Regional Regression Equations: Use as a Check for Other Hydrologic Methods

by

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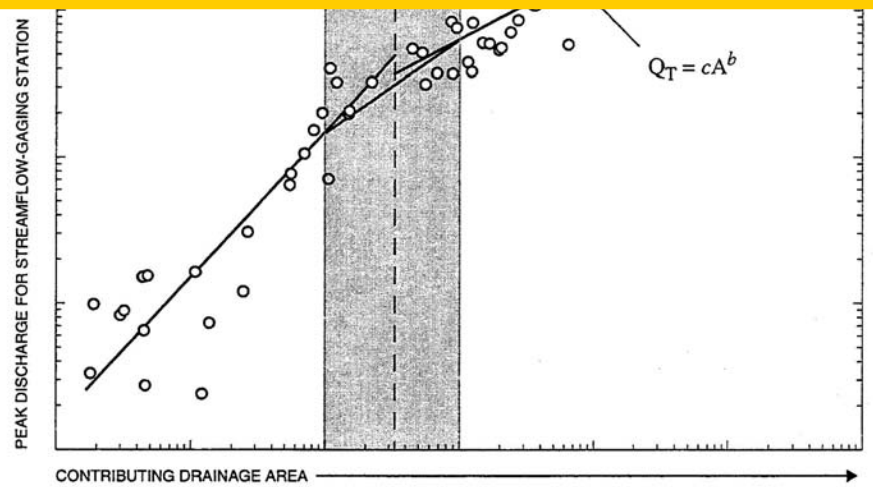
TxDOT 2007 Design & Bridge Conference

REGIONAL EQUATIONS FOR ESTIMATION OF PEAK-STREAMFLOW FREQUENCY FOR NATURAL BASINS IN TEXAS

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96–4307

http://pubs.usgs.gov/wri/wri964307/



Prepared in cooperation with the
TEXAS DEPARTMENT OF TRANSPORTATION

Regression Equation Peak Discharge Estimates

- USGS existing streamflow gage data
  - Statistical analysis limited by number of gage stations and period of record
- Compute predicted values of discharge for various risk levels (“return periods”)

11 hydrologic regions

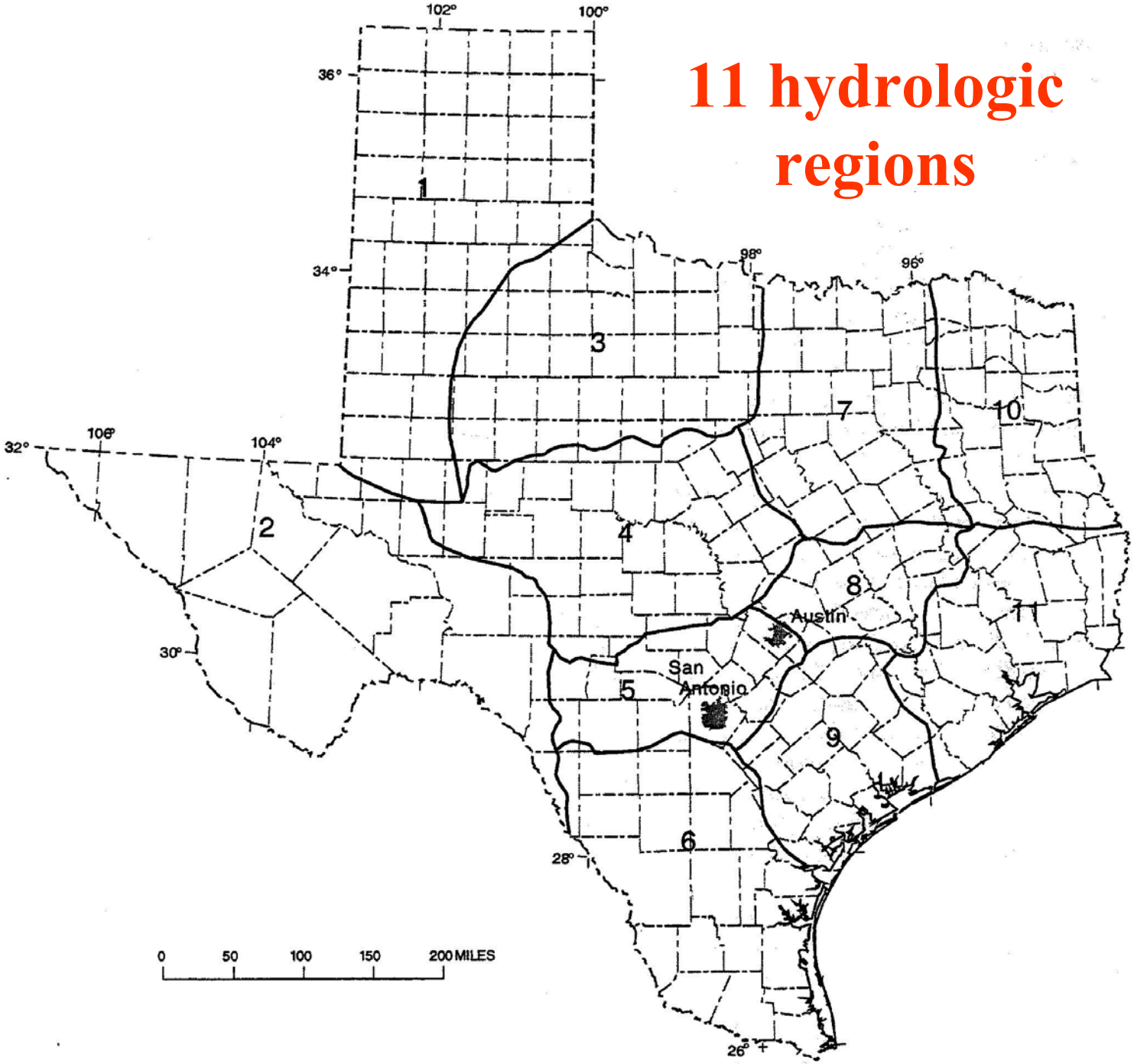


Table 2. Regression equations for estimation of peak-streamflow frequency for hydrologic regions of Texas—Continued

