin and routing parameters for Walnut Creek, Part 1.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
Lumped	A11	26.45	84	158	Outlet	-	-
3 - Unit Simulated	A31	7.40	83	79	R31	201	Outlet
	A32	4.20	84	81	R32	101	Outlet
	A33	14.85	84	140	Outlet	-	-
5 - Unit Simulated	A51	7.40	83	79	R51	36	R52
	A52	5.35	86	77	R52	121	R54
	A53	4.20	84	81	R53	13	R54
	A54	4.53	84	68	R54	95	Outlet
	A55	4.98	82	82	Outlet	-	-
7 - Unit Simulated	A71	1.29	86	43	R71	87	R72
	A72	6.11	83	70	R72	36	R73
	A73	5.35	86	77	R73	27	R74
	A74	1.13	87	54	R74	108	R76
	A75	3.39	83	52	R76	95	Outlet
	A76	4.20	84	81	R75	13	R76
	A77	4.98	82	82	Outlet	-	-
10 - Unit Simulated	A101	1.29	86	43	R101	87	R102
	A102	3.09	82	78	R102	36	R104
	A103	3.01	83	70	R102		
	A104	1.37	87	56	R103	29	R104
	A105	3.98	85	77	R104	27	R105
	A106	4.20	84	81	R106	13	R107
	A107	1.13	87	54	R105	117	R107
	A108	3.39	83	52	R107	95	Outlet
	A109	1.84	83	52	R108	110	Outlet
	A1010	3.13	82	48	Outlet	-	-
15 - Unit Simulated	A151	1.29	86	43	R151	87	R153
	A152	2.15	82	78	R153	36	R156
	A153	0.94	82	48	R152	42	R153
	A154	3.01	83	70	R153		
	A155	1.37	87	56	R154	30	R156
	A156	1.91	84	64	R155	36	R156
	A157	2.07	86	45	R156	27	R157
	A158	1.13	87	54	R157	117	R1511
	A159	2.67	83	52	R1511	95	Outlet
	A1510	0.72	81	43	R158	36	R1511
	A1511	2.70	84	62	R159	55	R1510
	A1512	1.51	82	61	R1510	13	R1511
	A1513	1.84	83	52	R1512	110	Outlet
	A1514	2.52	82	48	Outlet	-	-
	A1515	0.59	79	39	R1513	4	Outlet

Table B.2: Basin and routing parameters for Walnut Creek, Part 2.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
30 - Unit Simulated	A301	0.71	86	58	R301	87	R306
	A302	0.59	85	50	R301		
	A303	1.40	82	56	R306	36	R3011
	A304	0.76	82	53	R302	71	R306
	A305	0.94	82	48	R303	42	R306
	A306	0.54	81	35	R304	81	R306
	A307	2.14	84	62	R306		
	A308	0.33	86	25	R305	21	R306
	A309	0.57	89	31	R307	57	R308
	A3010	0.79	86	53	R308	29	R3011
	A3011	1.91	84	58	R309	36	R3011
	A3012	0.50	85	38	R309		
	A3013	0.90	88	33	R3010	31	R3011
	A3014	0.67	84	31	R3011	27	R3012
	A3015	1.13	87	52	R3012	117	R3018
	A3016	1.78	83	52	R3018	95	Outlet
	A3017	0.41	84	25	R3016	107	R3018
	A3018	0.48	84	29	R3018		
	A3019	0.72	81	43	R3017	36	R3018
	A3020	1.25	84	40	R3013	65	R3014
	A3021	1.45	85	46	R3014	55	R3015
	A3022	0.79	84	38	R3014		
	A3023	0.71	80	44	R3015	13	R3018
	A3024	0.58	82	41	R3019	37	R3020
	A3025	0.73	85	42	R3019		
	A3026	0.53	81	33	R3020	110	Outlet
	A3027	0.56	83	39	R3021	80	Outlet
	A3028	0.23	84	22	R3022	36	Outlet
	A3029	1.76	82	48	Outlet	-	-
	A3030	0.59	79	45	R3023	4	Outlet

Table B.3: Basin and routing parameters for Ash Creek, Part 1.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
Lumped	A11	7.65	82	119	Outlet	-	-
3 - Unit Simulated	A31	1.10	88	80	R31	98	Outlet
	A32	2.35	84	58	R32	57	Outlet
	A33	4.20	78	86	Outlet	-	-
5 - Unit Simulated	A51	1.25	87	80	R51	98	Outlet
	A52	0.91	83	57	R51		
	A53	1.12	83	49	R52	103	Outlet
	A54	2.35	84	58	R53	57	Outlet
	A55	2.03	74	75	Outlet	-	-
7 - Unit Simulated	A71	1.25	87	80	R71	38	R73
	A72	0.91	83	57	R71		
	A73	1.12	83	49	R72	39	R73
	A74	1.30	86	36	R74	51	R75
	A75	1.05	83	50	R75	57	Outlet
	A76	0.70	76	29	R73	82	Outlet
	A77	1.33	72	69	Outlet	-	-
10 - Unit Simulated	A101	0.71	90	76	R101	24	R103
	A102	0.54	83	59	R103	38	R105
	A103	0.51	82	53	R102	14	R103
	A104	0.39	83	45	R103		
	A105	1.12	83	49	R104	39	R105
	A106	1.30	86	48	R106	51	R107
	A107	1.05	83	50	R107	57	Outlet
	A108	0.70	76	44	R105	41	R107
	A109	0.66	75	51	R107		
	A1010	0.67	71	47	Outlet	-	-
15 - Unit Simulated	A151	0.71	90	76	R151	24	R153
	A152	0.54	83	59	R153	38	R156
	A153	0.51	82	53	R152	14	R153
	A154	0.39	84	45	R153		
	A155	0.57	83	39	R154	26	R155
	A156	0.54	83	48	R155	39	R156
	A157	0.86	85	42	R157	20	R158
	A158	0.44	88	38	R158	24	R159
	A159	0.53	86	37	R159	36	R1511
	A1510	0.51	79	43	R1511	57	Outlet
	A1511	0.35	76	48	R156	40	R1511
	A1512	0.36	76	43	R156		
	A1513	0.26	74	45	R1510	27	R1511
	A1514	0.40	75	42	R1511		
	A1515	0.67	71	47	Outlet	-	-

Table B.4: Basin and routing parameters for Ash Creek, Part 2.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
30 - Unit Simulated	A301	0.42	91	52	R301	61	R302
	A302	0.29	90	56	R302	24	R305
	A303	0.30	84	40	R303	43	R305
	A304	0.24	82	47	R305	38	R3011
	A305	0.51	82	53	R304	14	R305
	A306	0.29	85	40	R304		
	A307	0.10	77	32	R305		
	A308	0.28	83	35	R307	11	R308
	A309	0.29	84	23	R308	26	R3010
	A3010	0.29	85	37	R309	27	R3010
	A3011	0.26	81	42	R3010	39	R3011
	A3012	0.40	85	35	R3012	18	R3013
	A3013	0.13	85	33	R3013	20	R3015
	A3014	0.33	84	36	R3013		
	A3015	0.21	93	25	R3014	7	R3015
	A3016	0.23	84	38	R3015	10	R3017
	A3017	0.21	87	30	R3016	8	R3017
	A3018	0.11	86	29	R3017	18	R3018
	A3019	0.21	84	26	R3018	19	R3019
	A3020	0.16	79	30	R3019	28	R3022
	A3021	0.24	81	36	R3019		
	A3022	0.12	76	27	R3022	57	Outlet
	A3023	0.36	76	43	R3011	40	R3022
	A3024	0.17	78	40	R306	19	R3011
	A3025	0.18	75	38	R3011		
	A3026	0.26	74	45	R3020	27	R3022
	A3027	0.21	79	37	R3021	21	R3022
	A3028	0.18	69	39	R3022		
	A3029	0.23	69	34	R3023	54	Outlet
	A3030	0.44	71	43	Outlet	-	-

