Estimating Streamflow Frequency with Limited or No Gage Data

Flood Frequency Analysis PROSPECT

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Purpose

- Understand methods for improving estimates of streamflow frequency in data-poor environments

Outline

1. Record extension (in brief)
2. Routing frequency-based rainfall
3. Regional regression equations
4. Combining estimates (in brief)

Record Extension (in brief)

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Record Extension

- If you have a little gauge data, but not enough to perform a frequency analysis, extend the record
  - Record < 20 years, correlation > 0.8
- Add in other relevant methods to make the estimates more robust
  - Combine estimates (see last section)
- Of these three scenarios, this is the most desirable

See Prior *Record Extension* Lecture/Workshop!

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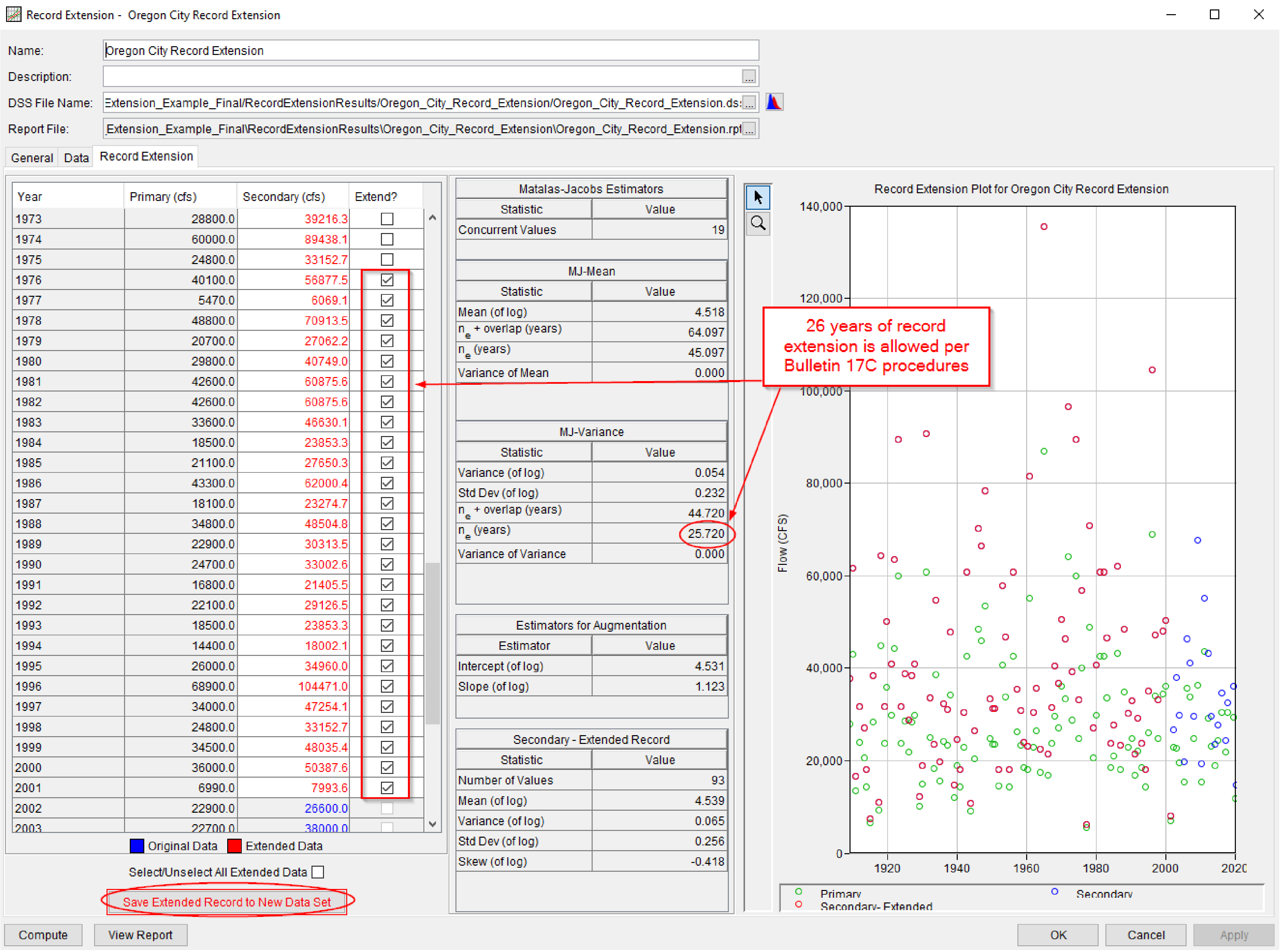

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Requirements

- Some at-site gage data
- Enough evidence to suggest the extension is credible
    - Long overlap length (minimum 10 years)
    - Very high correlation (minimum 0.8)
    - Strong physical evidence

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Frequency-Based Rainfall-Runoff Modeling

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Frequency-Based Rainfall Routing

For a specific watershed:

- Estimate of *watershed-average* precipitation depth-duration-frequency
- Hydrologic model

- Can be used in a true “no data” scenario

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Rainfall-Runoff Modeling

- Strengths
  - Precipitation frequency analyses are robust
  - Quantification of uncertainty
- Weaknesses
  - Requires calibrated hydrologic model
  - Requires assumptions about antecedent conditions
  - Assumptions required to take point precipitation to an area

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Frequency-Based Rainfall

- Precipitation frequency uncertainty can be input from A14
- 1:1 precipitation-flood frequency relationship assumption
    - Forced to assume the 1% rainfall will cause the 1% flood
- Storm duration vs. critical duration/time of concentration

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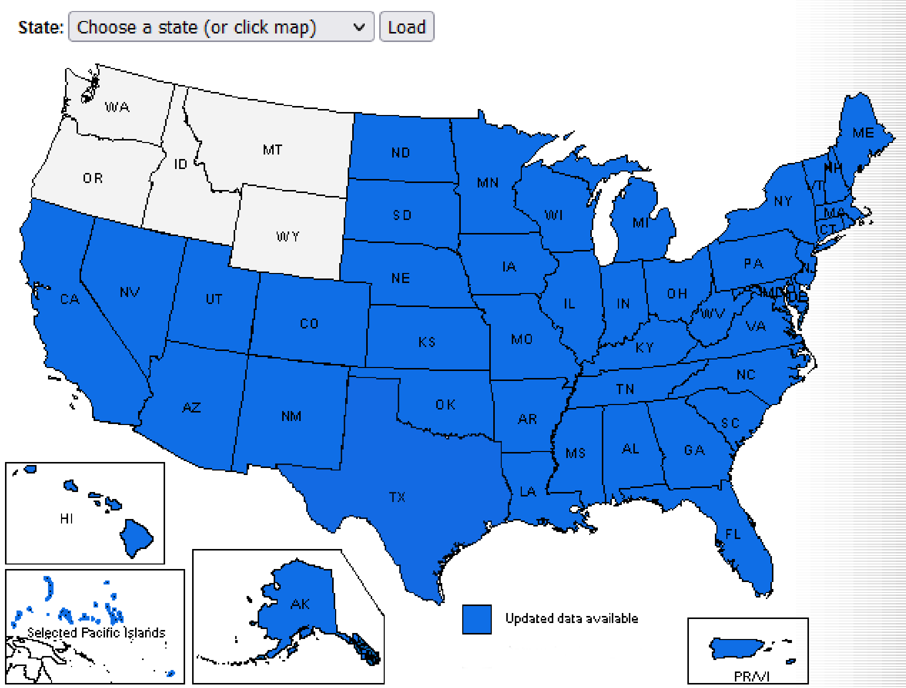
NOAA Atlas 14

- Regional rainfall frequency analysis product
  - Long equivalent record length
- **Point** precipitation for storms 5 min – 60 days
- Available for most of the US



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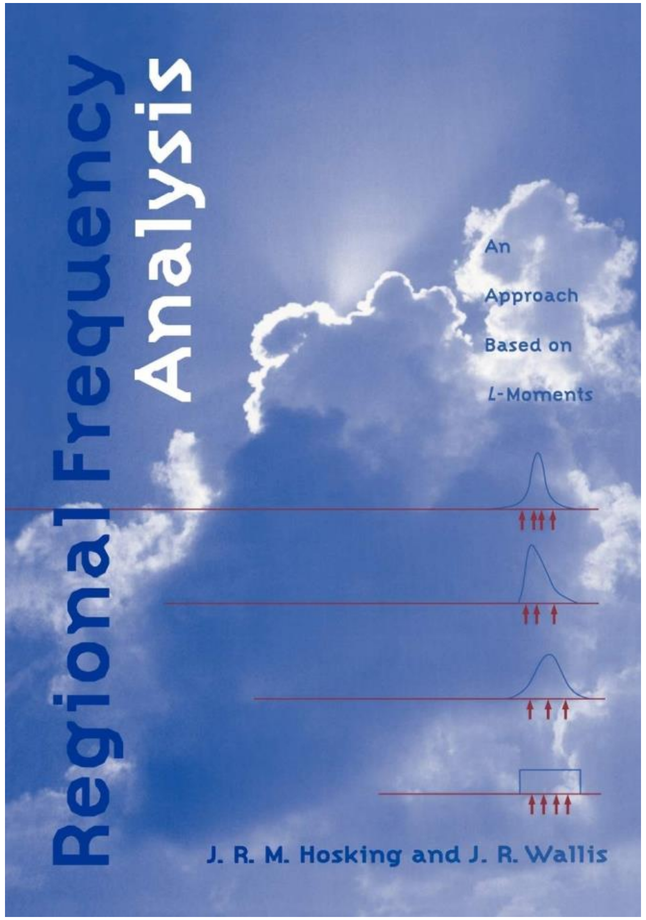
Creating Atlas 14

- Regional frequency analysis with L-moments
- Many high-quality precipitation stations
- Estimate regional dimensionless frequency curve
- Frequency curve scaled "anywhere" using estimate for the mean annual maximum rainfall



Much more detail in the *Statistical Methods* class!

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Regionalization

- Group together observations that are likely to be similar due to physical causes
- Test their similarity through a statistical lens
  - "Create physically, check statistically."
- Statistically we are usually most interested in extremes

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Creating Physical Regions

- For hydrometeorological data, climate divisions are a great start
- Other refining variables:
  - Location (lat/lon or planar coordinates)
  - Elevation
  - Climatology (annual or seasonal mean temperature, precipitation, etc.)
  - Proximity to coasts, mountains, etc.

