

Synthesis of Unit Hydrographs for Texas Watersheds

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Acknowledgements

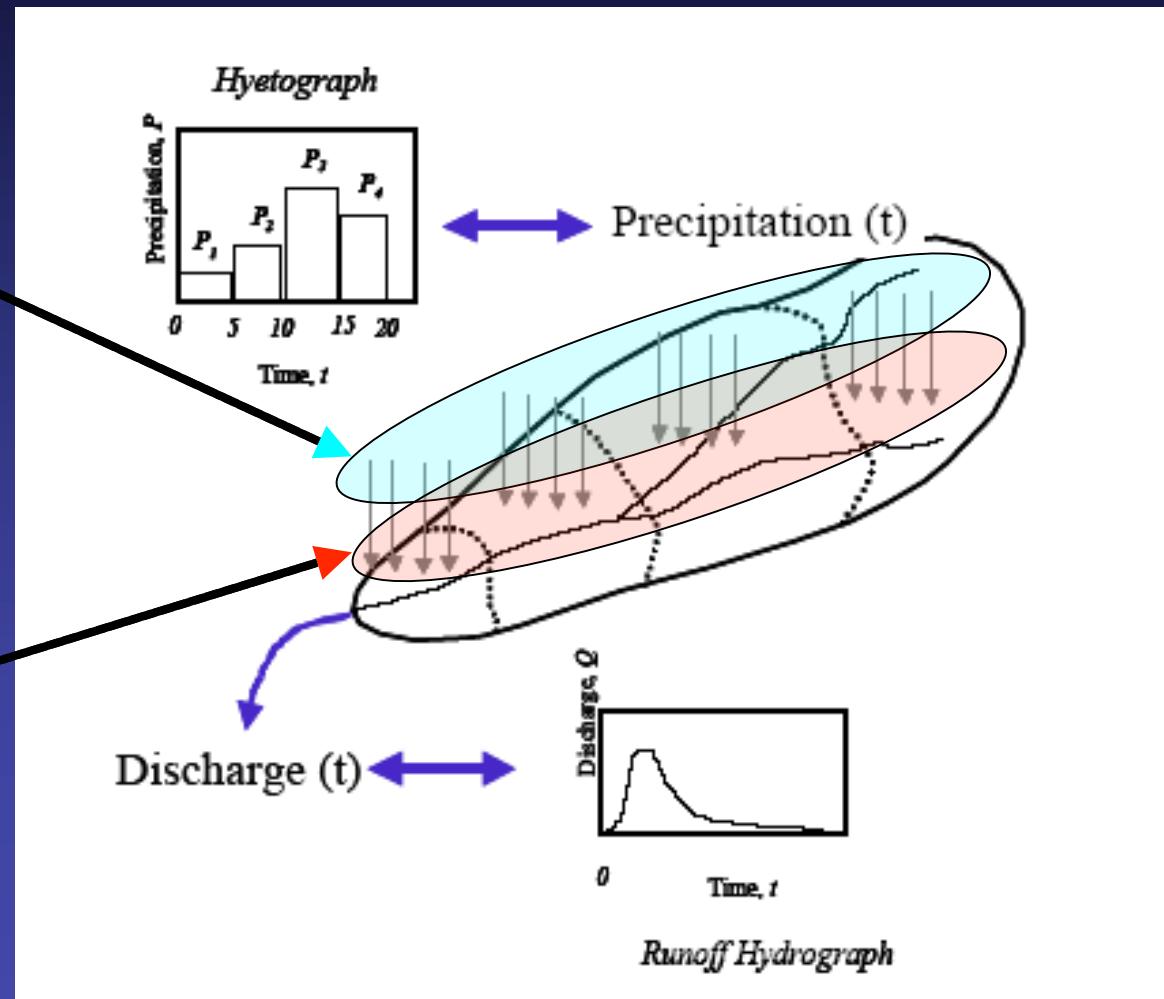
- Research colleagues:
 - Meghan Roussel, USGS
 - Amanda Garcia, USGS
 - George R. Herrmann, TxDOT
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 - 0-4193, 0-4194, 0-4696, 0-5822

Research Context

- Unit hydrograph (UH) methods are used to:
 - Obtain peak discharge and hydrograph shape for drainage design.
 - Compute a direct runoff hydrograph for a particular storm event when applied in conjunction with a hyetograph and rainfall-runoff model
 - Analyze complex problems in integrated arrangements of sub-watersheds which are combined using routing technology (e.g. HEC-HMS, HEC-RAS, SWMM).
- Typically used:
 - Drainage areas too large for rational methods.
 - For drainage areas small enough for lumped-parameter model.

Practical Application

- Loss model
 - Account for portion of rainfall that becomes available for runoff.
- UH model
 - Temporal redistribution of the available excess precipitation at the outlet.



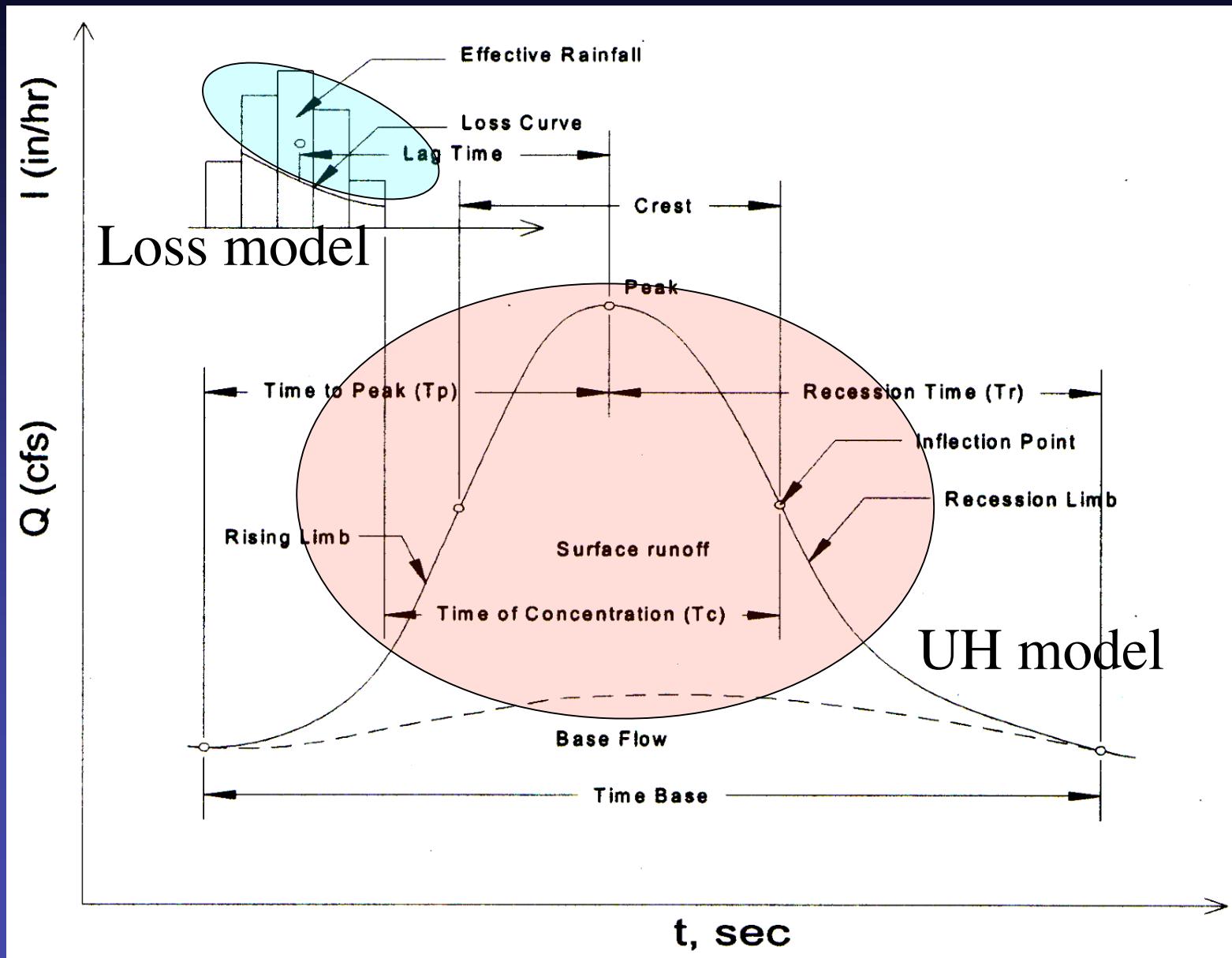
Definitions

- Loss Models
 - The “equation” that converts precipitation to excess precipitation; it does NOT redistribute the signal in time.
 - Proportional loss model
 - Phi-index
 - Initial Abstraction - Constant Rate
 - NRCS CN
 - Infiltration capacity (e.g. Green-Ampt)

Definitions

- UH Model
 - The “equation” that redistributes the excess precipitation the signal in time to the outlet.
 - Discrete unit hydrographs (e.g. Sherman)
 - Gamma-family unit hydrographs
 - Geomorphic unit hydrographs.

Definitions

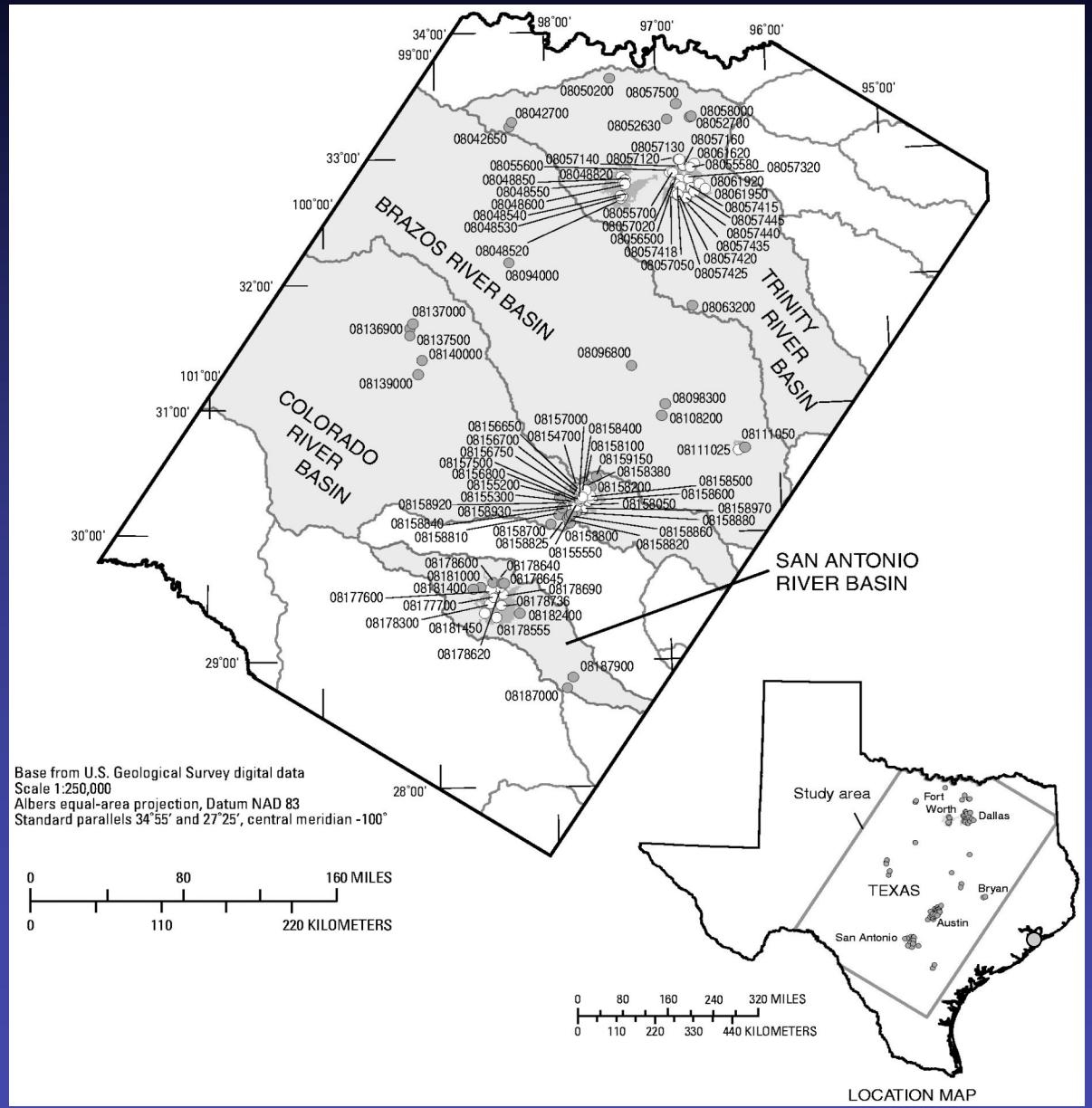


Definitions

- Characteristic Times
 - Time-to-peak
 - Time from inception of runoff to peak discharge value.
Often used as a parameter in hydrograph models.
 - Time-of-concentration
 - Time required for parcel of water to travel from the most distant (hydrologic) point in a watershed to the outlet.

Study Area

1. Over 1,600 storms analyzed.
 2. Multiple approaches for unit hydrograph estimation.
 3. Multiple approaches for time parameter estimation.
 4. Multiple approaches for rainfall losses.
 5. Data base now in excess of 3,400 storms.

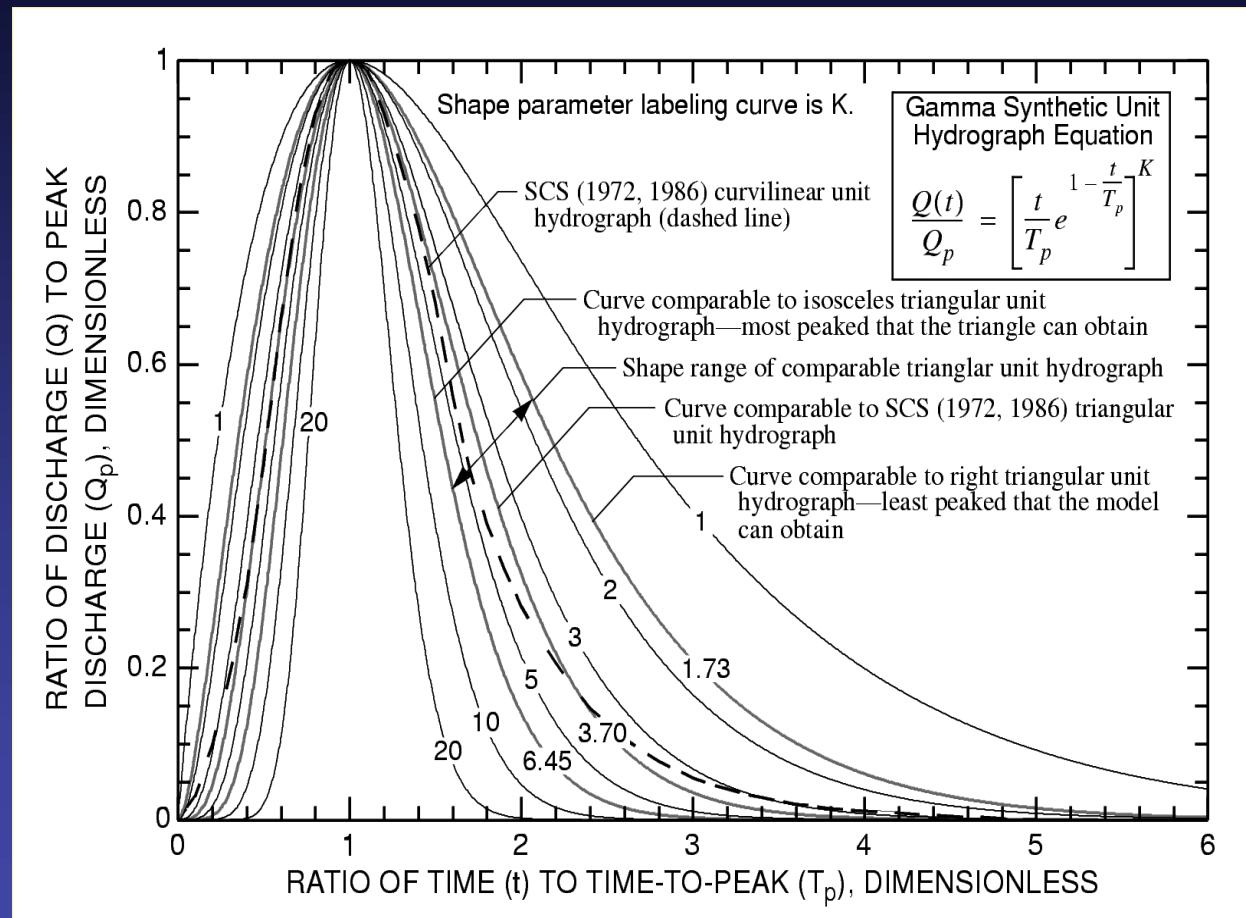


Research Approaches

- Multiple lines of research
 - Discrete Unit Graphs
 - Analyst directed and automated
 - Multiple regression for regionalization.
 - Gamma Unit Graph
 - Analyst directed
 - Multiple regression for regionalization.
 - Geomorphic Instantaneous Unit Graph (GIUH)
 - Automated
 - Independent comparison.

