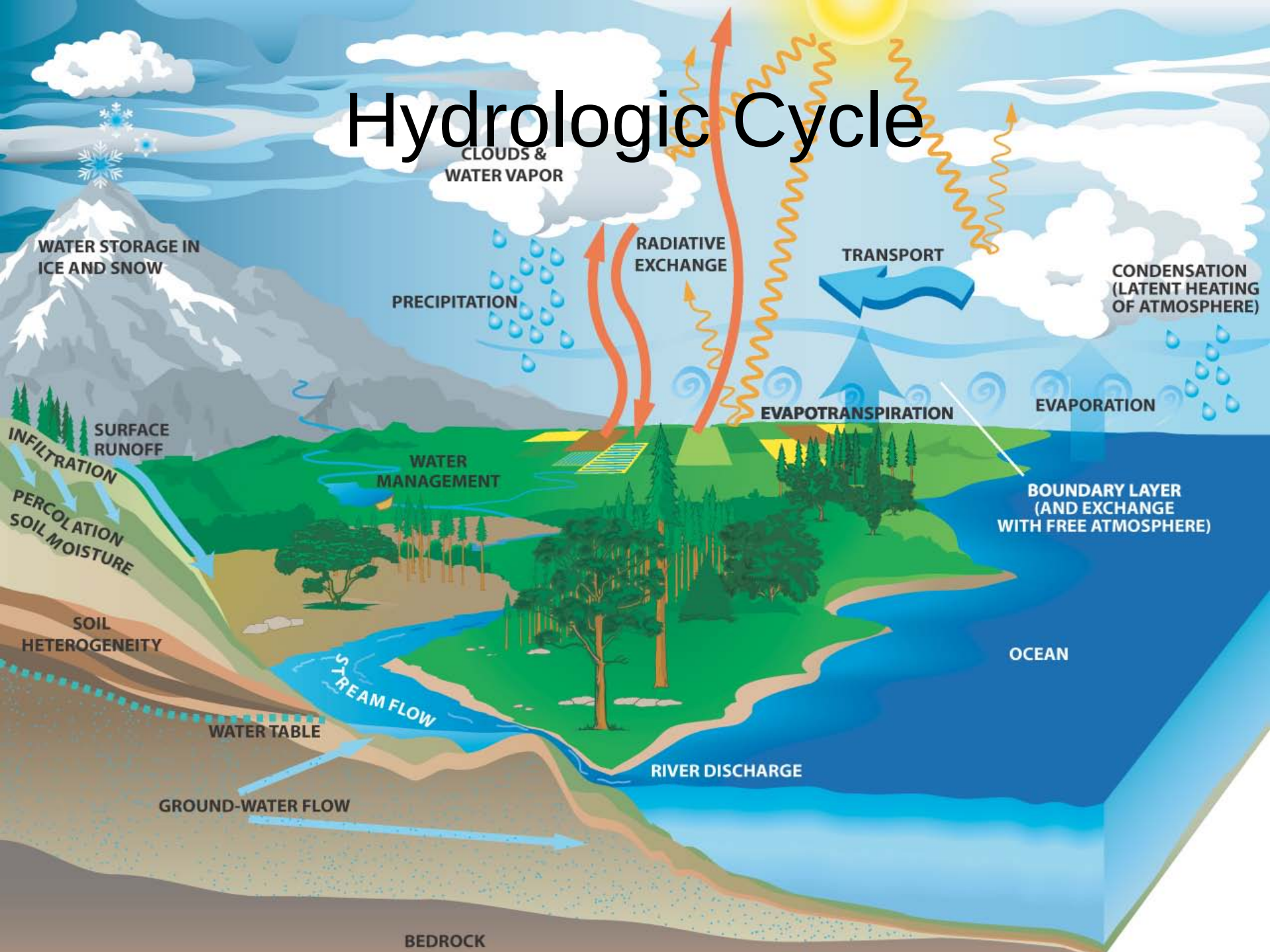
Hydrology

How Much
and
How Often

Hydrologic Cycle



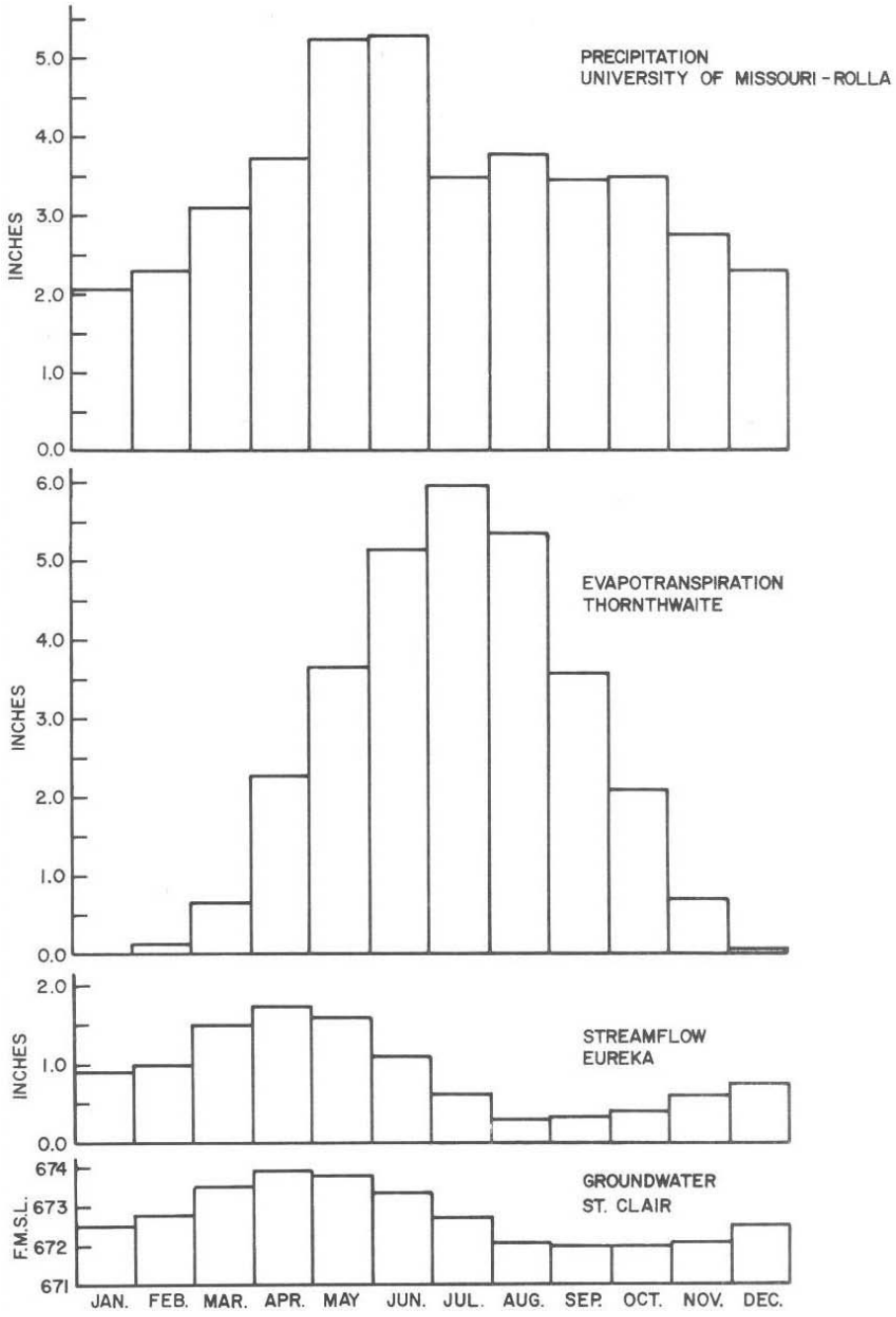
The Rivers Run to the Sea and yet the Sea is not Full?

Build the Relationship Between:

- **Precipitation**
- **Surface Runoff**
- **Evaporation**
- **Transpiration**
- **Groundwater flow**

Precipitation = Everything Else Added Together

Water Budget



Precipitation

- Occurrence
  - Spatially
  - Temporally
- Measurement
  - Gages
  - Gaging networks
  - Impacts of Density on Estimate Quality
  - Remote Sensing
- Common Terms and Units
- Extreme Events

Average Annual Precipitation

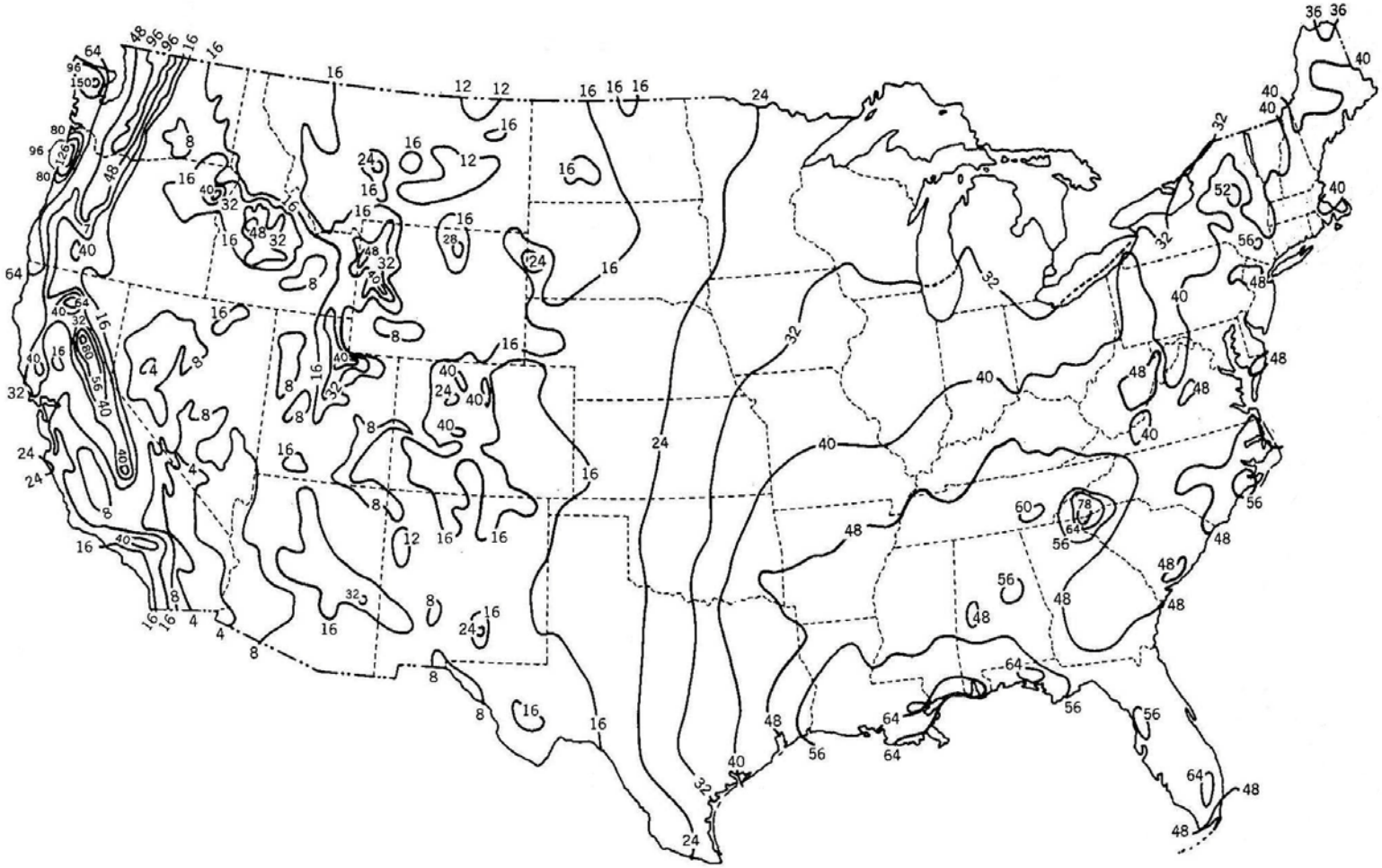


FIG. 2-5 Average annual precipitation in the United States. (National Weather Service)

Seasonal Precipitation Varies with Location

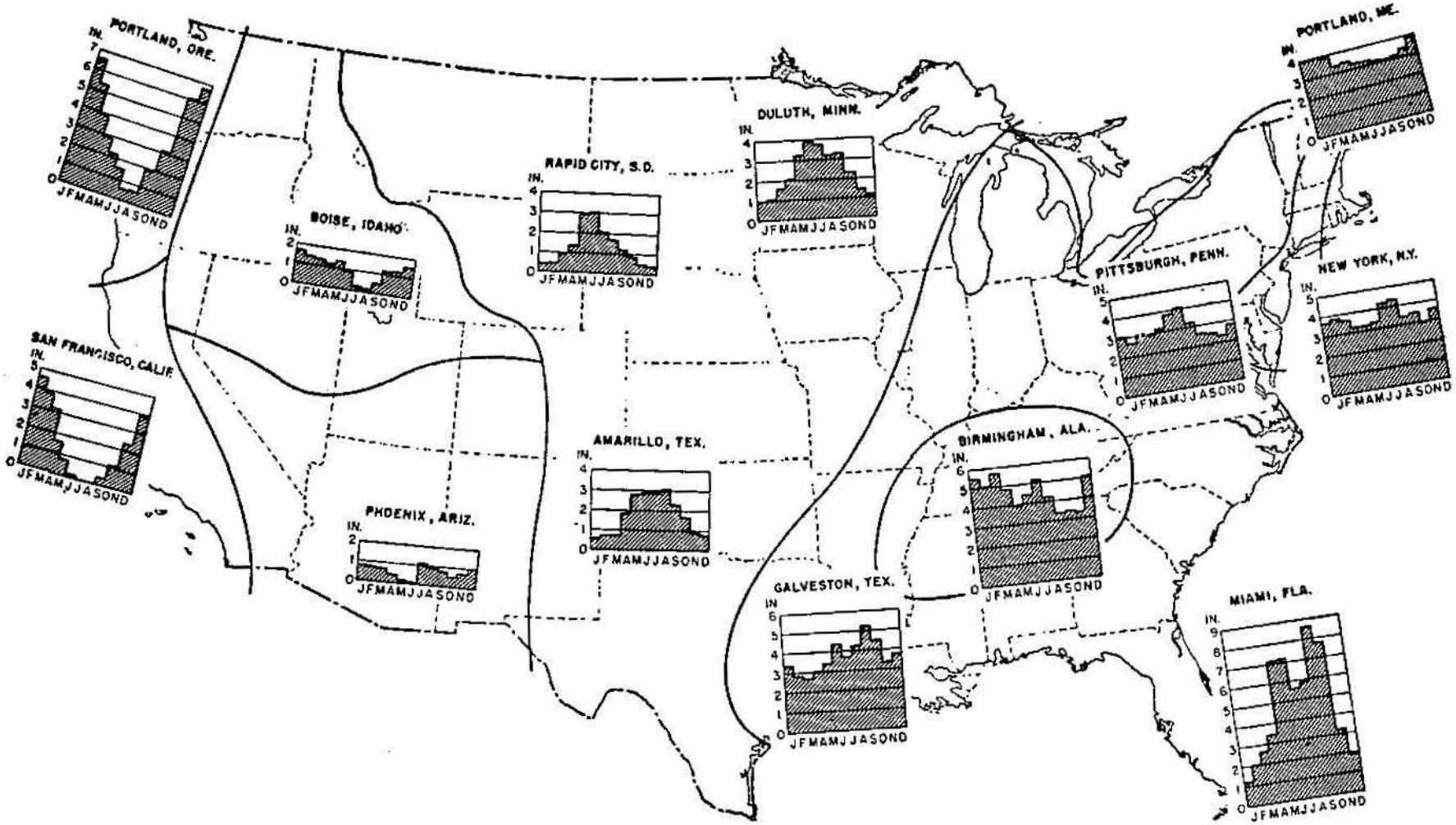
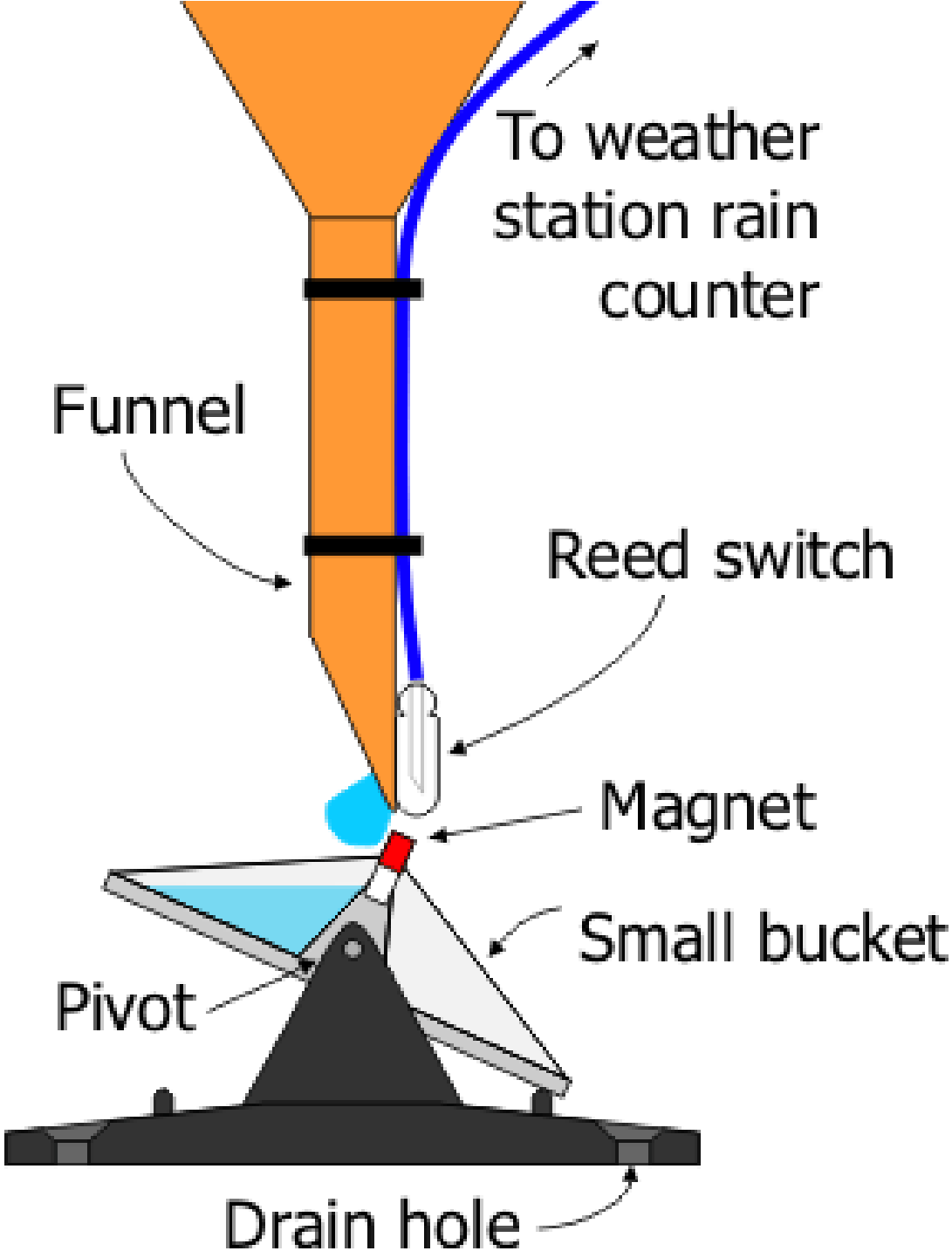


FIG. 2-6 Typical monthly distribution of precipitation in various climatic regions.