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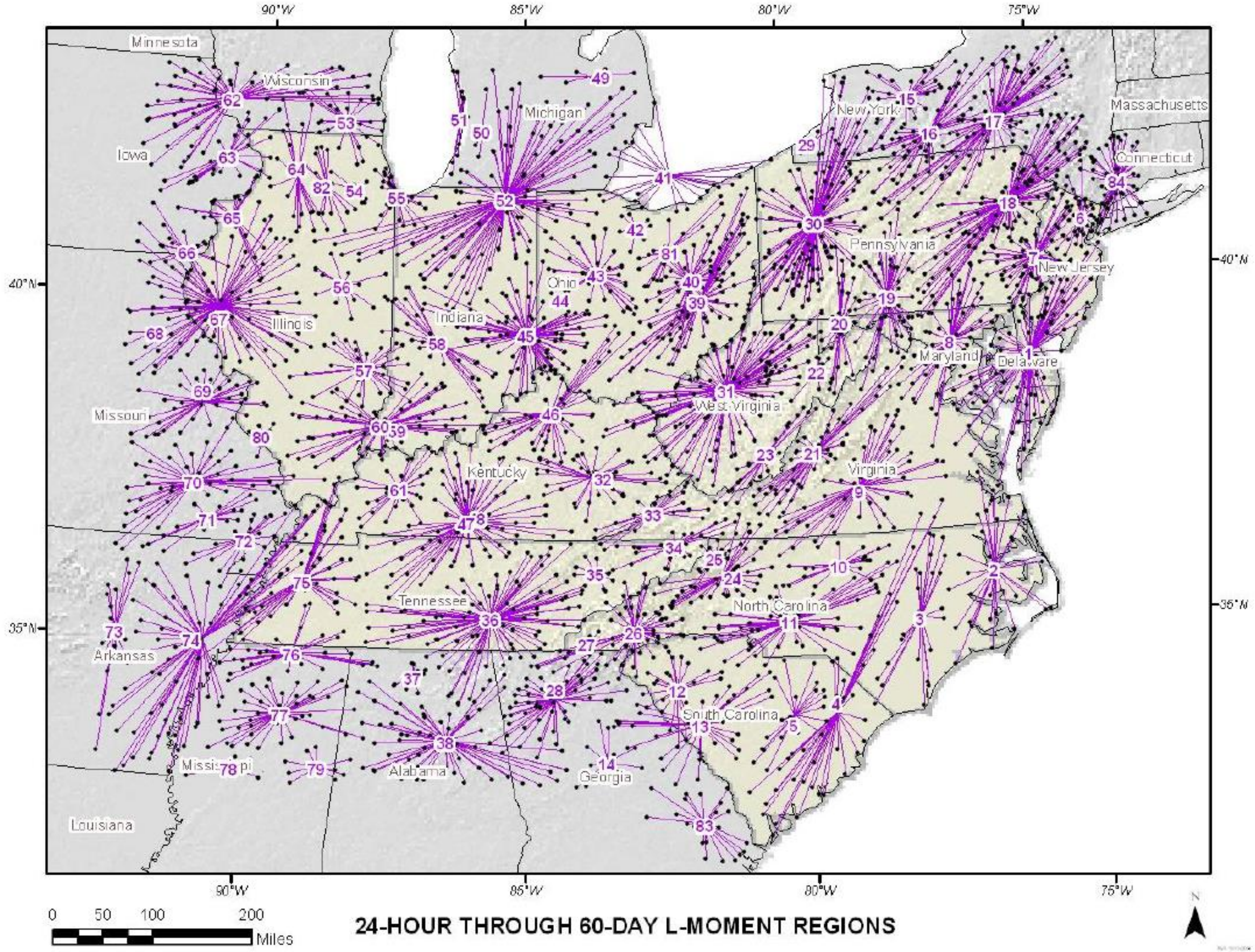

24-HOUR THROUGH 60-DAY L-MOMENT REGIONS

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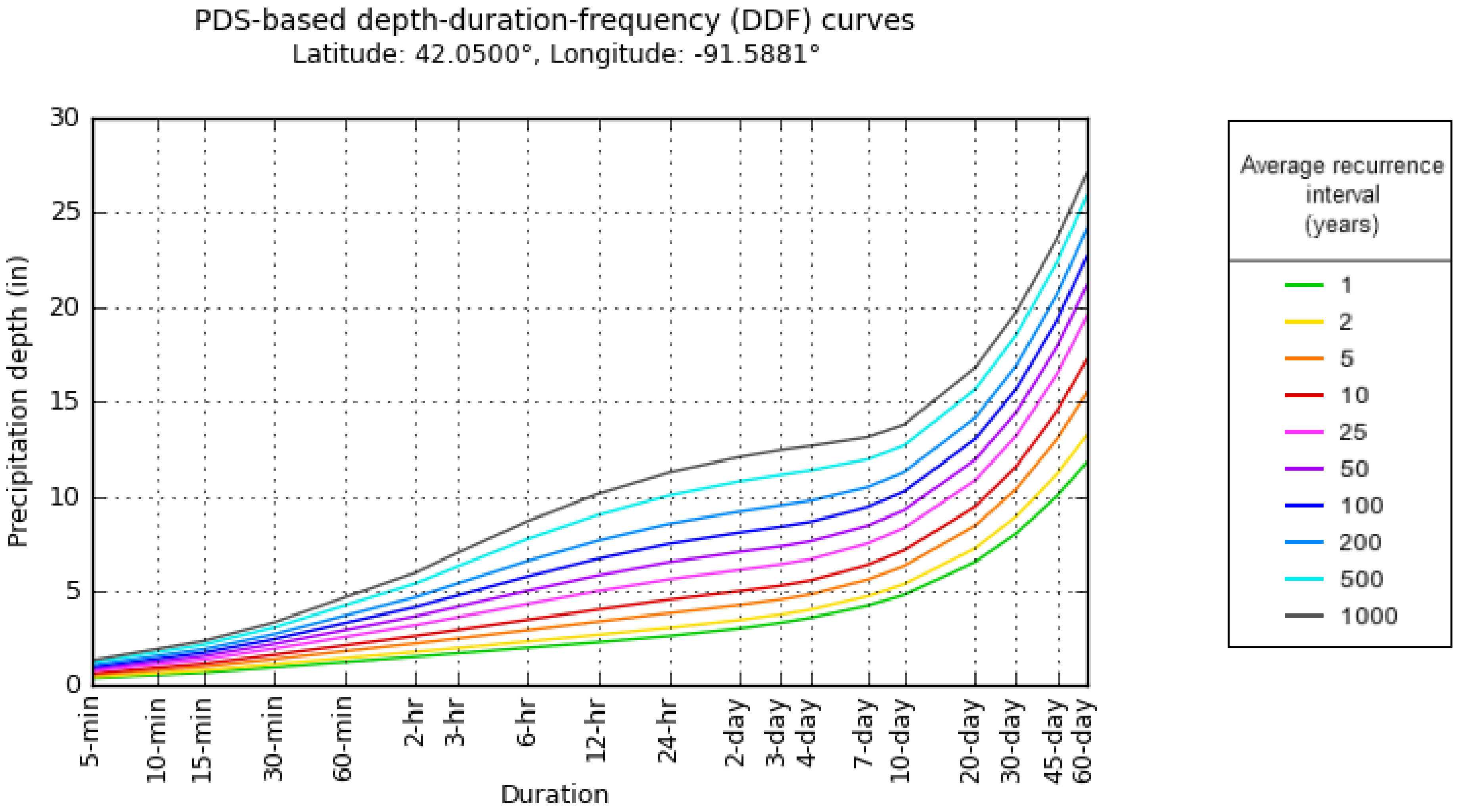
Atlas 14 Depth-Duration-Frequency



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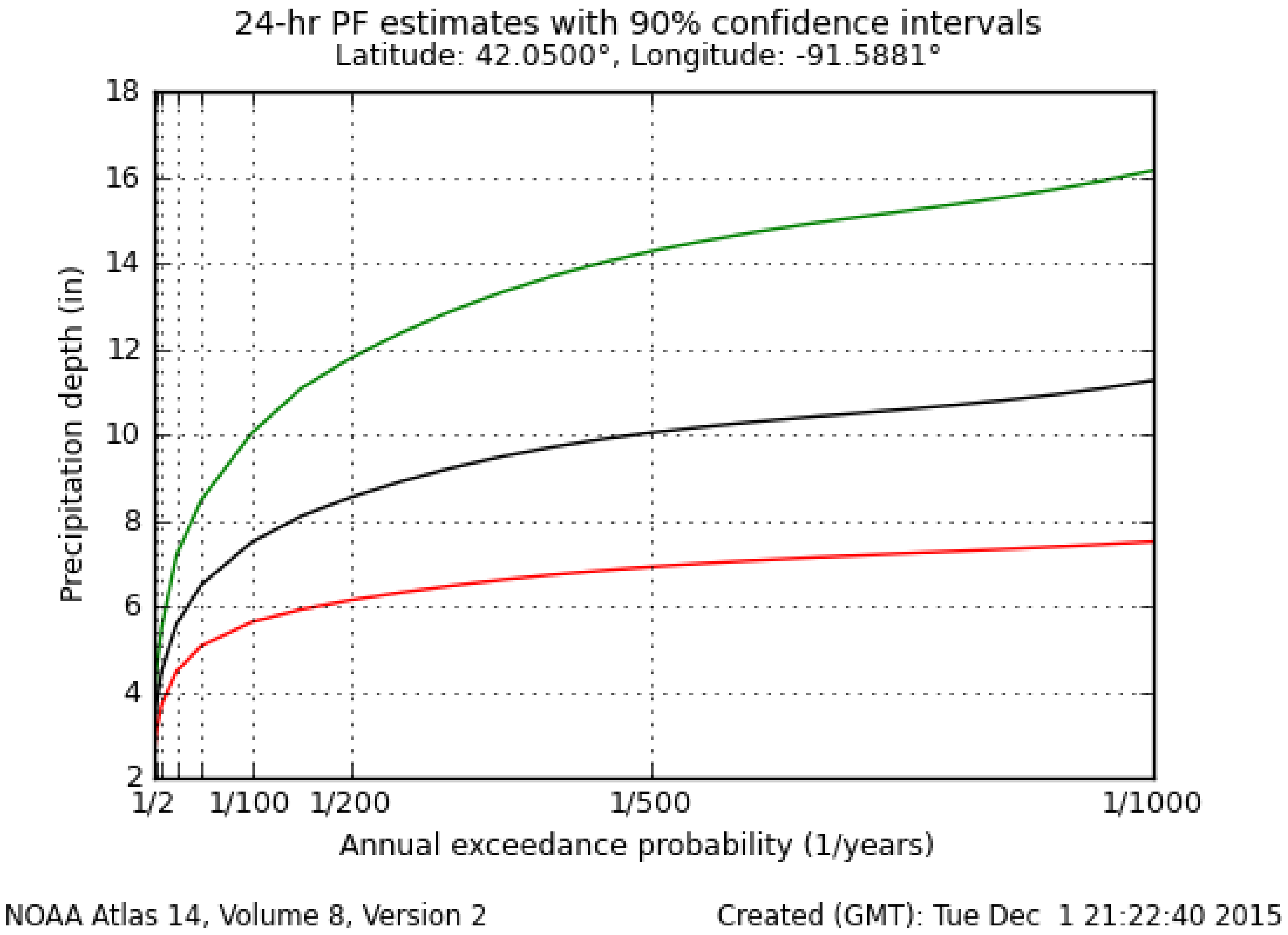
Atlas 14 – What do you get?



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Atlas 14 – What do you get?