Table B.5: Basin and routing parameters for South Mesquite Creek, Part 1.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
Lumped	A11	23.33	86	223	Outlet	-	-
3 - Unit Simulated	A31	6.59	88	115	R31	65	R32
	A32	6.89	87	93	R32	252	Outlet
	A33	9.84	84	132	Outlet	-	-
5 - Unit Simulated	A51	2.17	86	57	R51	146	R52
	A52	4.42	90	94	R52	96	R53
	A53	4.01	88	87	R52		
	A54	4.41	87	53	R53	231	Outlet
	A55	8.32	83	98	Outlet	-	-
7 - Unit Simulated	A71	2.17	86	57	R71	146	R73
	A72	4.42	90	94	R73	96	R74
	A73	1.13	87	66	R72	66	R73
	A74	2.89	88	87	R73		
	A75	4.41	87	53	R74	175	R75
	A76	5.48	84	75	R75	92	Outlet
	A77	2.83	82	56	Outlet	-	-
10 - Unit Simulated	A101	2.17	86	57	R101	146	R104
	A102	3.15	91	78	R104	96	R106
	A103	1.28	87	60	R102	105	R104
	A104	1.13	87	66	R103	66	R104
	A105	2.89	88	87	R104		
	A106	2.66	87	67	R106	175	R108
	A107	1.74	87	41	R105	48	R106
	A108	4.66	84	75	R108	92	Outlet
	A109	0.83	85	24	R107	106	R108
	A1010	2.83	82	56	Outlet	-	-
15 - Unit Simulated	A151	2.17	86	57	R151	71	R152
	A152	1.48	92	49	R152	105	R155
	A153	1.67	90	53	R155	96	R157
	A154	1.28	87	60	R152		
	A155	1.13	87	66	R153	66	R155
	A156	1.28	90	45	R154	91	R155
	A157	1.61	87	53	R155		
	A158	1.74	87	41	R156	48	R157
	A159	0.77	89	49	R157	101	R158
	A1510	1.90	86	67	R157		
	A1511	1.62	86	56	R158	106	R1510
	A1512	0.83	85	24	R158		
	A1513	0.66	82	47	R159	52	R1510
	A1514	2.37	84	76	R1510	92	Outlet
	A1515	2.83	82	56	Outlet	-	-

Table B.6: Basin and routing parameters for South Mesquite Creek, Part 2.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
30 - Unit Simulated	A301	1.74	86	56	R301	4	R302
	A302	0.43	86	34	R302	71	R305
	A303	0.60	90	31	R304	69	R305
	A304	0.88	83	43	R305	105	R3011
	A305	0.53	86	42	R303	41	R305
	A306	0.74	88	30	R305		
	A307	0.54	89	45	R3010	29	R3011
	A308	1.12	90	53	R3011	64	R3013
	A309	0.77	89	45	R308	35	R309
	A3010	0.51	90	34	R308		
	A3011	0.64	87	49	R306	42	R307
	A3012	0.49	88	32	R307	66	R3011
	A3013	0.71	88	23	R309	70	R3011
	A3014	0.90	87	40	R3011		
	A3015	0.95	88	32	R3012	24	R3013
	A3016	0.79	87	43	R3013	48	R3014
	A3017	1.14	86	54	R3013		
	A3018	0.76	87	50	R3014	102	R3017
	A3019	0.77	89	49	R3014		
	A3020	0.32	84	38	R3015	94	R3017
	A3021	0.36	87	47	R3016	58	R3017
	A3022	0.94	85	44	R3017	106	R3021
	A3023	0.83	85	24	R3017		
	A3024	0.65	86	56	R3019	86	R3021
	A3025	0.69	84	53	R3020	24	R3021
	A3026	1.02	82	40	R3021	92	Outlet
	A3027	0.66	82	47	R3018	52	R3021
	A3028	0.59	83	34	R3021		
	A3029	0.61	80	45	R3022	10	Outlet
	A3030	1.64	82	56	Outlet	-	-

Table B.7: Basin and routing parameters for Calaveras Creek, Part 1.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
Lumped	A11	7.11	77	95	Outlet	-	-
3 - Unit Simulated	A31	1.69	77	66	R31	83	Outlet
	A32	1.53	77	58	R31		
	A33	3.88	77	76	Outlet	-	-
5 - Unit Simulated	A51	1.69	77	66	R51	45	R52
	A52	1.53	77	58	R51		
	A53	1.90	77	64	R52	52	Outlet
	A54	0.77	78	80	R53	44	Outlet
	A55	1.21	77	70	Outlet	-	-
7 - Unit Simulated	A71	1.69	77	66	R72	45	R74
	A72	0.83	78	58	R72		
	A73	0.69	76	63	R71	10	R72
	A74	1.42	77	59	R74	52	Outlet
	A75	0.48	76	62	R73	32	R74
	A76	0.77	78	80	R75	44	Outlet
	A77	1.21	77	70	Outlet	-	-
10 - Unit Simulated	A101	0.83	77	45	R101	55	R103
	A102	0.87	76	46	R103	45	R105
	A103	0.83	78	58	R103		
	A104	0.69	76	63	R102	10	R103
	A105	0.48	76	62	R104	32	R105
	A106	0.70	77	59	R105	52	Outlet
	A107	0.72	78	56	R105		
	A108	0.77	78	80	R106	44	R105
	A109	0.77	76	72	R107	10	Outlet
	A1010	0.44	78	43	Outlet	-	-
15 - Unit Simulated	A151	0.24	82	41	R151	18	R152
	A152	0.33	75	44	R152	55	R155
	A153	0.26	75	28	R152		
	A154	0.87	76	46	R155	45	R158
	A155	0.44	77	46	R153	24	R155
	A156	0.39	78	40	R155		
	A157	0.69	76	63	R154	10	R155
	A158	0.48	76	62	R156	32	R158
	A159	0.70	77	59	R158	52	Outlet
	A1510	0.38	79	45	R157	24	R158
	A1511	0.35	76	45	R158		
	A1512	0.65	78	80	R1510	44	Outlet
	A1513	0.12	78	35	R159	22	R1510
	A1514	0.77	76	72	R1511	10	Outlet
	A1515	0.44	78	43	Outlet	-	-