Hydrologic region and recurrence interval	Weighted least-squares regression equation for corresponding recurrence interval	Range of indicated independent variables in corresponding region (units as noted)	Adjusted R-squared[1]	Weighted standard error of estimate (percent)	Weighted standard error of estimate ($\log_{10}$ units)	No. of stations in analysis for equation
Region 4 (sites with contributing drainage area less than 32 square miles)[2]						
2 yr	$Q_2 = 97.1\ A^{.626}$	A: 0.19 to 81.1	0.49	134	0.44	28
Region 5 (sites with contributing drainage area less than 32 squares miles)[2]						
2 yr	$Q_2 = 159\ A^{.680}$	A: 0.18 to 22.3	.73	75	.29	24
5 yr	$Q_5 = 396\ A^{.773}$		.82	63	.25	24
10 yr	$Q_{10} = 624\ A^{.820}$	SH: 0.50 to 84.9	.83	66	.26	24
25 yr	$Q_{25} = 997\ A^{.866}$		.83	69	.27	24
50 yr	$Q_{50} = 278\ A^{.973}\ SL^{.360}$	SL: 20.9 to 224	.83	72	.28	24
100 yr	$Q_{100} = 295\ A^{1.01}\ SL^{.405}$		.83	78	.30	24
Region 5 (sites with contributing drainage area greater than 32 squares miles)[2]						
2 yr	$Q_2 = 377\ A^{.498}$	A: 45.0 to 1,861	.60	43	.18	38
5 yr	$Q_5 = 1270\ A^{.534}\ SH^{-.145}$		.78	28	.12	38
10 yr	$Q_{10} = 2310\ A^{.552}\ SH^{-.221}$	SH: 3.14 to 20.8	.79	28	.12	38
25 yr	$Q_{25} = 4330\ A^{.571}\ SH^{-.307}$		.75	31	.13	38
50 yr	$Q_{50} = 6450\ A^{.583}\ SH^{-.366}$	SL: 9.86 to 48.8	.72	36	.15	38
100 yr	$Q_{100} = 9180\ A^{.594}\ SH^{-.420}$		.69	41	.17	38

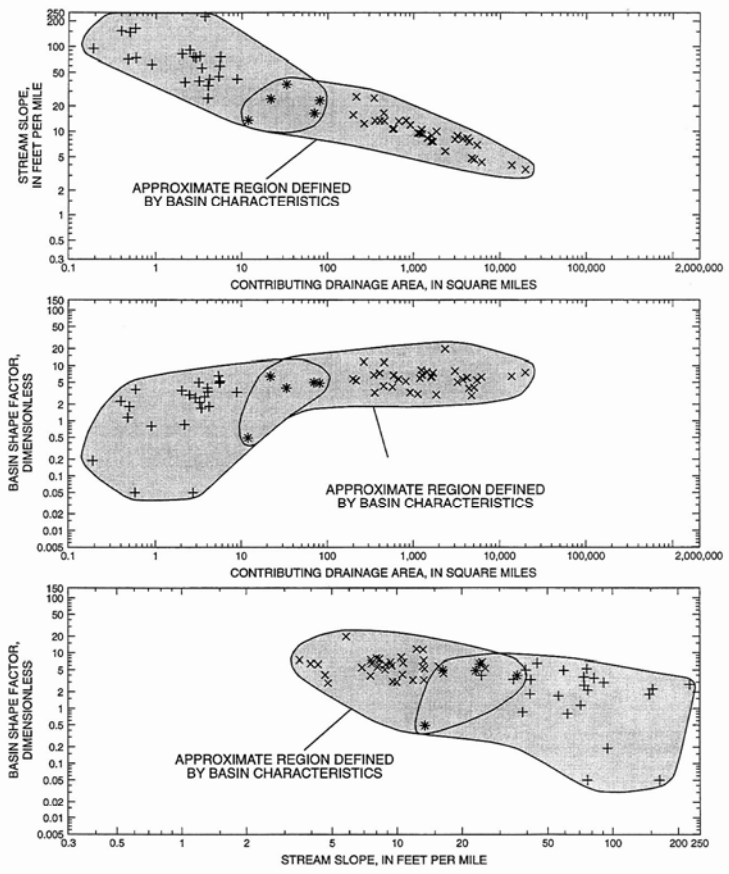
Footnotes at end of table.

Regression equations for estimation of peak-streamflow frequency for hydrologic regions of Texas

Predicted Peak Discharge

- $Q_T = a(A)^b(SH)^c(SL)^d$
  - Q_T = T-year discharge (cfs)
  - A = contributing drainage area (sq. mile)
  - SH = basin shape factor
  - SL = mean channel slope (ft./mile)
  - a, b, c, d = linear regression coefficients
- Pay attention to variable limits!

Predicted Peak Discharge



Explanation

+ **Basin characteristic for station included in regression analysis for contributing drainage area less than 32 square miles—✳ symbol represents station included in both sets of equations (table 2).**

× **Basin characteristic for station included in regression analysis for contributing drainage area greater than 32 square miles—✳ symbol represents station included in both sets of equations (table 2).**

Figure 7. Relation between basin characteristics for region 4.

Figure 7 19

Evaluate regression equation applicability by comparing basin characteristics of your site to regression analysis.

Figures 4 – 14; the "clouds"