AMS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

Duration	Annual exceedance probability (1/years)								
	1/2	1/5	1/10	1/25	1/50	1/100	1/200	1/500	1/1000
5-min	0.412 (0.325-0.534)	0.537 (0.422-0.697)	0.633 (0.494-0.825)	0.763 (0.575-1.02)	0.863 (0.635-1.17)	0.965 (0.686-1.34)	1.07 (0.728-1.52)	1.21 (0.791-1.76)	1.32 (0.838-1.95)
10-min	0.604 (0.476-0.782)	0.786 (0.618-1.02)	0.926 (0.724-1.21)	1.12 (0.841-1.50)	1.26 (0.930-1.72)	1.41 (1.00-1.96)	1.56 (1.06-2.23)	1.77 (1.16-2.58)	1.93 (1.23-2.85)
15-min	0.736 (0.581-0.954)	0.958 (0.753-1.25)	1.13 (0.883-1.47)	1.36 (1.03-1.83)	1.54 (1.14-2.09)	1.72 (1.22-2.39)	1.91 (1.30-2.72)	2.16 (1.41-3.15)	2.35 (1.50-3.48)
30-min	1.03 (0.816-1.34)	1.35 (1.06-1.76)	1.60 (1.25-2.09)	1.93 (1.46-2.59)	2.19 (1.61-2.98)	2.45 (1.74-3.40)	2.71 (1.85-3.86)	3.07 (2.00-4.47)	3.34 (2.13-4.94)
60-min	1.34 (1.06-1.74)	1.76 (1.38-2.29)	2.09 (1.64-2.73)	2.56 (1.93-3.44)	2.92 (2.15-3.98)	3.30 (2.35-4.59)	3.69 (2.52-5.27)	4.23 (2.77-6.19)	4.65 (2.96-6.88)
2-hr	1.65 (1.31-2.10)	2.17 (1.72-2.77)	2.58 (2.04-3.33)	3.18 (2.43-4.24)	3.65 (2.73-4.93)	4.15 (2.99-5.73)	4.67 (3.22-6.62)	5.39 (3.57-7.84)	5.97 (3.84-8.77)
3-hr	1.83 (1.47-2.32)	2.41 (1.93-3.07)	2.89 (2.30-3.69)	3.58 (2.77-4.77)	4.15 (3.12-5.58)	4.75 (3.44-6.54)	5.38 (3.74-7.61)	6.28 (4.18-9.10)	6.99 (4.52-10.2)
6-hr	2.15 (1.75-2.69)	2.84 (2.31-3.57)	3.43 (2.76-4.32)	4.29 (3.36-5.66)	5.00 (3.81-6.67)	5.76 (4.23-7.88)	6.58 (4.63-9.24)	7.74 (5.22-11.2)	8.69 (5.67-12.6)
12-hr	2.48 (2.04-3.05)	3.28 (2.69-4.06)	3.97 (3.24-4.93)	4.97 (3.94-6.49)	5.80 (4.48-7.66)	6.70 (4.98-9.07)	7.66 (5.44-10.7)	9.02 (6.15-12.9)	10.1 (6.68-14.6)
24-hr	2.82 (2.35-3.43)	3.72 (3.09-4.53)	4.48 (3.70-5.48)	5.58 (4.48-7.19)	6.50 (5.08-8.48)	7.49 (5.62-10.0)	8.54 (6.14-11.8)	10.0 (6.91-14.3)	11.3 (7.50-16.1)
2-day	3.23 (2.73-3.87)	4.15 (3.49-4.99)	4.93 (4.12-5.96)	6.09 (4.95-7.74)	7.05 (5.57-9.09)	8.08 (6.15-10.7)	9.20 (6.68-12.6)	10.8 (7.51-15.2)	12.1 (8.13-17.2)
3-day	3.53 (3.00-4.19)	4.44 (3.76-5.29)	5.22 (4.40-6.25)	6.37 (5.22-8.05)	7.34 (5.85-9.40)	8.39 (6.42-11.1)	9.52 (6.96-13.0)	11.1 (7.80-15.6)	12.4 (8.43-17.7)
4-day	3.79 (3.24-4.47)	4.71 (4.01-5.57)	5.49 (4.65-6.54)	6.64 (5.47-8.33)	7.61 (6.09-9.69)	8.65 (6.65-11.3)	9.77 (7.17-13.2)	11.4 (7.99-15.9)	12.7 (8.61-17.9)
7-day	4.46 (3.86-5.21)	5.48 (4.72-6.41)	6.31 (5.40-7.42)	7.48 (6.19-9.21)	8.43 (6.79-10.6)	9.43 (7.31-12.2)	10.5 (7.75-14.0)	12.0 (8.47-16.6)	13.1 (9.00-18.5)
10-day	5.07 (4.41-5.87)	6.19 (5.37-7.19)	7.07 (6.09-8.26)	8.29 (6.89-10.1)	9.25 (7.49-11.5)	10.2 (7.98-13.1)	11.3 (8.38-15.0)	12.7 (9.02-17.5)	13.8 (9.51-19.3)
20-day	6.87 (6.06-7.83)	8.28 (7.27-9.47)	9.35 (8.16-10.8)	10.8 (9.06-12.9)	11.9 (9.73-14.5)	13.0 (10.2-16.4)	14.1 (10.6-18.5)	15.6 (11.2-21.3)	16.8 (11.7-23.4)
30-day	8.47 (7.53-9.57)	10.2 (9.02-11.5)	11.5 (10.1-13.1)	13.1 (11.1-15.6)	14.4 (11.9-17.4)	15.7 (12.4-19.6)	16.9 (12.7-22.0)	18.5 (13.4-25.0)	19.7 (13.8-27.3)
45-day	10.6 (9.51-11.9)	12.8 (11.4-14.4)	14.4 (12.8-16.3)	16.4 (13.9-19.2)	17.9 (14.8-21.5)	19.3 (15.4-24.0)	20.7 (15.7-26.7)	22.4 (16.3-30.1)	23.6 (16.7-32.7)
60-day	12.5 (11.3-13.9)	15.2 (13.6-17.0)	17.1 (15.2-19.2)	19.5 (16.6-22.6)	21.1 (17.6-25.1)	22.7 (18.1-27.9)	24.1 (18.4-31.0)	25.9 (18.8-34.6)	27.1 (19.2-37.3)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of annual maxima series (AMS).

Numbers in parenthesis are PF estimates at lower and upper bounds of the 90% confidence interval. The probability that precipitation frequency estimates (for a given duration and annual exceedance probability) will be greater than the upper bound (or less than the lower bound) is 5%. Estimates at upper bounds are not checked against probable maximum precipitation (PMP) estimates and may be higher than currently valid PMP values.

Please refer to NOAA Atlas 14 document for more information.

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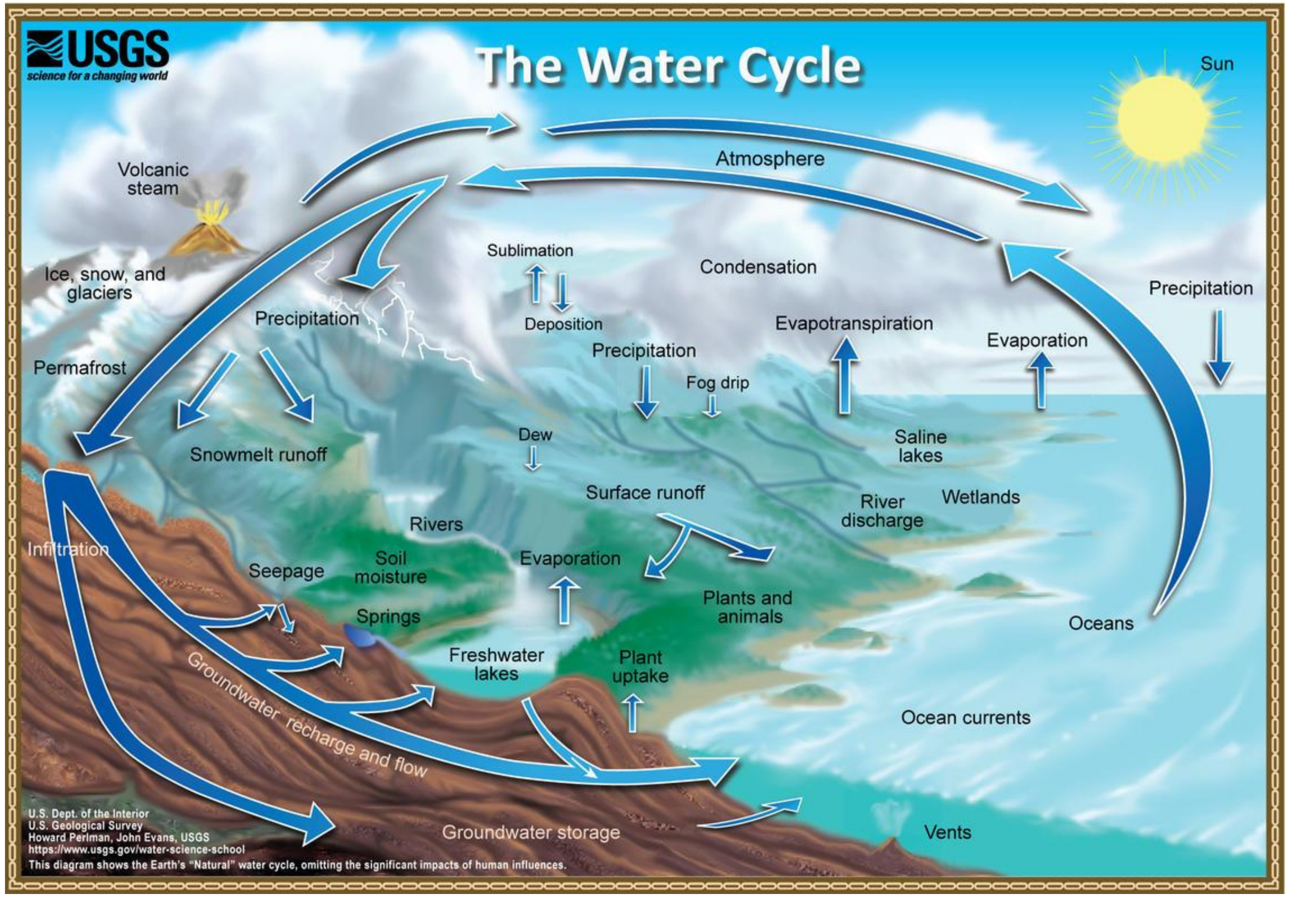
Rainfall to Runoff

- Hydrologic model must be set up to appropriately model flood events
- Details on Friday (lecture/workshop)



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Peak Discharge Prediction Equations

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Peak Discharge Prediction Equations

- Use linear regression from a large number of sites to predict flow quantiles
- Studies usually done on a state-by-state basis
- USGS StreamStats

- Can be used in a true “no data” scenario

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Regression – overview in brief

- Find the slope and intercept of a line that minimizes the distance between that line and a series of observed points
  - Measured using SSE (sum of squared errors)
  - This minimization is called "least-squares"
- Add in predictors that reduce the error
- Transform the data to improve linearity and constant variance of residuals

Much more detail in the *Statistical Methods* class!

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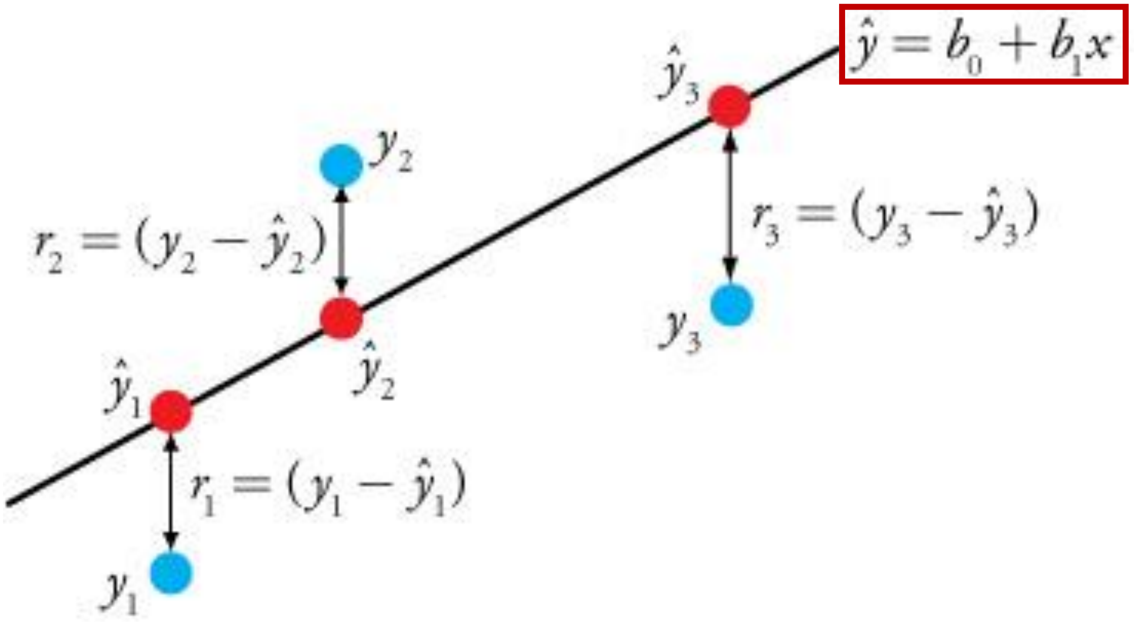
Getting the Line of Best Fit