Gamma Unit Hydrographs

- Analysis of rainfall and runoff data.
- Use gamma distribution as hydrograph model.
- Match T_p and Peak Q at all costs.
- Statistically summarize T_p and DH shape.
- Perform regression analysis.



- 0-4193 TxDOT Unit Hydrograph Report

Regionalization

- Multiple linear regression is used to define a relation between watershed characteristics and time-to-peak.
- Main channel length, dimensionless main channel slope, development (binary).

Figure 13. Relation between observed time to peak of 5-minute gamma unit hydrograph and main channel length for undeveloped and developed watersheds from GUHAS approach.

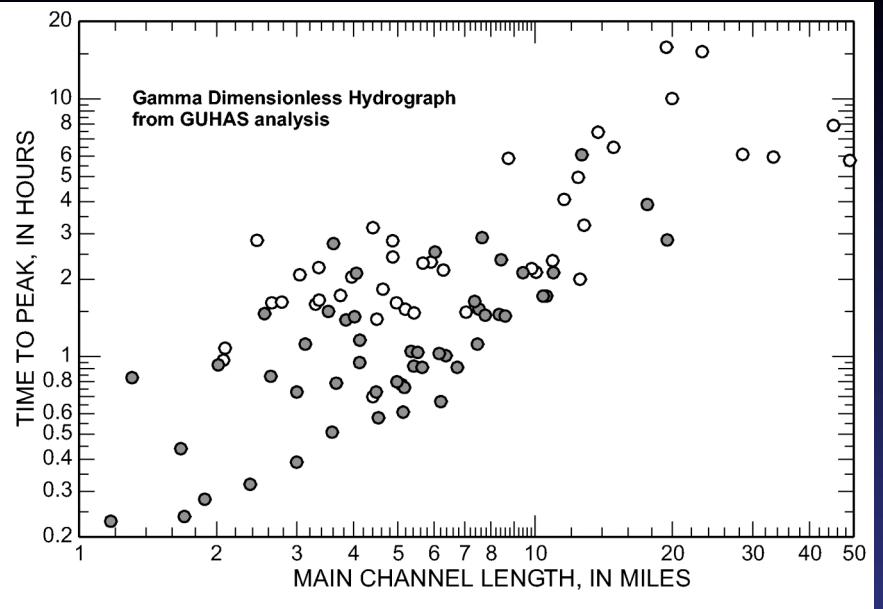
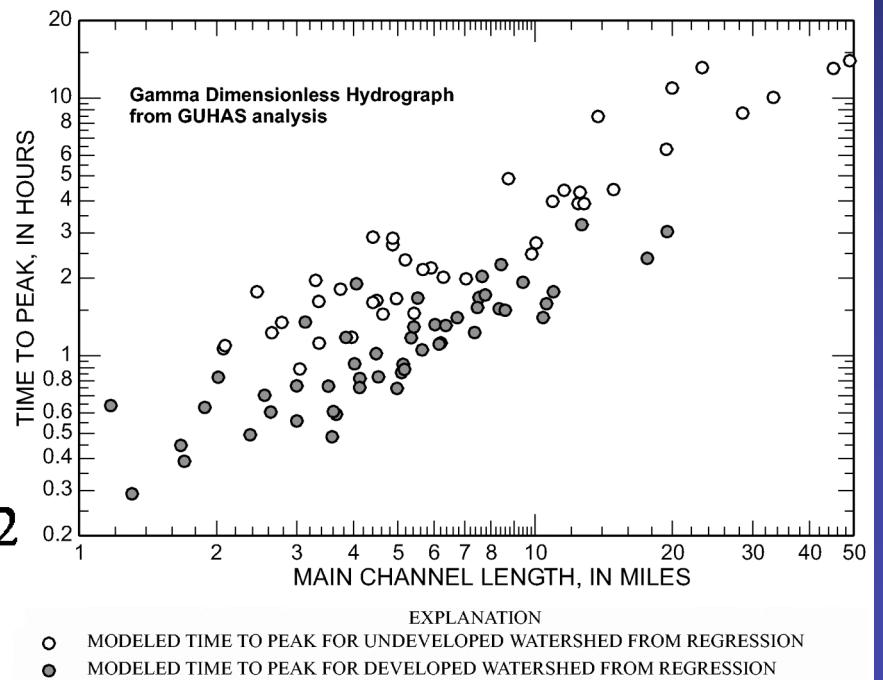
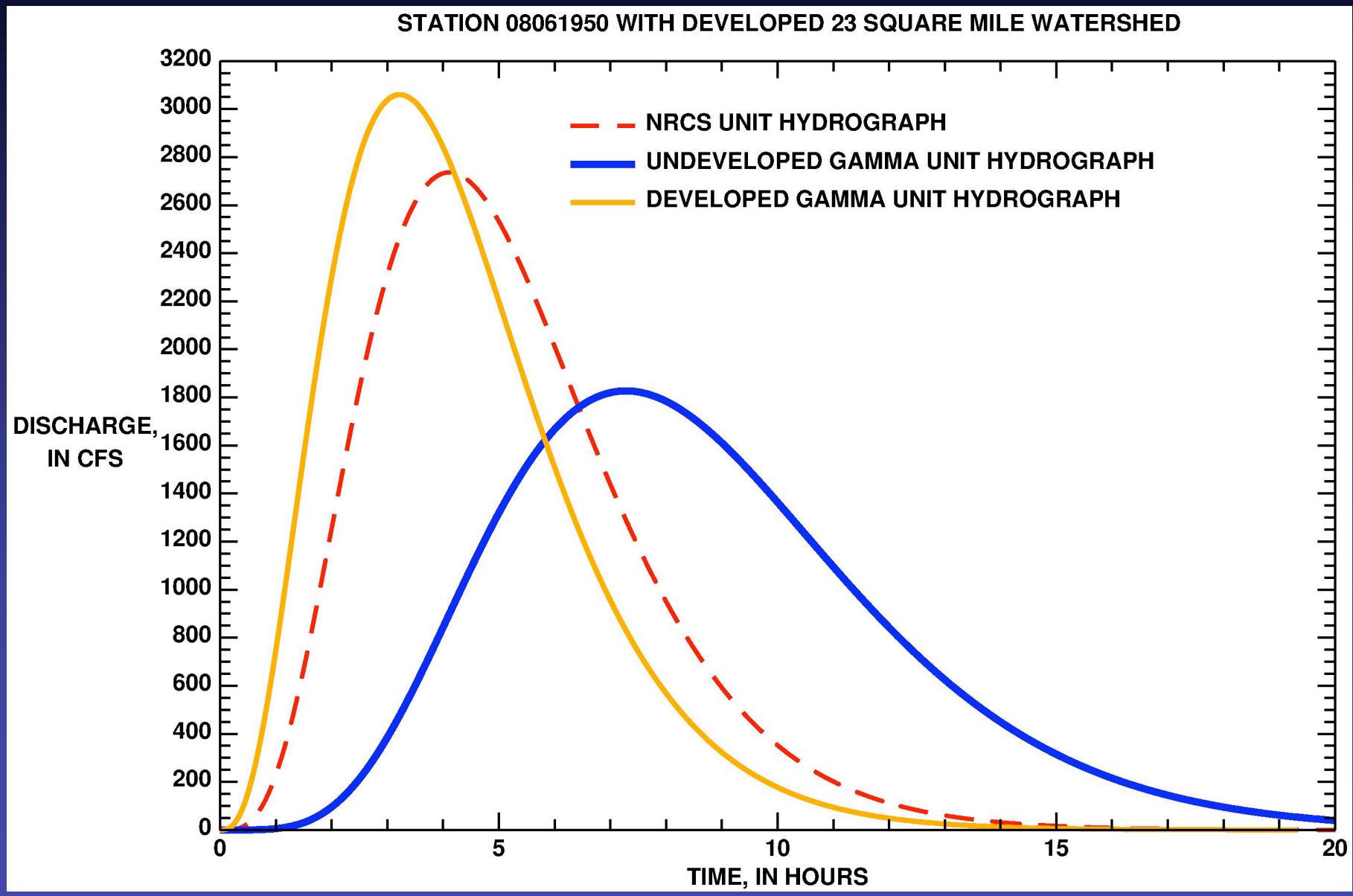


Figure 14. Relation between modeled time to peak of 5-minute gamma unit hydrograph and main channel length for undeveloped and developed watersheds from GUHAS approach.



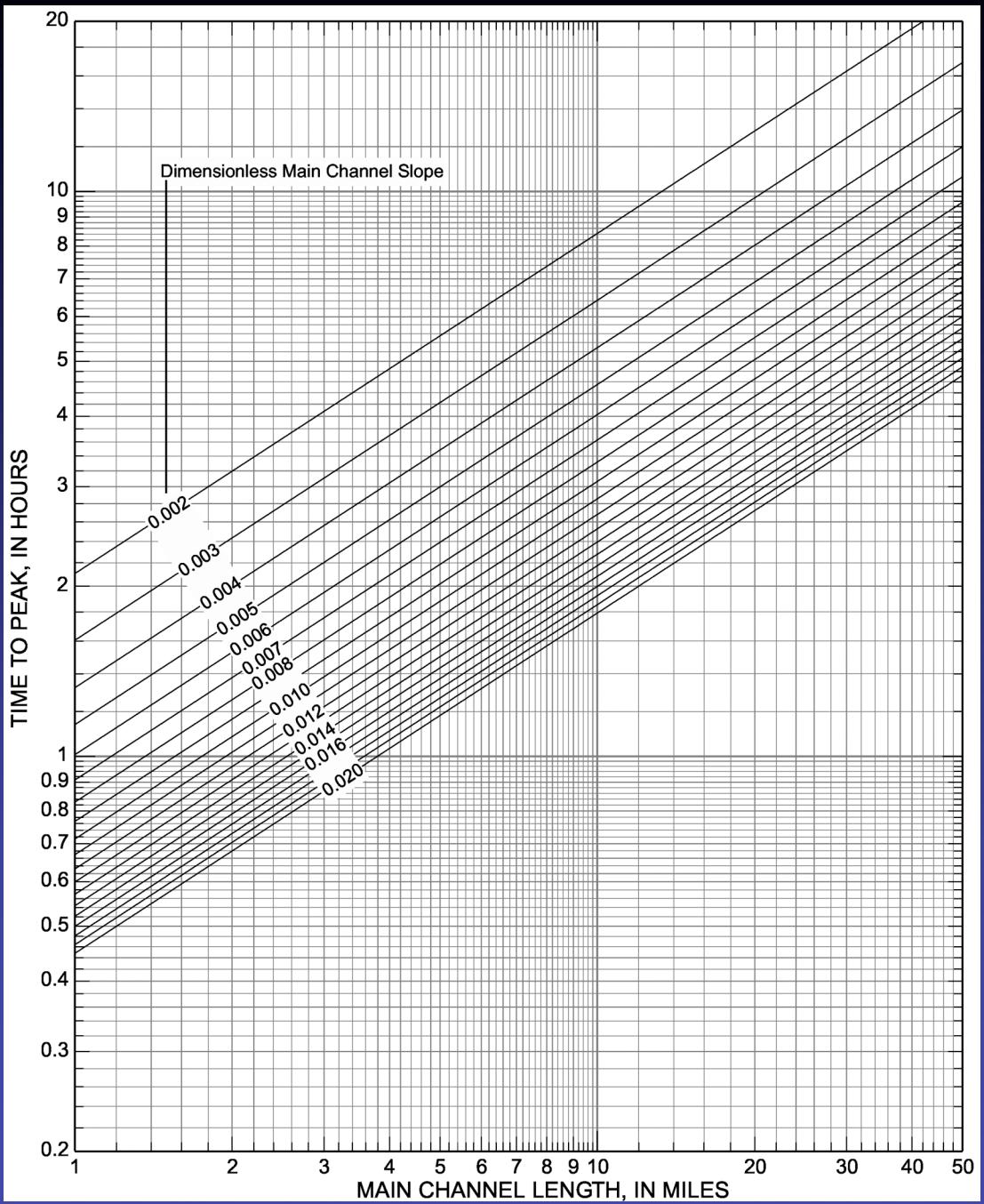
$$T_p = 10^{(-1.49 - 0.354D)} L^{0.602} S^{-0.672}$$

Comparison



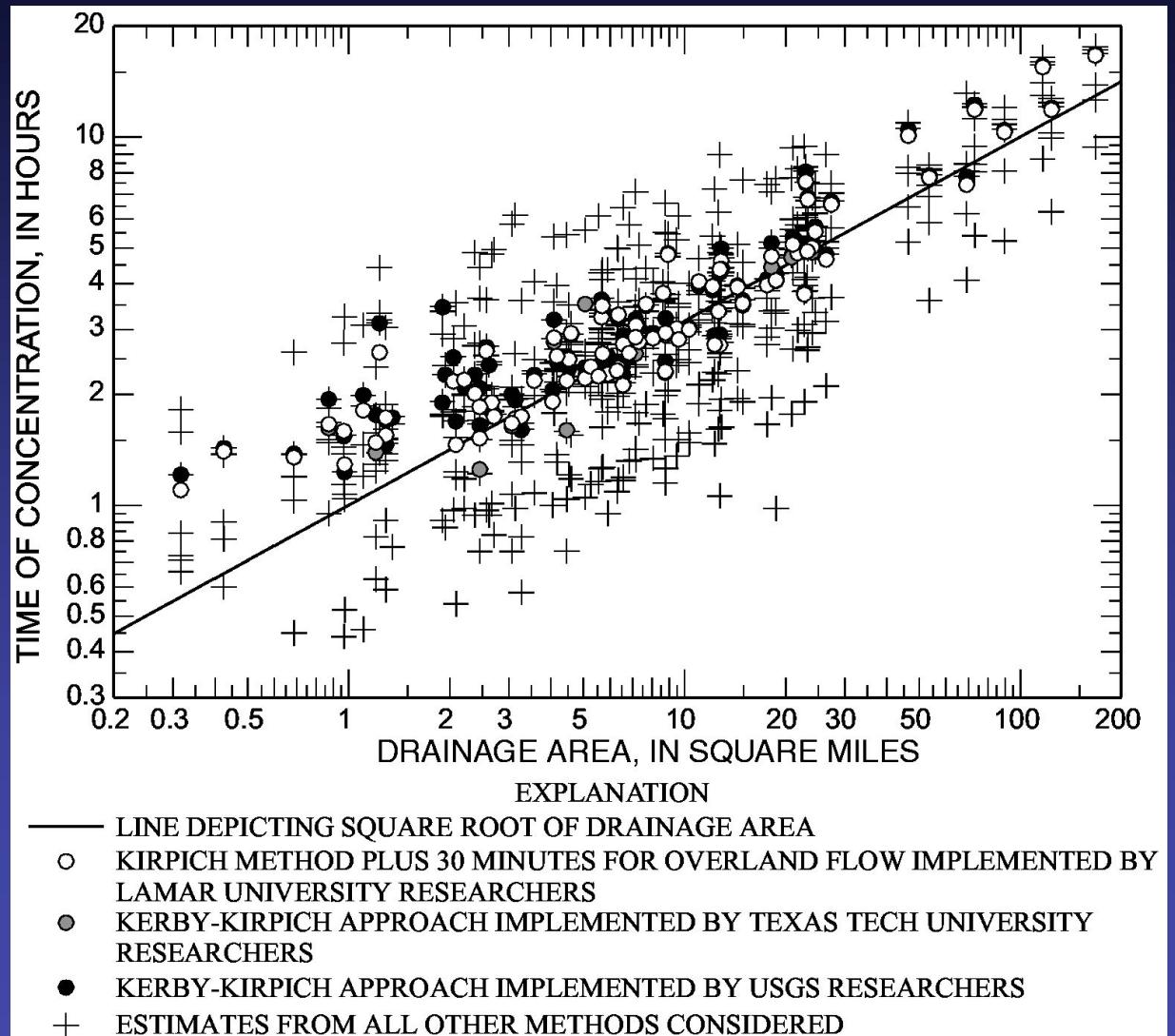
Time-to-Peak

- Equation to estimate time to peak from main channel length, main channel slope, and development classification has been developed.
- Measure of equation applicability
- Measure of equation prediction accuracy.
- Design nomograph(s)
 - Developed
 - Undeveloped