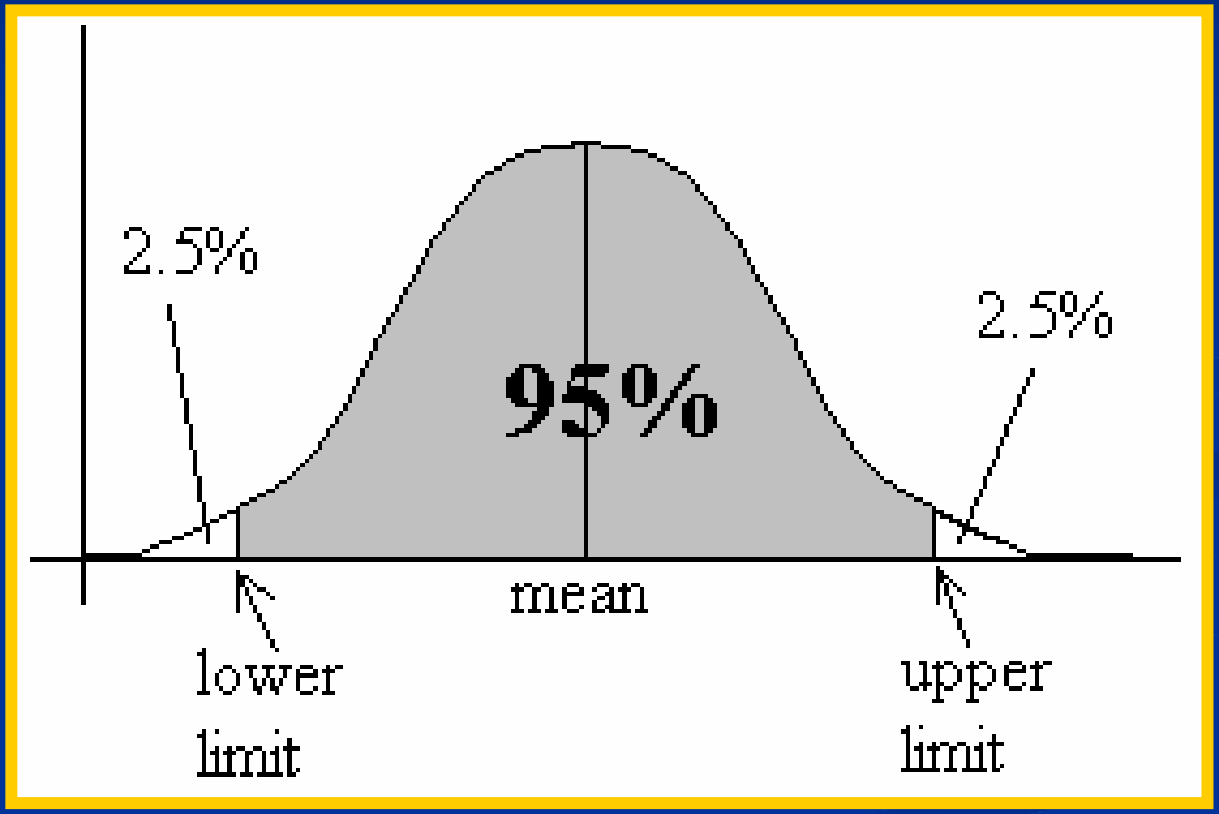
Confidence Limits

- Lower & upper confidence limits of predicted peak discharge
  - Procedures included in USGS publication
  - Compute 50-, 67-, & 90-percent confidence limits
  - Not in current *Hydraulic Design Manual*

Central Limit Theorem

- Basis of confidence limits
- The error between measured and actual (or predicted and actual) values is normally distributed for a discrete sample of data
- The central tendency or spread from the mean (predicted) value can estimate the normal distribution – leading to confidence values

95% Confidence Limits



Computation of Confidence Limits

$$\log Q_T - t_{(\propto/2,n-p)}\sqrt{s^2(1+h_0)}$$

$$\leq \log Q_T \leq$$

$$\log Q_T + t_{(\propto/2,n-p)}\sqrt{s^2(1+h_0)}$$

Computation of Confidence Limits

$$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$$

Computation of Confidence Limits

- $\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$
  - $\log Q_T = \log_{10}$ of T-year recurrence interval peak discharge
    - Example: Say $Q_{100} = 9350$ cfs

      then $\log(9350) = 3.9708$

$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$

Table 2. Regression equations for estimation of peak-streamflow frequency for hydrologic regions of Texas—Continued

Hydrologic region and recurrence interval	Weighted least-squares regression equation for corresponding recurrence interval	Range of indicated independent variables in corresponding region (units as noted)	Adjusted R-squared[1]	Weighted standard error of estimate (percent)	Weighted standard error of estimate ($\log_{10}$ units)	No. of stations in analysis for equation
Region 4 (sites with contributing drainage area less than 32 square miles)[2]						
2 yr	$Q_2 = 97.1\ A^{.626}$	A: 0.19 to 81.1	0.49	134	0.44	28
5 yr	$Q_5 = 196\ A^{.650}\ SH^{.257}$		.70	96	.35	28
10 yr	$Q_{10} = 293\ A^{.697}\ SH^{.281}$	SH: 0.05 to 6.52	.74	92	.34	28
25 yr	$Q_{25} = 455\ A^{.741}\ SH^{.311}$		.75	99	.36	28
50 yr	$Q_{50} = 53\ A^{.927}\ SL^{.558}\ SH^{.333}$	SL: 13.5 to 226	.74	107	.38	28
100 yr	$Q_{100} = 51\ A^{.968}\ SL^{.627}\ SH^{.353}$		.72	120	.41	28
Region 4 (sites with contributing drainage area greater than 32 square miles)[2]						
2 yr	$Q_2 = 0.00660\ A^{1.29}\ SL^{2.09}$	A: 12 to 19,819	.68	72	.28	39
5 yr	$Q_5 = 0.0212\ A^{1.24}\ SL^{2.18}$		.76	51	.21	39
10 yr	$Q_{10} = 0.0467\ A^{1.20}\ SL^{2.18}$	SH: 0.49 to 19.7	.76	49	.20	39
25 yr	$Q_{25} = 0.102\ A^{1.16}\ SL^{2.18}$		.70	54	.22	39
50 yr	$Q_{50} = 0.166\ A^{1.13}\ SL^{2.19}$	SL: 3.52 to 36.1	.64	60	.24	39
100 yr	$Q_{100} = 0.252\ A^{1.11}\ SL^{2.19}$		.57	69	.27	39
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2 yr	$Q_2 = 159\ A^{.680}$	A: 0.18 to 22.3	.73	75	.29	24
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100 yr	$Q_{100} = 9180\ A^{.594}\ SH^{-.420}$		.69	41	.17	38

Footnotes at end of table.

n = # of stations in analysis for regression equation;

lookup value from Table 2

$$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$$

p = # of independent variables (A, SH, SL) in specific equation, plus 1 (for regression constant)

$$Q_T = a(A)^b(SH)^c(SL)^d$$

$$p = \{A+SH+SL\}+1$$

$$= 3+1 = 4$$

$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$

Table 3. Critical values of the t-distribution for selected confidence limits for regression equations