- Goodness of fit is measured by the sum of squared errors (SSE)
- Line of best fit minimizes SSE
- $SSE = \sum_{i=1}^{n} r_i^2$



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https://community.asdlib.org/imageandvideoexchangeforum/2013/07/19/240/

Regression Equations

- Strengths
  - Regionalized prediction equations
  - Theoretically works in completely ungauged areas without relying on hydrologic models

- Weaknesses
  - Unique watersheds may be hard to predict
  - Challenging to quantify uncertainty
  - Result is not continuous, nor is it an analytical distribution

Peak Discharge Regression

- Q_p = f(basin characteristics)
- Considering what creates floods in a watershed, what measurable quantity is a proxy for that mechanism?
- Drainage area (DA) is a predictor in almost every watershed

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The Art of Choosing Predictors

- Many studies apply the kitchen sink principle
  - Start with as many predictors as possible
  - Try many combinations of predictors
  - Aim for a robust but parsimonious model
- Evaluation of fit should account for adding parameters
  - Adjusted R^2, AIC, BIC, etc.
  - Penalize for adding parameters
  - Increase in metric must overcome penalty to be “worth it”

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Peak Discharge Regression

- Other variables worth considering:
  - Mean annual temperature
  - Mean annual precipitation
  - Mean annual snowfall
  - Elevation
  - Mean channel slope/mean watershed slope
  - Percent of watershed in a particular landform
  - Percent of watershed urbanized
  - Many more

The trick: pick predictors available everywhere

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Example: Iowa

- "Techniques for Estimating Flood-Frequency Discharges for Streams in Iowa" (Eash, 2001) – WRI 00-4233
- There is a newer document (2013)
  - If you're doing a study in Iowa now, use that!

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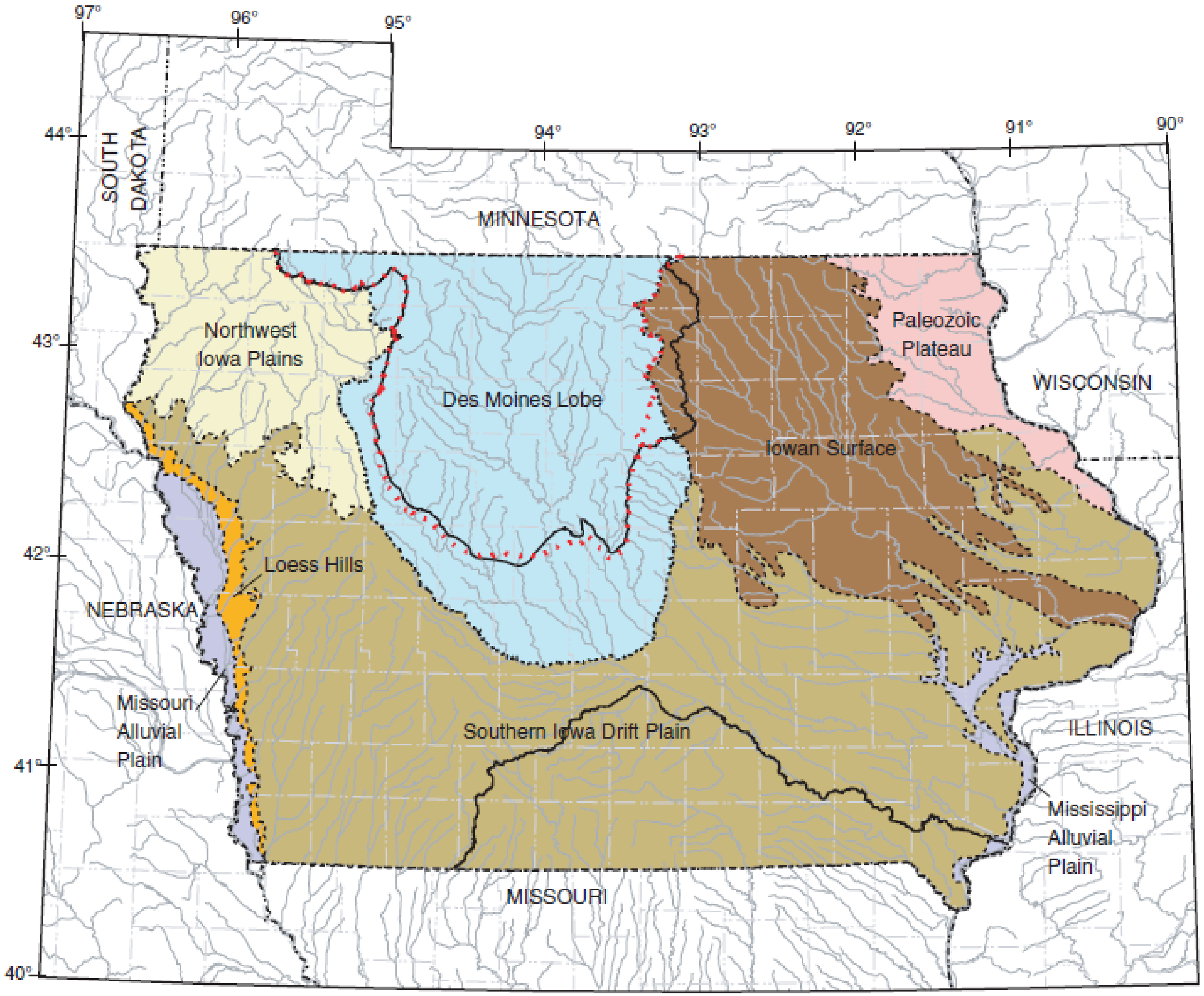

Base from U.S. Geological Survey digital data, 1:2,000,000, 1979
Universal Transverse Mercator projection, Zone 15

EXPLANATION

- Landform region boundary [modified from Prior (1991) and Tim Kemmis, Iowa Geological Survey Bureau, written commun., November 1998]
- Hydrologic region boundary (figure 7)
- Limit of Altamont glacial advance [modified from Prior (1991) and Tim Kemmis, Iowa Geological Survey Bureau, written commun., March 2000]

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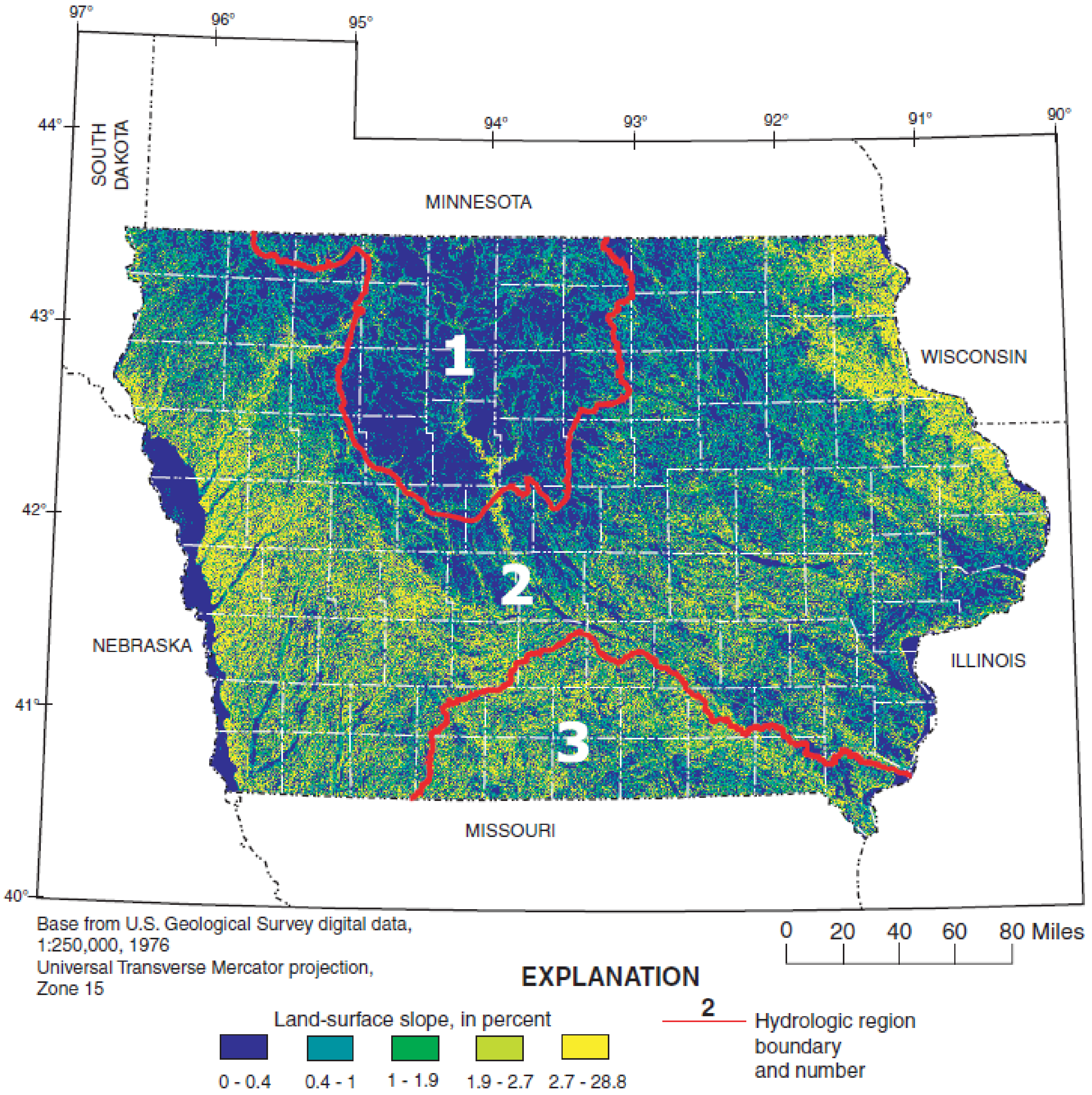