Table B.8: Basin and routing parameters for Calaveras Creek, Part 2.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
30 - Unit Simulated	A301	0.24	82	41	R301	18	R302
	A302	0.33	75	44	R302	35	R304
	A303	0.26	75	28	R302		
	A304	0.15	80	26	R303	30	R304
	A305	0.47	76	41	R304	32	R3010
	A306	0.25	74	42	R3010	15	R3011
	A307	0.29	78	45	R305	24	R3010
	A308	0.15	77	42	R305		
	A309	0.10	82	25	R306	23	R3010
	A3010	0.29	77	46	R3010		
	A3011	0.20	75	43	R307	16	R308
	A3012	0.20	77	36	R308	34	R309
	A3013	0.29	76	44	R309	10	R3010
	A3014	0.44	76	49	R3011	32	R3016
	A3015	0.20	75	48	R3012	31	R3013
	A3016	0.29	77	45	R3013	32	R3016
	A3017	0.25	78	32	R3016	61	R3021
	A3018	0.18	76	45	R3014	22	R3015
	A3019	0.20	72	29	R3014		
	A3020	0.18	76	42	R3015	9	R3016
	A3021	0.17	76	33	R3016		
	A3022	0.15	78	54	R3017	23	R3018
	A3023	0.23	76	35	R3018	40	R3020
	A3024	0.27	79	47	R3020	40	R3021
	A3025	0.12	78	35	R3019	22	R3020
	A3026	0.21	78	37	R3021	17	Outlet
	A3027	0.22	77	54	R3022	23	R3023
	A3028	0.25	76	41	R3023	22	R3024
	A3029	0.31	75	41	R3024	10	Outlet
	A3030	0.23	78	38	Outlet	-	-

Table B.9: Basin and routing parameters for Pond-Elm Creek, Part 1.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
Lumped	A11	46.07	86	373	Outlet	-	-
3 - Unit Simulated	A31	19.20	86	288	R31	248	Outlet
	A32	11.88	86	151	R32	74	Outlet
	A33	15.00	86	224	Outlet	-	-
5 - Unit Simulated	A51	8.68	86	115	R51	399	R52
	A52	10.51	86	200	R52	248	Outlet
	A53	5.42	87	131	R52		
	A54	11.88	86	151	R53	74	Outlet
	A55	9.58	86	182	Outlet	-	-
7 - Unit Simulated	A71	8.68	86	115	R71	399	R72
	A72	10.51	86	200	R72	169	R73
	A73	5.42	87	131	R72		
	A74	6.51	86	147	R73	121	Outlet
	A75	4.95	87	104	R74	131	Outlet
	A76	6.92	85	130	R75	74	Outlet
	A77	3.07	85	118	Outlet	-	-
10 - Unit Simulated	A101	3.29	86	60	R101	157	R102
	A102	5.39	86	90	R102	186	R103
	A103	5.00	87	96	R103	283	R104
	A104	5.52	86	147	R104	169	R106
	A105	5.42	87	131	R104		
	A106	2.70	88	108	R105	152	Outlet
	A107	3.82	85	89	R106	121	Outlet
	A108	4.95	87	104	R107	131	R108
	A109	6.92	84	130	R108	74	Outlet
	A1010	3.07	85	118	Outlet	-	-
15 - Unit Simulated	A151	3.29	86	60	R151	157	R152
	A152	5.39	86	90	R152	186	R153
	A153	5.00	87	96	R153	283	R155
	A154	5.52	86	147	R155	169	R157
	A155	3.01	88	101	R154	81	R155
	A156	2.41	87	100	R155		
	A157	2.70	88	108	R156	152	R157
	A158	3.82	85	89	R157	121	Outlet
	A159	2.30	88	72	R158	80	R159
	A1510	2.66	85	77	R159	131	R1511
	A1511	1.32	86	83	R157		
	A1512	2.71	83	83	R159		
	A1513	1.17	87	65	R1510	17	R1511
	A1514	3.05	85	93	R1511	74	Outlet
	A1515	1.75	84	61	Outlet	-	-

Table B.10: Basin and routing parameters for Pond-Elm Creek, Part 2.

Model Config.	SubBasin ID	Area (mi^2)	CN	t_{lag} (min)	Subbasin DownStream Routing Connection	Routing lag time (min)	Routing Downstream Connection
30 - Unit Simulated	A301	1.01	86	43	R301	33	R302
	A302	0.66	85	53	R302	199	R303
	A303	1.62	87	60	R302		
	A304	1.94	87	70	R303	58	R304
	A305	0.87	86	43	R303		
	A306	0.96	83	45	R304	99	R305
	A307	1.61	86	50	R304		
	A308	1.72	86	49	R305	125	R306
	A309	2.34	87	69	R306	83	R307
	A3010	0.93	87	74	R306		
	A3011	1.77	87	63	R307	167	R308
	A3012	2.40	87	86	R308	114	R3011
	A3013	1.35	85	55	R3011	93	R3013
	A3014	1.57	88	65	R309	79	R3010
	A3015	1.44	88	79	R3010	81	R3011
	A3016	1.02	87	68	R3010		
	A3017	1.39	86	77	R3011		
	A3018	2.70	88	108	R3012	74	R3013
	A3019	2.04	85	59	R3013	104	R3014
	A3020	1.77	84	60	R3014	121	Outlet
	A3021	1.32	86	83	R3014		
	A3022	2.30	88	72	R3015	80	R3018
	A3023	1.57	84	70	R3018	61	R3019
	A3024	1.09	86	63	R3016	41	R3018
	A3025	1.64	85	45	R3017	96	R3018
	A3026	1.07	81	64	R3018		
	A3027	1.85	85	63	R3019	92	R3020
	A3028	1.20	86	51	R3021	74	Outlet
	A3029	1.17	87	65	R3020	17	R3021
	A3030	1.75	84	61	Outlet	-	-

Table B.11: Summary of runoff volume analysis.

Watershed	Runoff Volume	Number of Subdivisions							Best Performing Subdivision Scheme
		1	3	5	7	10	15	30	
Walnut	AM (%)	168%	165%	166%	167%	166%	163%	166%	15
	RRMSE (%)	204%	201%	202%	203%	202%	199%	202%	15
	MIN_COUNT	0	1	0	0	0	5	0	15
Ash	AM (%)	29%	29%	29%	29%	28%	28%	29%	10
	RRMSE (%)	35%	36%	35%	35%	34%	34%	35%	10
	MIN_COUNT	1	2	0	0	2	0	0	3, 10
South Mesquite	AM (%)	32%	32%	31%	31%	31%	31%	32%	15
	RRMSE (%)	39%	38%	38%	38%	38%	38%	38%	15
	MIN_COUNT	2	0	0	0	0	6	1	15
Calaveras	AM (%)	93%	93%	93%	92%	93%	93%	93%	7
	RRMSE (%)	136%	136%	137%	136%	137%	136%	135%	30
	MIN_COUNT	2	0	1	0	2	0	1	1, 10
Pond-Elm	AM (%)	49%	49%	49%	49%	49%	49%	49%	5
	RRMSE (%)	77%	77%	77%	77%	77%	77%	77%	7
	MIN_COUNT	2	0	4	0	0	0	0	5

Table B.12: Summary of peak discharge analysis.

Watershed	Peak Flow	Number of Subdivisions							Best Performing Subdivision Scheme
		1	3	5	7	10	15	30	
Walnut	AM (%)	138%	122%	115%	111%	106%	100%	113%	15
	RRMSE (%)	173%	164%	154%	150%	146%	141%	150%	15
	MIN_COUNT	0	0	0	0	0	6	0	15
Ash	AM (%)	66%	60%	58%	58%	60%	58%	55%	30
	RRMSE (%)	67%	62%	60%	60%	62%	60%	58%	30
	MIN_COUNT	0	1	0	0	0	0	4	30
South Mesquite	AM (%)	33%	23%	21%	20%	20%	21%	23%	10
	RRMSE (%)	51%	38%	33%	31%	30%	29%	31%	15
	MIN_COUNT	2	2	1	1	0	0	3	30
Calaveras	AM (%)	43%	45%	44%	44%	44%	43%	48%	1
	RRMSE (%)	49%	50%	49%	49%	50%	50%	53%	5
	MIN_COUNT	1	0	4	0	0	0	1	5
Pond-Elm	AM (%)	33%	34%	30%	28%	27%	26%	27%	15
	RRMSE (%)	50%	49%	48%	46%	40%	42%	38%	30
	MIN_COUNT	1	0	1	1	0	1	2	30

Table B.13: Summary of time to peak analysis.