Tipping Bucket Rain Gauge



Storm Variability VS Gage Density

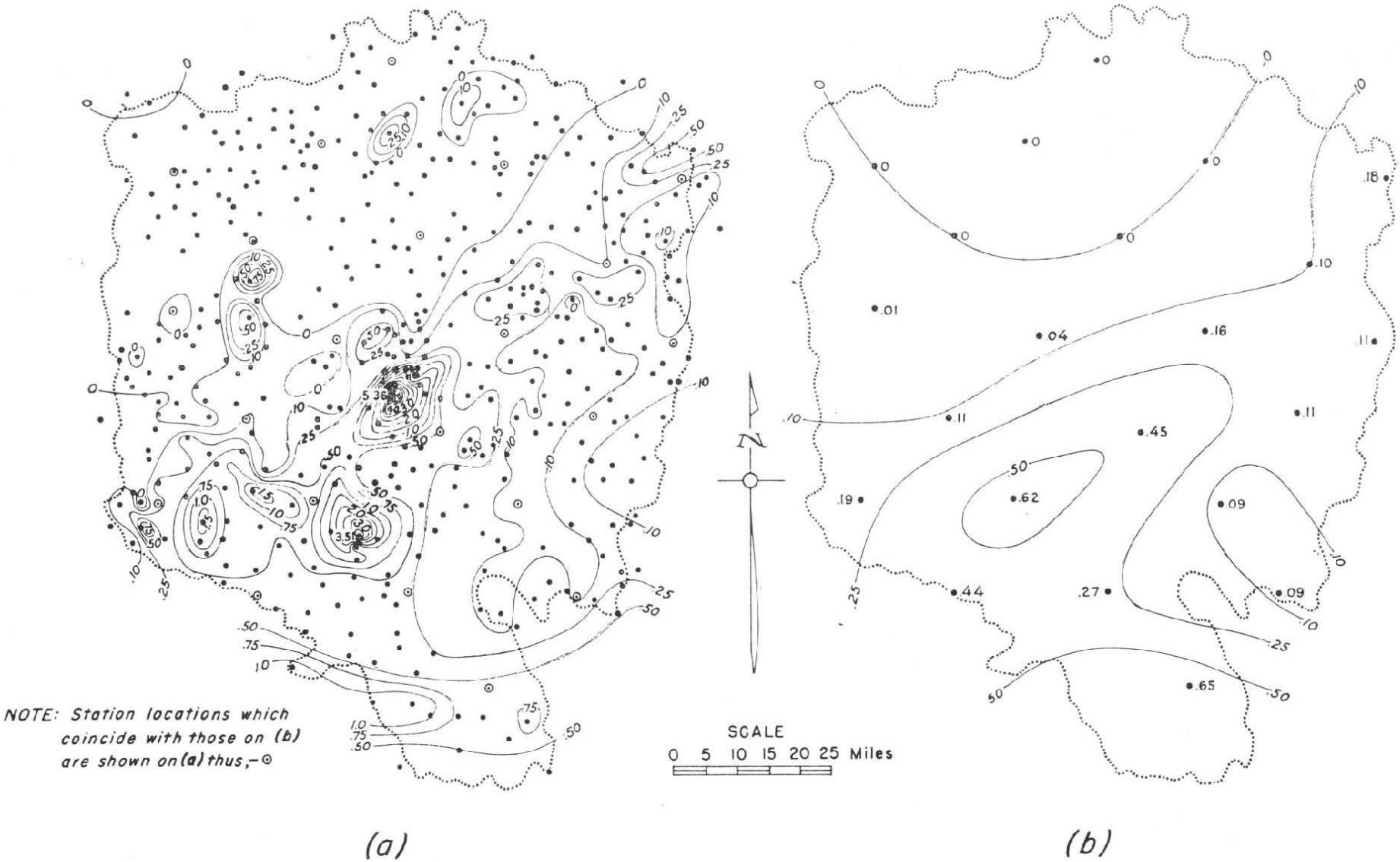
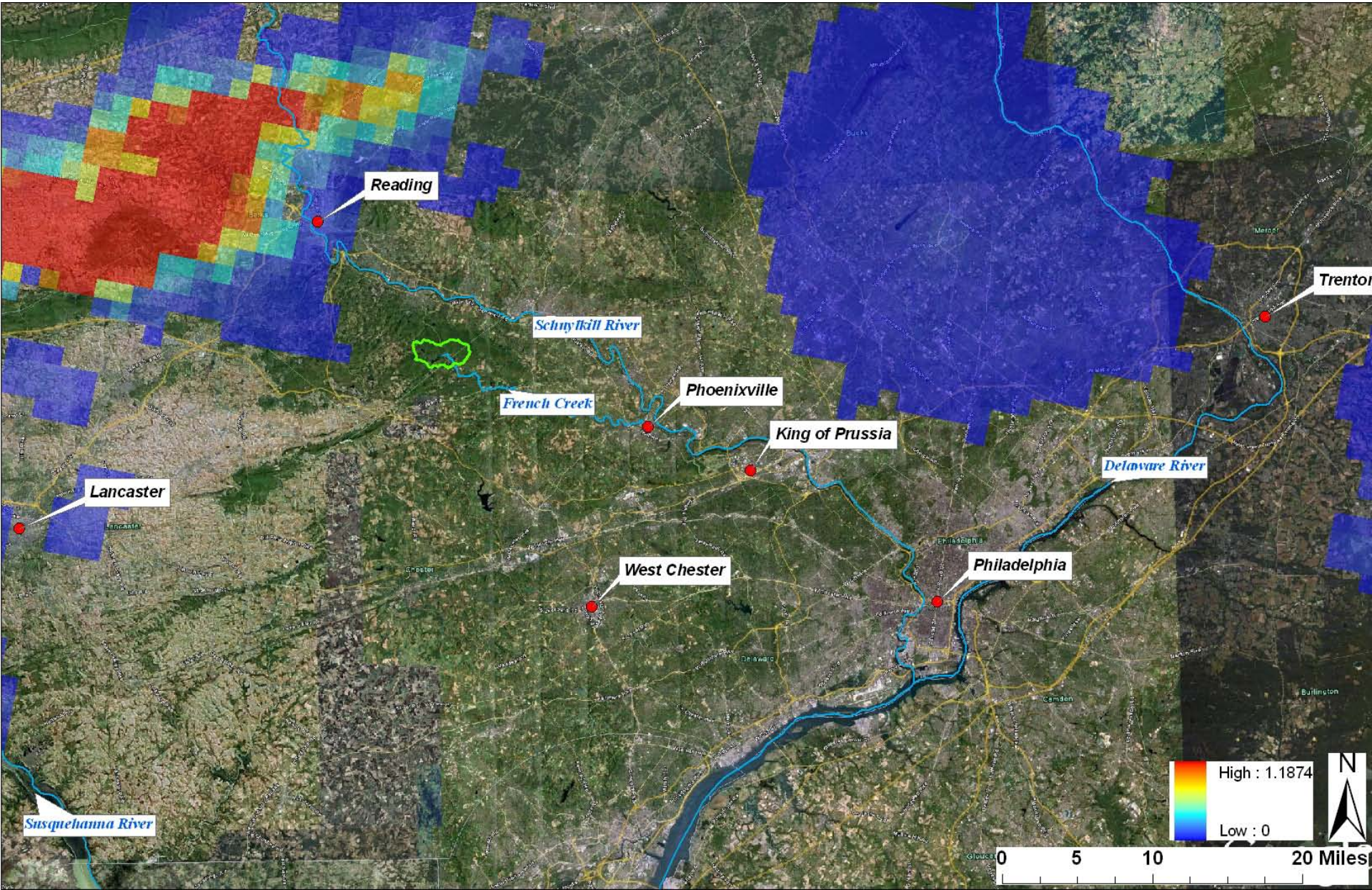
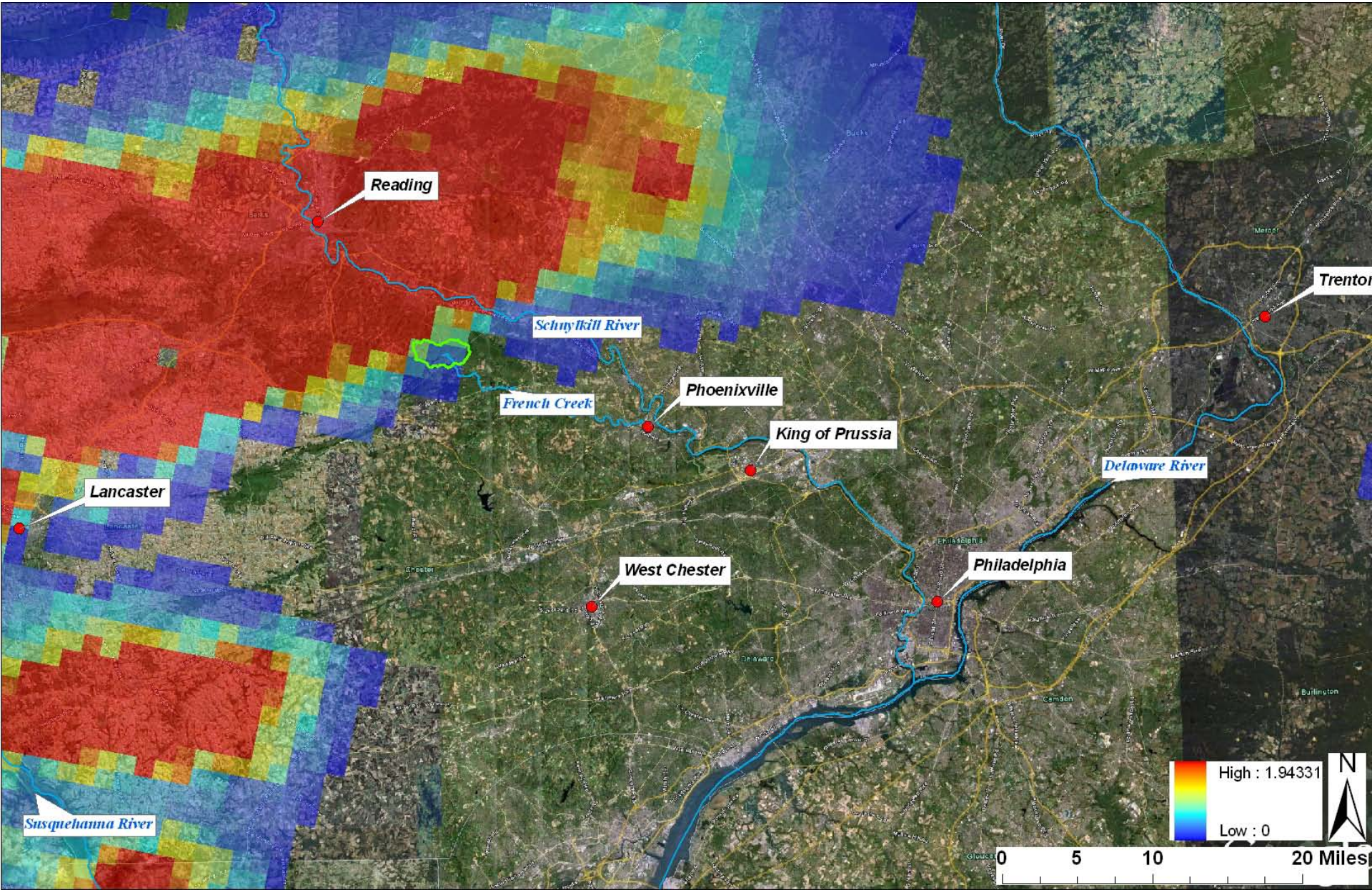


FIG. 9-21. Effect of rain-gage density on analysis of rainfall pattern. Isohyetal maps of Aug. 3, 1939 storm, Muskingum Basin, Ohio. (*a*) 449 rain gages (1 gage per 18 sq mi); (*b*) 22 rain gages (1 gage per 375 sq mi). (*U.S. Weather Bureau.*)