[Degrees of freedom are those associated with regression equations (table 2). n, number of stations upon which a regression equation is based; p, number of significant independent variables in regression equation plus 1 (for regression constant)]

Degrees of freedom (n - p)	Critical value of t-distribution for 50-percent confidence limits ($\alpha = 0.50$)[1]	Critical value of t-distribution for 67-percent confidence limits ($\alpha = 0.33$)[1]	Critical value of t-distribution for 90-percent confidence limits ($\alpha = 0.10$)[1]
18	0.6884	[illegible]	1.734
19	.6876	.9997	1.729
21	.6864	.9972	1.721
22	.6858	.9962	1.717
24	.6849	.9943	1.711
25	.6844	.9935	1.708
26	.6840	.9927	1.706
35	.6816	.9879	1.690
41	[illegible]	[illegible]	[illegible]
44	.6801	.9850	1.680
45	.6800	.9848	1.679
53	.6791	.9832	1.674
54	.6791	.9830	1.674
62	.6785	.9818	1.670
63	.6784	.9817	1.669

[1] Critical values of t-distribution reflect a two-tailed test; therefore, a 50-percent confidence limit ($\alpha = 0.50$) uses a $\alpha/2$ (0.25) critical t-value.

$t(\alpha/2,n-p)$ = critical value of t-distribution for selected confidence interval; lookup value from Table 3

$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$

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Footnotes at end of table.

s = weighted standard error of estimate of regression equation; lookup value from Table 2

Now things get a bit complicated…

$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$

- h_0 = leverage of site, which expresses the distance of the site's basin characteristics from the center of the space defined by the independent variables in the regression
- Confidence limits directly related to the magnitude of h_0
- $h_0 = \mathbf{x_0} \{ \mathbf{X}^T \mathbf{W}^{-1} \mathbf{X} \}^{-1} \mathbf{x_0}^T$

$$h_0 = x_0 \{ X^T W^{-1} X \}^{-1} x_0^T$$

- x_0 = row vector of basin characteristics of site
- x_0^T = column vector of basin characteristics of site

- x_0 = [log(A) log(SH) log(SL) 1]
  - use only basin characteristics as applicable to specific regression equation, plus 1 for the regression constant

$$h_0 = x_0 \{ X^T W^{-1} X \}^{-1} x_0^T$$

Table 4. Covariance matrix for regression equations—Continued

miles and 2-year recurrence interval)

	Area	Slope	Shape	Constant
Area	0.063865	0.12106	-0.045171	-0.25199
Slope	0.12106	0.75422	0.090103	-1.2004
Shape	-0.045171	0.090103	0.25245	-0.22949
Constant	-0.25199	-1.2004	-0.22949	2.1771

Region 3 (contributing drainage area greater than 32 square miles and recurrence intervals greater than 2-year)

	Area	Slope	Constant
Area	0.055783	0.13718	-0.29305
Slope	0.13718	0.72206	-1.1185
Constant	-0.29305	-1.1185	1.9685

Region 4 (contributing drainage area less than 32 square miles and 2-year recurrence interval)

	Area	Constant
Area	0.070227	-0.054414
Constant	-0.054414	0.077877

Region 4 (contributing drainage area less than 32 square miles and 5-, 10-, and 25-year recurrence intervals)

	Area	Shape	Constant
Area	0.096864	-0.073950	-0.048446
Shape	-0.073950	0.20529	-0.016569
Constant	-0.048446	-0.016569	0.079214

Region 4 (contributing drainage area less than 32 square miles and 50- and 100-year recurrence intervals)

	Area	Shape	Slope	Constant
Area	0.19104	-0.074162	0.32967	-0.67338
Shape	-0.074162	0.20529	-7.4307E-4	-0.015161
Slope	0.32967	-7.4307E-4	1.1540	-2.1876
Constant	-0.67338	-0.015161	-2.1876	4.2262

miles and all recurrence intervals)

	Area	Slope	Constant
Area	0.40976	1.0625	-2.3260
Slope	1.0625	3.3389	-6.6232
Constant	-2.3260	-6.6232	13.829

Region 5 (contributing drainage area less than 32 square miles and 2-, 5-, 10-, and 25-year recurrence intervals)

	Area	Constant
Area	0.089459	-0.042645
Constant	-0.042645	0.061995

Region 5 (contributing drainage area less than 32 square miles and 50- and 100-year recurrence intervals)

	Area	Slope	Constant
Area	0.14054	0.23520	-0.48936
Slope	0.23520	1.0829	-2.0568
Constant	-0.48936	-2.0568	3.9684

Region 5 (contributing drainage area greater than 32 square miles and 2-year recurrence interval)

	Area	Constant
Area	0.13836	-0.34985
Constant	-0.34985	0.91094

Region 5 (contributing drainage area greater than 32 square miles and 5-, 10-, 25-, 50-, and 100-year recurrence intervals)

	Area	Shape	Constant
Area	0.15134	-0.092122	-0.30560
Shape	-0.092122	0.65384	-0.31408
Constant	-0.30560	-0.31408	1.0618

Region 6 (2-year recurrence interval)

	Area	Shape	Constant
Area	0.097111	-0.16596	-0.18497
Shape	-0.16596	0.55383	0.10792
Constant	-0.18497	0.10792	0.56032

Region 6 (5-, 10-, 25-, 50-year recurrence intervals)

	Area	Slope	Constant
Area	0.074275	0.21725	-0.45192
Slope	0.21725	1.7549	-2.4175
Constant	-0.45192	-2.4175	3.8698

Region 6 (100-year recurrence interval)

	Area	Constant
Area	0.047378	-0.15262
Constant	-0.15262	0.53929

Region 7 (contributing drainage area less than 32 square miles and 2-year recurrence interval)

	Area	Slope	Constant
Area	0.079614	0.19151	-0.32236
Slope	0.19151	0.66027	-1.0641
Constant	-0.32236	-1.0641	1.7439

$\{ X^T W^{-1} X \}^{-1}$ = covariance matrix of regression model; lookup matrix from Table 4