Watershed	Time to Peak	Number of Subdivisions							Best Performing Subdivision Scheme
		1	3	5	7	10	15	30	
Walnut	AM (%)	63%	67%	143%	147%	154%	157%	150%	1
	RRMSE (%)	76%	81%	182%	189%	197%	201%	191%	1
	MIN_COUNT	4	0	0	1	1	0	0	1
Ash	AM (%)	31%	28%	39%	44%	52%	56%	58%	3
	RRMSE (%)	40%	37%	51%	56%	66%	71%	73%	3
	MIN_COUNT	1	4	0	0	0	0	0	3
South Mesquite	AM (%)	18%	19%	20%	25%	25%	39%	40%	1
	RRMSE (%)	24%	30%	32%	40%	39%	55%	58%	1
	MIN_COUNT	4	1	3	0	1	0	0	1
Calaveras	AM (%)	10%	11%	12%	13%	12%	12%	25%	1
	RRMSE (%)	14%	12%	15%	16%	16%	15%	32%	3
	MIN_COUNT	4	0	1	1	0	0	0	1
Pond-Elm	AM (%)	12%	22%	17%	12%	12%	10%	10%	15
	RRMSE (%)	15%	25%	21%	14%	15%	11%	11%	15
	MIN_COUNT	2	0	1	1	2	0	0	1, 10

C. Related Documents

Related Documents

The following are abstracts of papers and posters presented at the 2006 Fall American Geophysical Union Meeting. None of the posters were directly on the topic of "watershed subdivision," but the posters listed had some aspect that the researcher thought had merit in the context of the subdivision problem. The posters have additional value in presenting a "current-events" snapshot of the broader research questions being addressed by the geosciences community.

For citing these posters the AGU recomends the following citation structure: *Author(s) 2006. "Title." Eos Transactions of American Geophysics Union, Vol. 87, No. 52, Abstract XXXX-XXXX.*

H11A-1229

"Understanding Surface water – Ground water Interactions in Arkansas-Red River Basin using Coupled Modeling"

Joshi, C (cjoshi@tamu.edu), Texas A&M University, BAEN, Scoates Hall, TAMU-2117, College Station, Tx 77843, United States

Mohanty, B P (bmohanty@tamu.edu), Texas A&M University, BAEN, Scoates Hall, TAMU-2117, College Station, Tx 77843, United States

Subsurface water exists primarily as groundwater and also in small quantity as soil water in the unsaturated zone. This soil water plays a vital role in the hydrologic cycle by supporting plant growth, regulating the amount of water lost to evapo-transpiration and affecting the surface water – groundwater interaction to a certain extent. As such, the interaction between surface water and groundwater is complex and little understood. This study aims at investigating the surface water–groundwater interaction in the Arkansas-Red river basin, using a coupled modeling platform. For this purpose, an ecohydrological model (SWAP) has been coupled with the groundwater model (MODFLOW). Inputs to this coupled model are collected from NEXRAD precipitation data at a resolution of 4 km, meteorological forcings from Oklahoma mesonet and NCDC sites, STATSGO soil property data, LAI (Leaf Area Index) data from MODIS at a resolution of 1 km, and DEM (Digital Elevation Model). For numerical modeling, a spatial resolution of 1 km and a temporal resolution of one day is used. The modeled base flow and total groundwater storage change would be tested using ground water table observation data. The modeled ground water storage is further

improved using GRACE (Gravity Recovery and Climate Experiment) satellite data at a resolution of 400 km, with the help of appropriate data assimilation technique.

TxDOT Researcher's Comments: Used GIS to parameterize two models. Limited presentation on parameter uncertainty, not sure how applicable to smaller scale models approach has. Appears that ET and infiltration are used to adjust match to groundwater storage.

H11A-1230

"Solute Response To Arid-Climate Managed-River Flow During Storm Events"

McLean, B (bjmclean@asu.edu), Arizona State University, School of Earth and Space Exploration, POB 871404, Tempe, AZ 85287, United States

Shock, E (eshock@asu.edu), Arizona State University, School of Earth and Space Exploration, POB 871404, Tempe, AZ 85287, United States

Storm pulses are widely used in unmanaged, temperate and subtropical river systems to resolve in-stream surface and subsurface flow components. Resulting catchment-scale hydrochemical mixing models yield insight into mechanisms of solute transport. Managed systems are far more complicated due to the human need for high quality water resources, which drives processes that are superimposed on most, if not all, of the unmanaged components. As an example, an increasingly large portion of the water supply for the Phoenix metropolitan area is derived from multiple surface water sources that are impounded, diverted and otherwise managed upstream from the urban core that consumes the water and produces anthropogenic impacts. During large storm events this managed system is perturbed towards natural behavior as it receives inputs from natural hydrologic pathways in addition to impervious surfaces and storm water drainage channels. Our goals in studying managed river systems during this critical transition state are to determine how the well-characterized behavior of natural systems break down as the system responds then returns to its managed state. Using storm events as perturbations we can contrast an arid managed system with the unmanaged system it approaches during the storm event. In the process, we can extract geochemical consequences specifically related to unknown urban components in the form of chemical fingerprints. The effects of river management on solute behavior were assessed by taking advantage of several anomalously heavy winter storm events in late 2004 and early 2005 using a rigorous sampling routine. Several hundred samples collected between January and October 2005 were analyzed for major ion, isotopic, and trace metal concentrations with 78 individual measurements for each sample. The data are used to resolve managed watershed processes, mechanisms of solute transport and river mixing from anthropogenic inputs. Our results show that concentrations of major solutes change slowly and are independent of discharge downstream from the dams on two major tributaries. This is indicative of reservoir release water. In addition, a third input is derived from the Colorado River via the Central Arizona Project canal system. Cross plots including concentrations of solutes such as nitrate and sulfate from downstream of the confluence indicate at least three end-member sources, as do Piper diagrams using major anion and cation data. Dynamic contributions from natural event water and urban inputs can be resolved from the slowly changing release water, and may dictate the short-term transport of pollutants during the storm-induced transition state.

TxDOT Researcher's Comments: Used regulatory structures to introduce tracers. Transit times not clear in actual presentation. Clever use of tracers and controlled water releases.