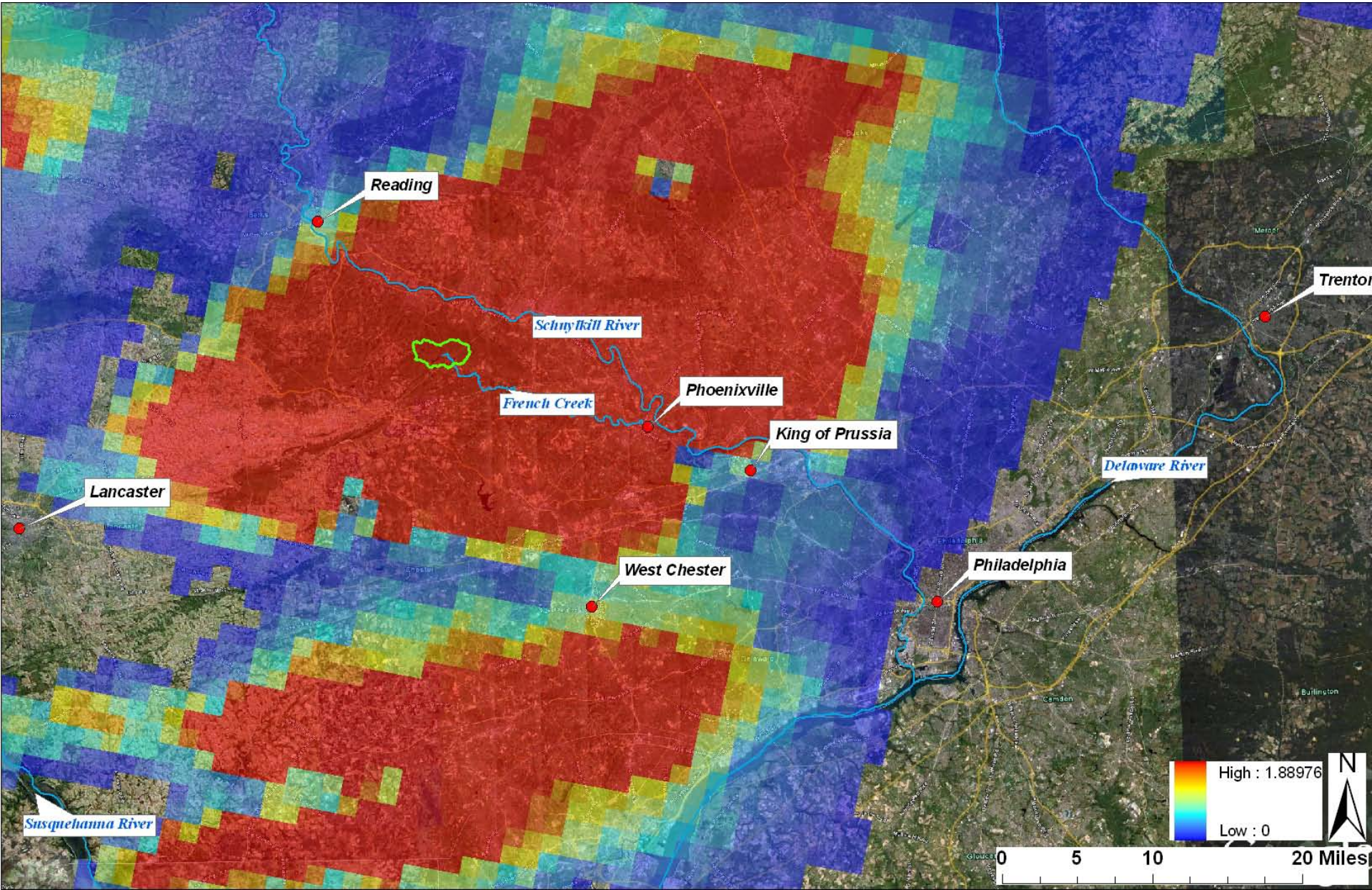
Radar Precip Estimates



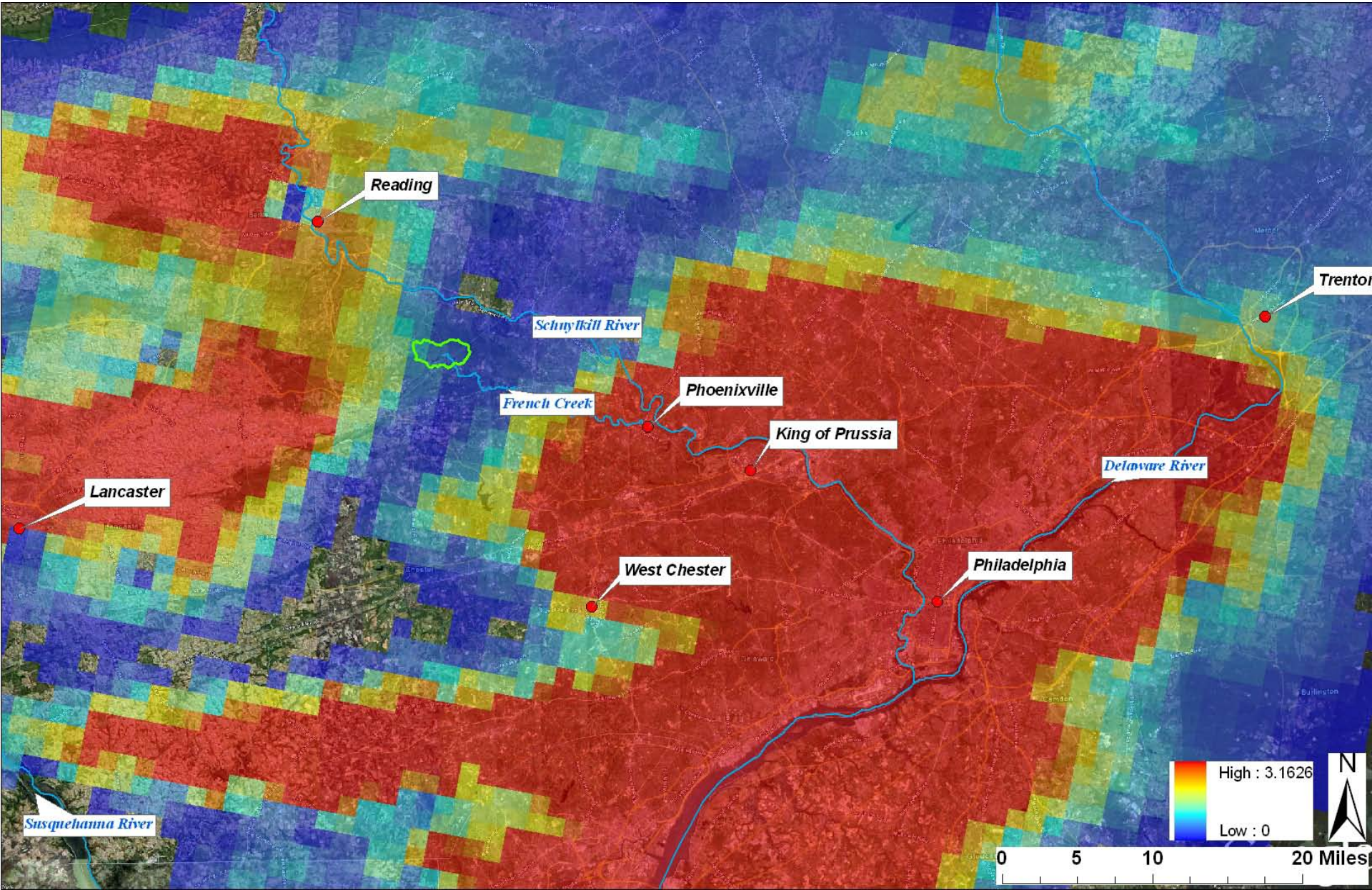
Radar Precip Estimates

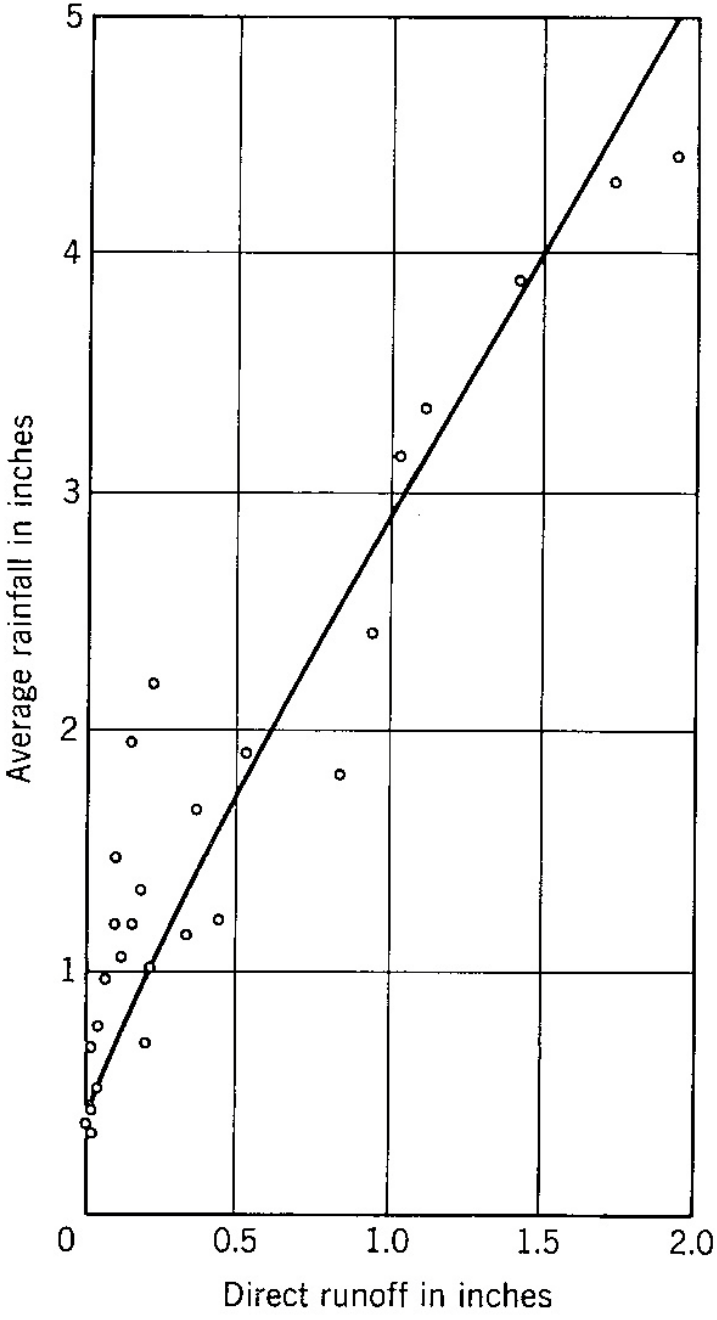


Radar Precip Estimates



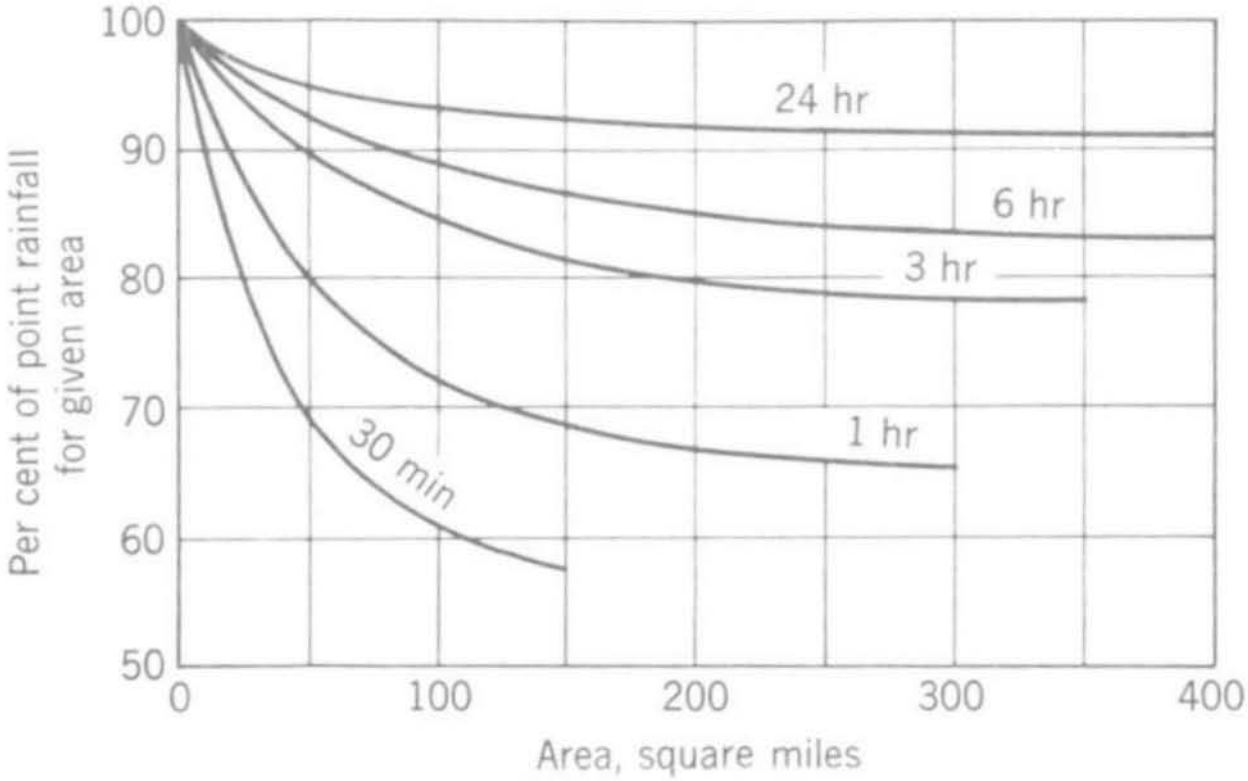
Radar Precip Estimates





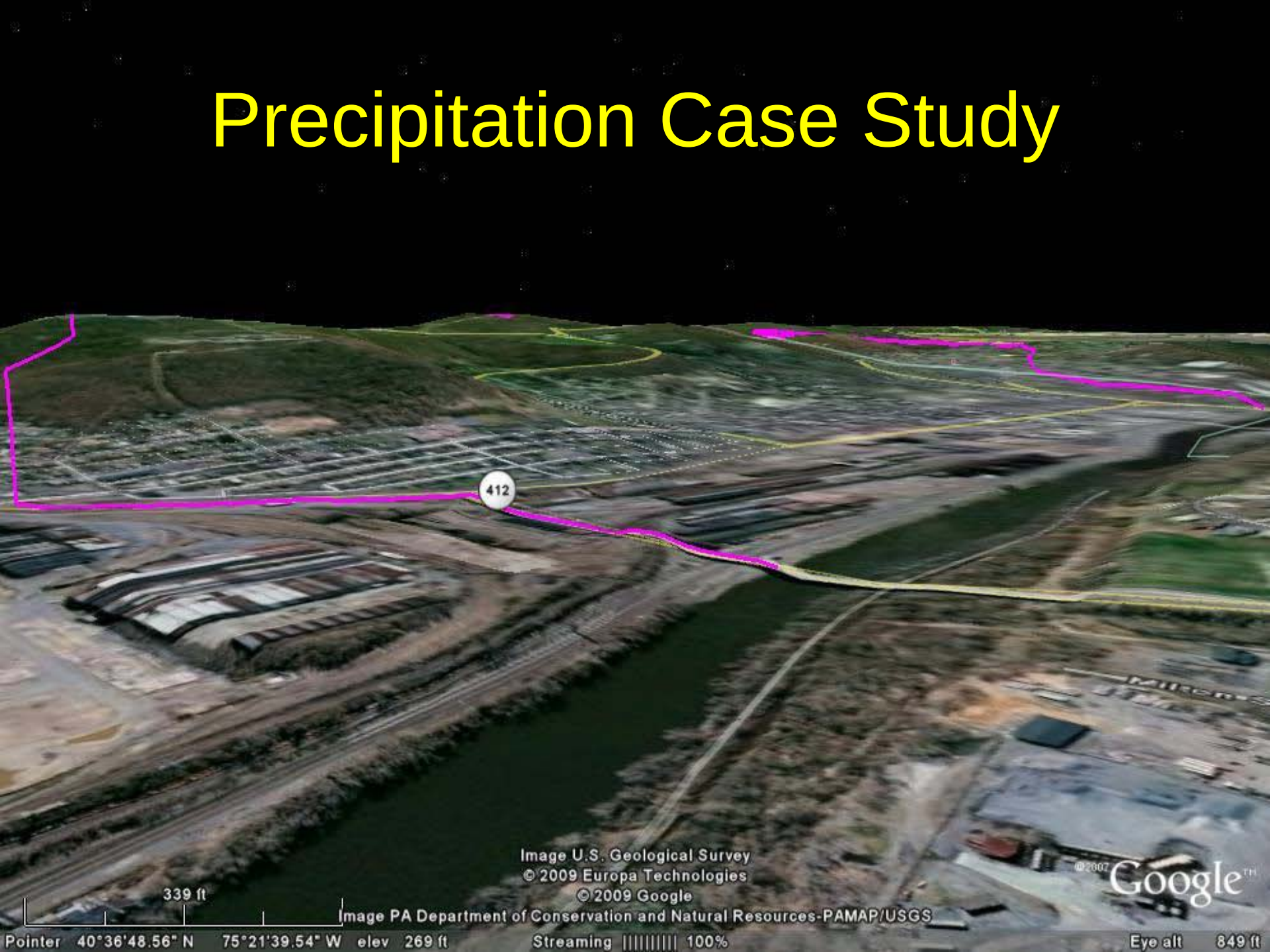
Can you Predict Runoff from Rainfall?

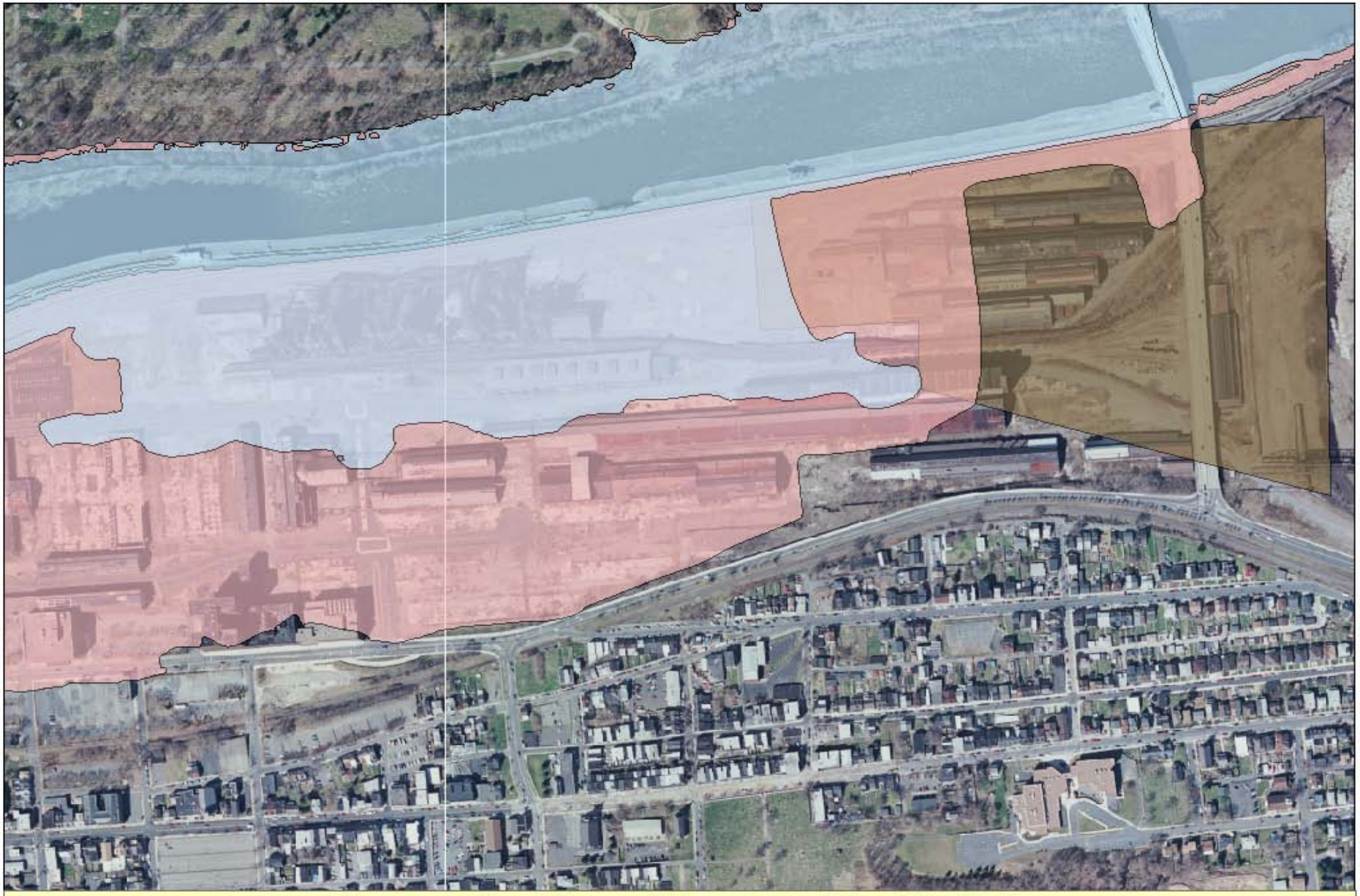
Is Rain Gauge Data Applicable to Larger Areas?