Alert: Table 4 Error

Table 4. Covariance matrix for regression equations—Continued

Region 7 (contributing drainage area less than 32 square miles and 5-, 10-, 25-, 50-, and 100-year recurrence intervals)

	Area	Constant
Area	0.024065	-0.013728
Constant	-0.013728	0.029106

Region 7 (contributing drainage area greater than 32 square miles and 2- and 5-year recurrence intervals)

	Area	Slope	Constant
Area	0.13654	0.26728	-0.59495
Slope	0.26728	1.2211	-1.8376
Constant	-0.59495	-1.8376	3.2641

Region 7 (contributing drainage area greater than 32 square miles and 10-, 25-, 50-, and 100-year recurrence intervals)

	Area	Slope	Shape	Constant
Area	0.14900	0.28119	-0.096212	-0.56427
Slope	0.28119	1.2366	-0.10739	-1.8034
Shape	-0.096212	-0.10739	0.74283	-0.23686
Constant	-0.56427	-1.8034	-0.23686	3.3397

Region 8 (all recurrence intervals)

	Area	Slope	Constant
Area	0.16975	0.38321	-0.78705
Slope	0.38321	1.4031	-2.2877
Constant	-0.78705	-2.2877	4.1821

Region 9 (2-year recurrence interval)

	Area	Constant
Area	0.037766	-0.089740
Constant	-0.089740	0.23888

Region 9 (5- and 10-year recurrence intervals)

	Area	Shape	Slope	Constant
Area	0.19332	-0.28044	0.22198	-0.43536
Shape	-0.28044	0.64673	-0.15191	0.26289
Slope	0.22198	-0.15191	0.75348	-1.1268

Region 9 (25-, 50-, and 100-year recurrence intervals)

	Area	Slope	Shape	Constant
Area	0.19332	0.22198	-0.28044	-0.43536
Slope	0.22198	0.75348	-0.15191	-1.1268
Shape	-0.28044	-0.15191	0.64673	0.26289

Region 10 (contributing drainage area less than 32 square miles and all recurrence intervals)

	Area	Slope	Constant
Area	0.18721	0.32999	-0.62684
Slope	0.32999	0.81005	-1.3718
Constant	-0.62684	-1.3718	2.4478

Region 10 (contributing drainage area greater than 32 square miles and all recurrence intervals)

	Area	Slope	Constant
Area	0.60170	1.3692	-2.5188
Slope	1.3692	3.4902	-5.9766
Constant	-2.5188	-5.9766	10.728

Region 11 (2-year recurrence interval)

	Area	Shape	Constant
Area	0.030010	-0.050613	-0.030238
Shape	-0.050613	0.2191	-0.042323
Constant	-0.030238	-0.042323	0.11073

Region 11 (5-year recurrence interval)

	Area	Shape	Slope	Constant
Area	0.039771	-0.054407	0.039783	-0.077090
Shape	-0.054407	0.22057	-0.015459	-0.024117
Slope	0.039783	-0.015459	0.16216	-0.19099
Constant	-0.077090	-0.024117	-0.19099	0.33567

Region 11 (10-year recurrence interval)

	Area	Slope	Shape	Constant
Area	0.039771	0.039783	0.054407	-0.077090
Slope	0.039783	0.16216	-0.15459	-0.19099
Shape	-0.054407	-0.015459	0.22057	-0.027117
Constant	-0.077090	-0.19099	-0.024117	0.33567

Region 11 (25-, 50-, and 100-year recurrence intervals)

	Area	Slope	Constant
Area	0.026351	0.035969	-0.083039
Slope	0.035969	0.16107	-0.19268
Constant	-0.083039	-0.19268	0.33304

Covariance matrix for Region 9 (25-, 50-, & 100-year recurrence intervals) is missing the last row for the constant values; it should be a 4 x 4 matrix.

Check back with us for corrected matrix.

$h_0 = x_0 \{ X^T W^{-1} X \}^{-1} x_0^T$

- Remember matrix multiplication?
- $h_0 = [A \;\; B \;\; C] \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix} \begin{pmatrix} A \\ B \\ C \end{pmatrix}$

$$\begin{array}{rrr} A1 & A2 & A3 \\ +B4 & B5 & B6 \\ +\underline{C7} & \underline{C8} & \underline{C9} \\ D & E & F \end{array} \rightarrow [D \;\; E \;\; F] \begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{array}{r} DA \\ +EB \\ \underline{+FC} \\ \mathbf{h_0} \end{array}$$

$\log Q_T \pm t_{(\alpha/2,n-p)}[s^2(1+h_0)]^{1/2}$

Now have all input to compute confidence limits:

$Q_{100} = 9350$ cfs

$\log(9350) = 3.9708 \rightarrow 3.9708 \pm 0.2124$

$3.7584 \leq 3.9708 \leq 4.1832$

Now convert back to discharge by taking 10^x of each value $\rightarrow 10^{3.7584} \leq 10^{3.9708} \leq 10^{4.1832}$

5730 cfs ≤ 9350 cfs ≤ 15,200 cfs

Computation of Confidence Limits

- 5730 cfs $\leq$ 9350 cfs $\leq$ 15,200 cfs
  - Predicted discharge Q_{100} = 9350 cfs
  - Lower confidence limit for Q_{100} is 5730 cfs
  - Upper confidence limit for Q_{100} is 15,200 cfs

- So what can you do with these confidence limits?

I’m glad you asked…

Why Confidence Limits?