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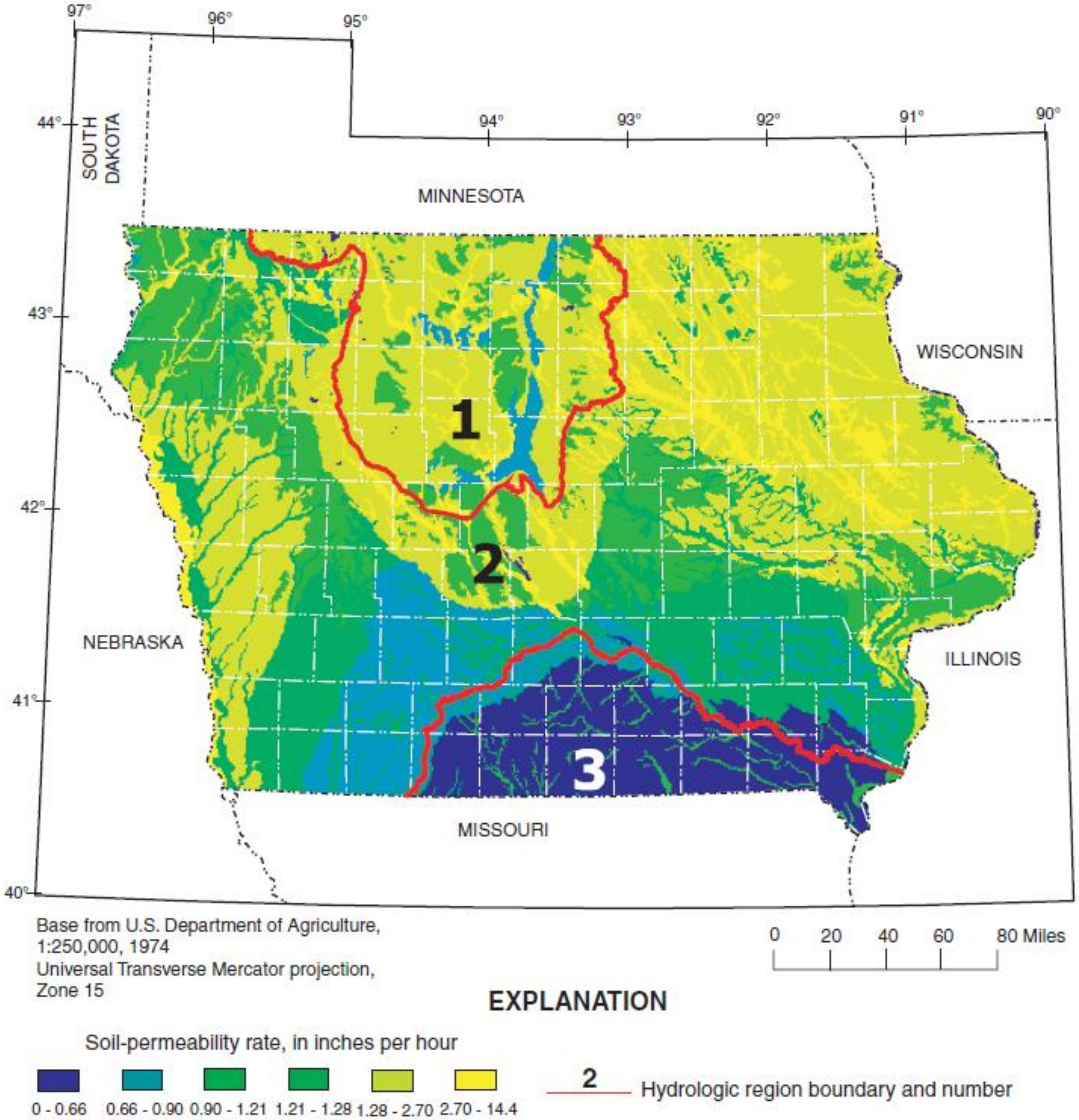

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Creating Regression Equations

1. Estimate flow for frequencies of interest at all available sites in the region
2. Find homogeneous hydrologic subregions
3. Evaluate watershed characteristics as predictors for peak flow quantiles
4. Estimate predictive error of regression equations by comparing to results in #1

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State Subregions for Regression

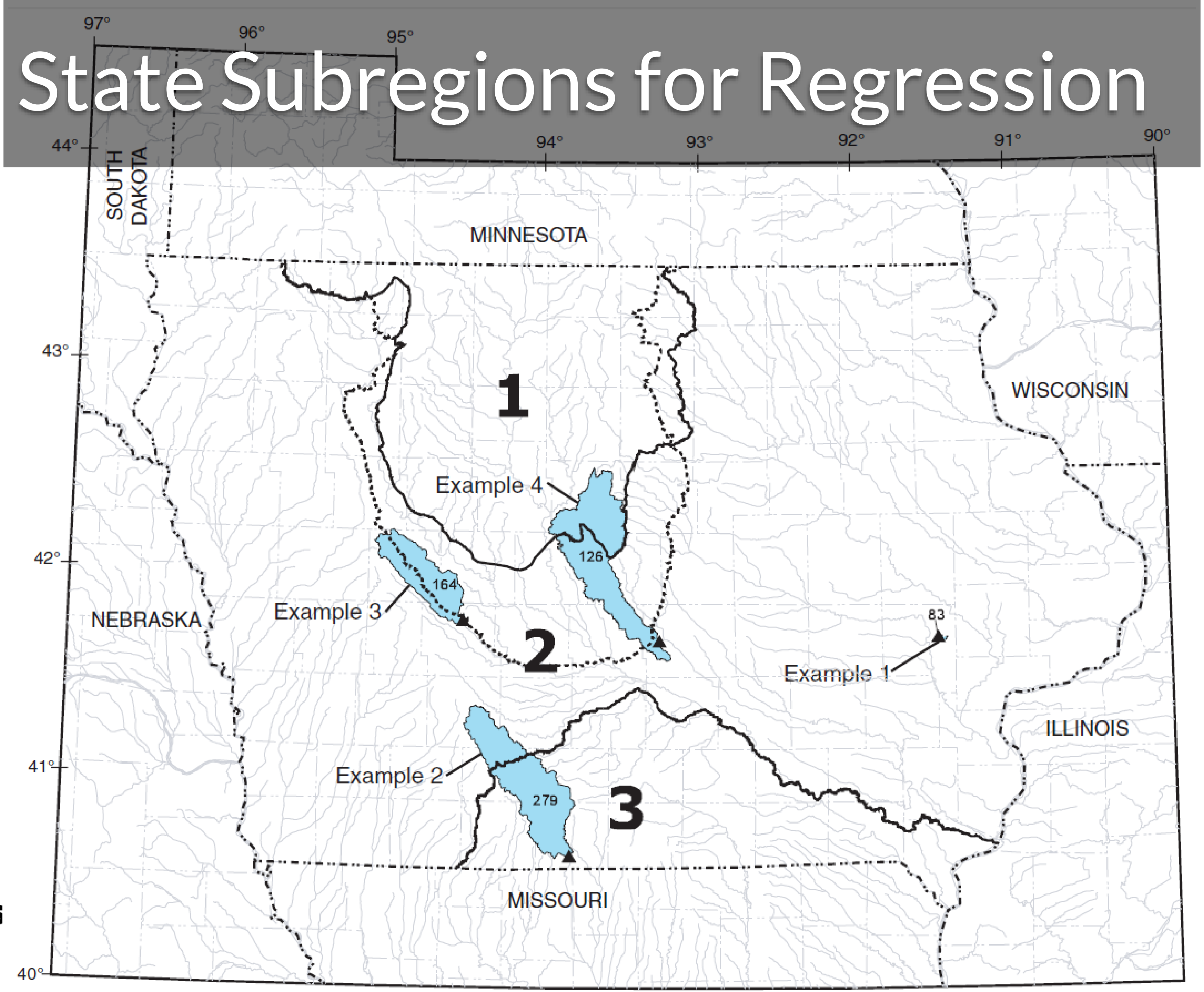

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Table 3. Flood-frequency estimation equations for Region 1

[SEE, standard error of estimate; SEP, average standard error of prediction; EYR, equivalent years of record; Q, peak discharge, in cubic feet per second for recurrence interval, in years, indicated as subscript; DA, drainage area, in square miles]

Estimation equation	Residual error	Error in ungauged sites	EYR (years)
(One-variable equations; number of streamflow-gaging stations = 26)			
$Q_2 = 33.8\ DA^{.656}$	35.3	41.4	4.2
$Q_5 = 60.8\ DA^{.658}$	32.0	39.4	5.8
$Q_{10} = 80.1\ DA^{.660}$	31.1	39.0	7.7
$Q_{25} = 105\ DA^{.663}$	31.3	39.2	10.1
$Q_{50} = 123\ DA^{.666}$	32.0	39.8	11.5
$Q_{100} = 141\ DA^{.669}$	33.1	40.5	12.5
$Q_{200} = 159\ DA^{.672}$	34.5	41.4	13.2
$Q_{500} = 183\ DA^{.676}$	36.5	42.7	13.7

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Table 4. Flood-frequency estimation equations for Region 2

[SEE, standard error of estimate; SEP, average standard error of prediction; EYR, equivalent years of record; Q, peak discharge, in cubic feet per second for recurrence interval, in years, indicated as subscript; DA, drainage area, in square miles; MCS, main-channel slope, in feet per mile; DML, Des Moines Lobe, ratio of basin area within Des Moines Lobe landform region to total area of basin]

Estimation equation	SEE (percent)	SEP (percent)	EYR (years)
(One-variable equations; number of streamflow-gaging stations = 188)			
$Q_2 = 182\ DA^{.540}$	43.0	44.6	3.6
$Q_5 = 464\ DA^{.490}$	31.2	38.1	7.9
$Q_{10} = 728\ DA^{.465}$	26.9	35.4	13.5
$Q_{25} = 1{,}120\ DA^{.441}$	25.2	34.4	20.5
$Q_{50} = 1{,}440\ DA^{.427}$	25.6	34.8	24.0
$Q_{100} = 1{,}800\ DA^{.415}$	26.8	35.6	25.9
$Q_{200} = 2{,}200\ DA^{.403}$	28.6	36.7	26.5
$Q_{500} = 2{,}790\ DA^{.389}$	31.4	38.4	26.0
(Three-variable equations; number of streamflow-gaging stations = 188)			
$Q_2 = 52.2\ DA^{.677}\ MCS^{.316}\ (DML+1)^{-.753}$	37.3	41.7	4.6
$Q_5 = 144\ DA^{.616}\ MCS^{.305}\ (DML+1)^{-.653}$	25.4	34.5	11.3
$Q_{10} = 225\ DA^{.590}\ MCS^{.306}\ (DML+1)^{-.601}$	21.6	32.0	19.9
$Q_{25} = 337\ DA^{.567}\ MCS^{.309}\ (DML+1)^{-.567}$	20.4	31.3	29.5
$Q_{50} = 430\ DA^{.554}\ MCS^{.311}\ (DML+1)^{-.555}$	21.2	31.9	33.2
$Q_{100} = 531\ DA^{.542}\ MCS^{.313}\ (DML+1)^{-.549}$	22.6	32.9	34.3
$Q_{200} = 641\ DA^{.532}\ MCS^{.316}\ (DML+1)^{-.545}$	24.6	34.4	33.7
$Q_{500} = 800\ DA^{.519}\ MCS^{.320}\ (DML+1)^{-.542}$	27.8	36.5	31.7

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Table 5. Flood-frequency estimation equations for Region 3

[SEE, standard error of estimate; SEP, average standard error of prediction; EYR, equivalent years of record; Q, peak discharge, in cubic feet per second for recurrence interval, in years, indicated as subscript; DA, drainage area, in square miles; MCS, main-channel slope, in feet per mile]

Estimation equation	SEE (percent)	SEP (percent)	EYR (years)
(One-variable equations; number of streamflow-gaging stations = 27)			
$Q_2 = 286\ DA^{.536}$	36.6	41.9	3.6
$Q_5 = 737\ DA^{.466}$	30.1	38.2	6.9
$Q_{10} = 1{,}180\ DA^{.431}$	27.1	36.4	11.0
$Q_{25} = 1{,}900\ DA^{.397}$	25.1	35.2	17.5
$Q_{50} = 2{,}550\ DA^{.376}$	24.3	34.8	22.2
$Q_{100} = 3{,}300\ DA^{.357}$	24.3	35.0	26.2
$Q_{200} = 4{,}160\ DA^{.340}$	24.7	35.4	29.0
$Q_{500} = 5{,}490\ DA^{.321}$	26.1	36.5	31.0
(Two-variable equations; number of streamflow-gaging stations = 27)			
$Q_2 = 7.75\ DA^{.888}\ MCS^{.977}$	29.4	38.0	5.2
$Q_5 = 22.6\ DA^{.805}\ MCS^{.939}$	22.2	33.3	11.5
$Q_{10} = 40.0\ DA^{.761}\ MCS^{.910}$	19.6	31.6	18.9
$Q_{25} = 72.3\ DA^{.715}\ MCS^{.875}$	18.0	30.8	29.2
$Q_{50} = 108\ DA^{.683}\ MCS^{.845}$	17.8	30.9	35.2
$Q_{100} = 158\ DA^{.652}\ MCS^{.809}$	18.6	31.6	38.5
$Q_{200} = 232\ DA^{.621}\ MCS^{.769}$	19.9	32.8	39.2
$Q_{500} = 382\ DA^{.580}\ MCS^{.709}$	22.4	34.8	37.4