H11A-1231

"The role of hillslopes in stream flow response: connectivity, flow path, and transit time"

McGuire, K J (kmcguire1@plymouth.edu), Plymouth State University & USDA Forest Service, Center for the Environment 17 High Street MSC 63, Plymouth, NH 03264, United States

McDonnell, J J (jeff.mcdonnell@oregonstate.edu), Oregon State University, Department of Forest Engineering, Corvalls, OR 97331, United States

Subsurface flow from hillslopes is widely recognized as an important contributor to stream flow generation; however, processes that control how and when hillslopes connect to streams remain unclear. Much of the difficulty in deciphering hillslope response in the stream is due to riparian zone modulation of these inputs. We investigated stream and hillslope runoff dynamics in a 10 ha catchment in the western Cascades of Oregon where the riparian zone has been removed by debris flows, providing an unambiguous hillslope hydrologic signal to the stream channel. Water transit time was used as a framework to develop a conceptual stream flow generation model for the small basin. We based our conceptualization on observations of hydrometric, stable isotope, and applied tracer responses and computed transit times for multiple runoff components using a simple linear systems model. Event water mean transit times (8 to 34 h) and rapid breakthrough from applied hillslope tracer additions, demonstrated that contributing areas extend far upslope during events. Despite rapid hillslope transport processes during events, vadose zone water and runoff mean transit times during non-storm conditions were greater than the timescale of storm events. Vadose zone water mean transit times ranged between 10 and 25 days. Hillslope seepage and catchment baseflow mean transit times were between 1 and 2 years. We describe a conceptual model that captures variable physical flow pathways and transit times through changing antecedent wetness conditions that illustrate the different stages of hillslope and stream connectivity.

TxDOT Researcher's Comments: Used GIS and slopes, soil types, and other characteristics. Grouped characteristics by location to identify subwatersheds. Goal was not same as our research but the use of hydrologic response units that are physically connected was clever. Tracer tests are used to test research hypotheses.

H11A-1232

"Linking Rainfall, Soil Water Movement, and Groundwater Dynamics to Runoff in a Steep Hillslope: A Topdown Approach"

McDonnell, J J (Jeffrey.McDonnell@oregonstate.edu), Oregon State University, 204 Peavy Hall, Department of Forest Engineering, Corvallis, OR 97331, United States

van Verseveld, W J (Willem.VanVerseveld@oregonstate.edu), Oregon State University, 204 Peavy Hall, Department of Forest Engineering, Corvallis, OR 97331, United States

The causal linkages between rainfall patterns, soil water response, development of transient ground-

water and resulting subsurface stormflow on steep hillslopes remains poorly understood. Most studies to date have relied on short term (hours to days) datasets to characterize the runoff generation process of hillslopes or focused on one part of the system. We link rainfall, soil water movement, and groundwater dynamics for a highly instrumented hillslope at Watershed 10 at the H.J. Andrews Experimental Forest in Oregon, USA. Our hydrometric data from groundwater wells, tensiometers, soil moisture probes and hillslope runoff from a 10 meter wide trench were collected for a period of one year beginning in Fall 2004. This dataset enabled us to isolate and identify through data mining techniques how rainfall patterns control soil water movement, groundwater dynamics and subsurface stormflow under different antecedent wetness conditions. (Un)saturated fluxes, both vertical and lateral at 30 and 70 cm, calculated from the tensiometers, increased exponentially with a linear increase in mean or maximum intensity. The timelag between rainfall intensity and soil water flux, based on linear regression analysis, decreased with wetter conditions. Transient saturation at subtle changes in hydraulic conductivity within the soil profile occurred during the storm peaks. Groundwater development was very patchy, with maximum heights of about 20 cm above the bedrock layer. The relationship between groundwater height and hillslope discharge was non-linear. Tree regression analysis of hillslope discharge showed that during high flow conditions, antecedent wetness and mean and maximum intensity dominated system behavior. At low flow conditions, antecedent wetness alone appeared to predict hillslope discharge. Applying these data mining techniques improved our understanding of the hierarchy of process controls on hillslope runoff and uncovered new predictive rules for subsurface flow generation.

TxDOT Researcher's Comments: Companion to McGuire paper. Focused on the infiltration (loss model) signal. Also explicit mention of lag time as a hydrologic variable of interest.

H11A-1234

"The Integrated Landscape Hydrology Model (ILHM), a Fully-Distributed Approach to Simulate Regional Watershed Hydrologic Processes"

Hyndman, D W (hyndman@msu.edu), Michigan State University, Department of Geological Sciences 206 Natural Science Building, East Lansing, MI 48824, United States

Kendall, A D (kendal30@yahoo.com), Michigan State University, Department of Geological Sciences 206 Natural Science Building, East Lansing, MI 48824, United States

Modeling fine-scale regional landscape and subsurface hydrology with fully-distributed process models requires data and computational resources that have only recently become available. For this reason most hydrologic models either do not represent crucial hydrologic processes or are not practical for regional-scale simulations. To overcome these limitations we linked a set of existing codes with novel approaches in the new Integrated Landscape Hydrology Model (ILHM), designed to integrate widely-available GIS and remotely-sensed data using a simple parameterization The ILHM is a loosely-coupled suite of codes that allows fine-scale numerical modeling for some processes while integrating simpler water-balance models at disparate temporal and spatial scales. This approach enables individual process models to be swapped with different modules or with measured data. Currently, the ILHM includes codes that simulate canopy and soil processes, snowpack accumulation and melt, surface ponding and runoff, shallow sub-surface flow, and both unsaturated and

saturated groundwater flow. The ILHM also has potential as a tool to simulate fluxes through large ungaged basins and evaluate historical and future hydrologic scenarios. We present an application of the ILHM to a 137 square kilometer catchment within the larger Muskegon River Watershed in northern-lower Michigan. A comparison of model outputs to measured and gaged stream discharges demonstrates that the ILHM is capable of predicting hydrologic fluxes with reasonable accuracy without significant parameter calibration. In addition, the model results suggest interesting and important linkages between land use and groundwater recharge.

TxDOT Researcher's Comments: Used GIS and existing computer codes to develop continuous simulation responses. Performance seems about same as lumped parameter (researcher opinion). Vague presentation on how results were interpreted.

H11A-1242

"Coupling of Hydrological Models to Assess the Impacts of Changes in Surface and Subsurface Water Extraction on Stream Flows"

guzha, a C (acguzha@cc.usu.edu), Utah State University, College of Engineering, Logan, UT 84321, United States

Bulatewicz, T (tombz@ksu.edu), Kansas State University, Computing and Information Science, Manhattan, KS 66506, United States

Hardy, T (hardy@cc.usu.edu), Utah State University, College of Engineering, Logan, UT 84321, United States

Although it is commonly understood that the extraction of groundwater from the natural environment can have a significant affect on the hydrological processes throughout a watershed, the precise affect on different processes is not well understood. Existing models are able to accurately simulate the effect of extraction on individual systems, but holistic models are needed to study the effect across different systems. The primary objective of this study is the development, application and investigation of a coupled modeling approach, combining two well- known models, the United States Geological Survey's Modular Finite-Difference Groundwater Flow Model (MODFLOW) and the topography based TopModel, in order to simulate complex hydrological processes in a mesoscale watershed. The models have been coupled through the use of the InCouple model coupling framework. Through the use of lightweight model interfaces, prototype couplings between the models were quickly created with minimal changes to the model source codes. These couplings, though, were largely simplified (not spatially distributed, one-way interaction only, and used preliminary data from the Tenmile watershed in Washington State, USA). The water table elevations simulated by MODFLOW were used by TopModel in its simulation of runoff. In our current work, we extend this simple coupling such that the spatial distribution of the groundwater is represented in MODFLOW, and the interaction between the models is bidirectional such that TopModel uses the water table elevations simulated by MODFLOW, and the recharge calculated by TopModel affects the water table elevation simulation in MODFLOW. We present the results of this bidirectional interaction between the models as applied to our study site. Our long term goal is to use the rapid prototyping capability of the InCouple framework to couple other models to MODFLOW

to develop holistic models that can be used to study the effects of groundwater extraction at the mesoscale watershed level.