- Use as check for other hydrologic methods
  - Fundamentally different approaches can be complimentary
  - Reflection in hydrologic design process
  - Develop more complete picture for judgment call

General Hydrologic Methods

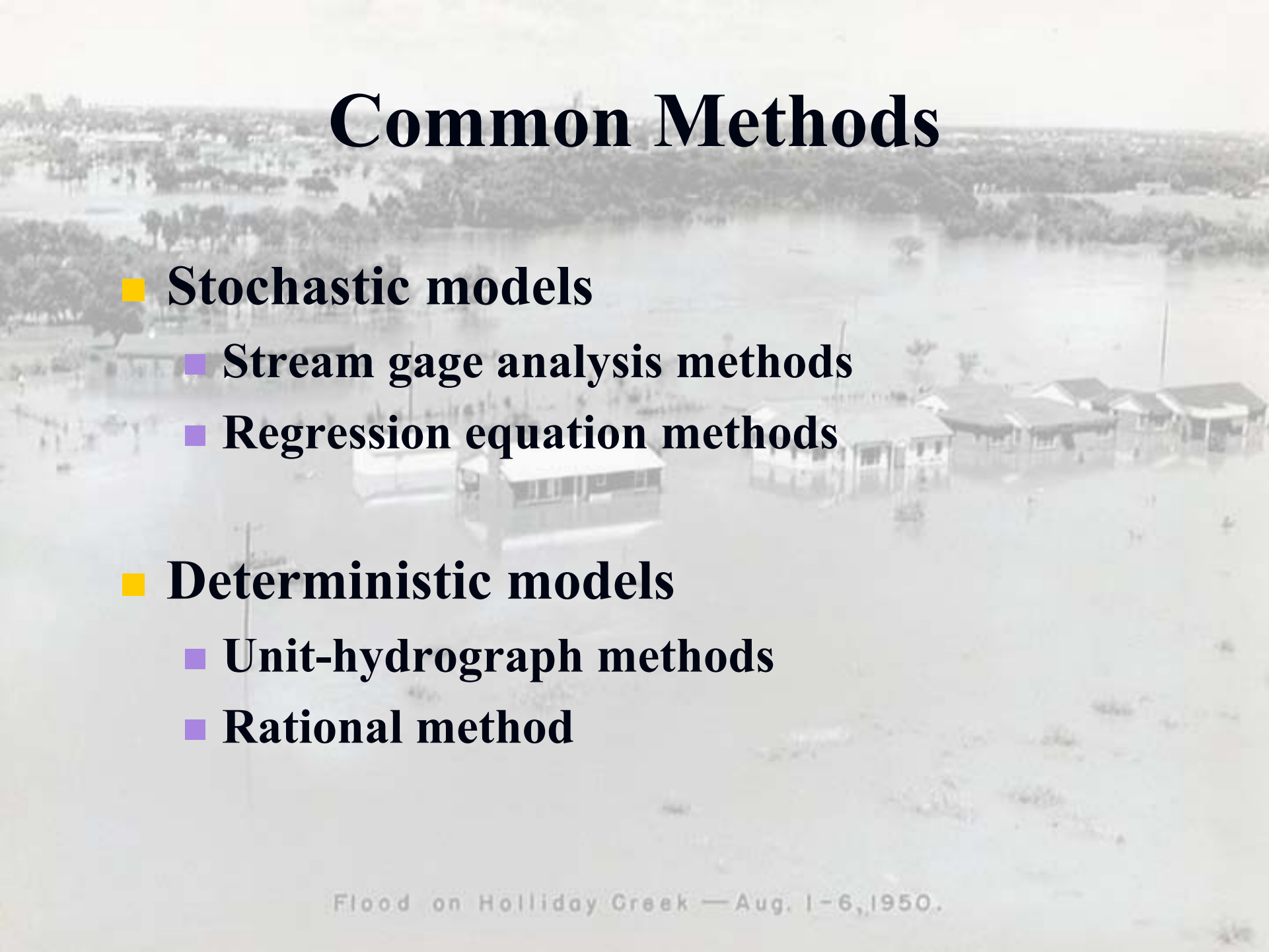
- Stochastic (statistically-based) methods
  - Use real streamflow data
  - Minimum consideration of basin characteristics
  - Disadvantages –
    - Inadequate "sample"
    - Lack of gage coverage
    - Inadequate period of record
    - Basin changes (urbanization)
    - Basin regulation (dams or diversions)

General Hydrologic Methods

- Deterministic methods
  - Rainfall-runoff process
  - Ungaged basins
  - Basin changes
  - Historic events
  - Disadvantages –
    - Validity of input
    - Standardized by practice/regulatory requirements

Common Methods

- Stochastic models
  - Stream gage analysis methods
  - Regression equation methods
- Deterministic models
  - Unit-hydrograph methods
  - Rational method



Hydrologic Method Comparison

- Recommended in *Hydraulic Design Manual*
- Two or more methods
- Don’t simply be conservative
  - More costly
  - Unnecessary stream modifications
  - Undesirable environmental permitting
  - Floodplain management concerns
  - Upgrading adequate structure

Hydrologic Method Comparison

- Stochastic method vs. deterministic method
  - “Real data” model compliments rainfall-runoff model
  - Typical to compare unit-hydrograph approach with regression equations
  - Regional regression equations as a check

Computer Programs

- Hydrologic methods are not computer programs
- TR-20, TR-55, HEC-1, HEC-HMS
  - Popular programs
    - All use unit-hydrograph method
  - Comparing results between these models is not sufficient

Time for a brief illustration…

Bridge example

- Consider proposed bridge replacement in Travis County
- Regional regression equation data:
  - Drainage area = 16 square miles
  - Stream length = 9 miles
  - Mean channel slope = 9 feet/mile
  - Basin shape factor = 5.1