Timing Estimates

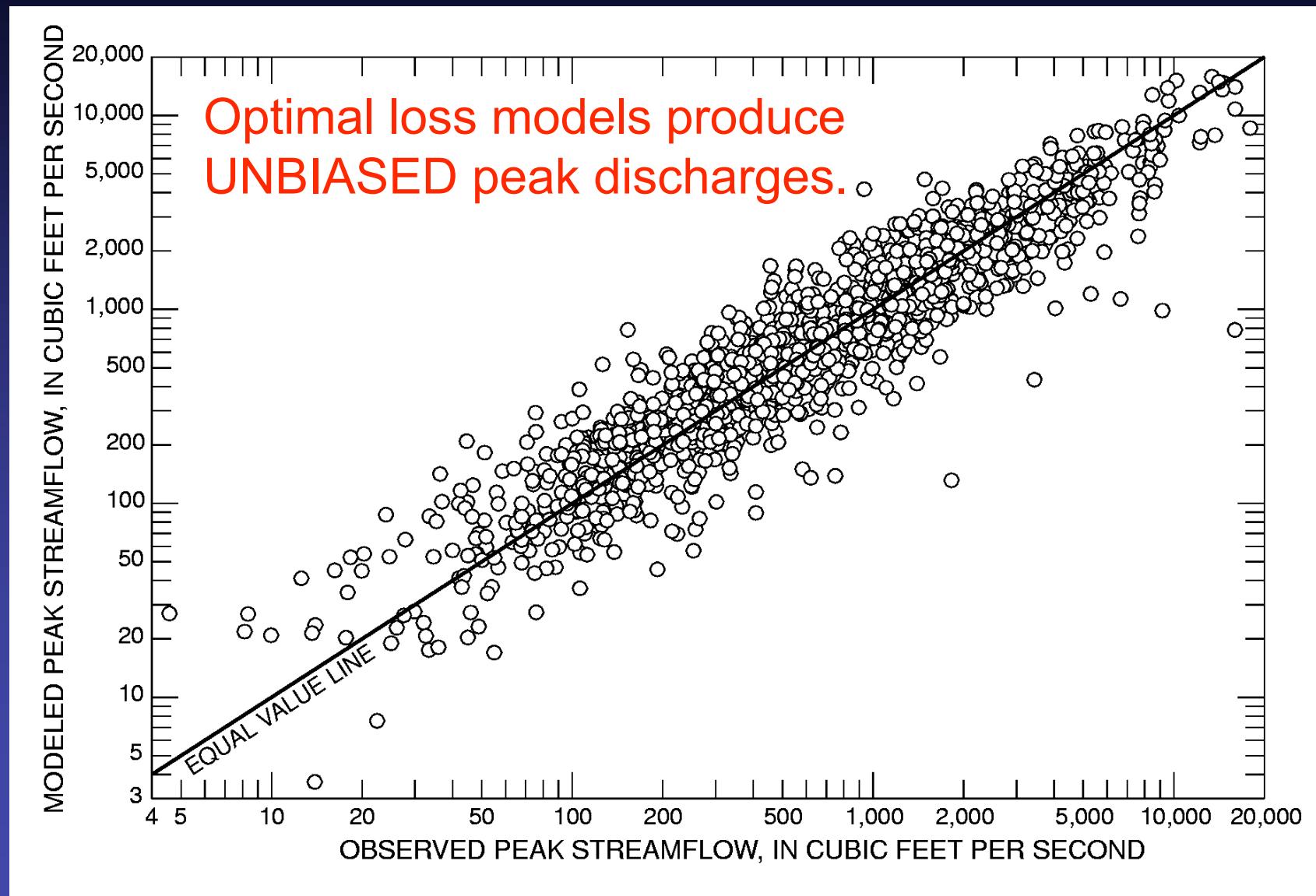
- Variety of single metric approaches
 - A reliable method for estimation of time of concentration is the Kerby (overland flow) Kirpich (channel flow) method.
 - Single metric: one slope, one characteristic length, etc.
- Compare to observed behavior.
- 0-4696-2 (TxDOT Timing Report)



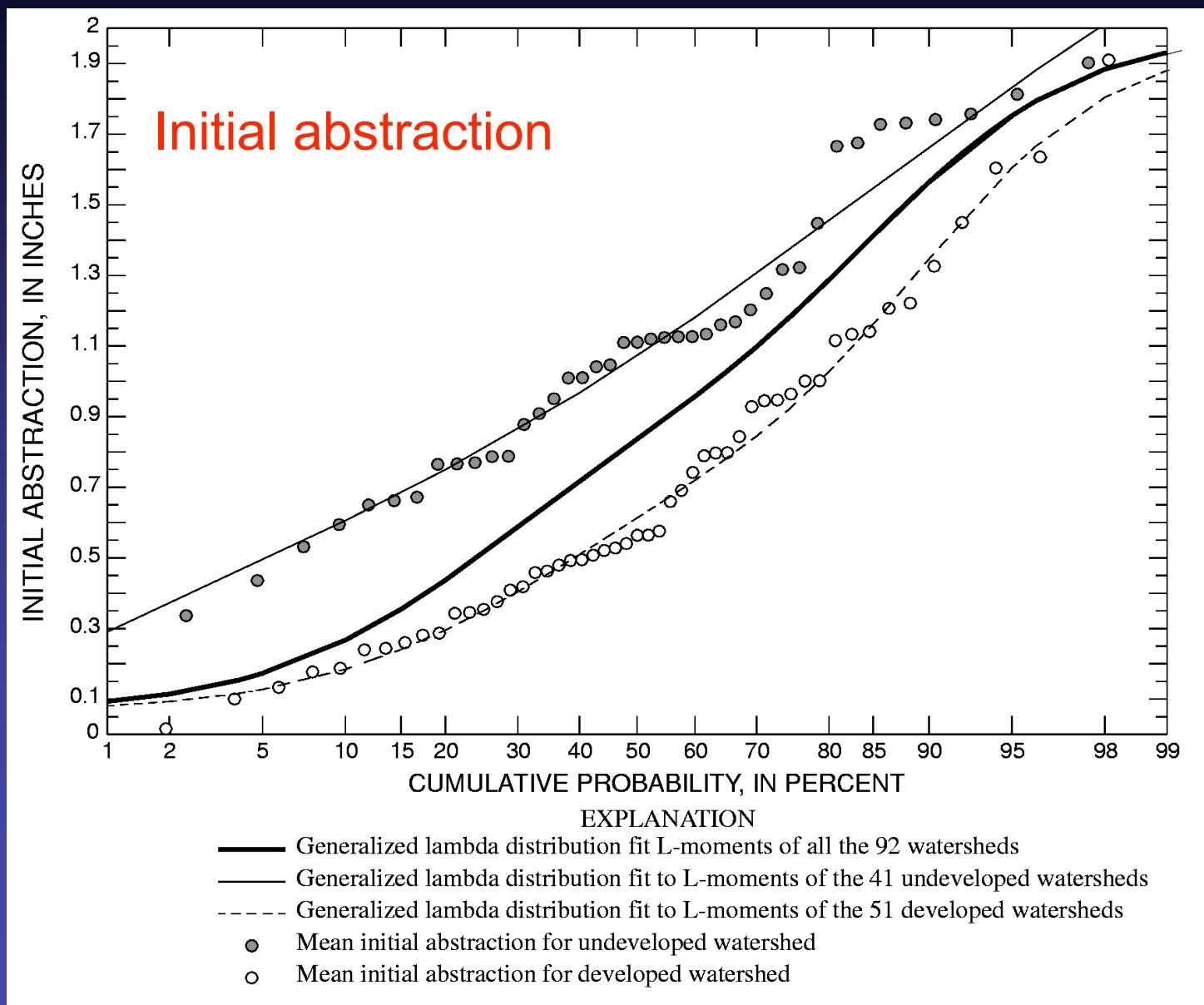
Loss Models

- Let us use that UH with real rainfall to estimate the parameters of an initial abstraction-constant loss model.
- Estimate those loss-model parameters through optimization by constraining the parameters to realistic values, constraining the optimization to volume match, and minimizing on the residuals of the modeled and observed hydrographs.

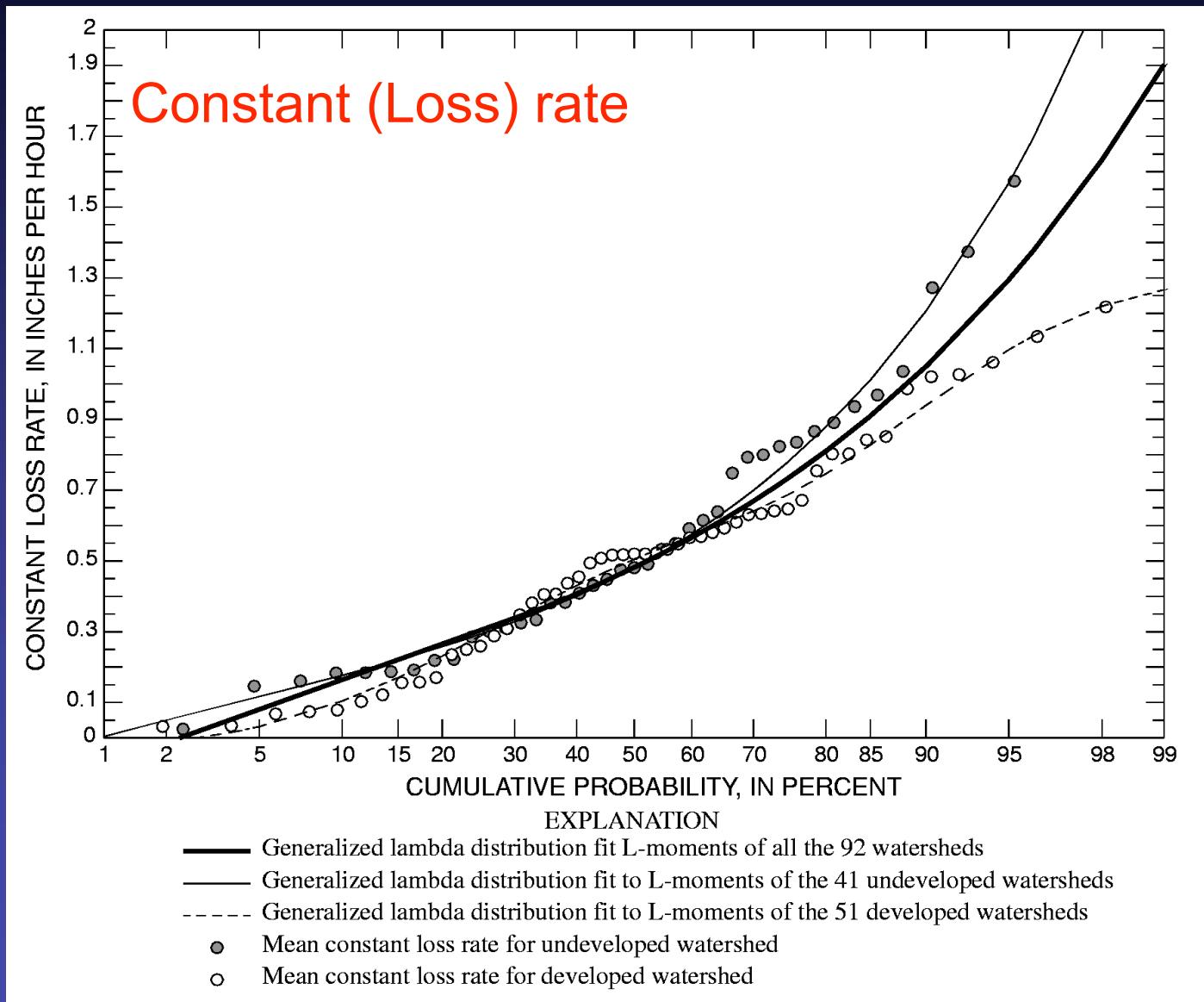
Loss Models



Loss Models



Loss Models



Geomorphic IUH Approach

- Timing values are property of physical characteristics.
 - Same as regression approach.
 - Same as other approaches.
- Ensemble of properties extracted from DEM raster (paths, slopes along paths, etc.)
 - Set of metrics instead of a single metric.

Estimating Timing Parameters

- Representative formulas:
 - Channel Flow

The NRCS travel-time method (NRCS, 2004) was implemented for shallow-concentrated and channel flow using eq. 1, by substituting the length of shallow-concentrated flow or the main channel length for L as appropriate. The average velocity (V_i) was computed for shallow-concentrated flow and channel flow by solving Manning's equation (eq. 5) and extracting average velocity using continuity (eq. 6). The equations are as follows

$$Q = \frac{1.486}{n} A R_h^{0.67} S^{0.5}, \text{ and} \quad (5)$$

$$Q = A V_i, \quad (6)$$

The Kirpich (1940) method was implemented using the following equation,

$$T_t^i = 0.0078 L^{0.77} S^{-0.385}, \quad (7)$$

The Haktanir and Sezen (1990) method was implemented using the following equation

$$T_L = 0.401 L_m^{0.841} \text{ and} \quad (8)$$

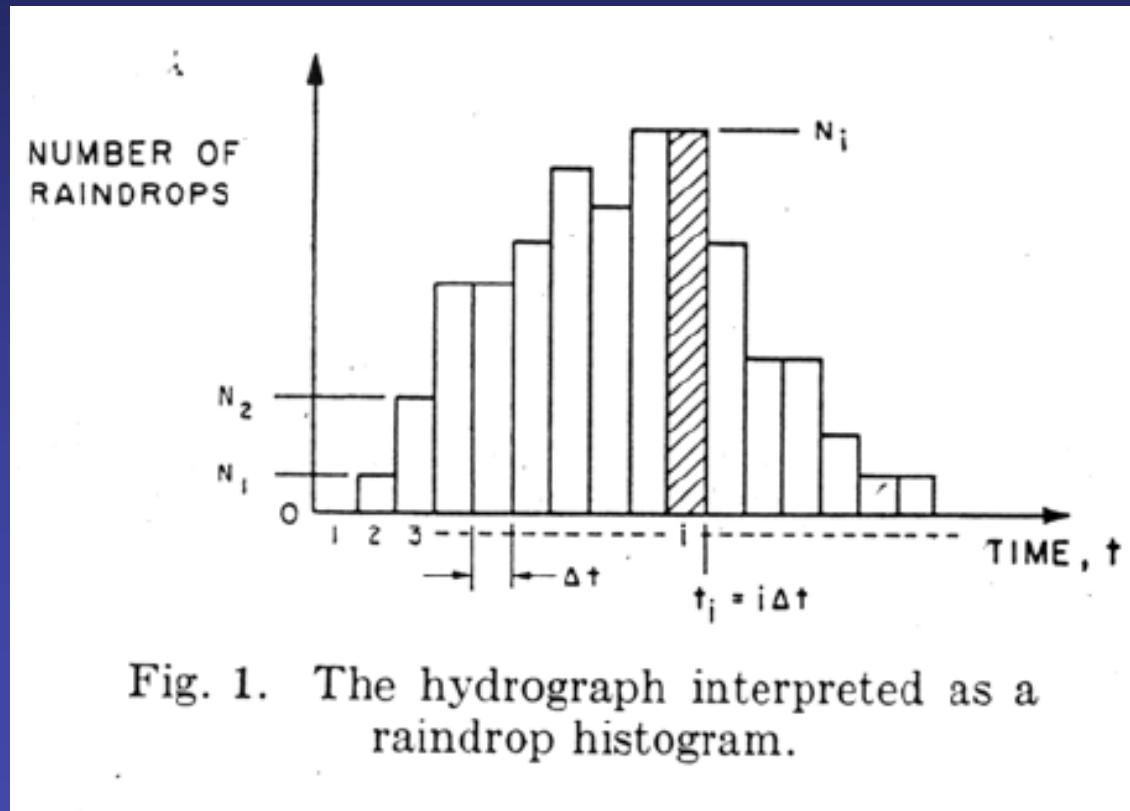
$$T_c = \frac{T_L}{0.6}, \quad (9)$$

Estimating Timing Parameters

- The formulas beg the questions:
 - Which “lengths, slopes, friction factors” ?
 - What is “bankful discharge” on an ungaged watershed ?
 - Which “paths” to examine ?

Statistical-Mechanical Hydrograph

- Leinhard (1964) postulated that the unit hydrograph is a raindrop arrival time distribution.



Statistical-Mechanical Hydrograph

- Further Assumed:
 - The arrival time of a raindrop is proportional to the distance it must travel, l .
 - The number of drops arriving at the outlet in a time interval is proportional to the square of travel time (and l^2).
 - By enumerating **all** possible arrival time histograms, and selecting the most probable from maximum likelihood arrived at a probability distribution that represents the temporal redistribution of rainfall on the watershed.