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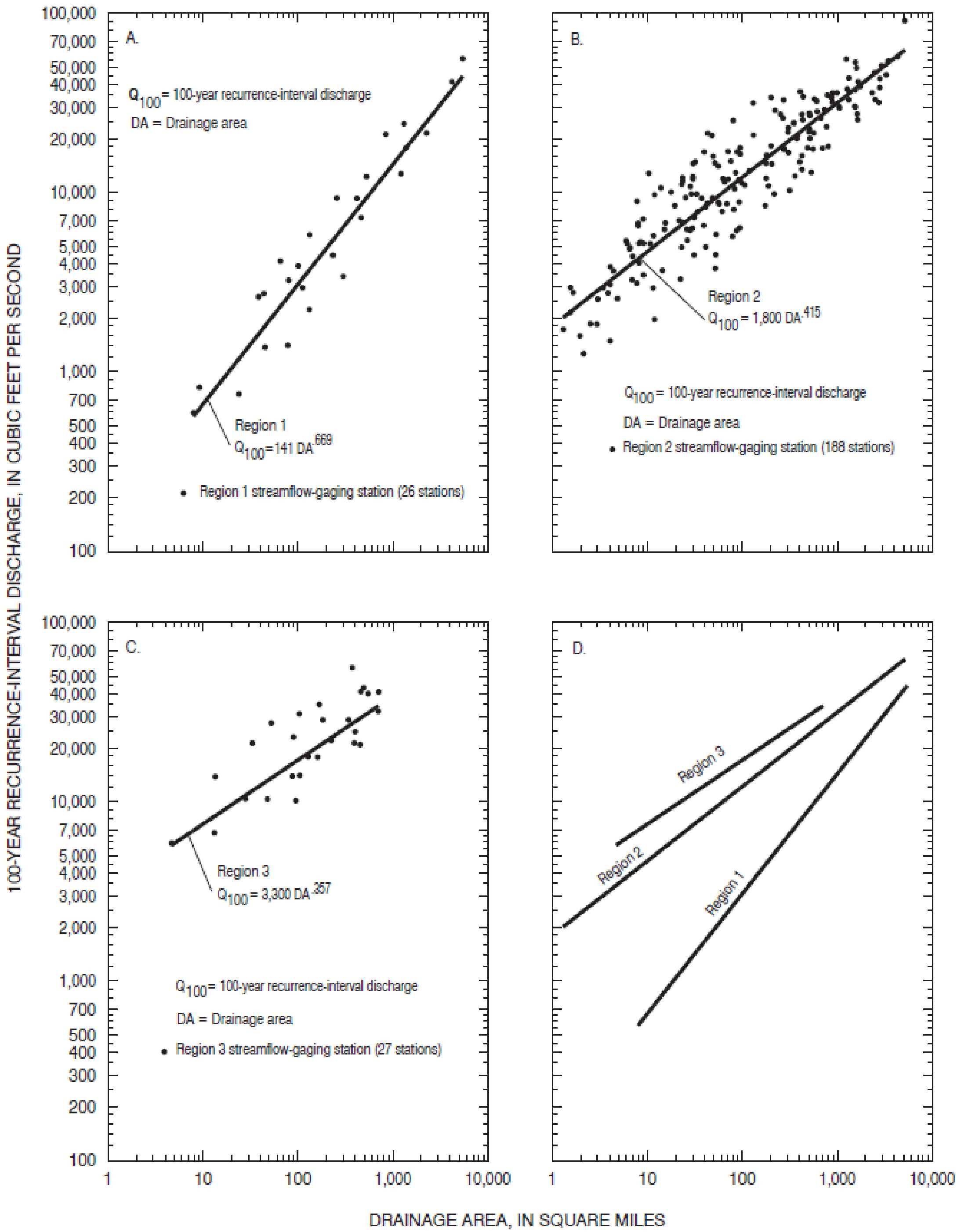

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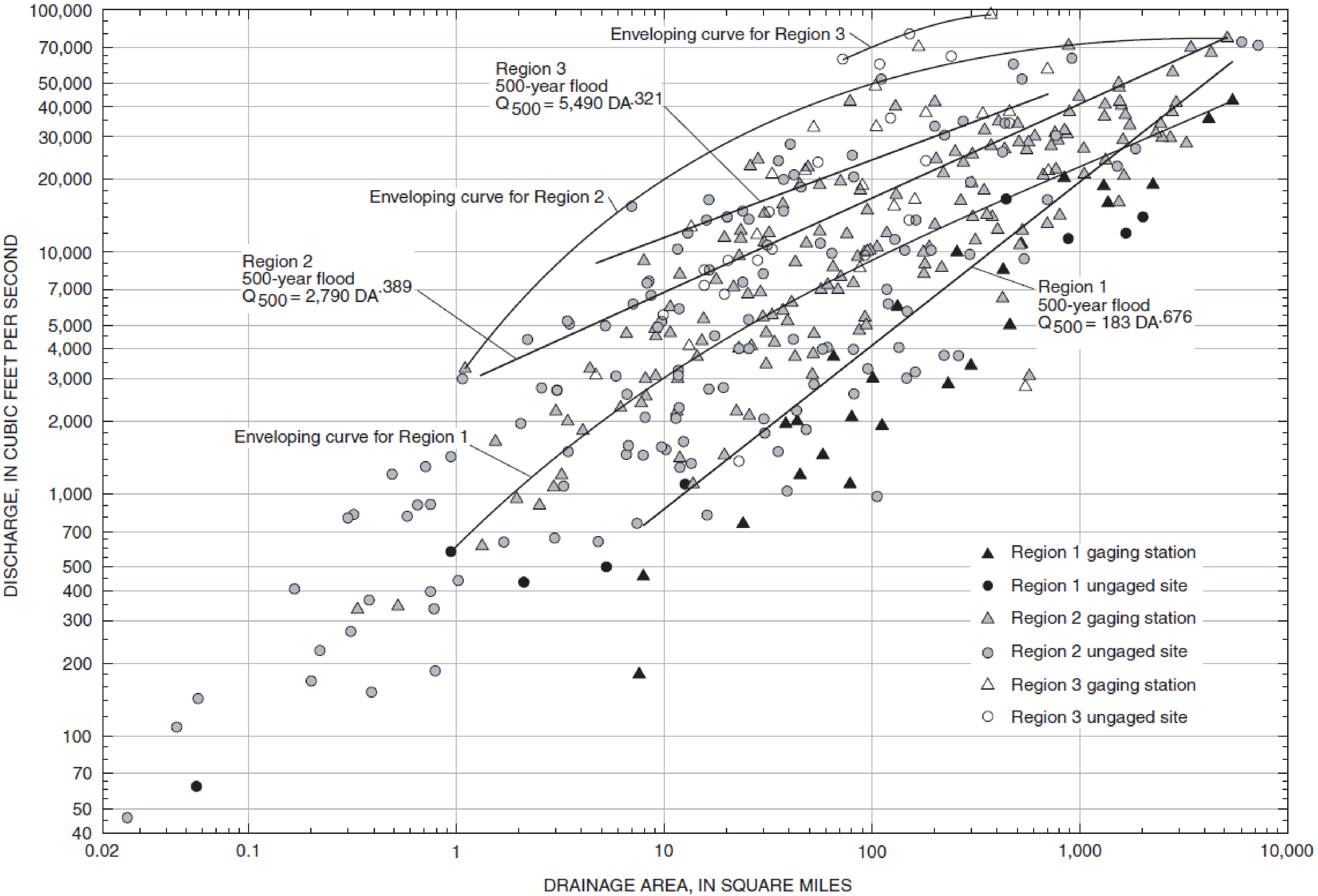

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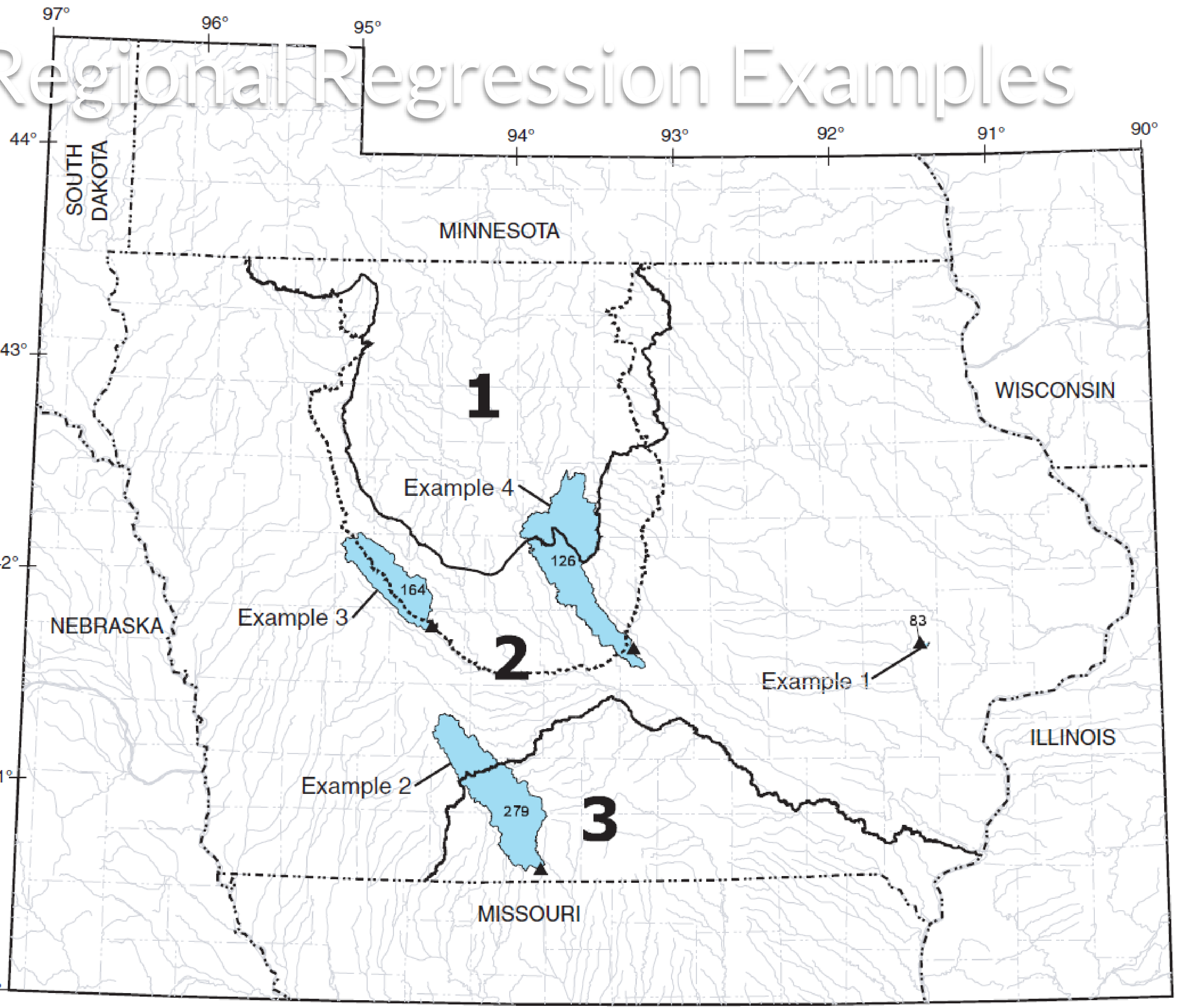
Figure 16.--Relation between maximum flood discharge and drainage area for streams in Iowa.