8 *Reduction of point rainfall for application to basins of specific size. (National Weather Service)*

Precipitation Case Study

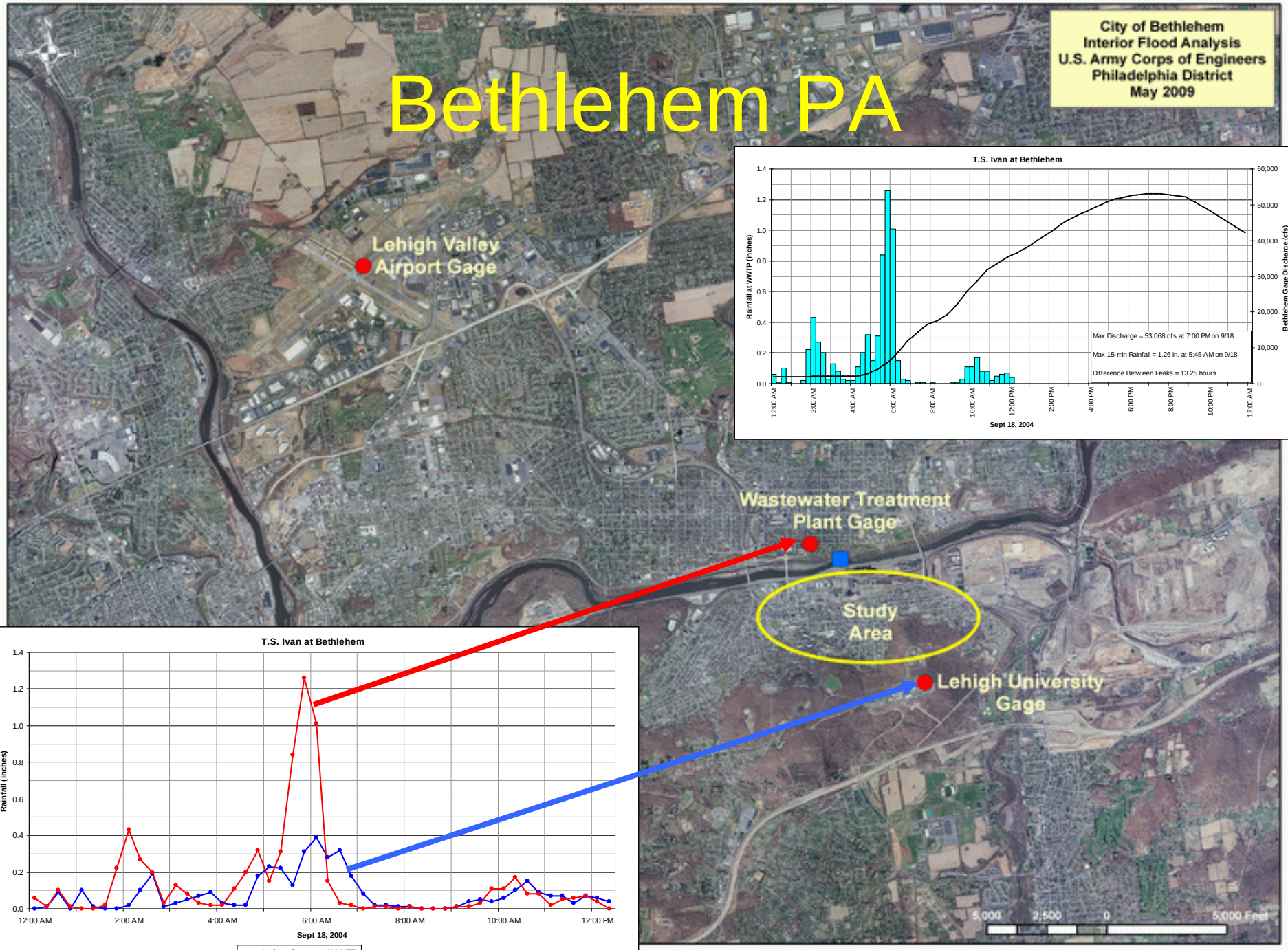




Revised Flood Hazard Mapping - City of Bethlehem
EL 231.1 NAVD (231.8 NGVD)
May 2009 - USACE Philadelphia District

Bethlehem PA

City of Bethlehem
Interior Flood Analysis
U.S. Army Corps of Engineers
Philadelphia District
May 2009



Rainfall Duration Frequencies

	Lehigh University		Wastewater Treatment Plant		Lehigh Intl Air Port	
Duration Minutes	**Precip Inches**	**Frequency YR**	**Precip Inches**	**Frequency YR**	**Precip Inches**	**Frequency YR**
15	**0.39**	**less than 2**	**1.26**	**65**	**n/a**	**n/a**
30	**0.70**	**less than 2**	**2.27**	**350**	**n/a**	**n/a**
60 (1 hr)	**1.30**	**4**	**3.42**	**550**	**1.10**	**less than 2**
120 (2 hrs)	**2.06**	**7**	**4.24**	**375**	**2.08**	**7**
240 (3 hrs)	**2.36**	**8**	**4.42**	**290**	**2.86**	**20**
360 (6 hrs)	**3.00**	**9**	**5.91**	**280**	**3.53**	**20**
720 (12 hrs)	**4.09**	**12**	**6.95**	**160**	**4.59**	**22**

Volume Rainfall Example

- rainfall = 2.0 inch

- land area receiving rain = 50 acre

- volume rainfall =100 acre-inch

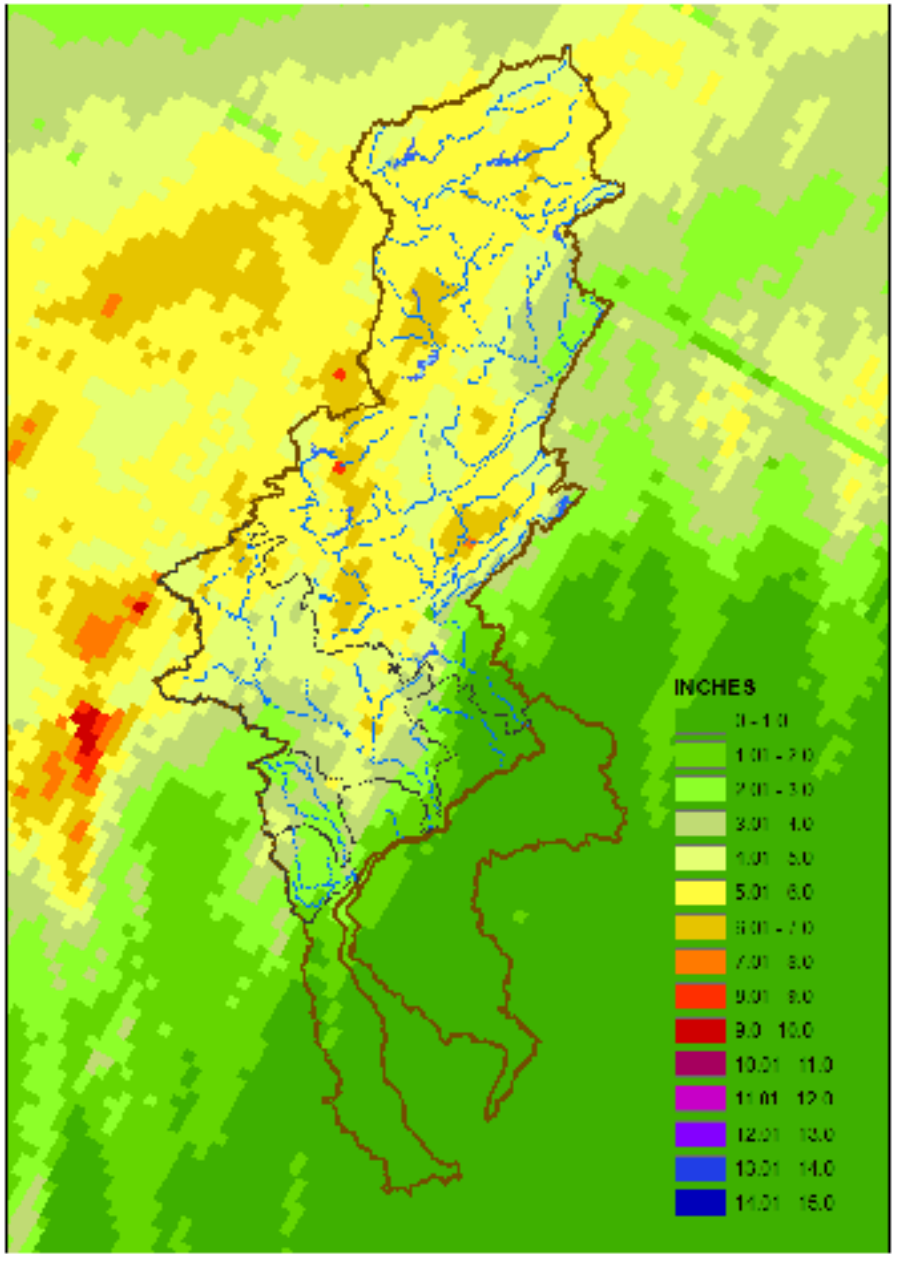
Volume Rainfall, Time Step Example

- rainfall intensity = 0.5 inch/hour

- time step length = 4.0 hour

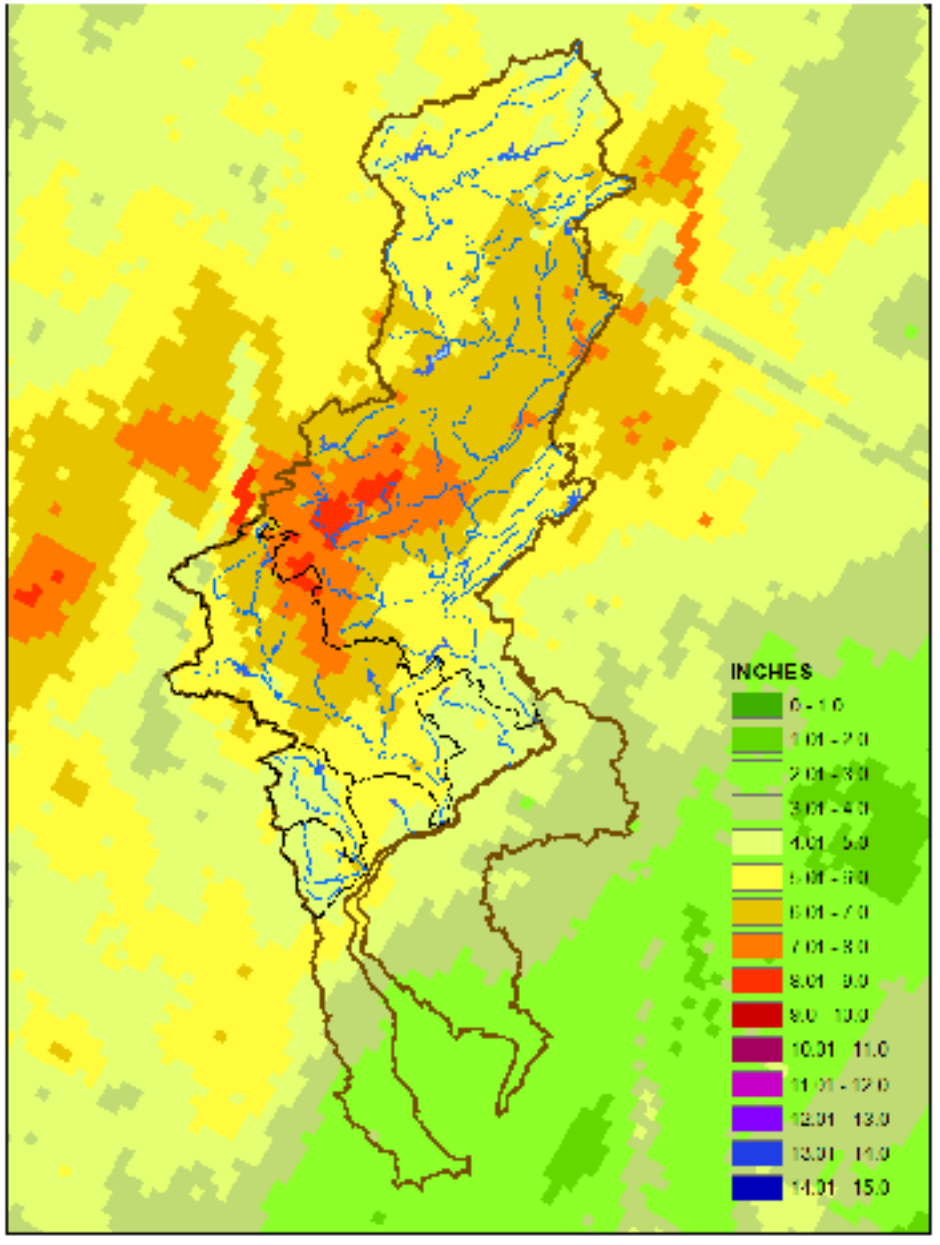
- land area receiving rain = 50 acre

- volume rainfall = 100 acre-inch



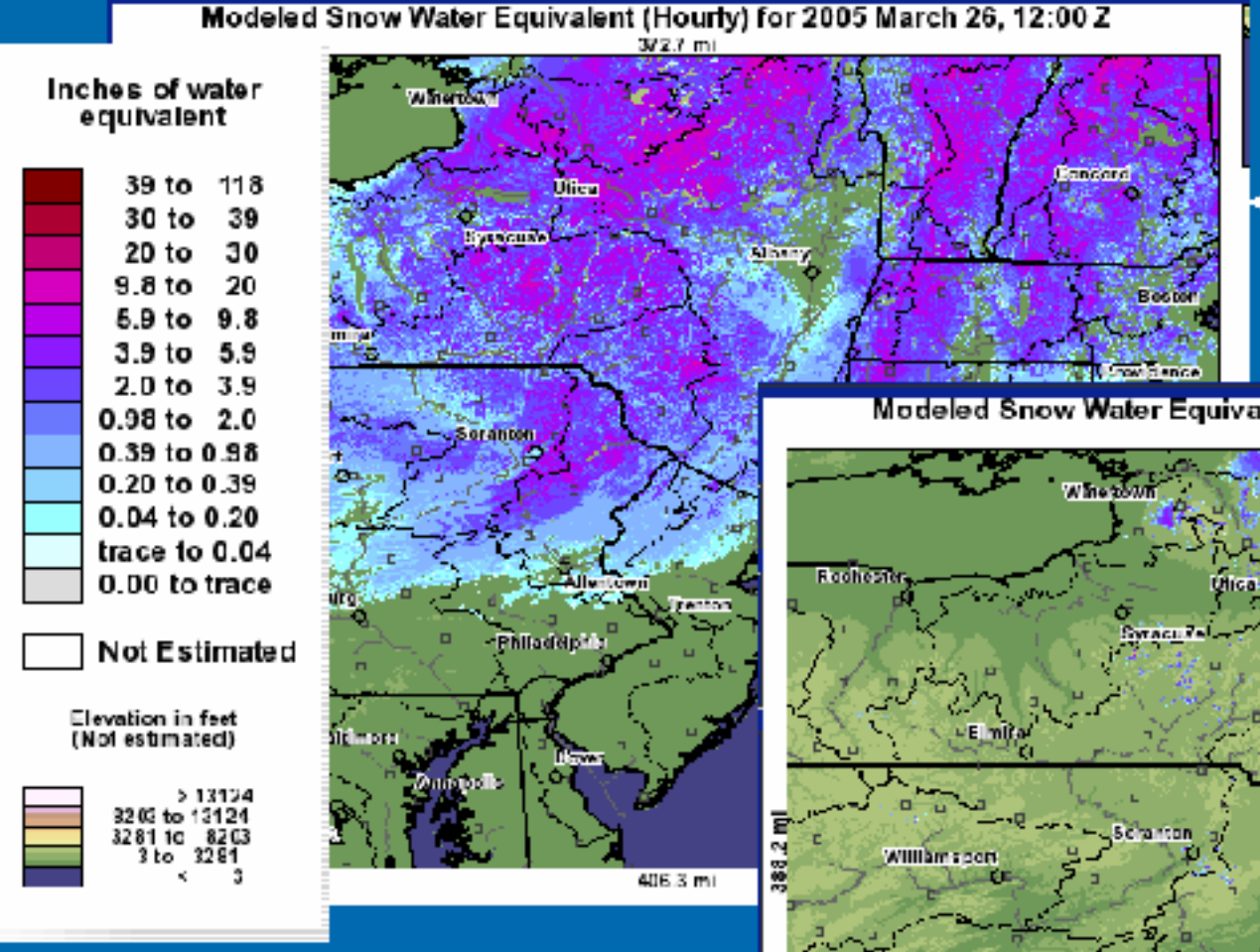
September 17, 2004

- Remnants of Tropical Storm Ivan interacted with cold front.
- Soils heavily saturated prior to event from Tropical Storm Frances.
- Pre-event flows in the main stem were 298 percent of normal at Montague and 265 percent of normal at Trenton.
- Heavy rain fell in Poconos and Catskills.
- Rainfall rates of three to five inches within a 12-hour period.
- Isolated areas received as much as seven or eight inches.