Statistical-Mechanical Hydrograph

- Resulting distribution is a generalized gamma distribution.

$$\frac{Q}{Q_p} = \left(\frac{t}{T_p} \right)^{n-1} \exp \left[-\frac{n-1}{\beta} \left(\left(\frac{t}{T_p} \right)^\beta - 1 \right) \right]$$

- The distribution parameters have physical significance.
- T_p is related to a mean residence time of a raindrop on the watershed.
- n , is an accessibility number, related to the exponent on the distance-area relationship (a shape parameter).
 - β , is the degree of the moment of the residence time;
 - $\beta = 1$ is an arithmetic mean time
 - $\beta = 2$ is a root-mean-square time

Estimating Timing Parameters

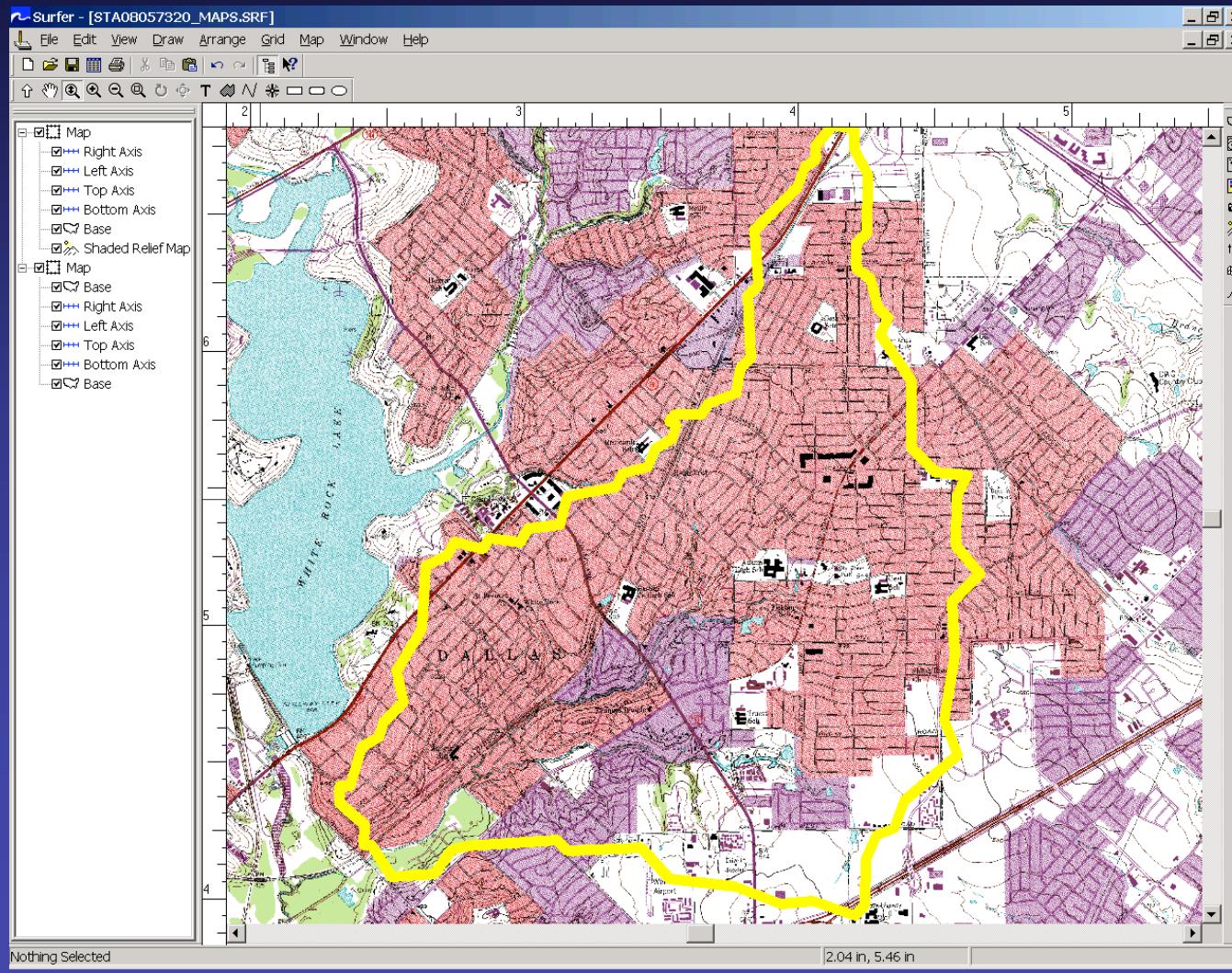
- The derivation based on enumeration suggests an algorithm to approximate watershed behavior.
 - Place many “raindrops” on the watershed.
 - Allow them to travel to the outlet based on some reasonable kinematics. (Explained later - significant variable is a “ k ” term - represents friction)
 - Record the cumulative arrival time.
 - Infer T_p and n from the cumulative arrival time distribution.
 - The result is an instantaneous unit hydrograph.

Estimating Timing Parameters

- Illustrate with Ash Creek Watershed
 - Calibration watershed – the “ k ” term was selected by analysis of one storm on this watershed, and applied to all **developed** watersheds studied.
 - About 7 square miles. (20,000+ different “paths”)

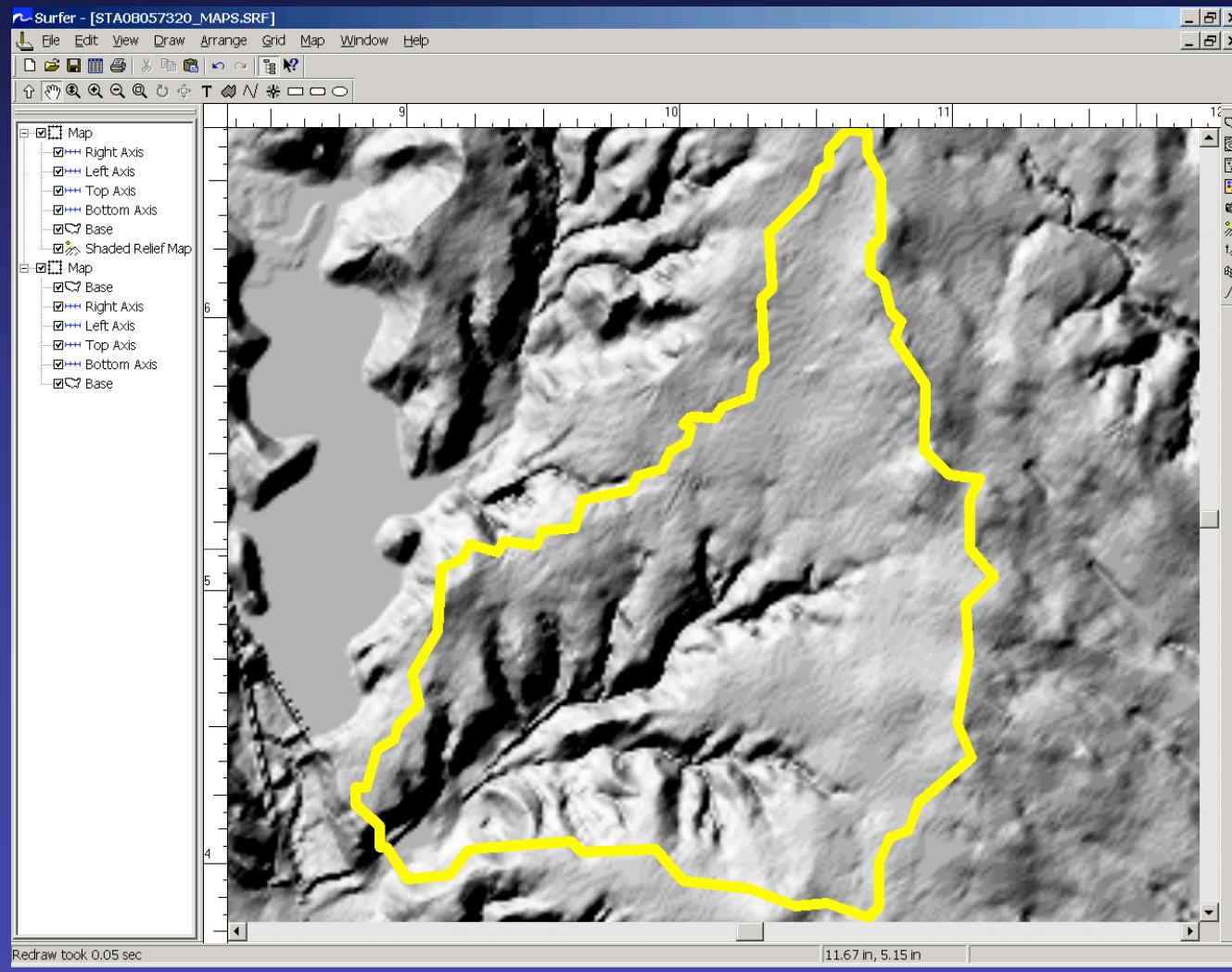
Ash Creek Watershed

(sta08057320)



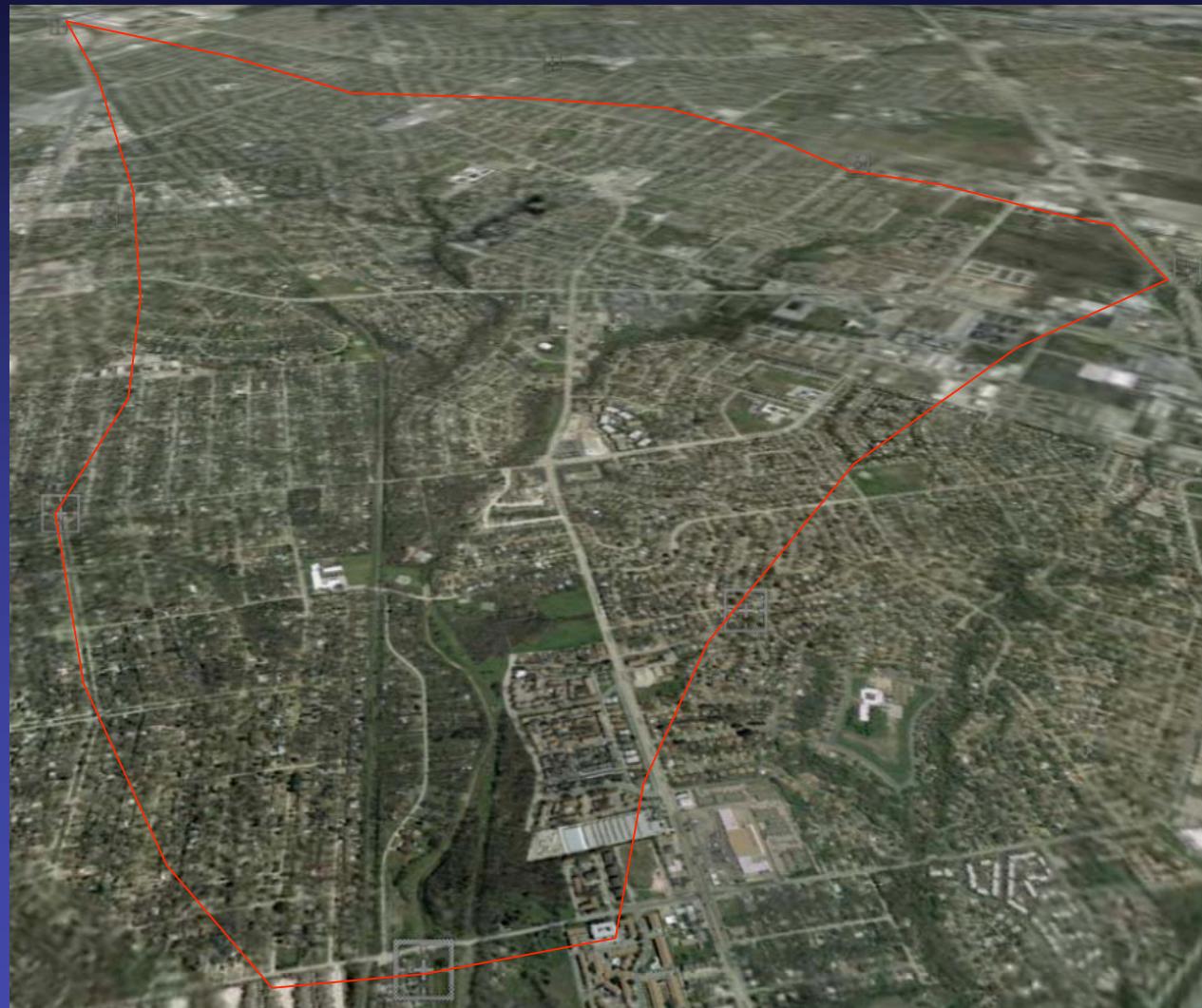
Ash Creek Watershed

(sta08057320)



Ash Creek Watershed

(sta08057320)



Estimating Timing Parameters

- Place many “raindrops” on the watershed.

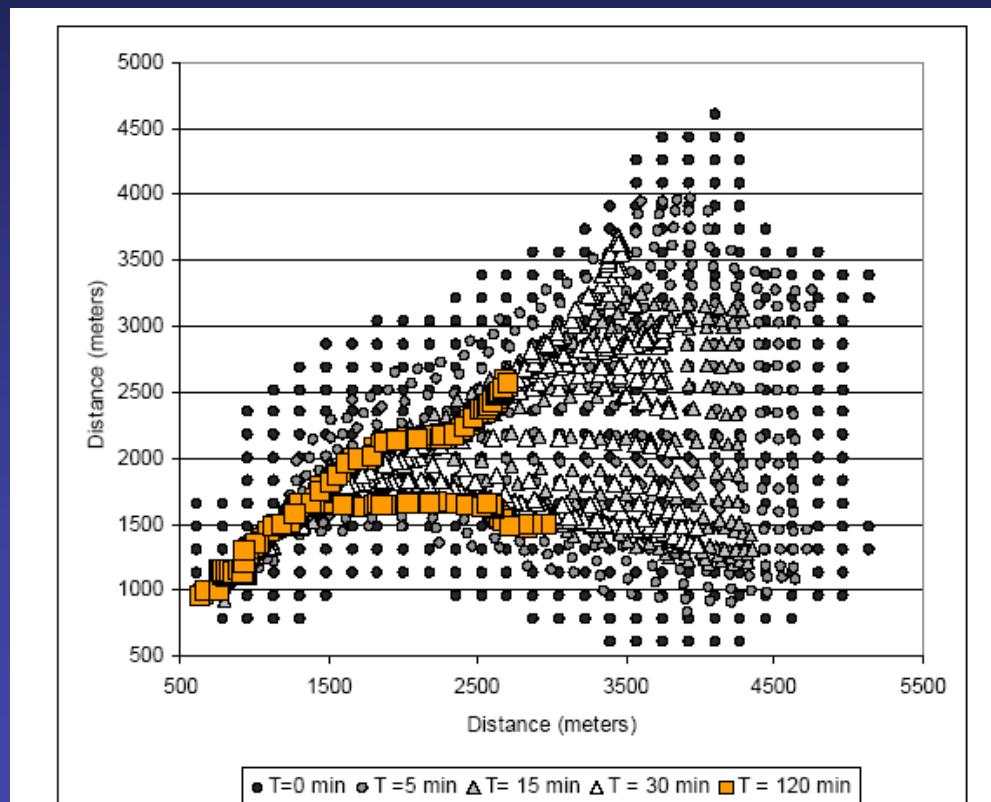
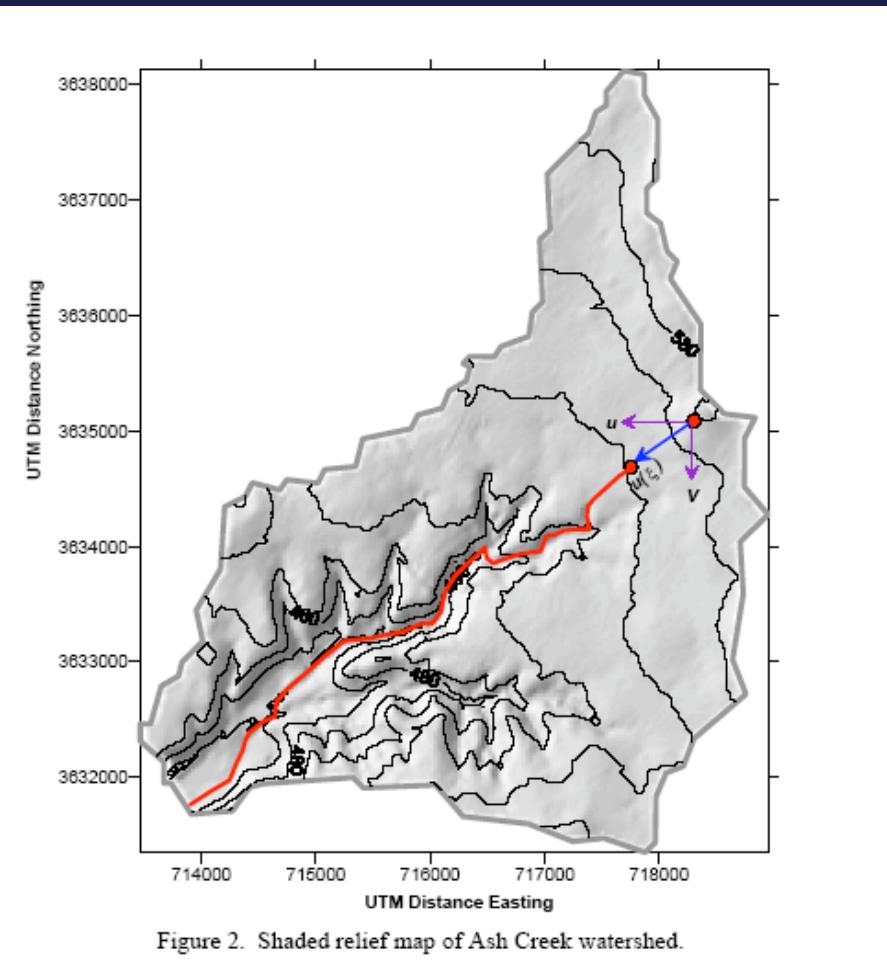


Figure 5 Particle positions at various times; Ash Creek watershed.