Regional Regression Examples



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Example 1 – 1-Predictor Equation

For the stream site with map number 83 (fig. 15), the basin is located within Region 2. The 100-year flood-estimation equation listed for Region 2 in table 4 is:

$$Q_{100} = 1{,}800\ DA^{.415}$$

DA for the basin was determined to be 3.43 mi^2. The flood-discharge estimate is calculated as:

$$Q_{100} = 1{,}800\ (3.43)^{.415}$$

$$Q_{100} = 3{,}000\ ft^3/s$$

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Example 1 – 3-Predictor Equation

For the stream site with map number 83 (fig. 15), the basin is located within Region 2. The 100-year flood-estimation equation listed for Region 2 in table 4 is:

$$Q_{100} = 531\ DA^{.542}\ MCS^{.313}\ (DML{+}1)^{-.549}$$

DA for the basin was determined to be 3.43 mi^2 and MCS for the basin was determined to be 30.0 ft/mi. Because the basin is located completely outside the Des Moines Lobe landform region, the value for DML was determined to be 0.00. The flood-discharge estimate is calculated as:

$$Q_{100} = 531\ (3.43)^{.542}\ (30.0)^{.313}\ (0.00 + 1)^{-.549}$$

$$Q_{100} = 3{,}000\ ft^3/s$$

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Example 2 – Watershed Spans Two Subregions

For the stream site with map number 279 (fig. 15), the basin is located within Regions 2 and 3. The 50-year flood-estimation equations listed for Regions 2 and 3 in tables 4 and 5 are:

$$Q_{50} = 1{,}440\ DA^{.427}\ \text{(Region 2)}$$

$$Q_{50} = 2{,}550\ DA^{.376}\ \text{(Region 3)}$$

DA for the basin was determined to be 701 mi^2. By overlaying the basin boundary on figure 7, it was determined that approximately 215 mi^2 of the drainage area is located within Region 2 and 486 mi^2 is located within Region 3. The flood-discharge estimate for each hydrologic region is calculated as:

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Example 2 – Watershed Spans Two Subregions (Continued)

$$Q_{50} = 1{,}440\ (701)^{.427}\ \text{(Region 2)}$$

$$Q_{50} = 23{,}600\ \text{ft}^3/\text{s (Region 2)}$$

$$Q_{50} = 2{,}550\ (701)^{.376}\ \text{(Region 3)}$$

$$Q_{50} = 30{,}000\ \text{ft}^3/\text{s (Region 3)}$$

The mixed-region estimate calculated from the two regional estimates using equation 1 is:

$$Q_{50(mr)} = (215\ /\ 701)\ (23{,}600) + (486\ /\ 701)\ (30{,}000)$$

$$Q_{50(mr)} = 28{,}000\ \text{ft}^3/\text{s}$$

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Additional Uses for Regional Regression

- Weighted estimates on gauged streams
  - Improve estimates for flow at important quantiles by combining 17C results with regional regression
- Weighted estimates for ungauged sites on gauged streams
  - Combine regional regression with drainage area relationship to a gauged site on the same stream

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Skew Isolines/Contours

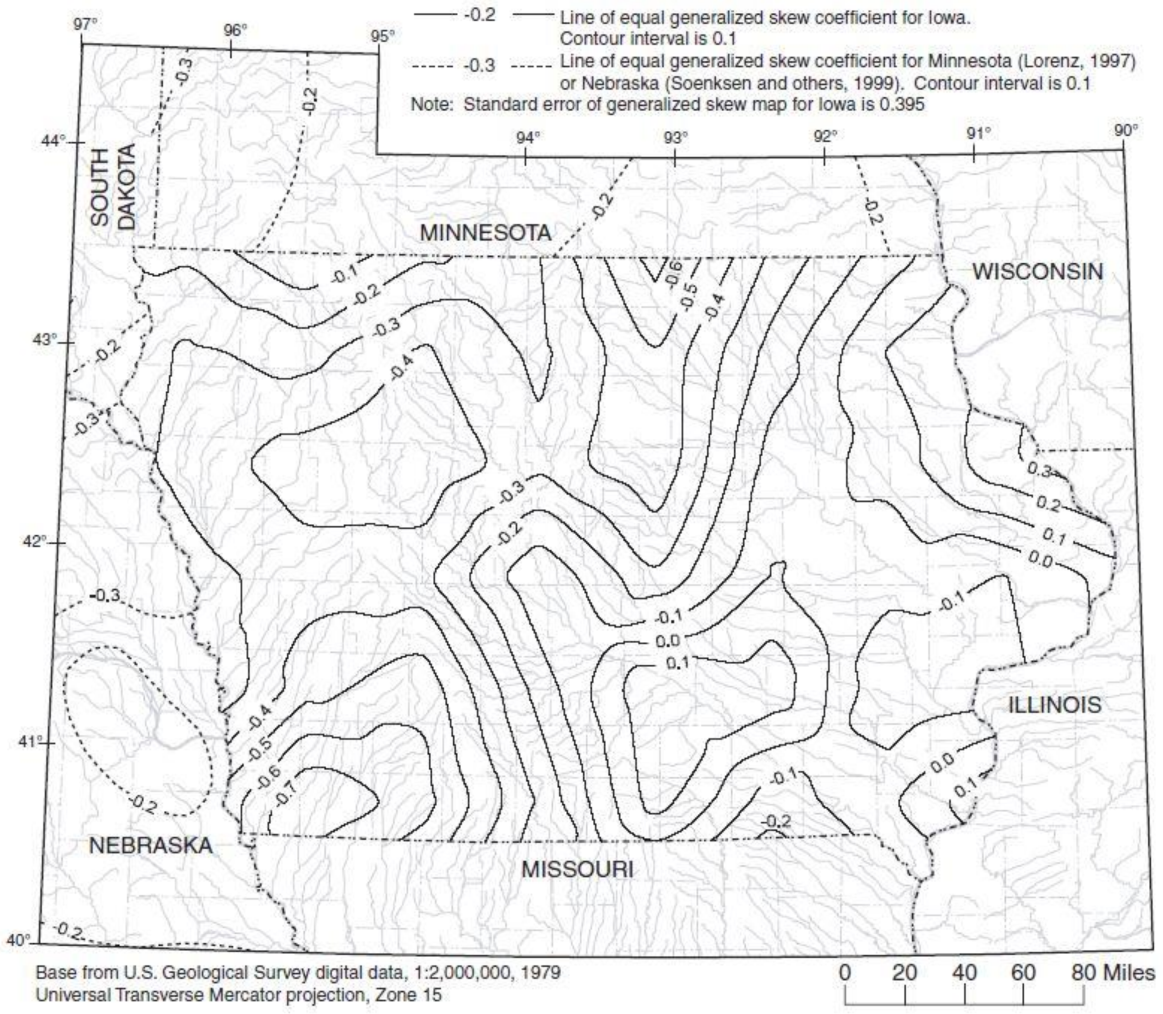

Figure 2.--Generalized-skew-coefficient isolines for Iowa.

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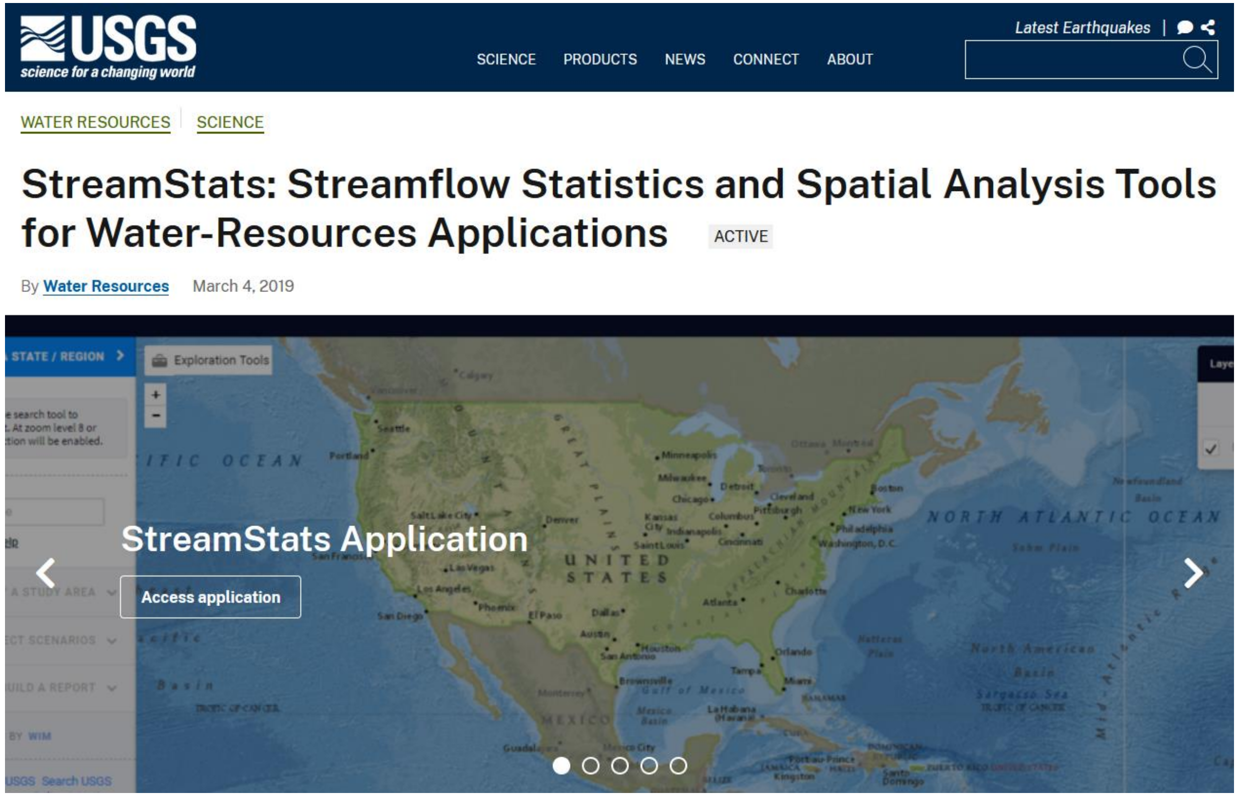
USGS StreamStats

- If you’re not sure where to find your regional study reports, use USGS StreamStats (https://streamstats.usgs.gov)