Bridge example

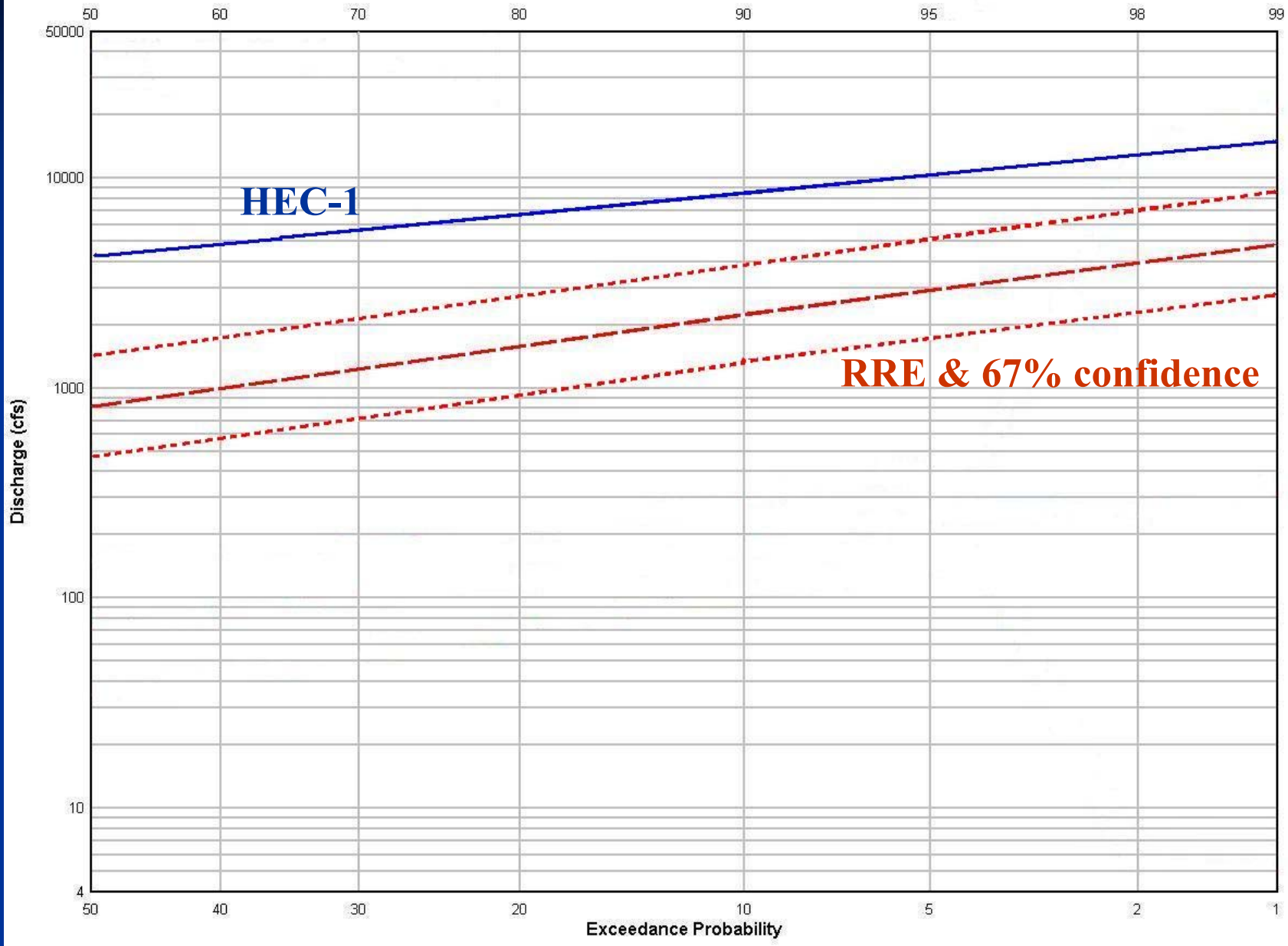
- NRCS dimensionless unit-hydrograph standard application data, using HEC-1:
  - TP-40 rainfall depths
  - NRCS Type III, 24-hour storm
  - NRCS RCN = 82 (AMC II)
  - T_c = 4.0 hours; ➔ lag time = $0.6T_c$

Comparing Q_{peak} Results

Storm	HEC-1	Regression
2-yr	4360 cfs	830 cfs
5-yr	7265	1750
10-yr	8490	2475
25-yr	10,980	3435
50-yr	13,130	4165
100-yr	15,275	4905

Evaluating Q_{peak} Results

- Substantial difference in peak discharge
- Regression equations based on 21 gages, but only 1 with basin characteristics similar to site
  - LP III analysis indicates regression results low?
  - What about confidence limits?