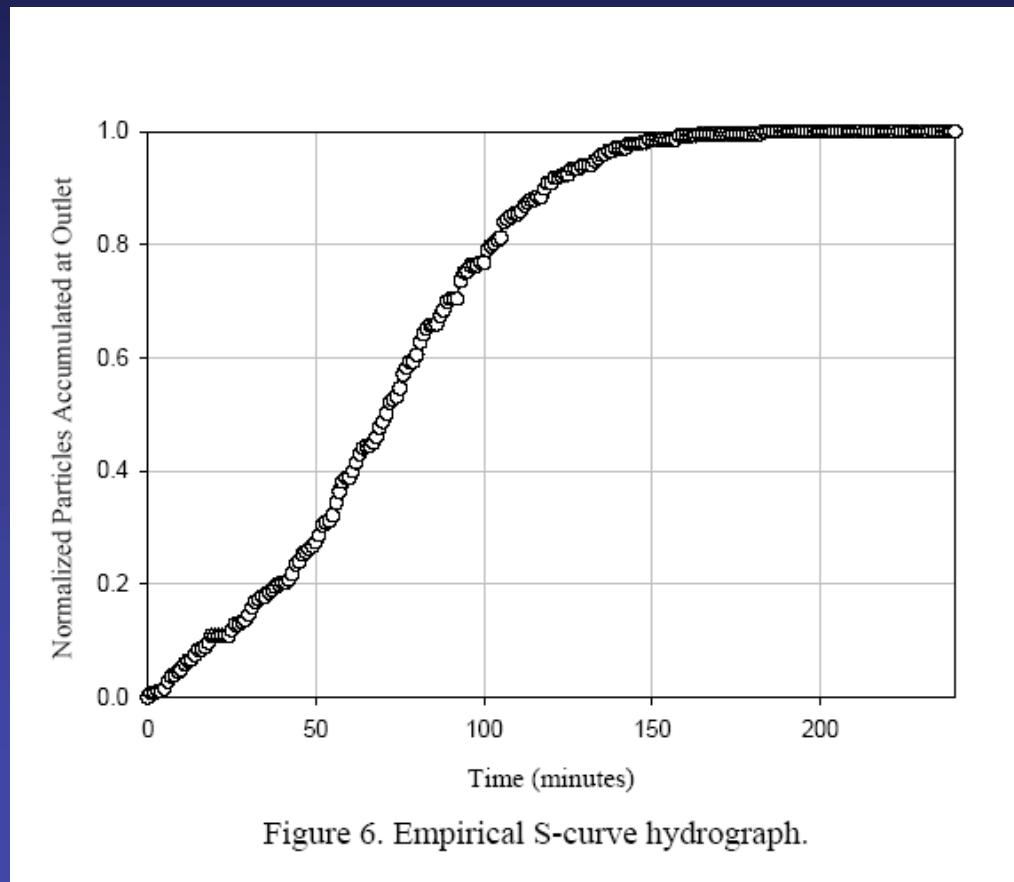
Estimating Timing Parameters

- Allow them to travel to the outlet based on some reasonable kinematics.
 - Path determined by 8-cell pour point model.
 - Speed from local topographic slope and *characteristic* velocity (k)
 - Each particle has a unique pathline.
 - Pathlines converge at outlet.



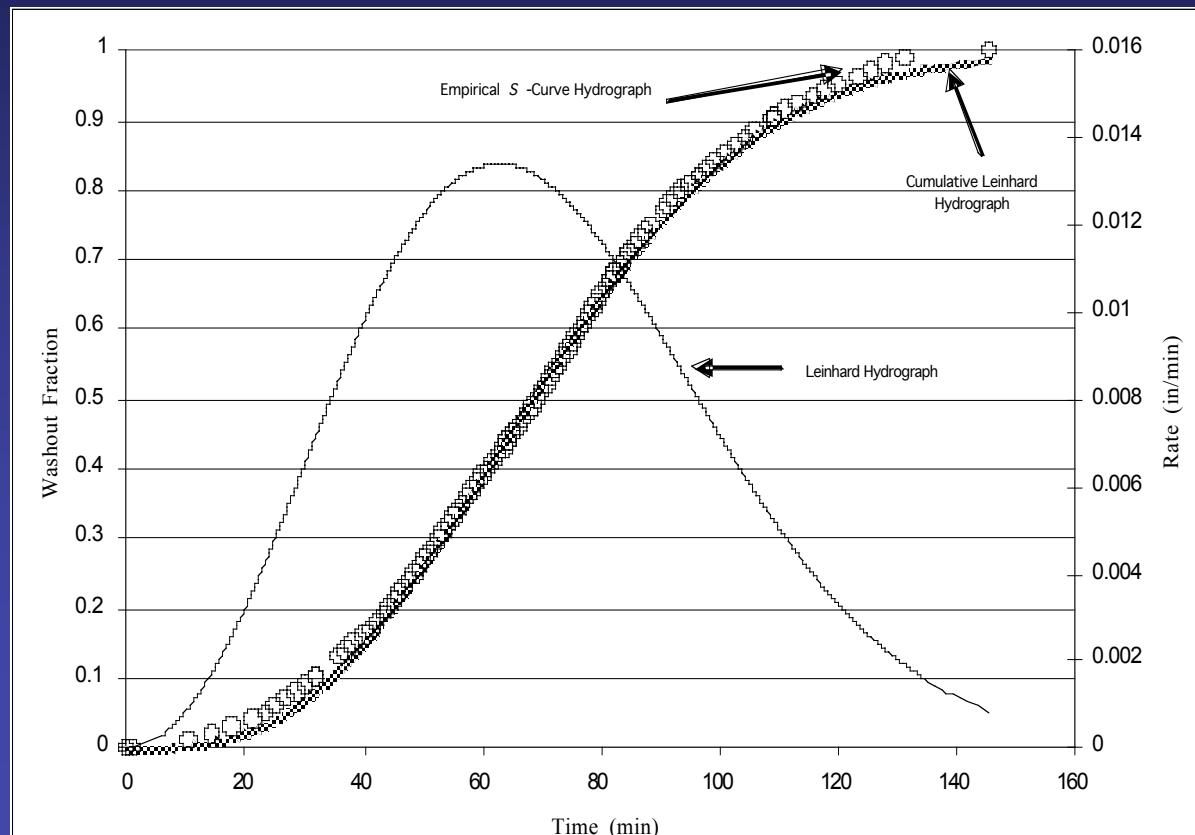
Estimating Timing Parameters

- Record the cumulative arrival time.



Estimating Timing Parameters

- Infer T_p and n from the cumulative arrival time distribution.



Estimating Timing Parameters

- The result is an instantaneous unit hydrograph (IUH).
 - IUH and observed storm to produce simulated runoff hydrograph.
 - Only change from watershed to watershed is topographic data (elevation maps)

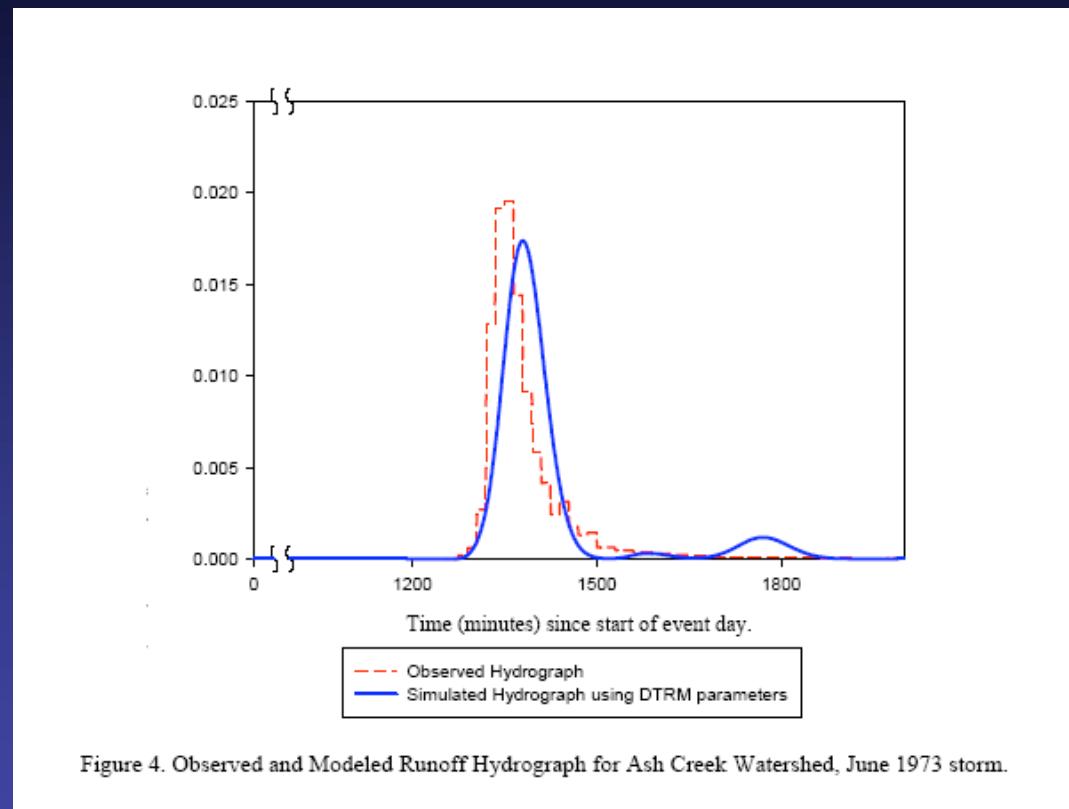


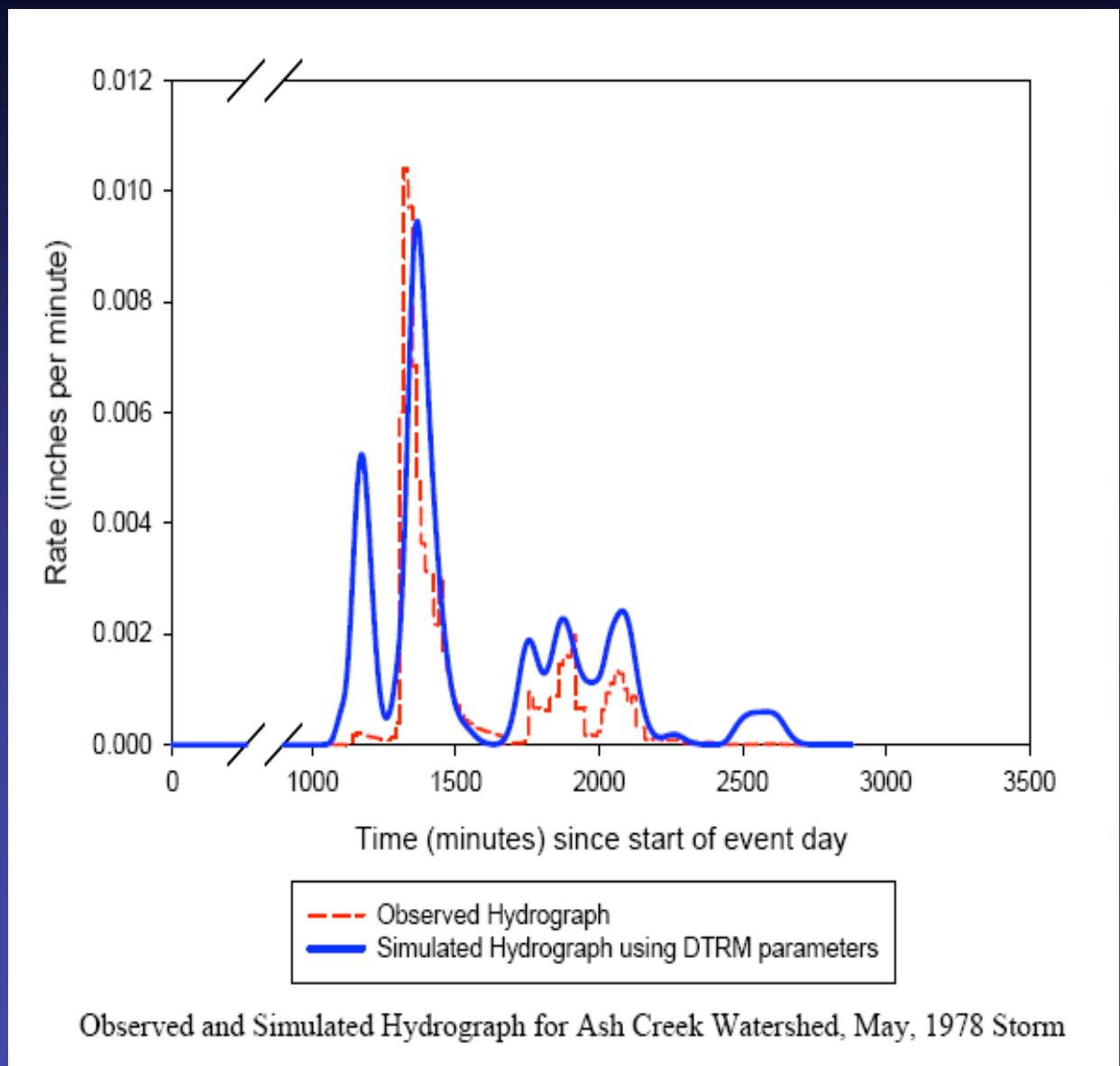
Figure 4. Observed and Modeled Runoff Hydrograph for Ash Creek Watershed, June 1973 storm.