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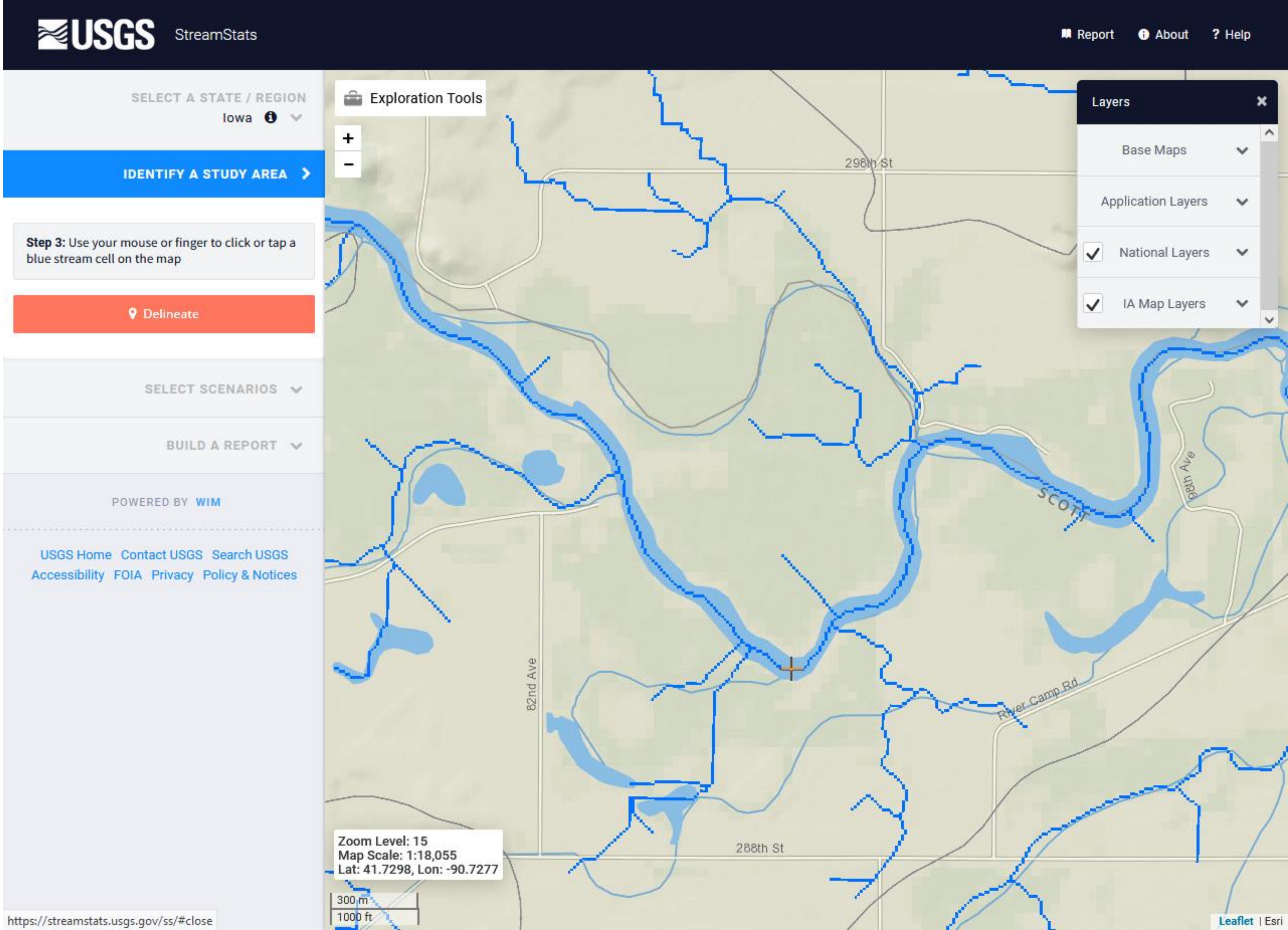

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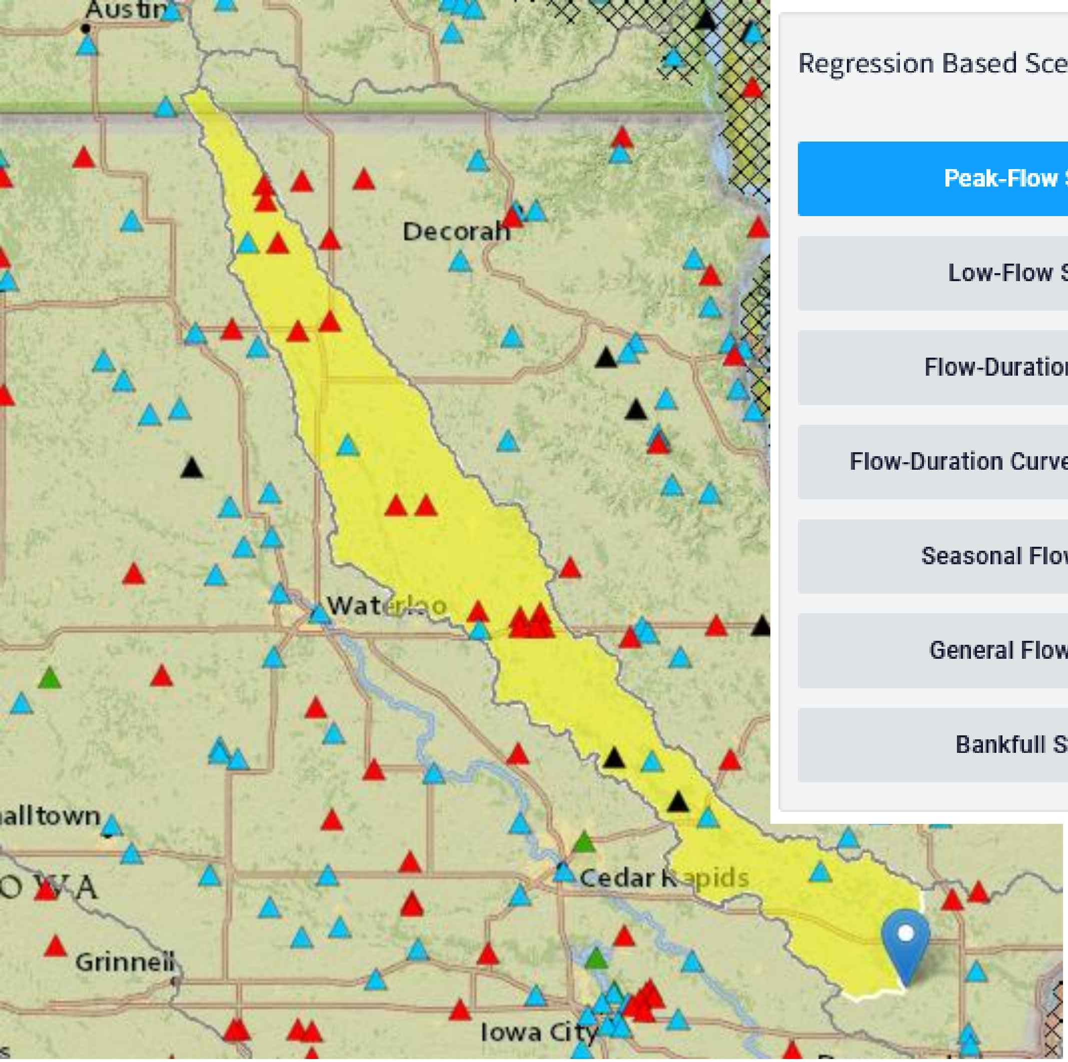

Regression Based Scenarios

- **Peak-Flow Statistics**
- Low-Flow Statistics
- Flow-Duration Statistics
- Flow-Duration Curve Transfer Method
- Seasonal Flow Statistics
- General Flow Statistics
- Bankfull Statistics

Peak-Flow Statistics Flow Report [Peak Region 2 2013 5086]

Statistic	Value	Unit
50-percent AEP flood	15700	ft^3/s
20-percent AEP flood	16600	ft^3/s
10-percent AEP flood	20400	ft^3/s
4-percent AEP flood	25800	ft^3/s
2-percent AEP flood	28500	ft^3/s
1-percent AEP flood	31300	ft^3/s
0.5-percent AEP flood	37800	ft^3/s
0.2-percent AEP flood	37800	ft^3/s

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Combining Estimates

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Combining Estimates

- When data are sparse, combining methods may be your only hope
- When in doubt, reduce assumptions
- Treating assumptions as random variables instead of fixed values helps avoid too-conservative assumptions
- When results are different, try to identify the limitations in the methods

Weighting of Independent Frequency Estimates

- Bulletin 17C recommends *quantile weighting*
- If the variance for each quantile can be estimated, the curves can be pairwise combined
- Quantile estimate with more variance gets less weight

$$X_{weighted,i} = \frac{X_{site,i} \times V_{reg,i} + X_{reg,i} \times V_{site,i}}{V_{site,i} + V_{reg,i}} \tag{9–2}$$

$$V_{weighted,i} = \frac{V_{site,i} \times V_{reg,i}}{V_{site,i} + V_{reg,i}}. \tag{9–3}$$

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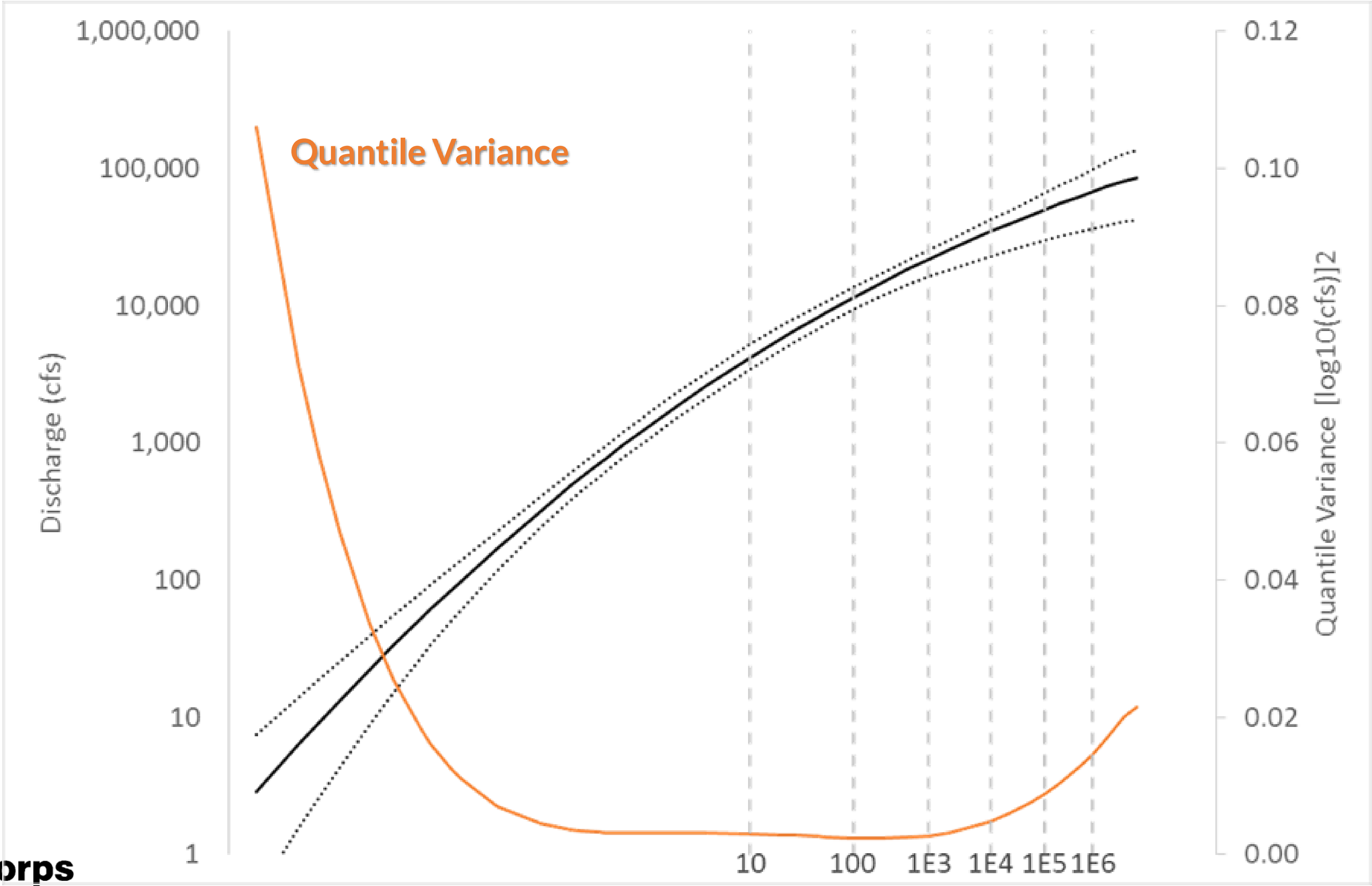

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The Final Word

Analysts are encouraged to include flood frequency information from all sources, as appropriate. In some cases, information from numerous sources can be combined.

-Bulletin 17C

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Questions?

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