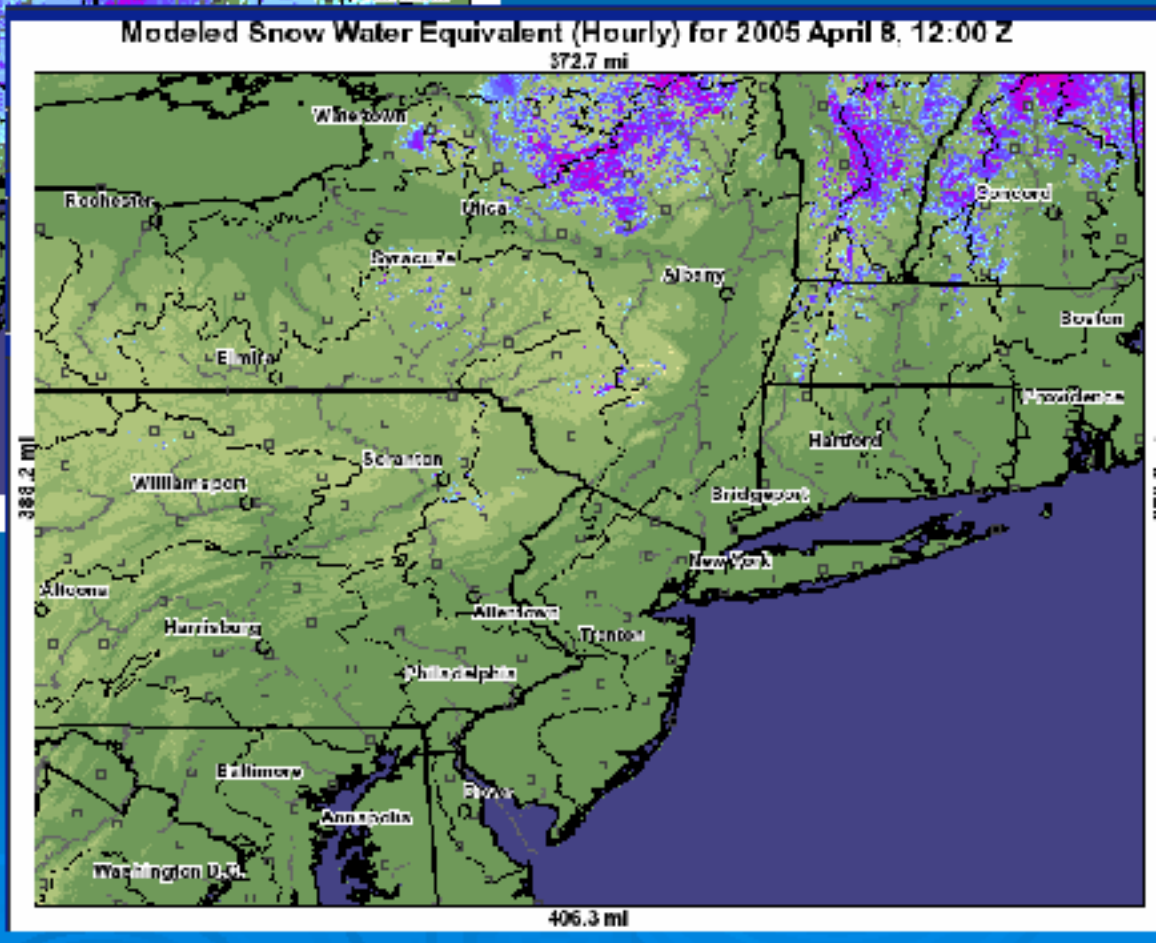


March 28-29 and April 2-3, 2005

- The first event dropped two inches of precipitation.
- Warmer temperatures during and after the first event melted the equivalent of three inches of water stored in the snow pack.
- The second event produced two to five inches of rain throughout the basin and melted the remaining snow pack.
- Prior to the second event, streamflows were high.

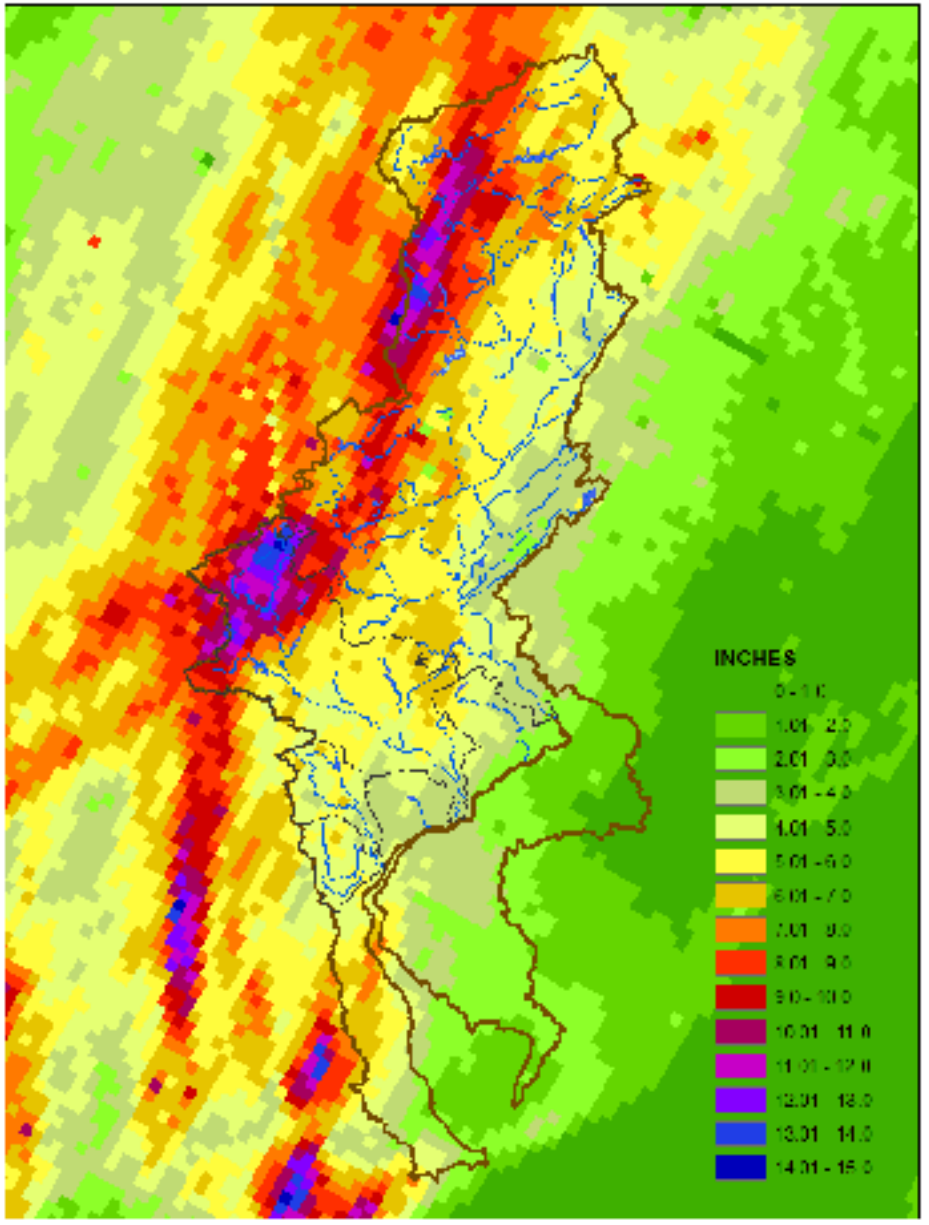


Pre-event Snow Pack March 26, 2005



Post-event Snow Pack April 8, 2005

PRELIMINARY CONFIDENTIAL DO NOT CITE



June 24-28, 2006

- Conditions were dry prior to the event.
- Between six and fifteen inches of rain fell in western portion of the upper basin.
- Up to five inches of rain fell in most of the basin except southern NJ and the Philadelphia area.

Max. Observed Rainfalls

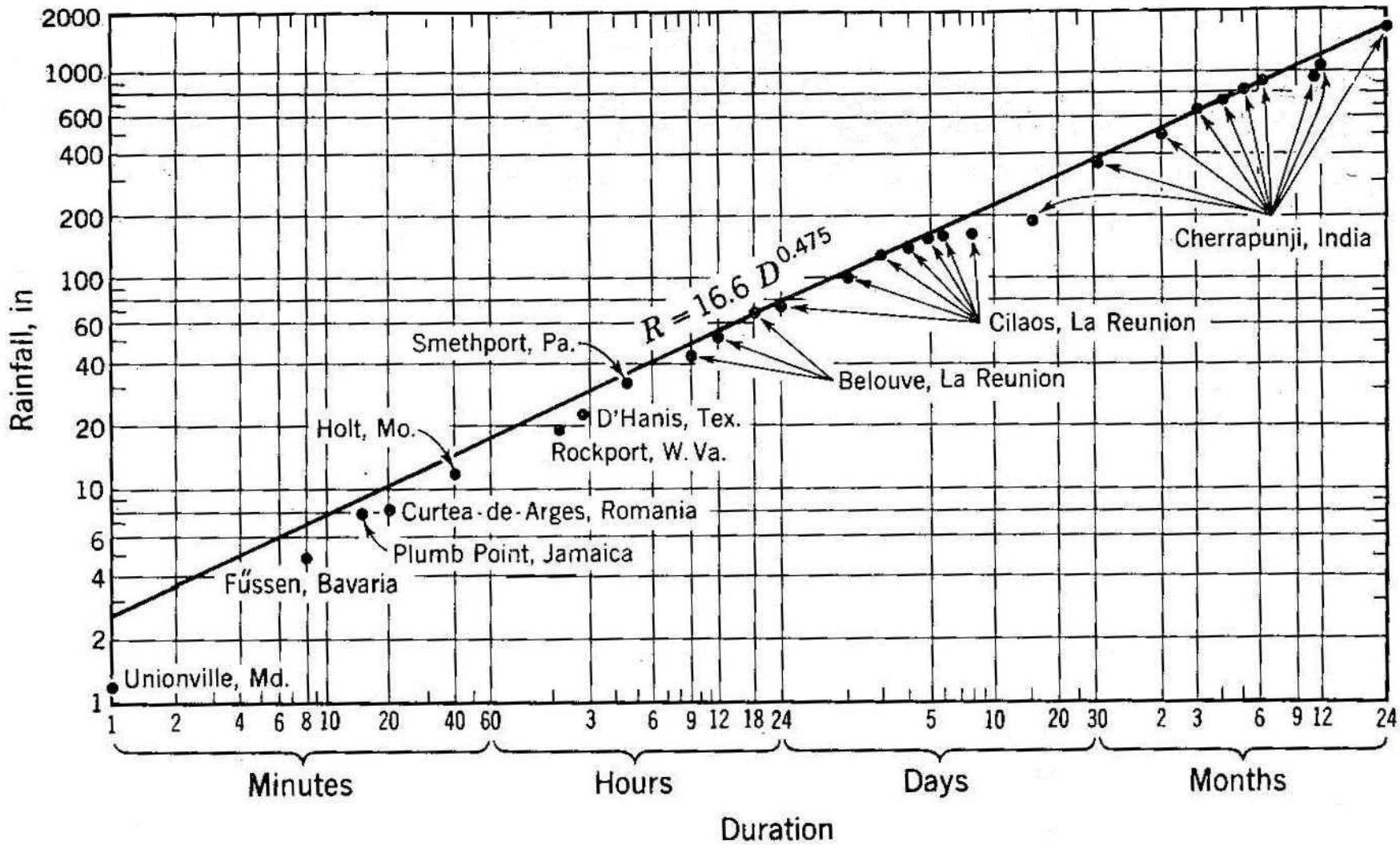


FIG. 2-7 Maximum observed world rainfalls for various durations.

PMP

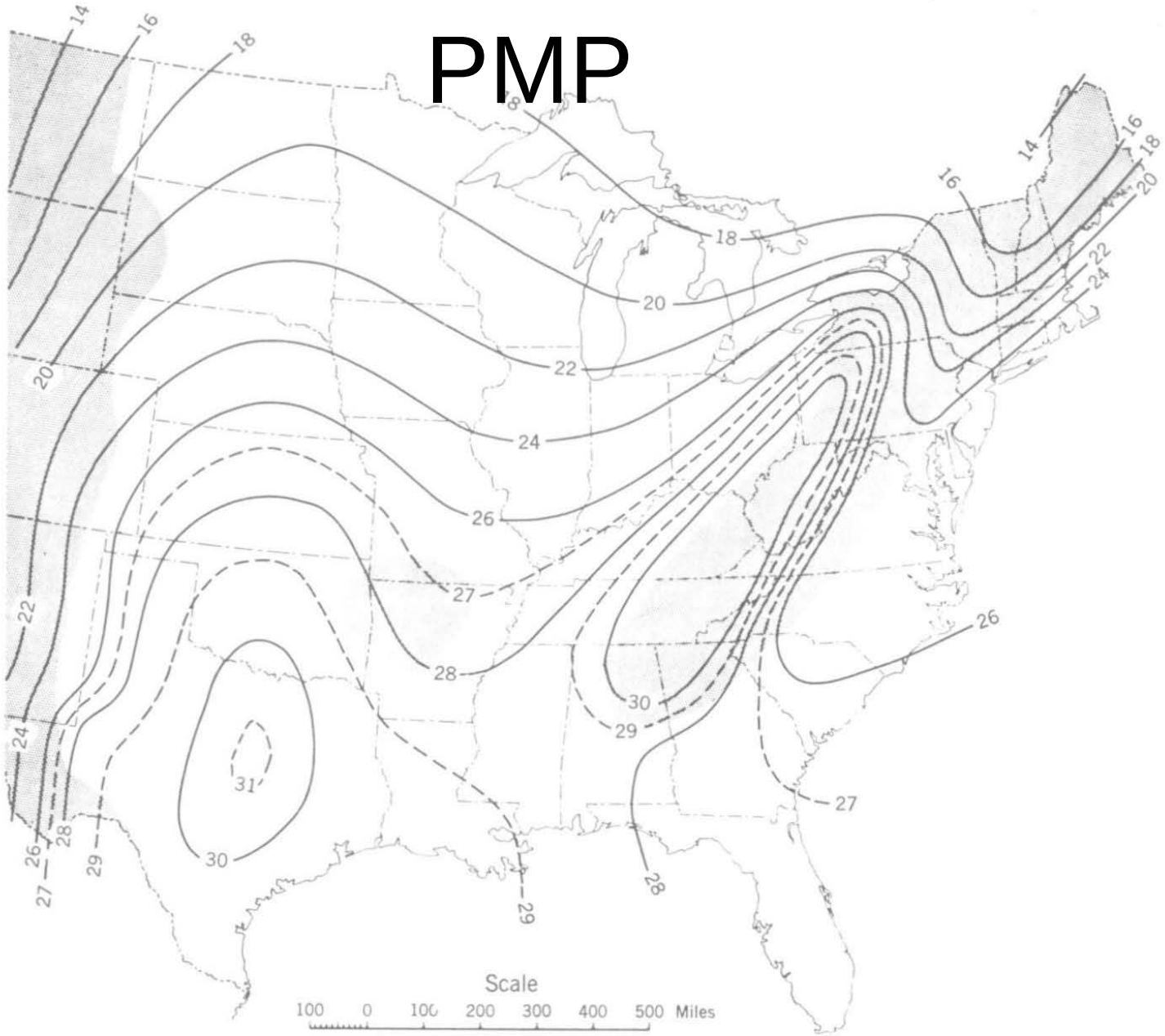


FIG. 5-11 Probable maximum precipitation in inches for areas of 10 *sq mi and duration of* 6 *hr.* (*National Weather Service; U.S. Corps of Engineers*)