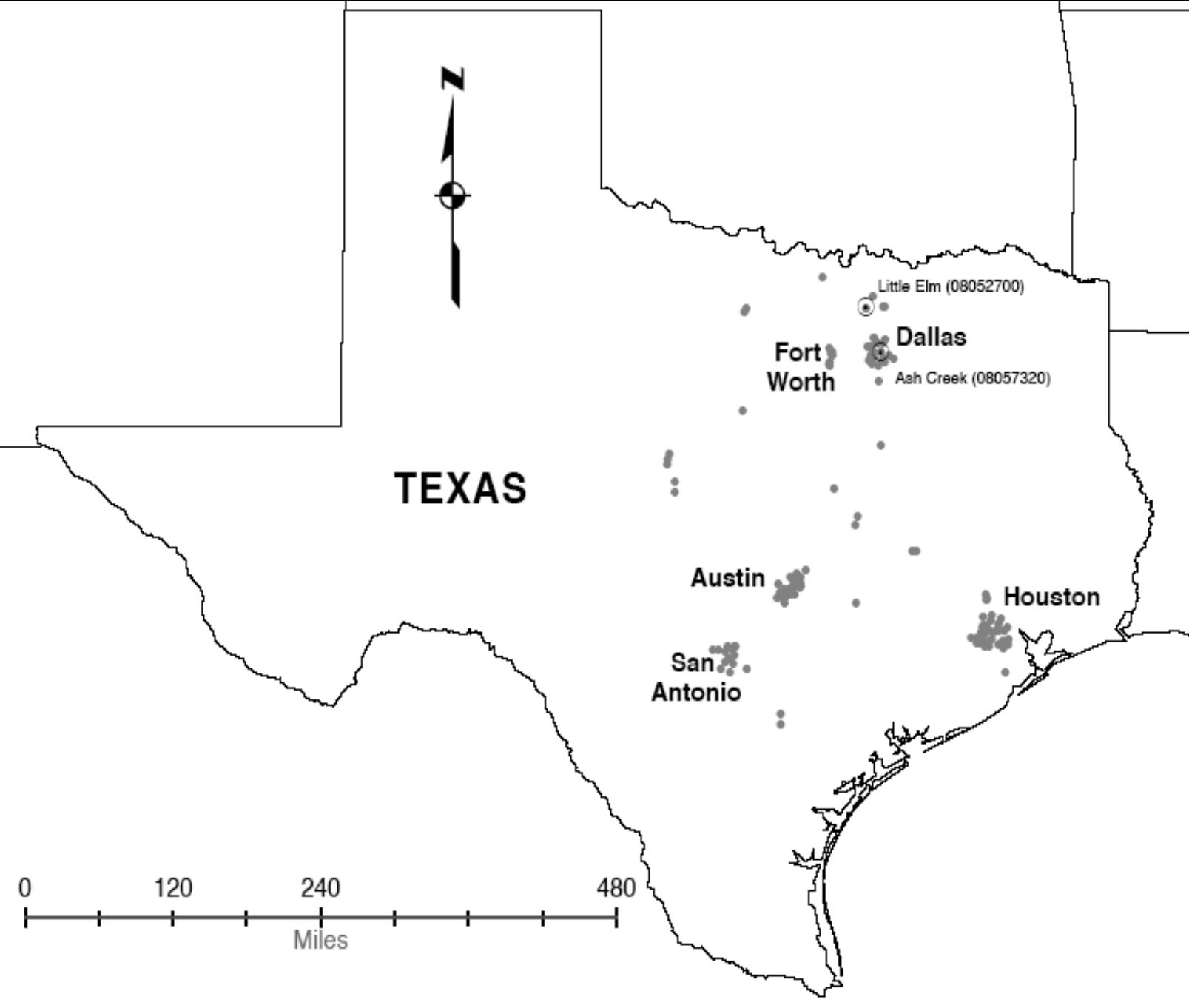
Parameterization

- Need to know “ k ”.
 - Can make reasonable guess based on intuition: larger than zero, smaller than terminal velocity of a large water balloon; probably on the order of 100-1000 feet/minute - but really have no clue.
 - Used a SINGLE storm in Dallas, adjust “ k ” to get good “match” - use this “ k ” for every other watershed without further adjustment.

Estimating Timing Parameters

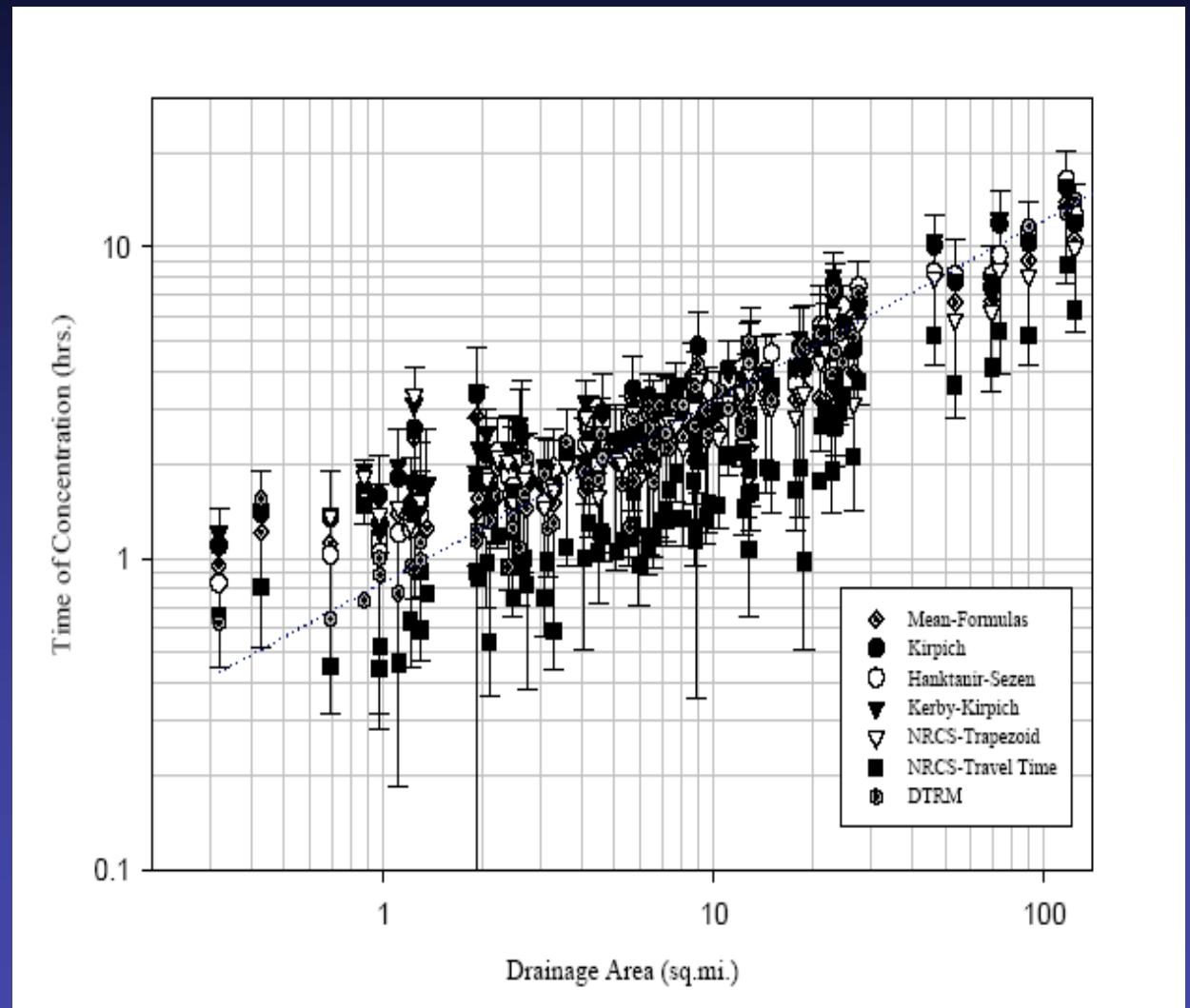
- Typical result





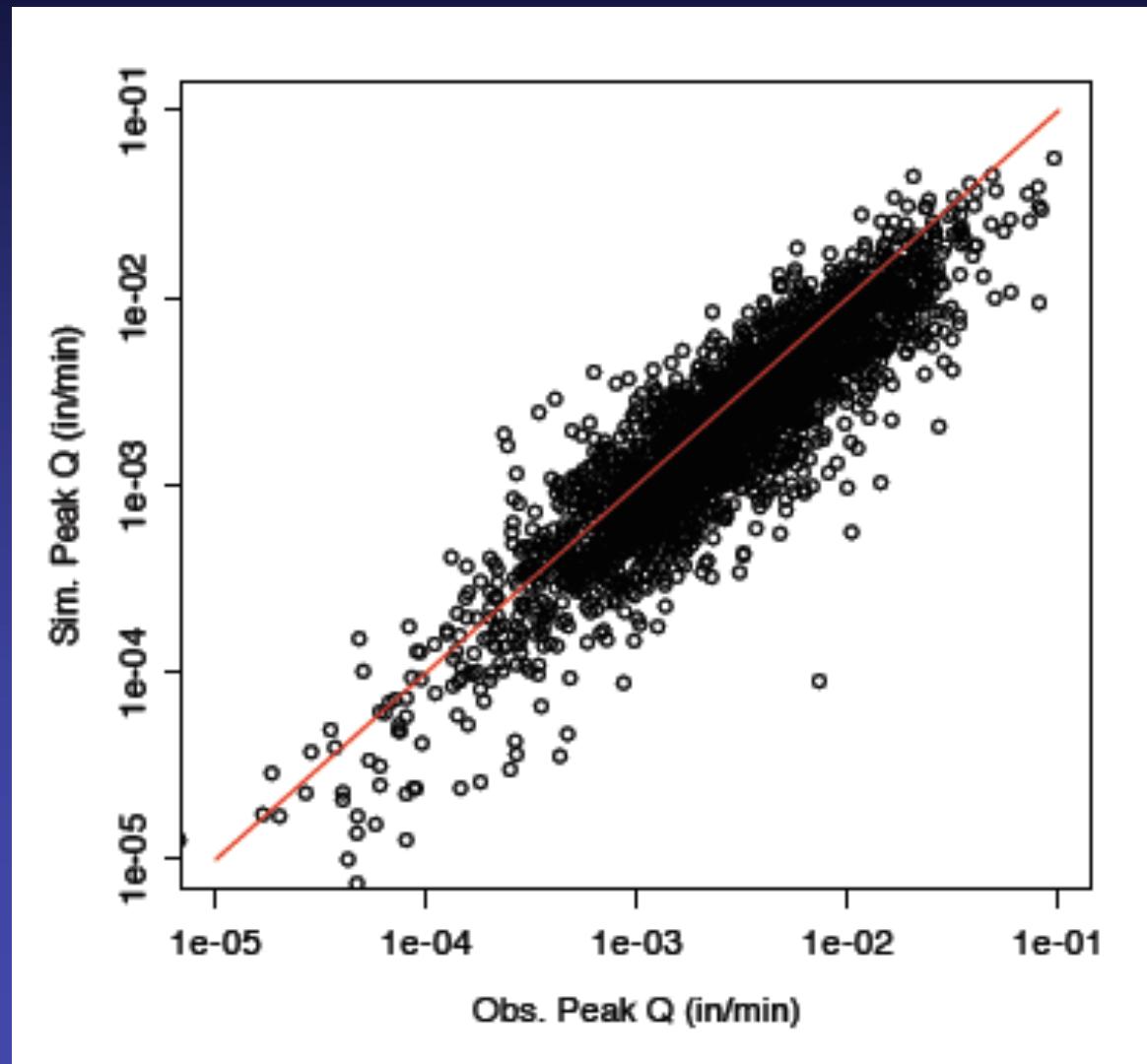
Timing Estimates

- Ensemble metric approach (GIUH)
 - Similar results.
 - Multiple metric: many characteristic length (paths); many slopes, etc.
- Compare to observed behavior.
- 0-4696-3 (TxDOT Particle Tracking Report)

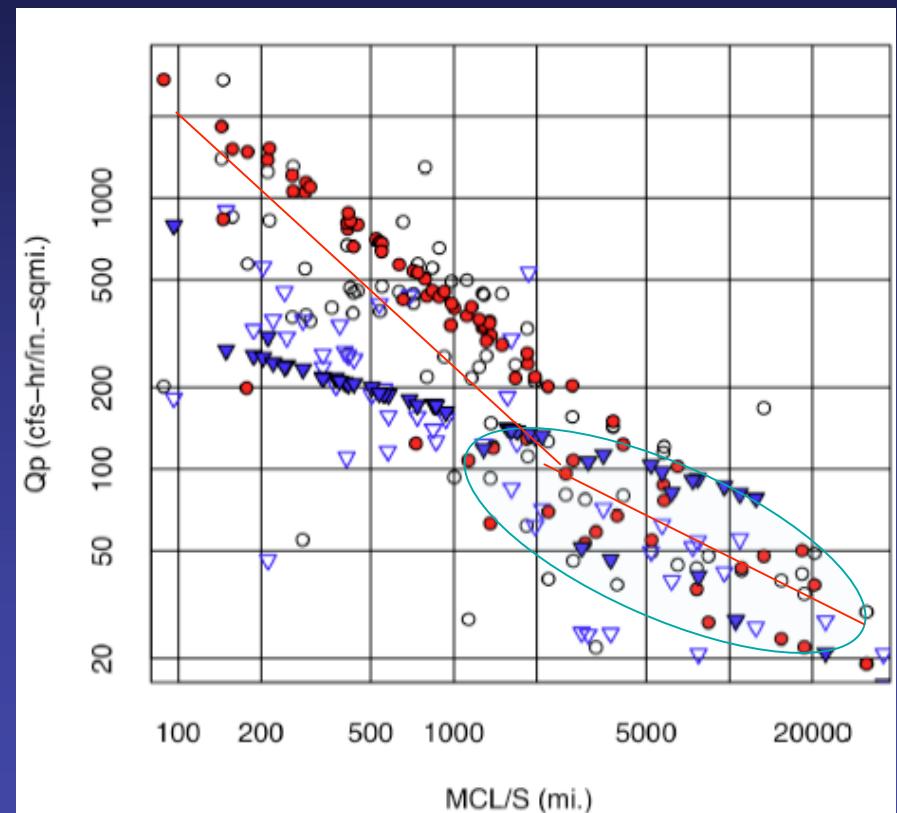
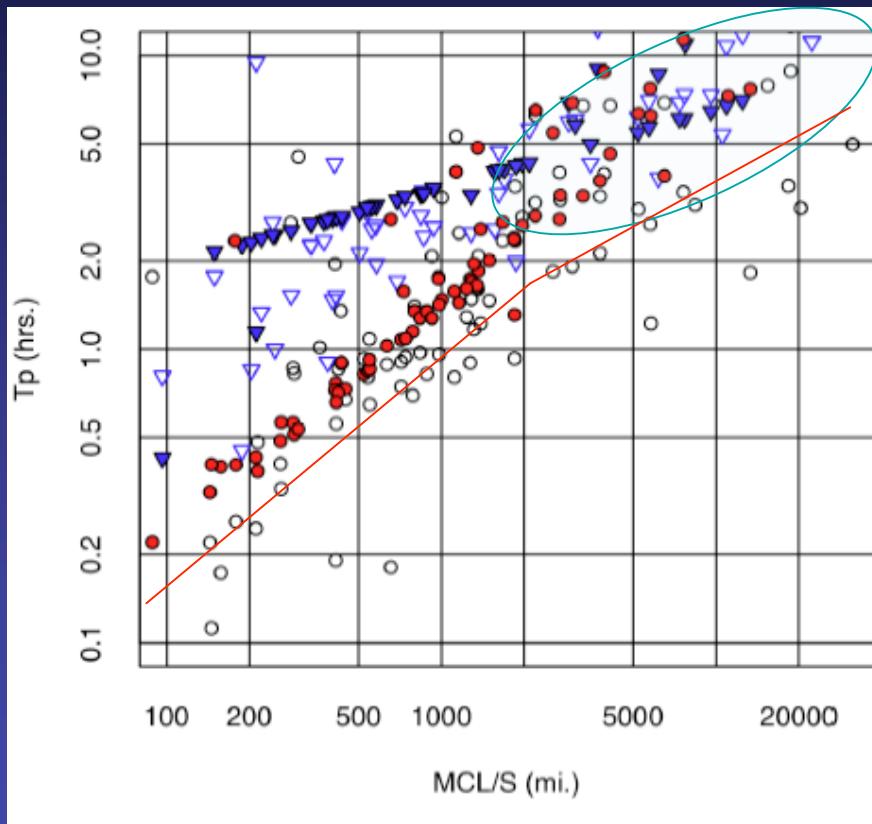


Illustrative Results (GIUH)

- Peak comparison.
- Bias (low)
 - “ k ” value same all developed.
 - “ k ” value same all undeveloped.