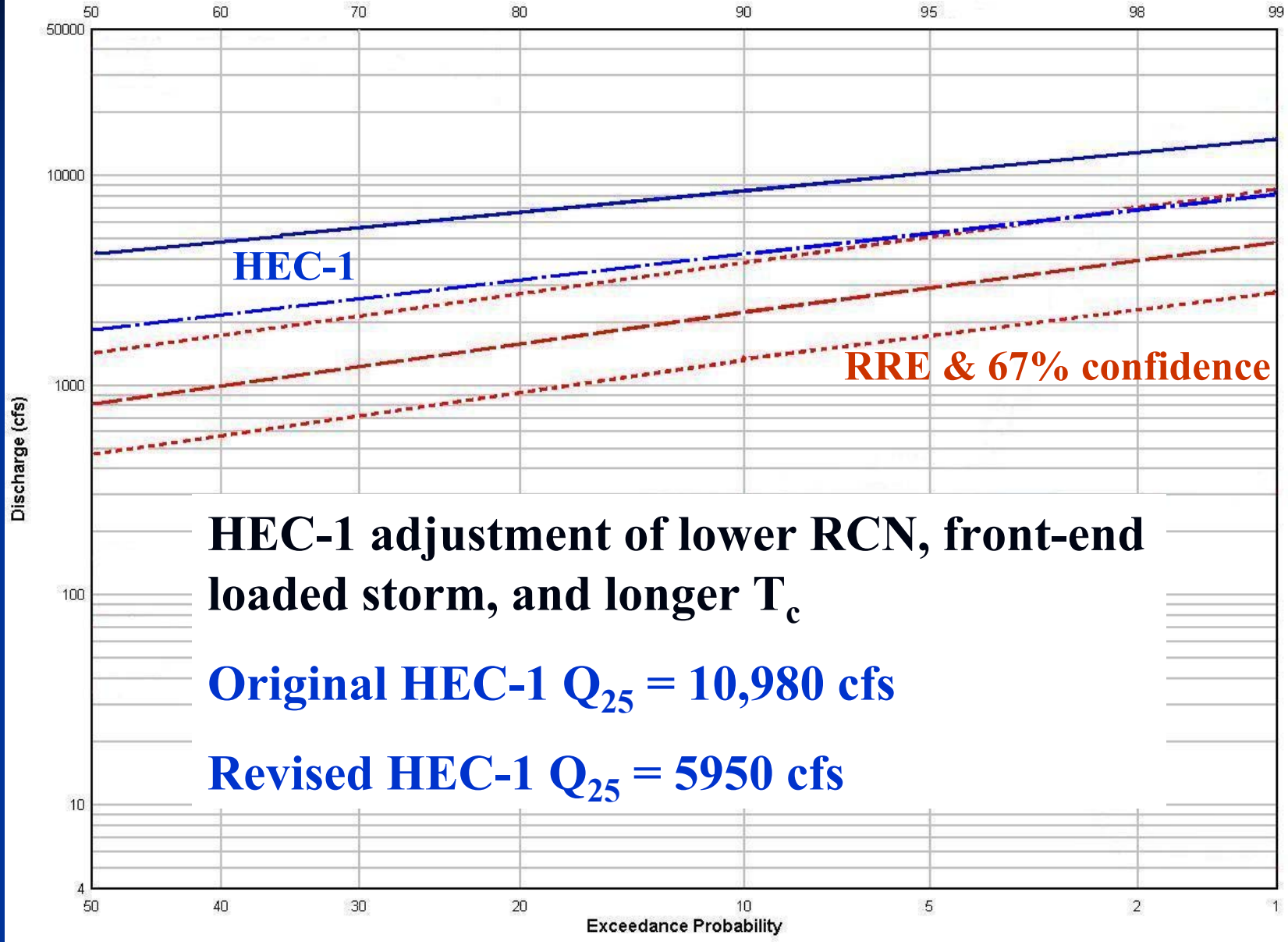

50
60
70
80
90
95
98
99
50000
10000
1000
100
10
4
Discharge (cfs)
HEC-1
RRE & 67% confidence
50
40
30
20
10
5
2
1
Exceedance Probability

Revisit Unit-Hydrograph Application

- Initial assumed inputs based on “standard practice”
  - Reflective of past performance?
  - Alternative inputs?
- Recent TxDOT hydrologic research findings
  - Most appropriate for Texas

Alternative Inputs

- New rainfall depths
- New storm distribution
- Storm duration
- Loss model
- T_c



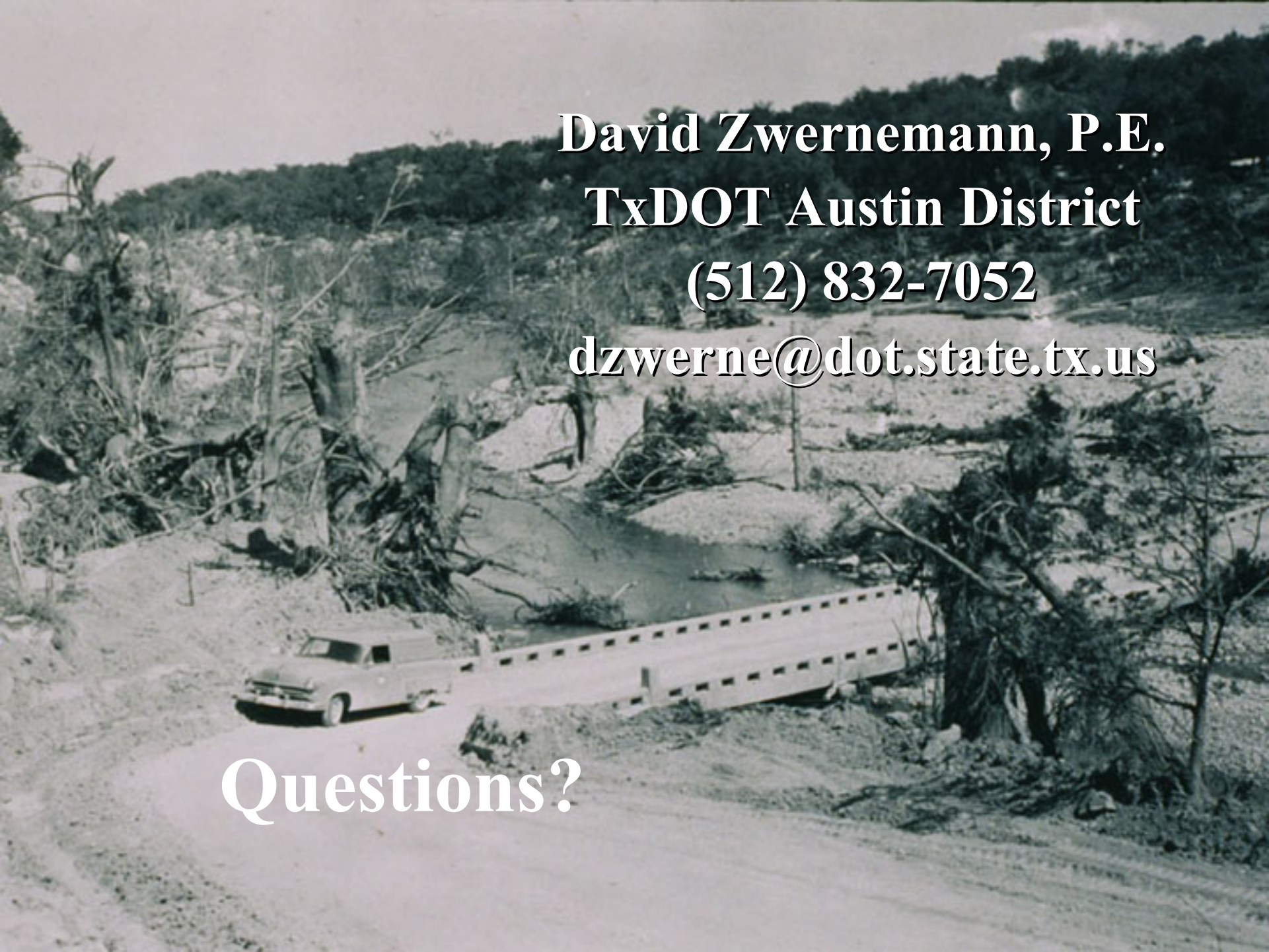
HEC-1 adjustment of lower RCN, front-end loaded storm, and longer T_c

Original HEC-1 Q_{25} = 10,980 cfs

Revised HEC-1 Q_{25} = 5950 cfs

Summary

- Compare two or more hydrologic methods for significant drainage facilities
- For existing facilities, review hydraulic performance history of site
- Use engineering judgment & document all analyses



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Questions?