Evaporation & Transpiration

- How it’s Measured?
- Change with Location
- Change with Season

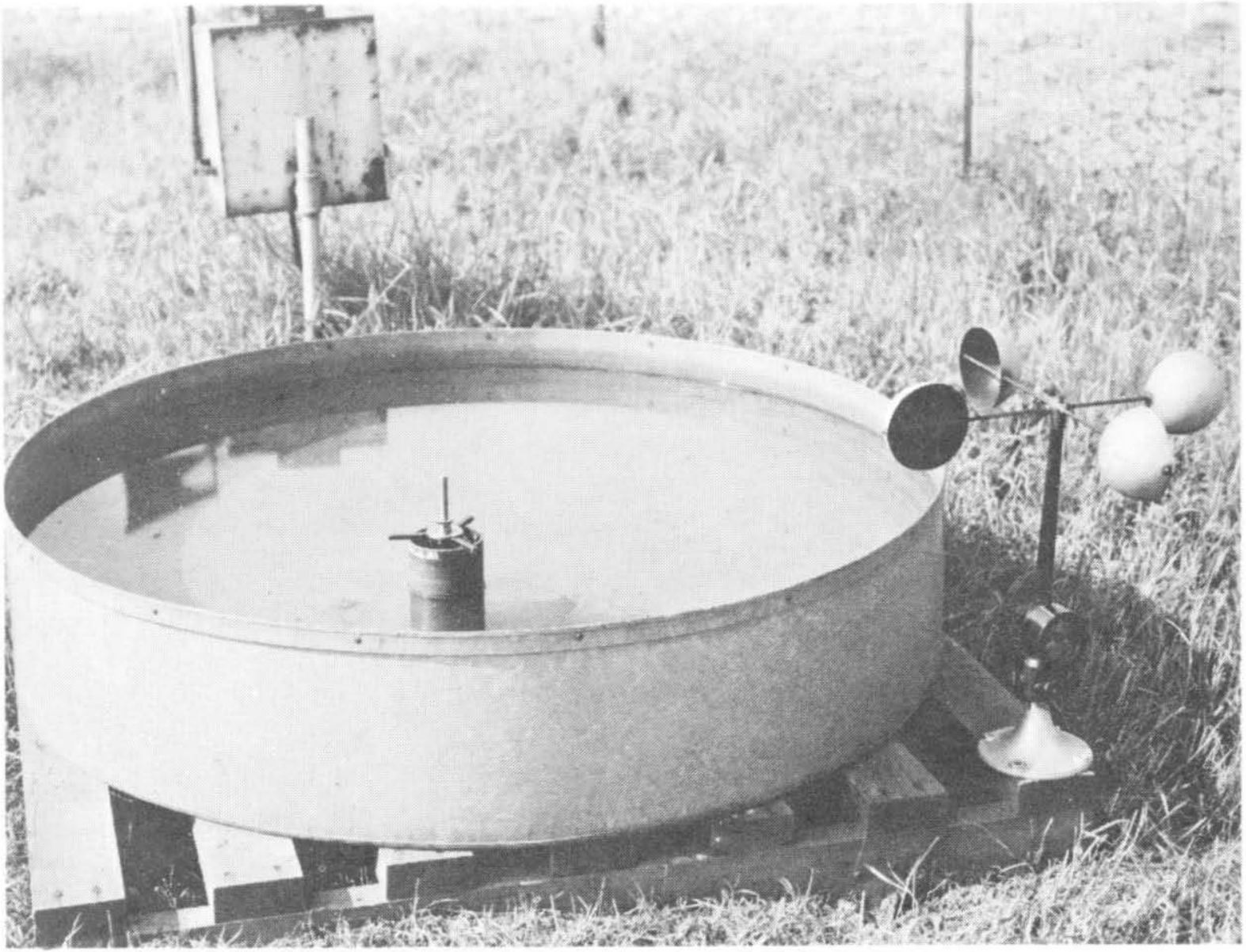
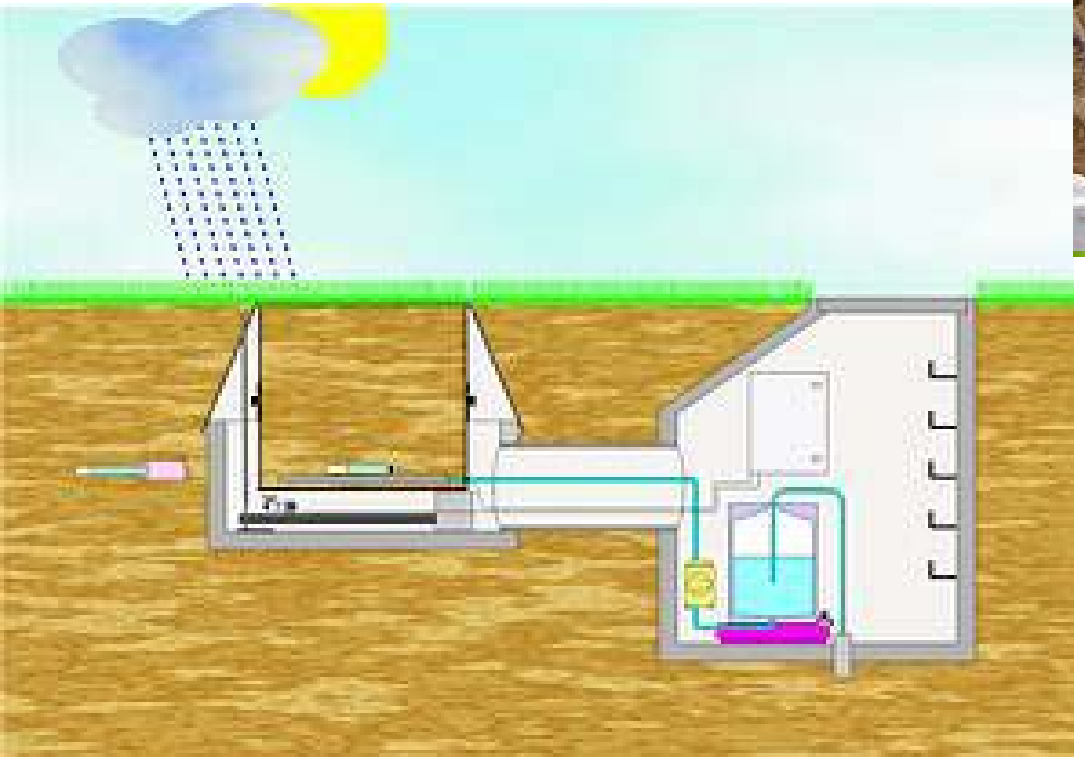


FIG. 2-15 Class A land pan showing hook gage and anemometer. (National Weather Service)

Lysimeters



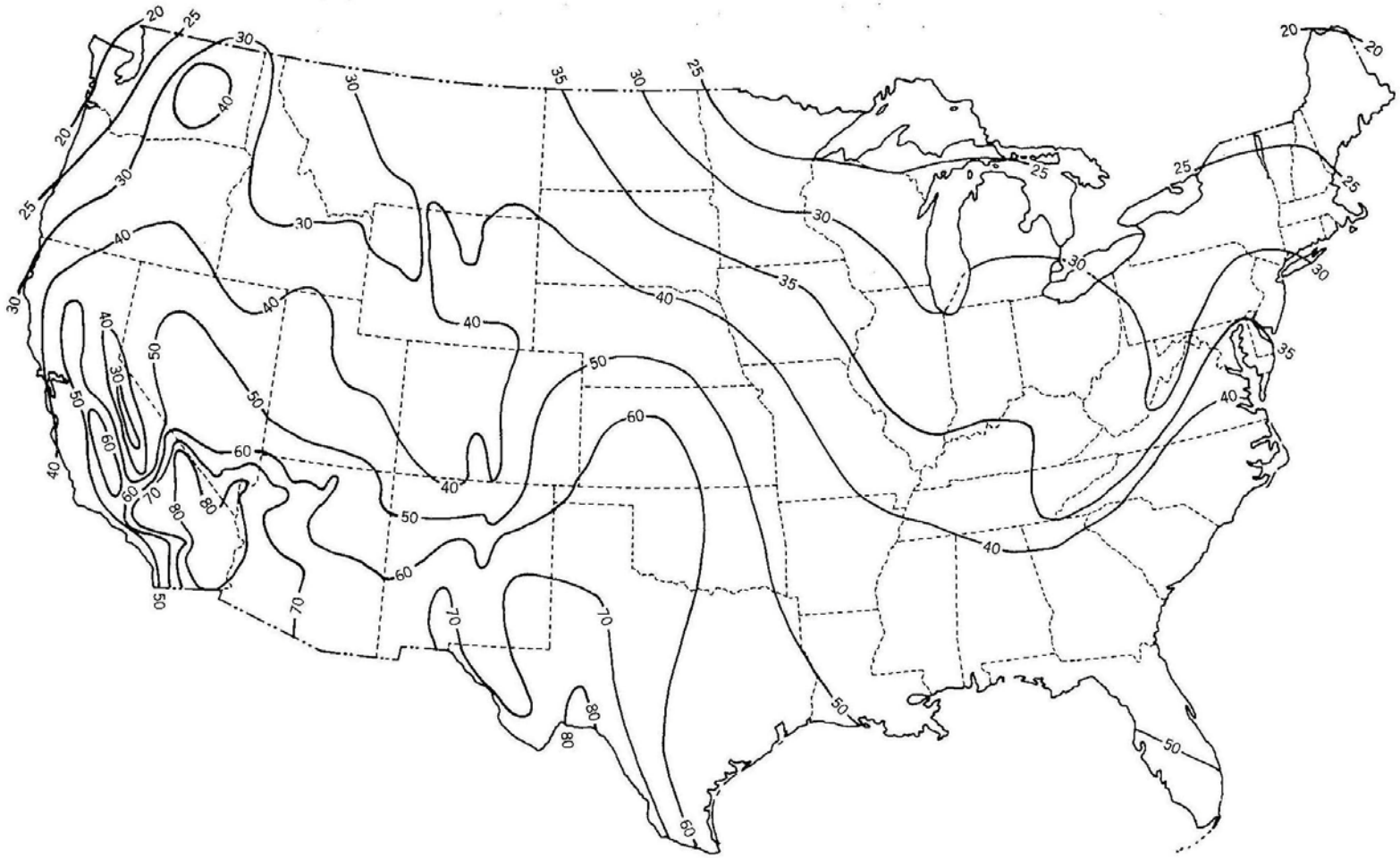


FIG. 2-16 Average annual lake evaporation in inches. (National Weather Service)

Average Annual Precipitation

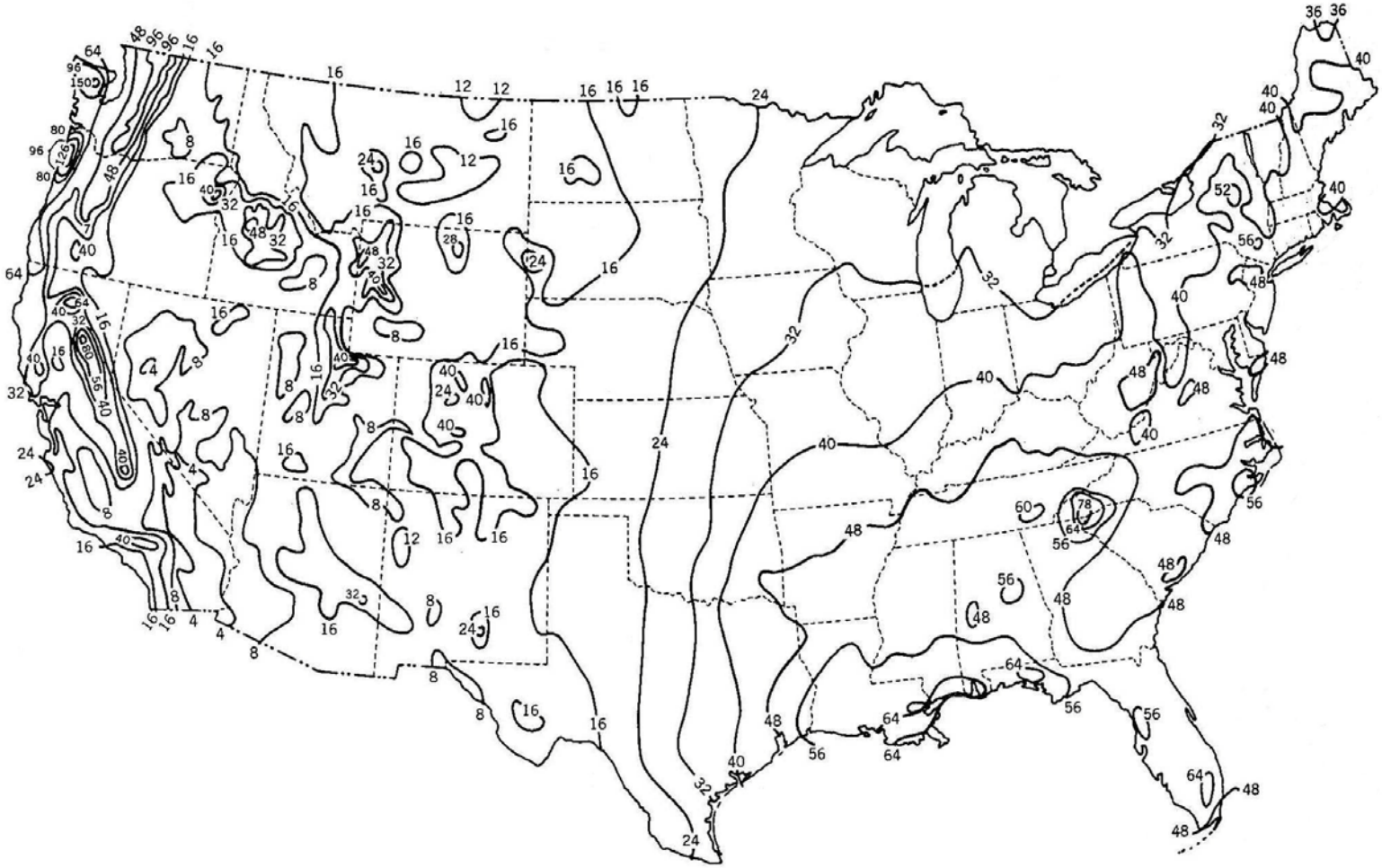


FIG. 2-5 Average annual precipitation in the United States. (National Weather Service)

*TABLE 2-4 Mean Monthly and Annual Class A Pan Evaporation at Selected Stations**
(*In inches*)

Month	*Newark, Calif.*	*W. Palm Beach, Fla.*	*Vicks-burg, Miss.*	*Seattle, Wash.*	*Norris, Tenn.*	*Ithaca, N.Y.*	*Lincoln, Nebr.*	*Hoaeae, Hawaii*	*Bartlett Dam, Ariz.*
January	1.36	3.42	1.67	†	1.01	†	†	3.56	4.09
February	1.90	3.73	2.10	0.89	1.32	†	†	3.85	4.50
March	3.42	4.99	3.79	1.76	2.65	†	†	4.73	7.10
April	5.05	6.11	4.96	2.91	4.08	†	5.73	5.44	10.43
May	7.19	6.54	5.95	4.40	5.52	4.29	7.00	5.99	14.55
June	8.27	6.20	6.60	4.77	6.15	5.16	8.58	6.37	17.03
July	8.75	6.88	7.13	6.28	5.88	5.87	10.54	7.00	17.23
August	7.73	6.37	6.68	4.97	5.24	4.94	8.78	7.00	14.50
September	6.60	5.18	5.06	3.25	4.33	3.35	6.94	5.88	12.70
October	4.32	4.87	3.91	1.55	2.96	2.14	4.63	5.28	9.25
November	2.35	3.60	2.34	0.65	1.61	†	†	3.88	6.06
December	1.26	2.98	1.42	0.53	0.94	†	†	3.57	4.19
Year	58.20	60.87	51.61	...	41.69	...	...	62.55	121.63

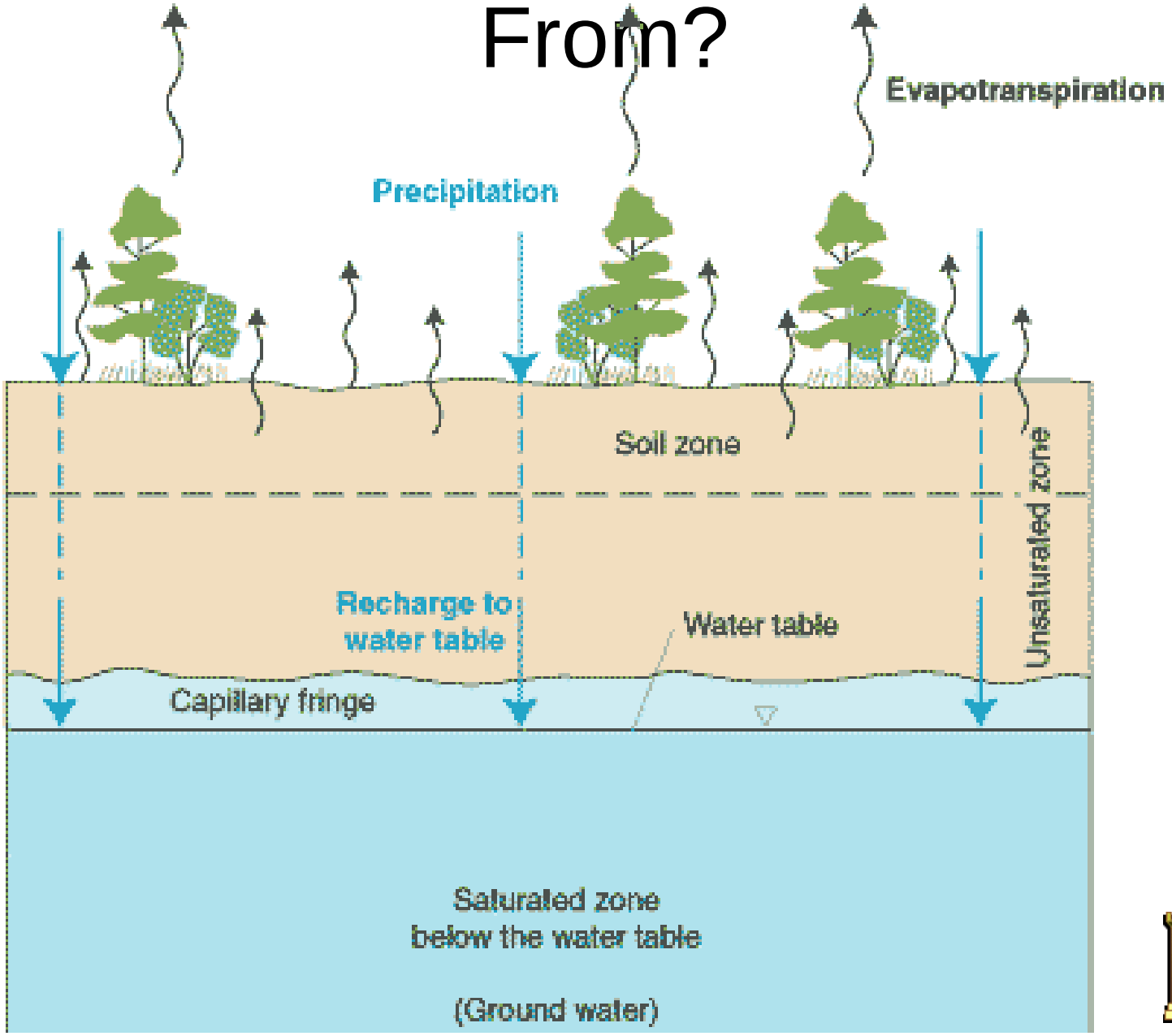
*Mean Monthly and Annual Evaporation from Free Water Surface, *U.S. Weather Bur. Tech. Paper* 13, 1950.

†Pan inoperative because of ice.