TxDOT Researcher's Comments: Integrated MODFLOW and TOPMODEL for large-scale watershed simulations. Appears to be continuous simulation. Limited performance results (none) were presented in the poster. No attempt to lump – all watersheds are discritized to the DEM resolution.

H13A-1349

"Linking the topography signature of LIDAR-derived vegetation types and geomorphic processes as preliminary steps in integrating landscape evolution with vegetation dynamics"

Tarolli, P (paolo.tarolli@unipd.it), Department of Land and Agroforest Environments, University of Padova, viale dell Universitiy – 16, Legnaro, PD 35020 Italy

Istanbulluoglu, E (erkan2@unl.edu), Departments of Geosciences and Biological Systems Engineering, University of Nebraska-Lincoln, 200 Bessey Hall, Lincoln, NE 68588, United States

Dalla Fontana, G (giancarlo.dallafontana@unipd.it), Department of Land and Agroforest Environments, University of Padova, viale dell'Universit? 16, Legnaro, PD 35020 Italy

In the Italian Alps, dominated by a high altitude climate and characterized by extreme slope movement processes, topography plays a key role in the redistribution of vegetation over the landscape. There is significant evidence that vegetation distribution on the Alpine basins influences the frequency and magnitude of sediment yields. In this study we investigate the links between topography and vegetation species in a small Alpine catchment with an elevation range of 1500 to 2000 m a.s.l., with cold snowy winters, and wet summers, in order to decipher the influence of biota on geomorphic processes in atypical high-latitude Alpine headwater setting. In the study area vegetation is mostly represented by grass species (high altitude grassland), but also shrubs (Alnus viridis), and high tree forest (Picea abies) are common. We evaluate the distribution of vegetation canopies using LIDAR- derived vegetation data. We analyzed the vertical elevation of different vegetation canopy surface layers, and we derived the spatial variation of vegetation species following their heights as surveyed in the field. Then we use a high resolution DTM (Digital Terrain Model), evaluated from filtered bare ground LIDAR points, to derive some mathematical attributes of landscape morphology including slope gradient, drainage area, aspect, convergence and topographic wetness index, slope – area diagrams and power-law distribution of areas. We discussed the relationships between vegetation species distribution and landform properties.

TxDOT Researcher's Comments: Note the emphasis on morphology at end of abstract. These researchers are attempting to address very similar issue, but focus in on solids (sediment) production. Concepts of slope, area, and slope-area may have value in subdivision research.

H13A-1352

"Upscaling biological quantities in a watershed: combining local predictors with hydro- geomorphological scaling laws"

Barnes, E A (barn0333@umn.edu), National Center for Earth-surface Dynamics, St. Anthony Falls

Lab, University of Minnesota, 2 Third Avenue SE, Minneapolis, MN 55414, United States

Foufoula-Georgiou, E (efi@umn.edu), National Center for Earth-surface Dynamics, St. Anthony Falls Lab, University of Minnesota, 2 Third Avenue SE, Minneapolis, MN 55414, United States

Hondzo, M (mhondzo@umn.edu), National Center for Earth-surface Dynamics, St. Anthony Falls Lab, University of Minnesota, 2 Third Avenue SE, Minneapolis, MN 55414, United States

Power, M E (mepower@berkeley.edu), Department of Integrative Biology, 4184 Valley Life Sciences Building University of California, Berkeley, Berkeley, CA 94720-3140, United States

Recent efforts have demonstrated that local periphyton biomass can be predicted to satisfactory accuracy by local physiographic and geomorphic properties in a steep upland stream. For example, periphyton biomass at a point along a river can be predicted by a nonlinear relationship that involves average cross-sectional depth, maximum width, average velocity, exposure to light and nitrate concentration. In this paper, we demonstrate how such local relationships between biotic and abiotic variables can be upscaled to a river reach by using known scaling laws between discharge and channel properties, known as hydraulic geometry. Using high resolution topography to resolve the spatial variability of channel quantities, we show that average reach periphyton biomass can be estimated to greater accuracy using upscaling of local geomorphic predictors rather than traditional averaging of discrete samples. The implications of this work for sampling design and for interpreting sparse local observations in the context of reach average quantities are also discussed.

TxDOT Researcher's Comments: Not directly related. Scaling laws to locate where to make measurements and to convert averaged and point measurements is worth future study.

H13A-1365

"On the topographic imprint of vegetation: Results from field observations and DEM analysis of small semiarid basins"

Istanbulluoglu, E (erkan2@unl.edu), University of Nebraska, Department of Geosciences Department of Biol. Sys. Eng., Lincoln, NE 68588, United States

Vivoni, E R (vivoni@nmt.edu), New Mexico Institute of Mining and Technology, Department of Earth and Environmental Science, Socorro, NM 87801, United States

Gutierrez-Jurado, H A (hugo@nmt.edu), New Mexico Institute of Mining and Technology, Department of Earth and Environmental Science, Socorro, NM 87801, United States

Bras, R R (rlbras@mit.edu), Massachusetts Institute of Technology, Civil and Environmental Engineering, Cambridge, MA 02139, United States

Terrestrial landforms result from the complex interactions between biotic and abiotic earth surface processes forced by climate and tectonics. Understanding the coupled evolution of the physical landscape system with its biology is a fundamental problem in hydrological sciences. One efficient way to study this coupling is to quantify the differences in vegetation patterns on neighboring hillslopes that are within the same climate, geology and catchment area. Vegetation patterns in

the southwestern US are typically organized with respect to the topographic texture with repeated bands consisting of more mesic plant species in the wetter north-facing slopes, and communities dominated by xeric species on the drier south-facing slopes, especially where climate promotes ecosystem coexistence. There is evidence that over the long-term such differences in plant species lead to differential soil and landform development on hillslopes with opposing aspects. In this study we report preliminary results on the mathematical properties of landscape morphology of various hillslope aspects in several small-scale (¡10km2) semiarid catchments near Socorro New Mexico based on field measurements of hillslope profiles and digital elevation model analysis. In the basins studied, the north-facing hillslopes are composed of oneseed juniper (Juniperus monosperma) and several grass species, have convex hilltops and planar slopes atypical of diffusive landforms. The south-facing slopes are primarily creosote bush (Larrea tridentata), and visually more dissected and concave than the north facing slopes, displaying geomorphic signatures of fluvial erosion. Along the head slopes, often an active ecotone serves as a boundary between the ecosystems. Our results suggest that even subtle differences in the vegetation type under essentially the same climate and geologic controls leave detectable signatures on the mathematical properties of landscape organization and morphology.

TxDOT Researcher's Comments: More GIS and DEM work – related to biology and solids production. Paper notes that orientation matters (North slopes are different than South slopes) in the context of vegetation type and consequently erosion patterns. Limited practical use for subdivision project, but again an area worthy of future consideration.