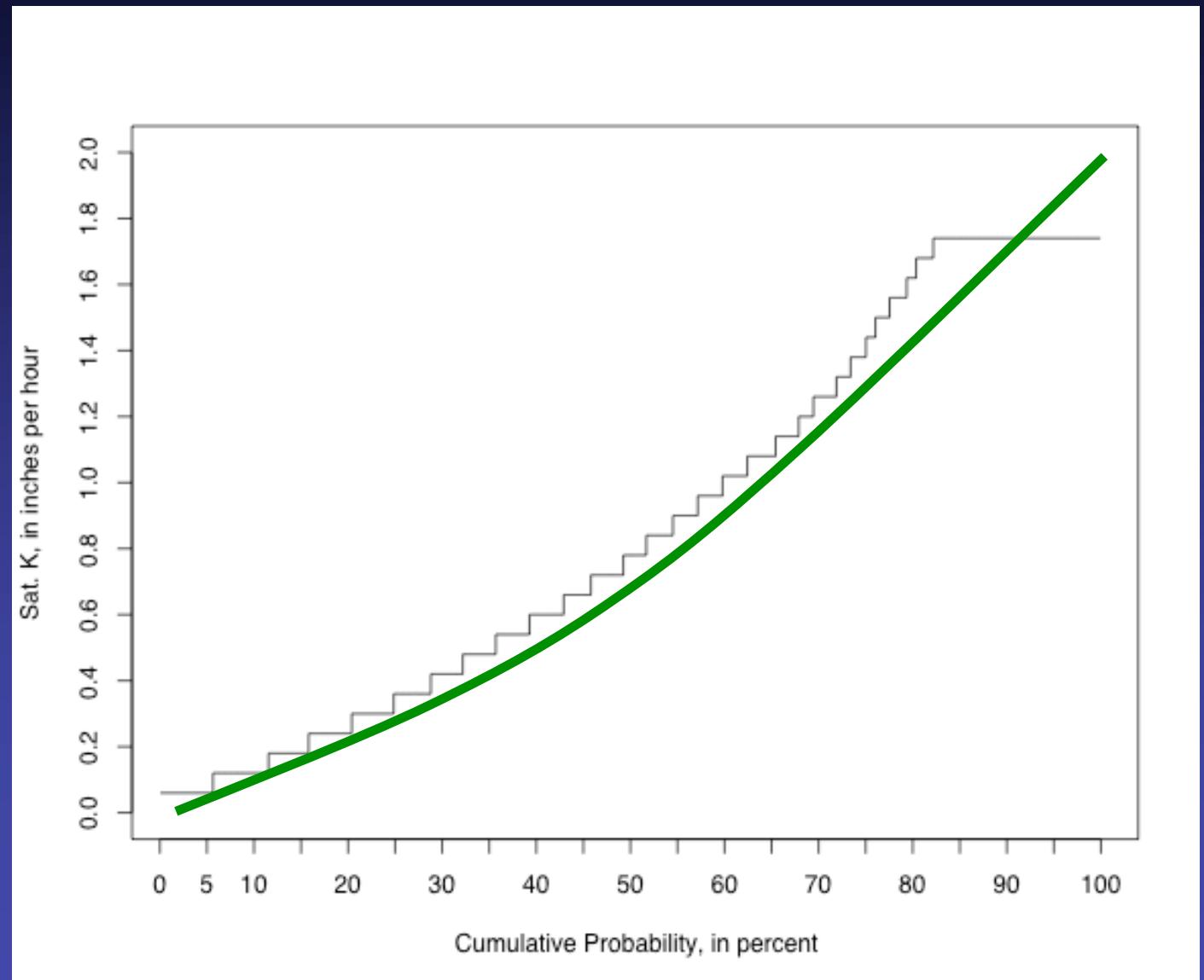


Development Distinction



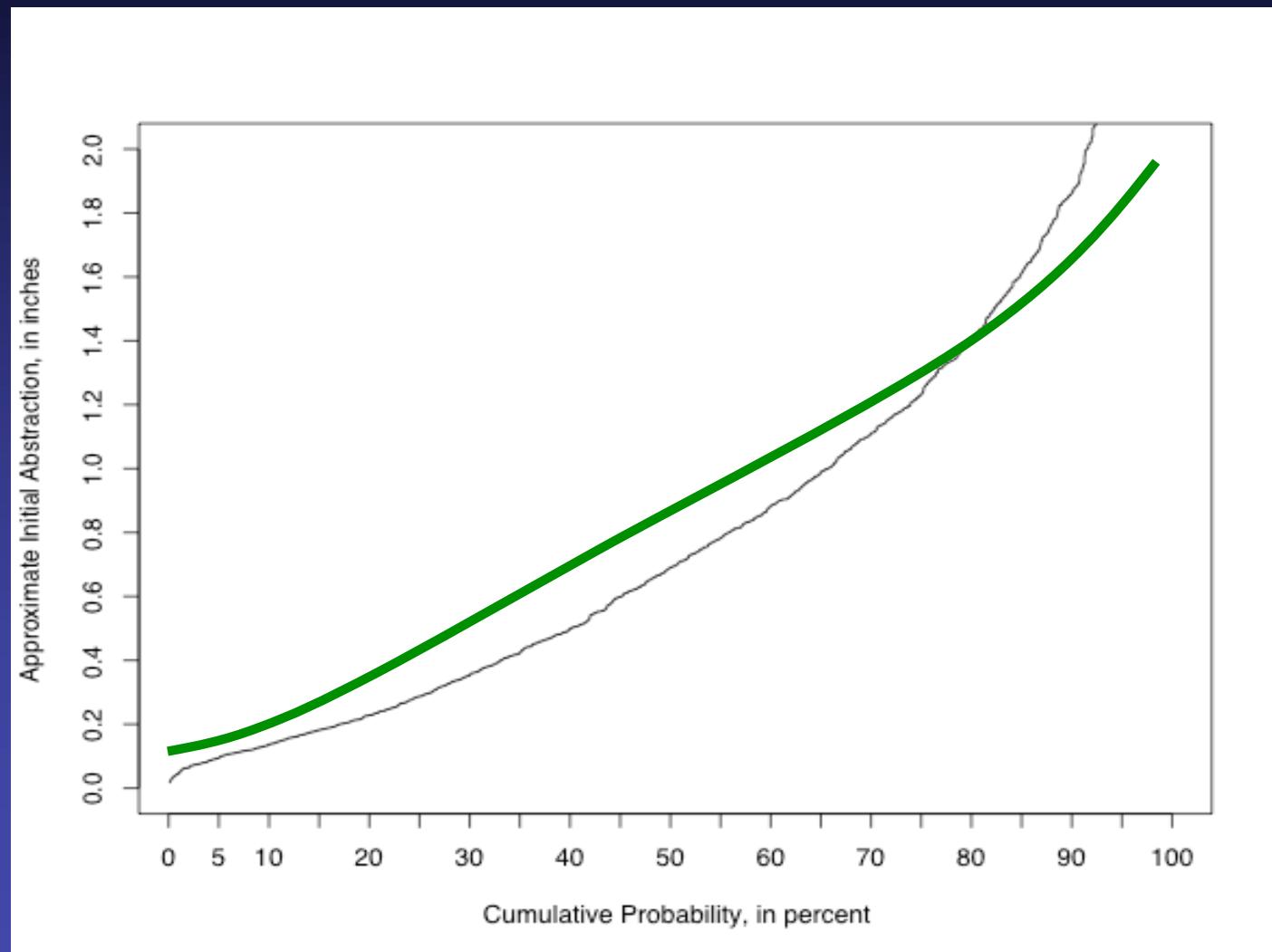
Infiltration Capacity Model

- Direct comparison with GUH approach not possible, but: K should be similar to loss rate.
- Green curve is “hand-drawn” GUH result



Infiltration Capacity Model

- Direct comparison with GUH approach not possible; an approximate comparison is displayed.
- Green curve is “hand-drawn” GUH result



Summary

- Based on all approaches:
 - Urbanization cuts time to peak in half, which substantially increases peak discharge.
 - Unit hydrographs can be reliably estimated for many watersheds based on physical characteristics.
 - **Understand time and one understands the hydrograph.**
 - Dimensionless hydrograph shapes for developed and undeveloped watersheds are similar.

Summary

- Based on Gamma approach:
 - Constant loss (0.5 in/hr)
 - Initial abstraction is about 1.1 in. (undeveloped) and 0.5 in. (developed).
 - Urbanization cuts initial abstraction by about half.
 - Urbanization apparently has limited influence on constant loss for macrowatersheds?

Summary

- Based on GIUH approach:
 - Asymptotic loss (0.8 in/hr) (Comparable).
 - Initial abstraction approximation is 0.6 inches (Smaller but comparable).
 - Urbanization distinction is expected to be comparable.

Summary

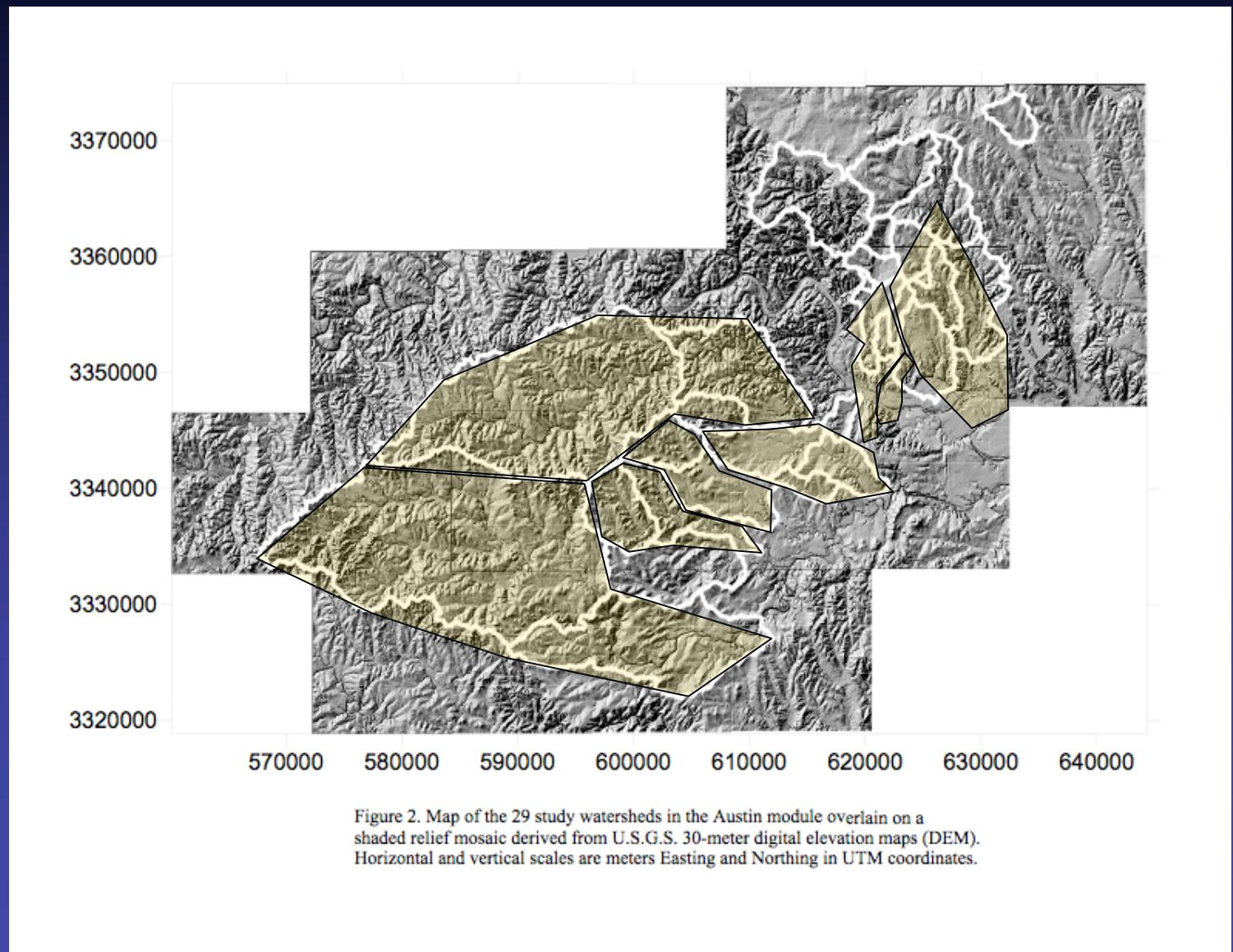
- Common rainfall-runoff database.
- Common concept of temporal redistribution of excess rainfall.
- Otherwise independent procedures produce comparable results!
- For appropriate watersheds:
 - GUH tool is developed.
 - GIUH is a research tool to explore ensemble approaches.

Subdivision For Modeling

- From the existing database
 - 17 Superset watersheds with gaged subset sub-areas.
 - 8 Austin
 - 3 Dallas
 - 2 Fort Worth
 - 1 San Antonio
 - 3 Small Rural Watersheds
 - 15 Supersets have paired rainfall-runoff events for all sub-areas.

Subdivision For Modeling

- Austin Area



Subdivision For Modeling

- Dallas Area

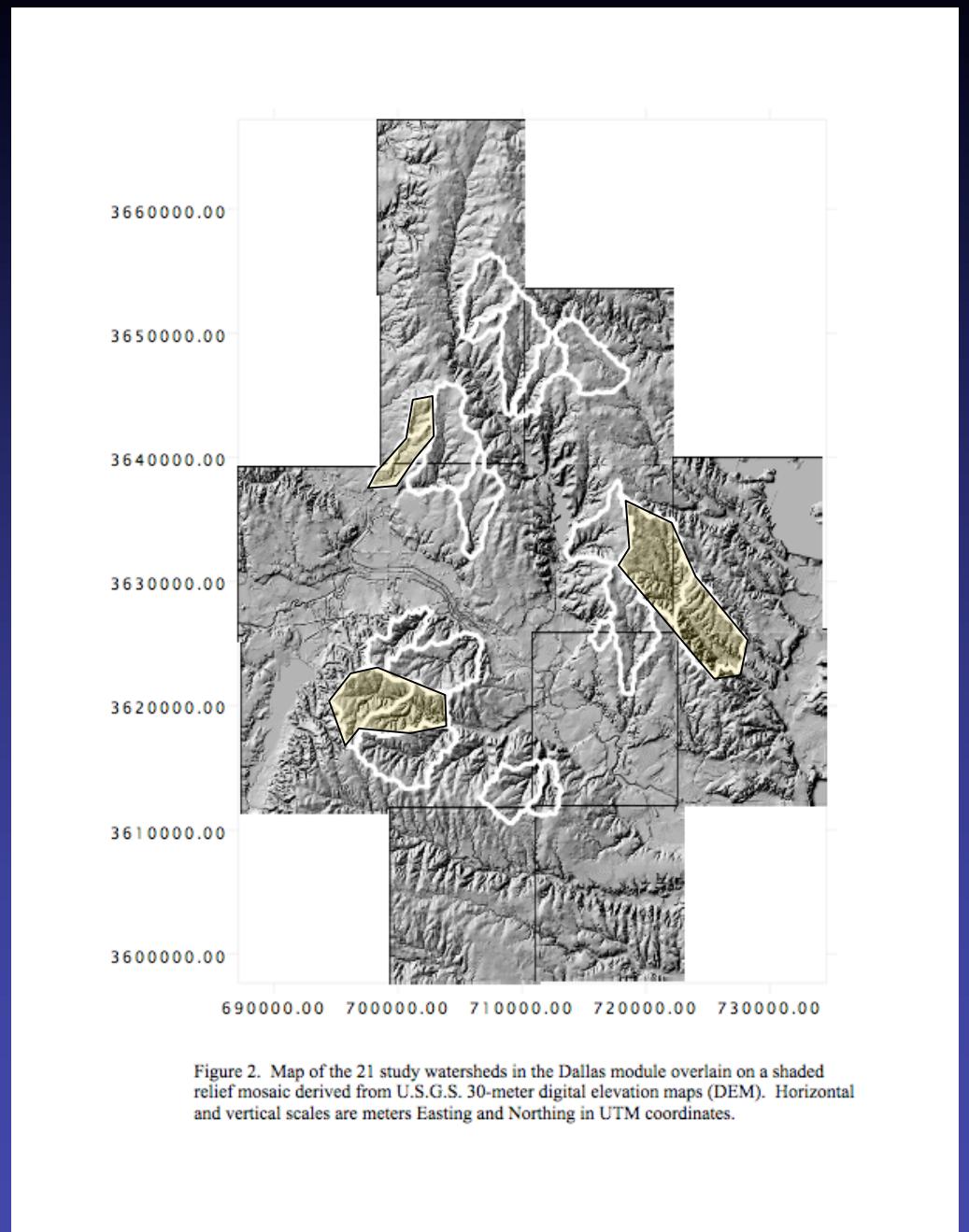


Figure 2. Map of the 21 study watersheds in the Dallas module overlaid on a shaded relief mosaic derived from U.S.G.S. 30-meter digital elevation maps (DEM). Horizontal and vertical scales are meters Easting and Northing in UTM coordinates.