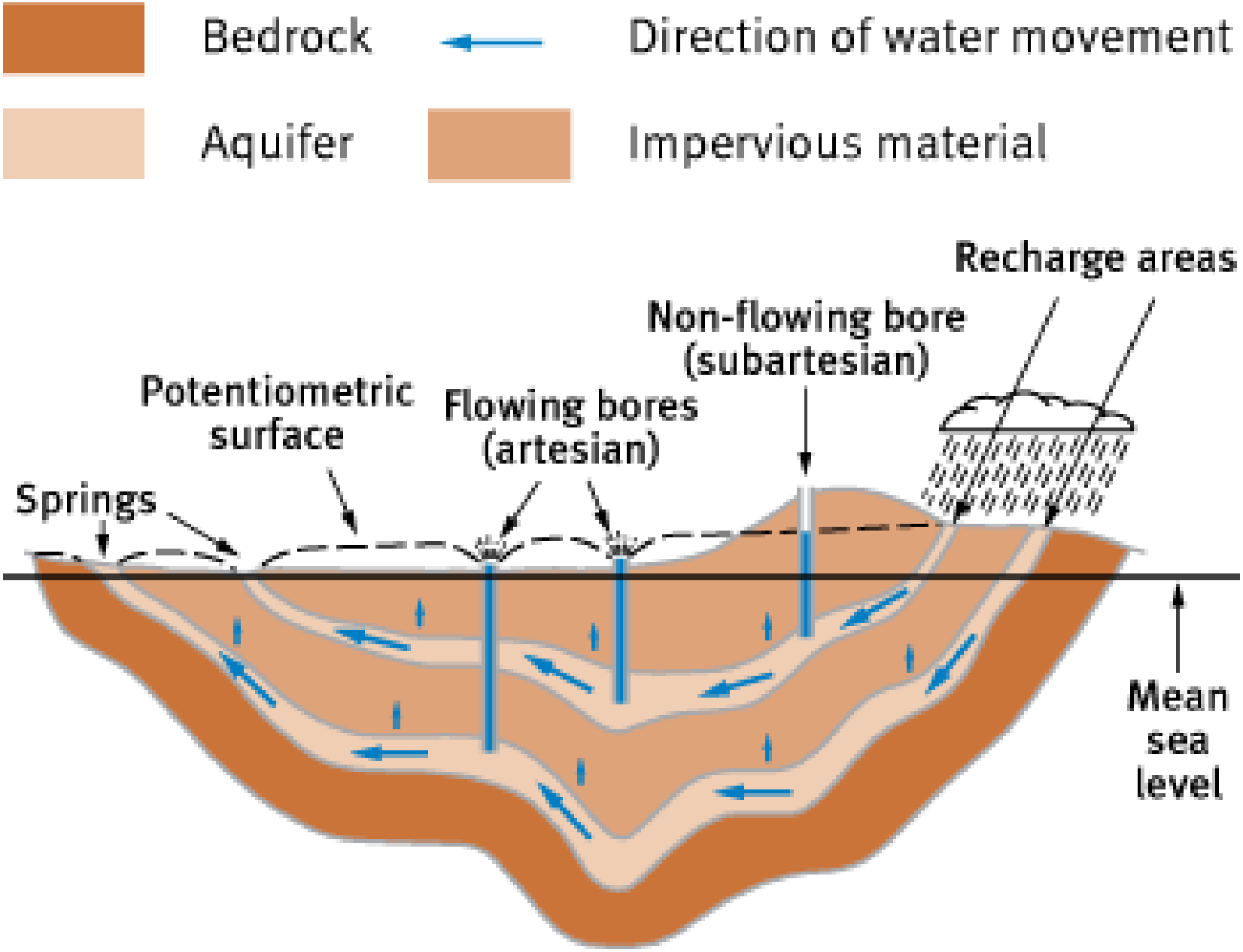
Groundwater

- Where did all the Rainfall Go?
- Surface-Subsurface Interaction
- Groundwater Movement
- Recharge & Discharge Areas
- Well Hydraulics
- Contaminant Transport
- How Safe is Safe Yield?

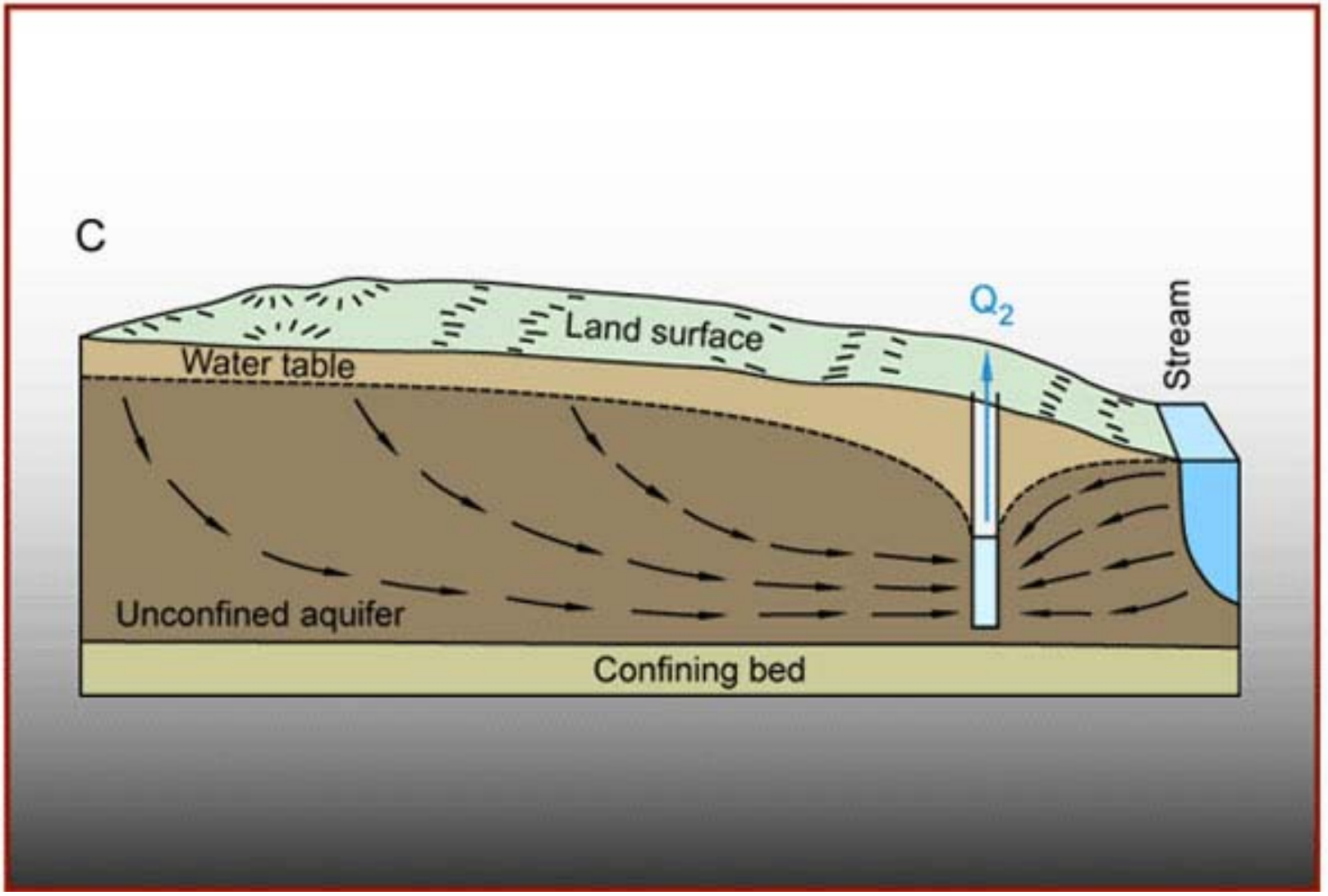
Where Does Groundwater Come From?



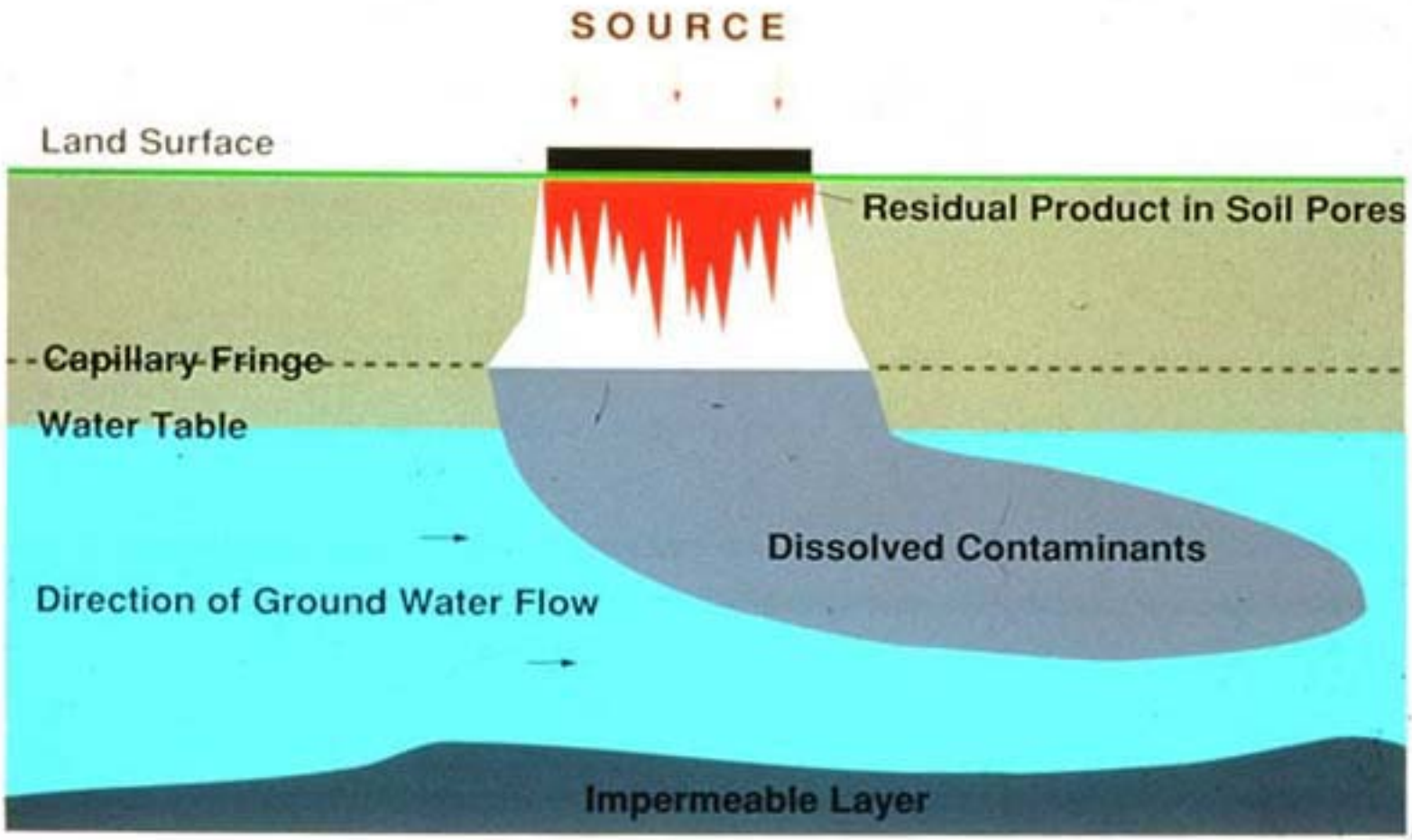
How Does It Move?



Well Drawdown

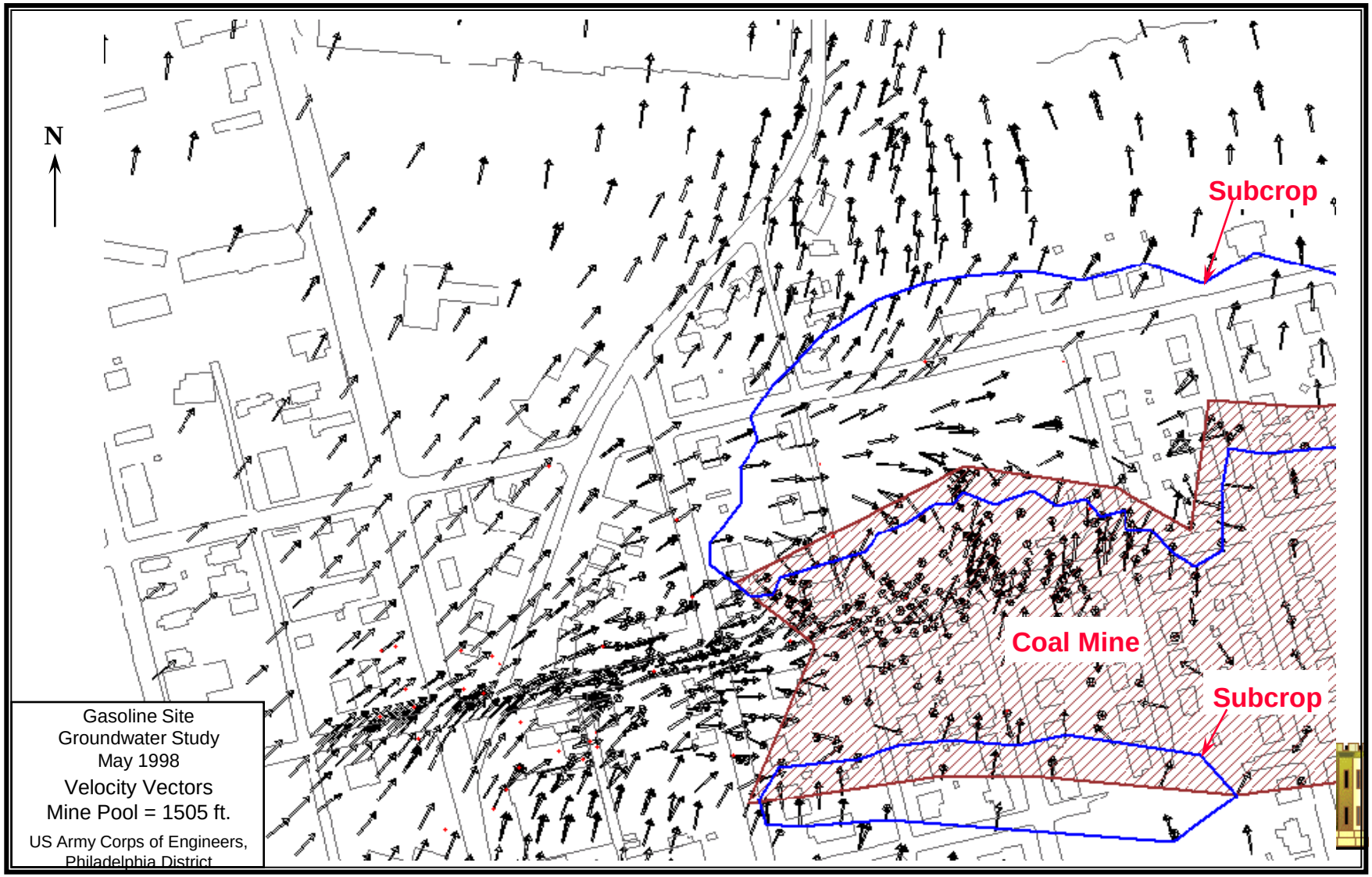


How Does Contamination Travel?



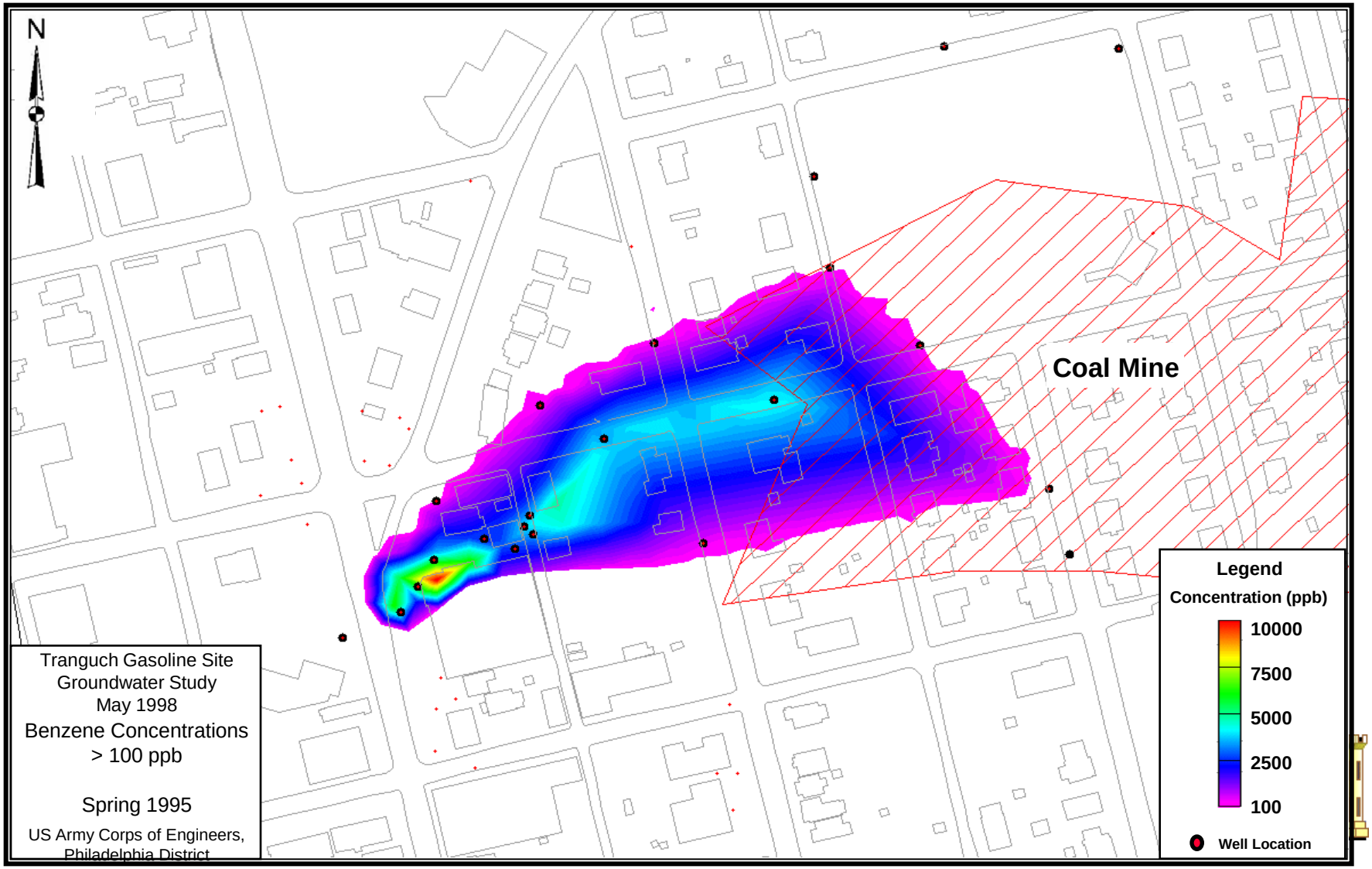
Flow Models – Potential Pathways

US Army Corps of Engineers
Philadelphia District



Data Visualization – Plume Plots

US Army Corps of Engineers
Philadelphia District



How Safe is Safe Yield?