H13A-1372

"Exploring possible tight inter-connections between climate, soil, topography through constraining by empirical measure of annual water balance"

Li, H (hli23@uiuc.edu), University of Illinois at Urbana-Champaign, 2521 Hydrosystems Lab, Department of Civil and Environmental Engineering, 250 N. Matthews Avenue, Urbana, IL 61801, United States

Sivapalan, M (sivapala@uiuc.edu), University of Illinois at Urbana-Champaign, 220 Davenport Hall, 607 S. Matthews Avenue, Urbana, IL 61801, United States

Horton overland flow, Dunne overland flow and subsurface flow are the three dominant mechanisms contributing to runoff generation. The Dunne diagram (Dunne, 1978) qualitatively interprets that the occurrence and dominance of different mechanisms are significantly affected by climatic conditions, soil characteristics and topography. In this work, the climate, soil and topographic controls on annual water balance are examined. A simple distributed hydrologic model has been built for this purpose, which is comprehensive enough to simulate the effects of different combinations of climate, soil and topography, and generate a diversity of runoff generation mechanisms. A small set of dimensionless similarity variables, which are physically meaningful, have been shown to explain the competition between the wetting, drying, storage and drainage functions of the watershed that underlie this model predicted behavior. Each combination of these dimensionless numbers could be feasible in theory, but only some combinations actually occur in nature. By constraining the predictions of the model with the empirical Budyko curve, we narrow down to these feasible combinations.

At the very least the resulting quantitative climate, soil and topography interconnections could be potentially tested in the field, and if deemed reasonable, also used to constrain hydrological model predictions. The paper will present results from this thought experiment and the ramifications of the results for future field studies and hydrological modeling.

TxDOT Researcher's Comments: Significant work in our context. Researchers have examined loss models and highly distributed models, then by non-dimensionalizing have lumped results (unintentionally). Little immediate practical value, but suggests current research directions are meaningful.

H13B-1376

"Impacts of climate variability and change on flood frequency: a comparative study of catchments in Perth, Newcastle and Darwin, Australia"

Samuel, J (samuel@sese.uwa.edu.au), School of Environmental Engineering, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 Australia

Sivapalan, M (sivapala@uiuc.edu), Department of Geography University of Illinois at Urbana-Champaign, 220 Davenport Hall, MC-150, 607 S. Mathews Avenue, Urbana, IL 61801, United States

Struthers, I (struther@sese.uwa.edu.au), School of Environmental Engineering, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009 Australia

Traditional flood frequency analysis assumes stationarity, and thus cannot account for non-satationarity caused by long-term climate variability and change. In this study, we demonstrate that the probability distribution of annual maximum floods is functional upon multi-annual, multi-decadal trends and climate change in local climate. Three locations in Australia, namely Perth, Newcastle and Darwin are selected and compared to explore the impact of climate variability and change on flood frequency. Analysis is performed using a stochastic rainfall model coupled with a continuous rainfall-runoff model that captures the water balance variability at a multiplicity of time scales ranging from event to seasonal, inter-annual and inter-decadal time scales. Climate variability and change are incorporated using different parameterisations of the rainfall model, based upon analysis of observed rainfall data and selected climate scenarios. We present six climate scenarios linked between ENSO (El Nino Southern Oscillation) and IPO (Interdecadal Pacific Oscillation) in Newcastle, and six different climate scenarios for Perth and Darwin that are related to ENSO and an apparent shift in climate, identified by statistical analysis, occurring from 1970. The results show that La Nina (ENSO negative) years cause higher annual maximum floods compared to El Nino (ENSO positive) and ENSO neutral years during both IPO (+) and IPO(-) in Newcastle and pre- and post-1970 in Darwin and Perth. The impact of ENSO on annual maximum floods in Newcastle cacthment is enhanced when the IPO is negative. For Perth, the impact of ENSO weakens post-1970, while it strengthens in Darwin. This research shows that non-stationarity in climate associated with ENSO and long term climate shifts has a significant impact upon flood frequency in a variety of Australian climates.

TxDOT Researcher's Comments: Comparative study of two watersheds was of interest in this poster. Authors alluded to difficulty in finding otherwise similar watersheds to examine spatial *effect of climate on response. Such problem is related to subdivision issue.*

H13B-1377

"The Effects of Land use on Soil Properties and Runoff Response at the CATIE Farm, Turrialba, Costa Rica."

Toohey, R (ryantoohey@uidaho.edu), University of Idaho Environmental Science Program, Morrill Hall 216 P.O. Box 443006, Moscow, ID 83844-3006, United States

Toohey, R (ryantoohey@uidaho.edu), Centro Agronómico Tropical de Investigación y Enseñanza, Apartado Postal 7170 Sede Central, Turrialba, 7150 Costa Rica

Brooks, E S (broo2789@uidaho.edu), University of Idaho Department of Biological and Agricultural Engineering, P.O. Box 440904, Moscow, ID 83844-0904, United States

Jones, J (jjones@catie.ac.cr), Centro Agronómico Tropical de Investigación y Enseñanza, Apartado Postal 7170 Sede Central, Turrialba, 7150 Costa Rica

Boll, J (jboll@uidaho.edu), University of Idaho Department of Biological and Agricultural Engineering, P.O. Box 440904, Moscow, ID 83844-0904, United States

Runoff response in humid tropical areas often is assumed to occur due to infiltration excess. Rainfall intensities in these areas can be monstruous. However, at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) farm near Turrialba in Costa Rica, we have observed that volcanically derived soils have very high infiltration capacities, depending on the land use type, suggesting that saturation excess overland flow mechanism are important in explaining the runoff response. In this study we compared field-scale (1-6 ha) runoff response of four different types of prominent land use on the CATIE farm: forest, a coffee agroforestry system, sugar cane, and pasture. The research site is located at approximately 650 masl in deep soils on the tropical wet Caribbean slope of Costa Rica. Hydrograph analysis of observed runoff data suggest that the runoff mechanism in forest, coffee and sugar cane sites depends much more on the amount of soil storage (e.g. saturated-excess overland flow) than in the pasture site. The pasture site exhibits more of an infiltration-excess response. In this presentation we present differences in several soil properties that correlate with land use. We simulated measured runoff responses using the Soil Moisture Routing (SMR) model in this high rainfall, deep soil environment because of its ability to simulate saturation-excess overland flow and lateral flows.

TxDOT Researcher's Comments: A loss model study, sample sites were located ad-hoc. In our TxDOT work we have all used the infiltration-excess (Hortonian) approach as opposed to saturation-excess (Dunne) approach.

H13B-1385

"Evaluating the effect of land use land cover change in a rapidly urbanizing semi-arid watershed on estuarine freshwater inflows"

Sahoo, D (dsahoo@tamu.edu), Biological and Agricultural Engineering, 201, Scoates Hall, Texas A and M University, 2117 TAMU, College Station, TX 77843, United States

Smith, P (patti-smith@tamu.edu), Biological and Agricultural Engineering, 201, Scoates Hall, Texas A and M University, 2117 TAMU, College Station, TX 77843, United States

Popescu, S (s-popescu@tamu.edu), Spatial Sciences Laboratory, 1500 Research Parkway Suite B223, 2120 TAMU, College Station, TX 77843-2120, United States

Estuarine freshwater inflows along with their associated nutrient and metal delivery are influenced by the land use/land cover (LULC) and water management practices in the contributing watershed. This study evaluates the effect of rapid urbanization in the San Antonio River Watershed on the amount of freshwater inflow reaching the San Antonio-Guadalupe estuary on the Gulf Coast of Texas. Remotely sensed data from satellite imagery provided a source of reliable data for land use classification and land cover change analysis; while long time series of the geophysical signals of stream flow and precipitation provided the data needed to assess change in flow in the watershed. LULC was determined using LANDSAT (5 TM and 7 ETM) satellite images over 20 years (1985-2003). The LANDSAT images were classified using an ENVI. ISODATA classification scheme. Changes were quantified in terms of the urban expansion that had occurred in past 20 years using an urban index. Streamflow was analyzed using 20 years (1985-2004) of average daily discharge obtained from the USGS gauging station (08188500) closest to the headwaters of the estuary. Baseflow and storm flow were partitioned from total flow using a universally used baseflow separation technique. Precipitation data was obtained from an NCDC station in the watershed. Preliminary results indicate that the most significant change in land use over the 20 year period was an increase in the total amount of impervious area in the watershed. This increase in impervious area was accompanied by an increase in both total streamflow and in baseflow over the same period. The investigation did not show a significant change in total annual precipitation from 1990 to 2004. This suggests that the increase in streamflow was more influenced by LULC than climate change. One explanation for the increase in baseflow may be an increase in return flows resulting from an increase in the total number of wastewater treatment plants in the watershed.