Subdivision For Modeling

- Fort Worth Area

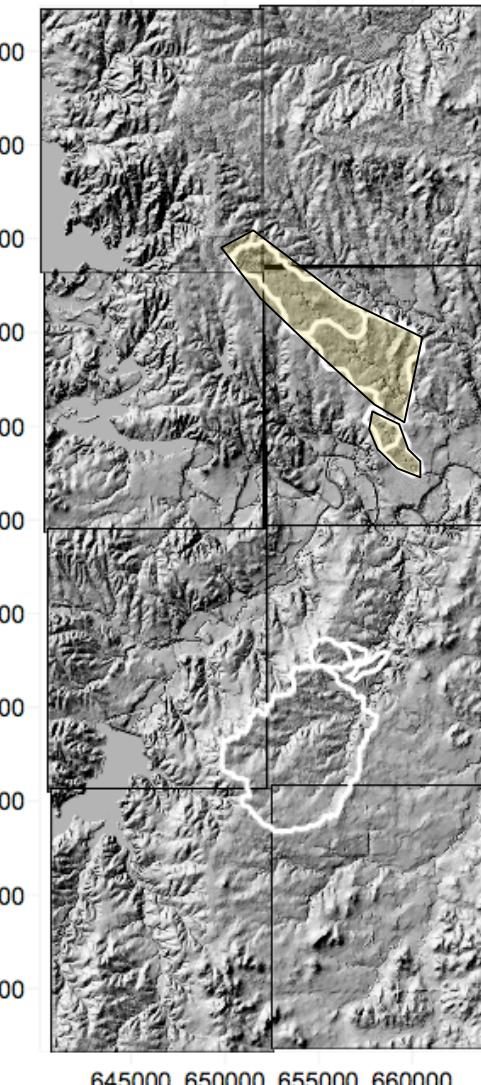
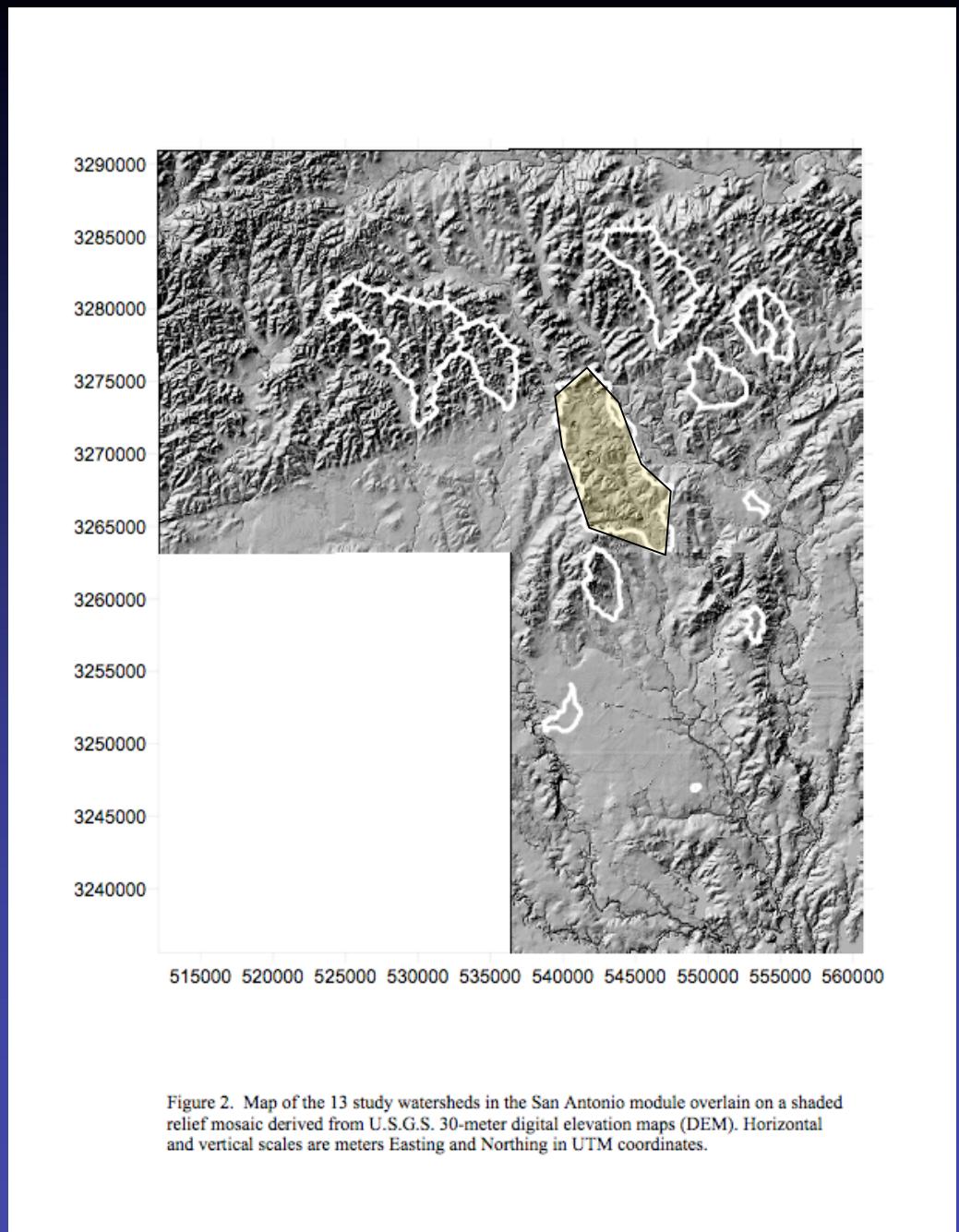


Figure 2. Map of the 8 study watersheds in the Fort Worth Module overlain on a mosaic of shaded relief maps derived from U.S.G.S. 30-meter digital elevation maps (DEM). Horizontal and vertical scales are meters Easting and Northing in UTM coordinates.

Subdivision For Modeling

- San Antonio Area



Subdivision For Modeling

- Small Rural Watersheds

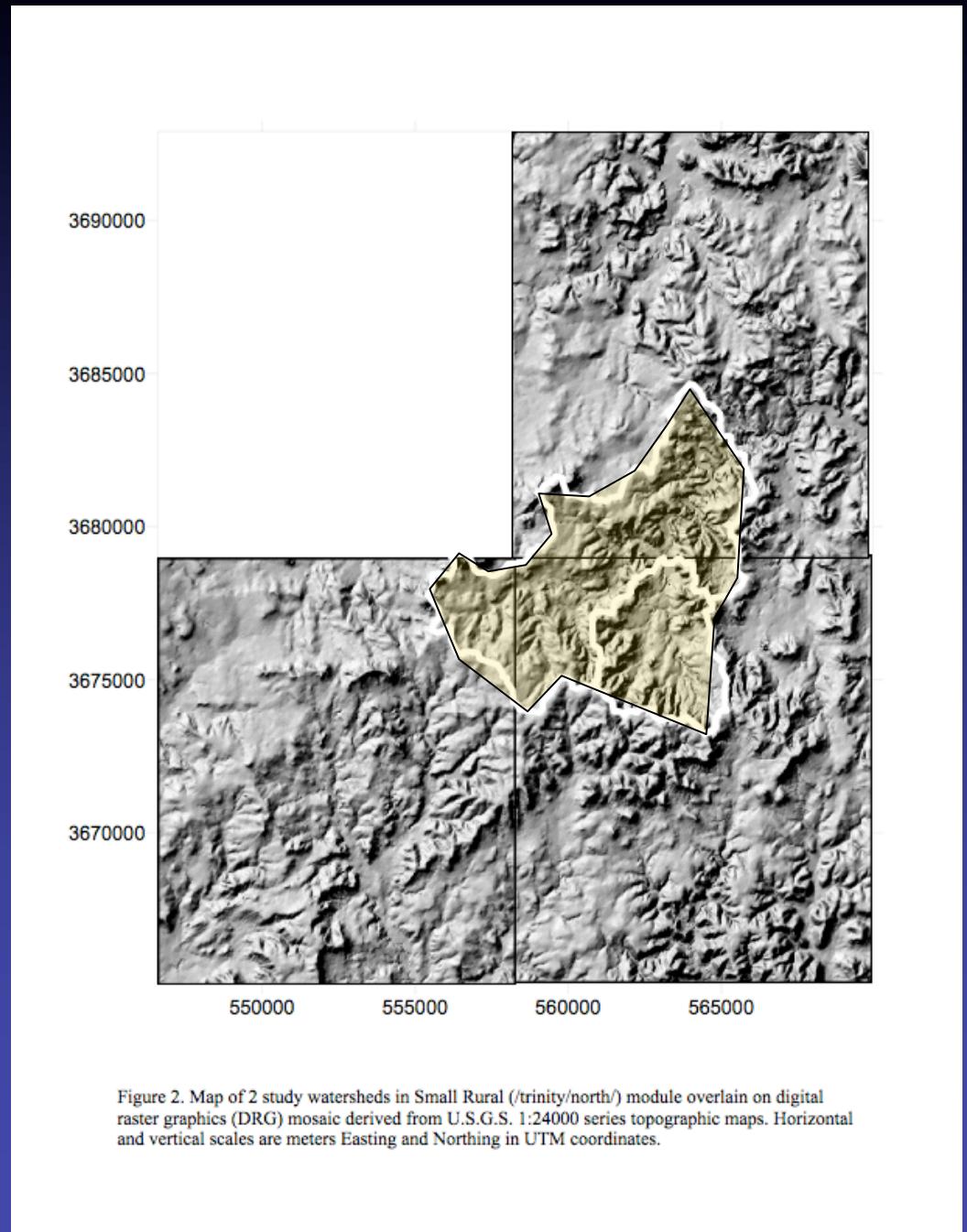


Figure 2. Map of 2 study watersheds in Small Rural (/trinity/north/) module overlain on digital raster graphics (DRG) mosaic derived from U.S.G.S. 1:24000 series topographic maps. Horizontal and vertical scales are meters Easting and Northing in UTM coordinates.

Subdivision For Modeling

- Small Rural Watersheds

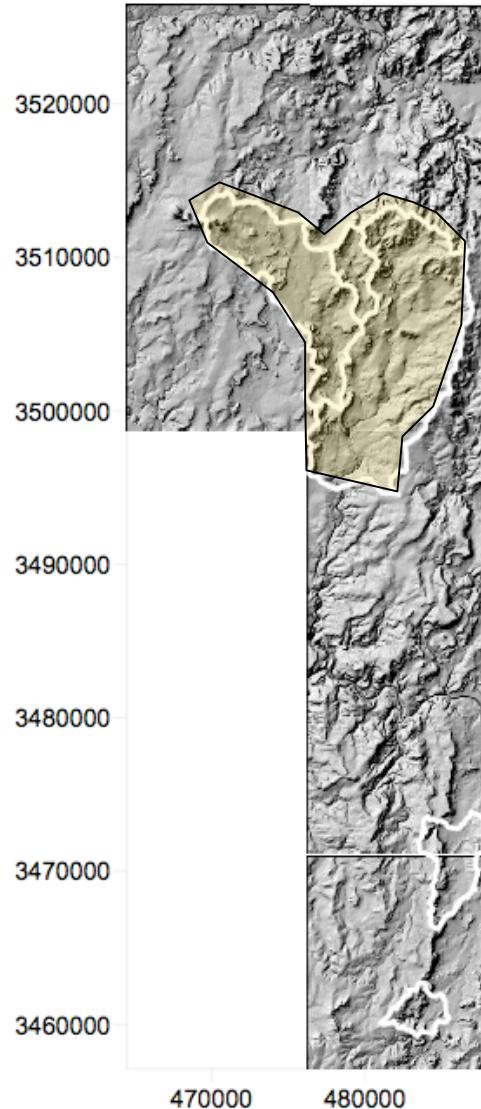
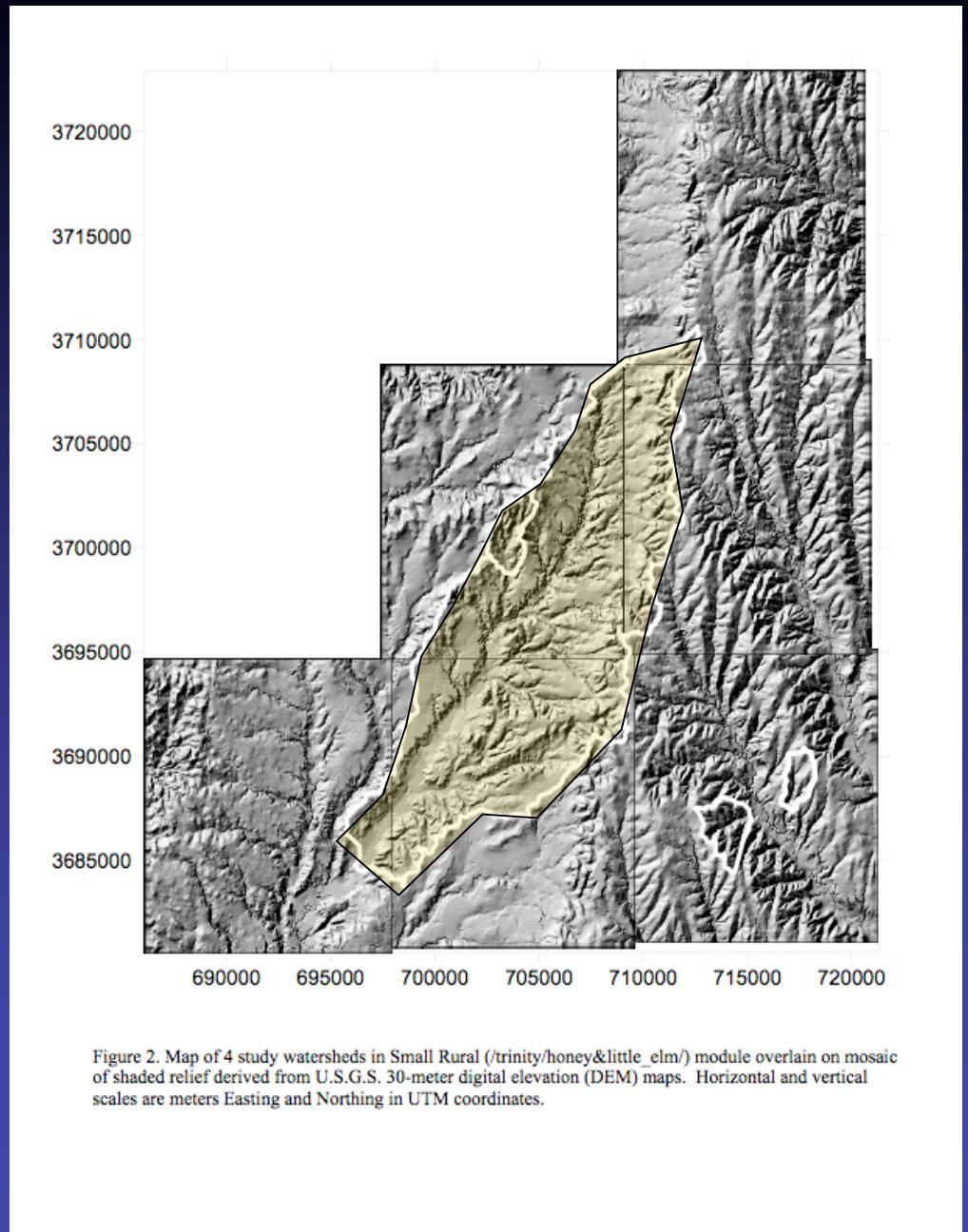


Figure 2. Map of 5 study watersheds in Small Rural (/colorado/deep&mukewater/) module overlain on a shaded relief mosaic derived from U.S.G.S. 30-meter digital elevation maps (DEM). Horizontal and vertical scales are meters Easting and Northing in UTM coordinates.

Subdivision For Modeling

- Small Rural Watersheds



Subdivision For Modeling

- These watersheds represent a set of test cases for subdivision testing.
 - Some are divided roughly equal area.
 - Some have vastly different sub-areas.
- These differences are serendipitous because they allow some testing of schemes suggested by literature

Subdivision For Modeling

- Modeling schemes (for subdividing):
 - Equal sub-watershed areas.
 - Equal characteristic path lengths.
 - Specified sub-watershed area ratios.
 - Equal slope and contiguous (HRU approach).
 - Equal characteristic times.
 - Specified characteristic time ratios.
 - Ad-hoc based on gaging convenience.
 - Random

Subdivision For Modeling

- Investigation approaches
 - Model each superset using HEC-HMS and TxDOT design manual (using recent reports where applicable).
 - Avoid calibration using observed runoff.
 - Apply historical storms, predict runoff, compute residuals between observed and these predictions.
 - These residuals are “declared” the standard residual against which all subdivision models will be compared.

Subdivision For Modeling

- Investigation approaches (continued)
 - Model the gage subdivisions in same fashion.
(Actually classify these subdivisions into one of the categories, if possible)
 - Measure change in residuals -- this change represents what we expect in terms of increased accuracy if any.
 - Then model each subdivision scheme in same fashion and tabulate residuals for different schemes.
 - Determine if any scheme can perform at least as well as the actual subdivision or lumped system.

Subdivision For Modeling

- Investigation approaches (Using the GIUH)
 - Similar approach, except that the GIUH model can be programmed to make the subdivisions according to the various rules, including “random”.
 - Determine if there is any variance (residual) reduction using a subdivision scheme.

Publications:

- <http://library.ctr.utexas.edu/dbtw-wpd/textbase/websearchcat.htm> (Search for authors: Asquith; Roussel; Thompson; Fang; or Cleveland).
- <http://cleveland1.cive.uh.edu/publications> (selected papers on-line).
- <http://infotrek.er.usgs.gov/pubs/> (Search for author Asquith; Roussel)
- <http://www.techmrt.ttu.edu/reports.php> (Search for author Thompson)
- <http://ceserver.lamar.edu/People/fang/research.html>