TxDOT Researcher's Comments: Related to our unitgraph work, esp. the developed/undeveloped scoring approach. Limited value in watershed subdivision, but classification of watershed "types" implies subdivision in some sense.

H13B-1386

"Impacts of Land Cover Change on Natural Recharge Levels in the Semi-Arid Edwards Aquifer Region of Texas"

Smith, P K (phaan@tamu.edu), Texas A&M University, Department of Biological & Agricultural Engineering 2117 TAMU, College Station, TX 77843-3136, United States

Peschel, J M (peschel@tamu.edu), Texas A&M University, Zachry Department of Civil Engineering 3136 TAMU, College Station, TX 77843-3136, United States

Understanding historical land cover and land use, and other related changes within the hydrologic signals of a region is advantageous when modeling efforts are considered. However, incorporating

different types of land cover changes for hydrologic prediction is not a well-understood task. From a water resources planning and management perspective, this is of unique interest in semi-arid regions where water availability is often low and thus, water balance sensitivity may be high. The semi-arid Edwards Aquifer region of Texas has undergone measurable increases in both population and impervious surface area over the last twenty years, particularly in the greater metropolitan areas of San Antonio and Austin, the eighth and nineteenth largest cities in the United States, respectively. Consequently, it is expected that the hydrologic response of the Edwards Aquifer has also undergone changes. The Soil and Water Assessment Tool (SWAT) is a physically- based modeling tool for predicting the impacts of land management practices on water, sediment, and agricultural chemical yields. This work presents the results of an algorithm developed to utilize the SWAT model for estimating natural recharge levels in the semi-arid Edwards Aquifer region of Texas when land cover and land use, and other related system input changes are considered.

TxDOT Researcher's Comments: Used SWAT, poster implicitly subdivided by using different land use classifications. Responses are aggregated at watershed scale – effect of subdivision unable to be accessed.

H13I-05

"Modeled Response of the low Gradient Portions of the Fly and Strickland Rivers to Post- Glacial Sea-Level Rise"

Lauer, J W (lauerj@seattleu.edu), Seattle University, Department of Civil & Environmental Engineering Seattle University, Seattle, WA 98122-1090, United States

Parker, G (parkerg@uiuc.edu), University of Illinois, Department of Civil Engineering and Department of Geology 2527c Hydrosystems Lab, MC-250 205 N Matthews Avenue, Urbana, IL 61801, United States

Dietrich, W E (bill@geomorph.berkeley.edu), Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767

River valleys evolve in response to upstream boundary conditions such as water and sediment supply and to downstream conditions such as sea level. The low gradient sand-bed portion of the Fly River System in Papua New Guinea provides a unique opportunity to study the effect of sea level change on a system with significantly different sediment supplies to its two major tributaries. In its present-day state, the larger of the two main tributaries, the Strickland River, is significantly steeper and less flood prone than the smaller tributary, the middle Fly River (i.e. the Fly River above the confluence with the Strickland). The difference is usually ascribed to a more rapid and complete response to sea-level change along the Strickland River than along the middle Fly River driven by the significantly larger sediment supply to the Strickland. This hypothesis is tested using a numerical model for river valley evolution over 1000 to 10000 year timescales. The model includes the three main low- gradient sand-bed reaches in the system, the middle Fly and Strickland Rivers (above the confluence) and the Lower Fly River (below the confluence). The model is theoretically similar to other diffusion-based numerical models for valley infilling. However, the inclusion of backwater in the theory results in an advective-diffusive form that allows a new

delta to automatically form upstream of an abandoned delta once sea level stabilizes. The low-stand longitudinal profile is not well constrained along any of the three low gradient reaches of the Fly River system. However, model results confirm that for several different hypothetical low-stand profiles and for sediment loads similar to those observed at present, the middle Fly River would not have been able to keep up with aggradation along the Lower Fly/Strickland axis of the system. The results imply that it is unlikely that the low- stand river channel bed was more than approximately 10 m below the present-day channel bed near the confluence, consistent with the few available field observations. This is not necessarily apparent if the evolution of Strickland/Lower Fly axis of the system is considered alone without the inclusion of the middle Fly River. The results further imply that at glacial low stand, the Lower Fly River may have passed through a – hard zone – that was significantly steeper than the present-day Lower Fly River.

TxDOT Researcher's Comments: Related to low-slope hydrology. Suggested stream-gradient evolution can be explained/predicted by tail-water history.

H13H-01 INVITED

"Doing Hydrology Backwards: Inferring Landscape-Scale Rainfall and Evapotranspiration From Streamflow Time Series"

Kirchner, J W (kirchner@berkeley.edu), Dept. of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, United States

Catchment hydrology is controlled by processes and material properties that are complex, heterogeneous on all scales, and poorly characterized by direct measurement. This spatial heterogeneity and process complexity implies that any hydrologic model will necessarily entail substantial simplifications and generalizations. The essential question is which simplifications and generalizations are appropriate for the case at hand. Many 'physically based' hydrologic models are grounded in an implicit up-scaling premise, which assumes that the small-scale physics in the subsurface will 'scale up' such that the behavior at larger scales (e.g., hillslopes or catchments) will be described by the same governing equations (e.g., Darcy's Law, Richards' equation), with state variables (e.g., water flux, volumetric water content, hydraulic potential) that are averaged, and with 'effective' parameters that somehow subsume the heterogeneity of the subsurface. There are reasons to believe that this upscaling premise may often be incorrect, and that the effective governing equations for these heterogeneous systems may be different in form (not just different in the parameters) from the equations that describe the small- scale physics. Here I describe an approach for determining the constitutive equations that describe catchment behavior at the small-catchment scale. This approach considers the catchment as a first-order nonlinear dynamical system, and estimates its (nonlinear) governing equations at catchment scale, directly from field data. This approach assumes that discharge depends on the aggregate volume of water stored in the catchment, but makes no *a priori* assumption about the functional form of this storage-discharge relationship, instead determining it from rainfall-runoff data. This approach not only allows one to predict runoff from measurements of rainfall, but also allows one to do hydrology backwards: that is, to infer effective rainfall and evapotranspiration at whole-catchment scale, directly from runoff time-series data. This approach can potentially be used to ground-truth remote sensing estimates of rainfall and evapotranspiration time series.

TxDOT Researcher's Comments: Related to all our work. While not specifically on subdivision, the author's implication that doing hydrology backwards is a strong argument for our team's pursuit of the ad-hoc division research method as well as ensuring that any subdivision scheme aggregrate and dis-aggregate without impacting the lumped response signal.

TEXAS TECH UNIVERSITY
Multidisciplinary Research in Transportation

Texas Tech University | Lubbock, Texas 79409
P 806.742.3503 | F 806.742.4168