- Safe Yield is:
  - All rainfall?
  - All streamflow?
  - All Stream Baseflow?
  - A percent of Stream Baseflow?

http://ponce.sdsu.edu/groundwater_sustainable_yield.html

Streamflow

- About 1/3 of all Precipitation Runs off as Streamflow or Groundwater Flow
- Streamflow Changes with Season and Location
- How it’s measured
- Common Units

Runoff Calculation

Runoff comprises about 1/3 of all Precipitation

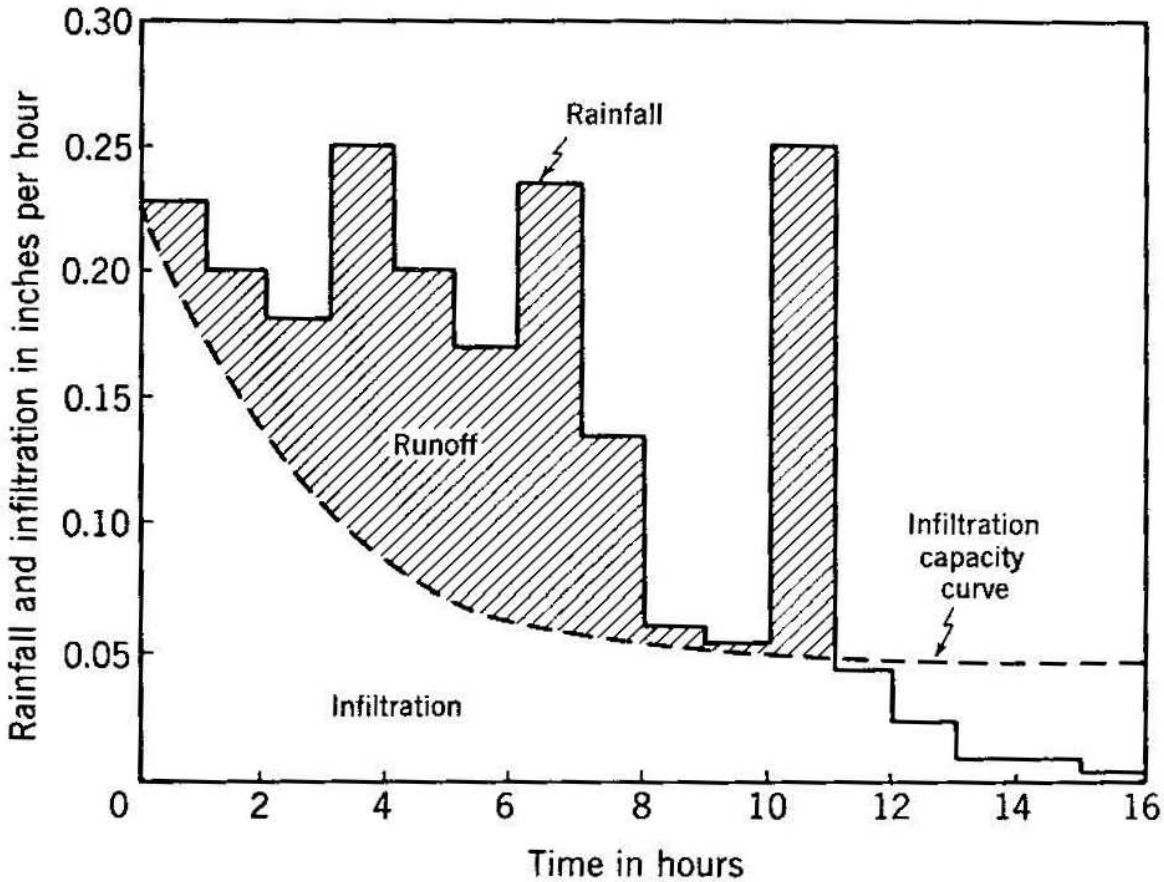


FIG. 3-2 Typical infiltration curve superimposed on a rainfall diagram to illustrate method of calculating runoff.

Normal Annual Runoff

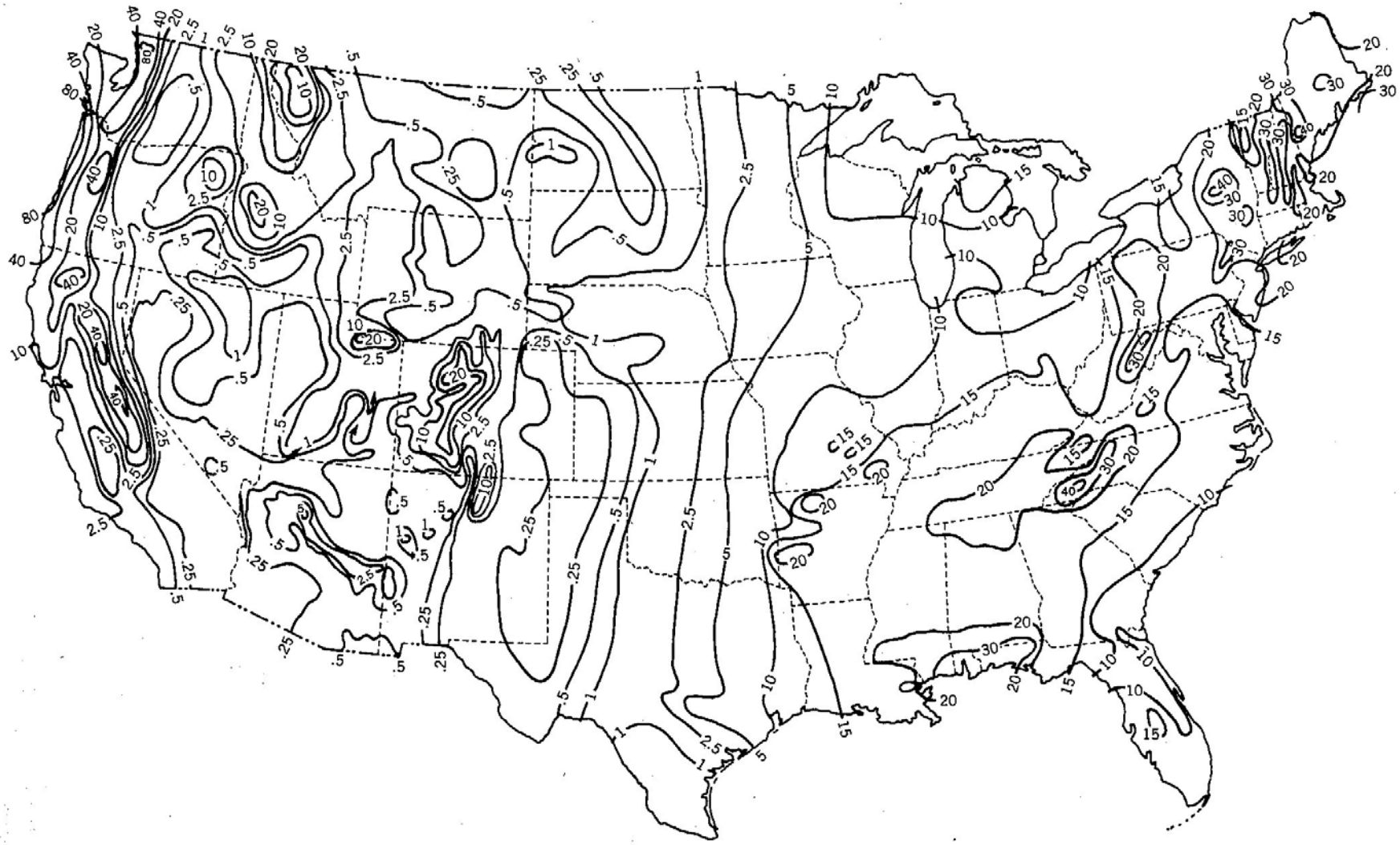


FIG. 2-12 Normal annual runoff in the United States in inches. (U.S. Geological Survey)

Mean Monthly Runoff

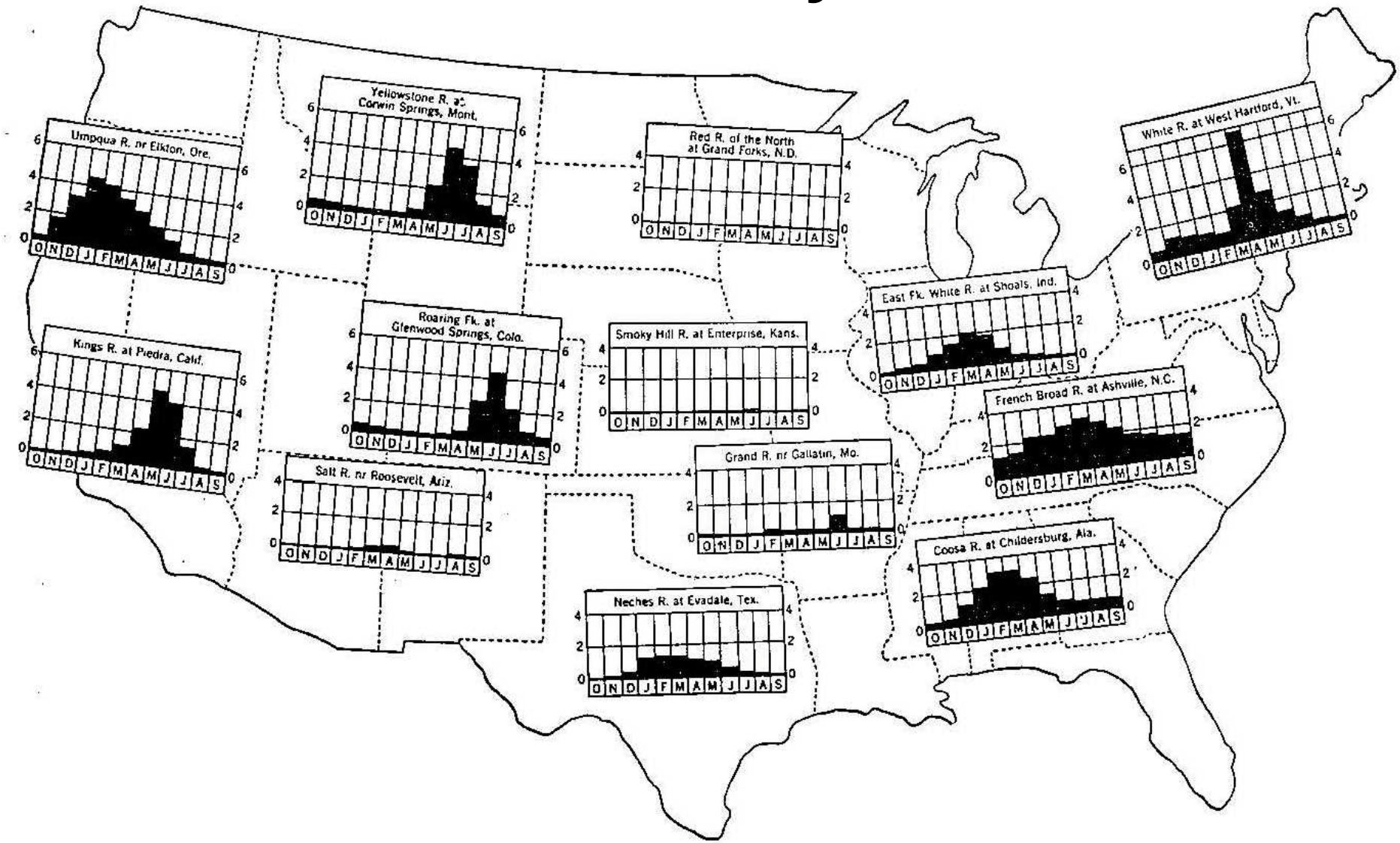
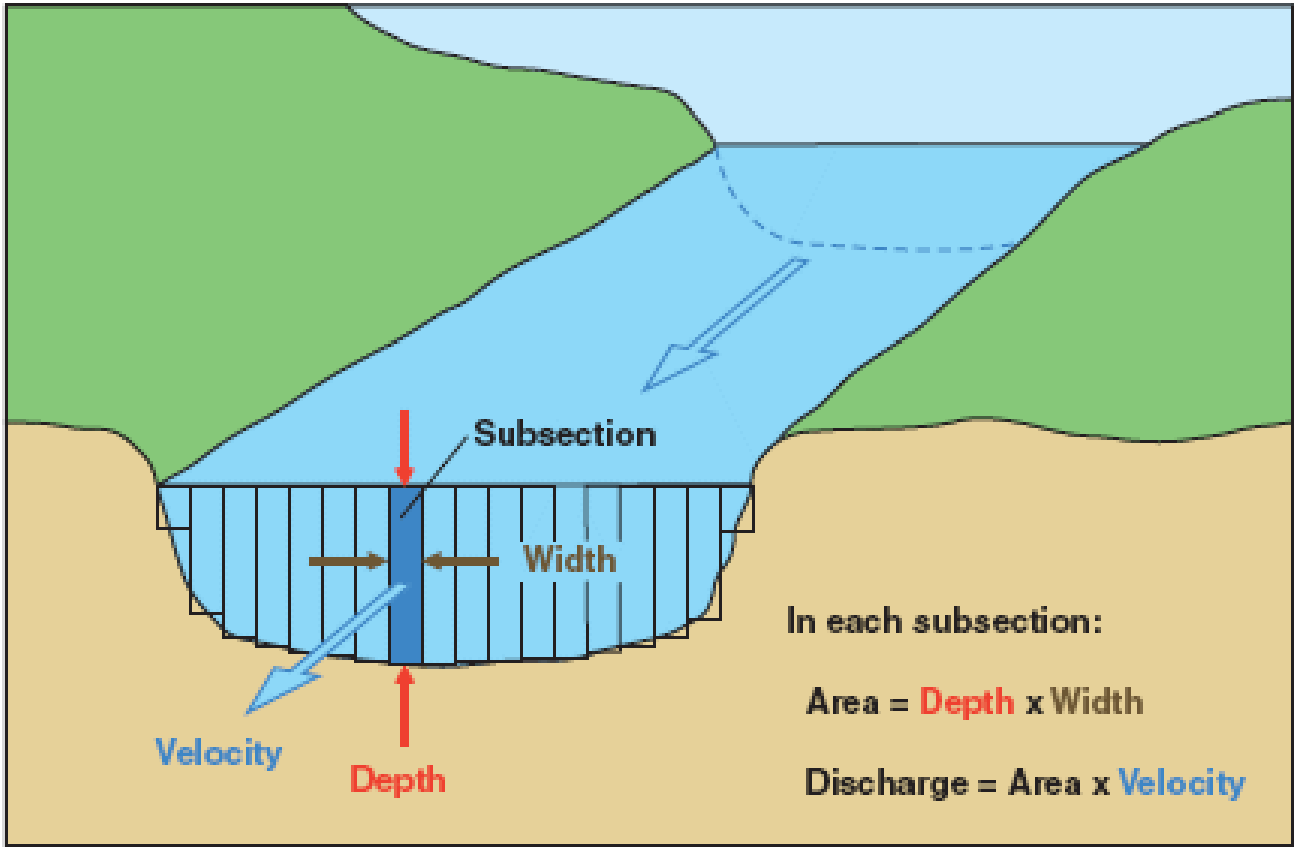


FIG. 2-13 Median monthly runoff in inches at selected stations in the United States.

Measuring Flow



Q=AV
Q=Flow
A=Area
V=Velocity

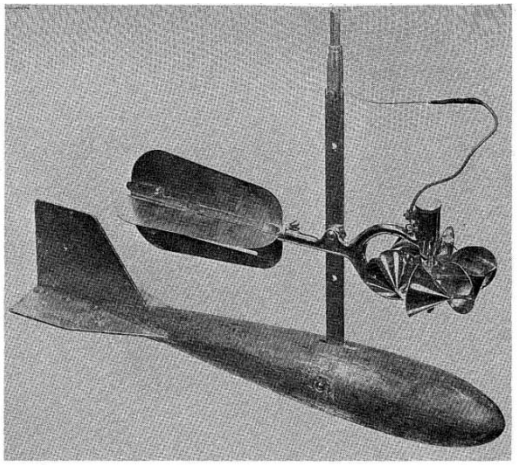
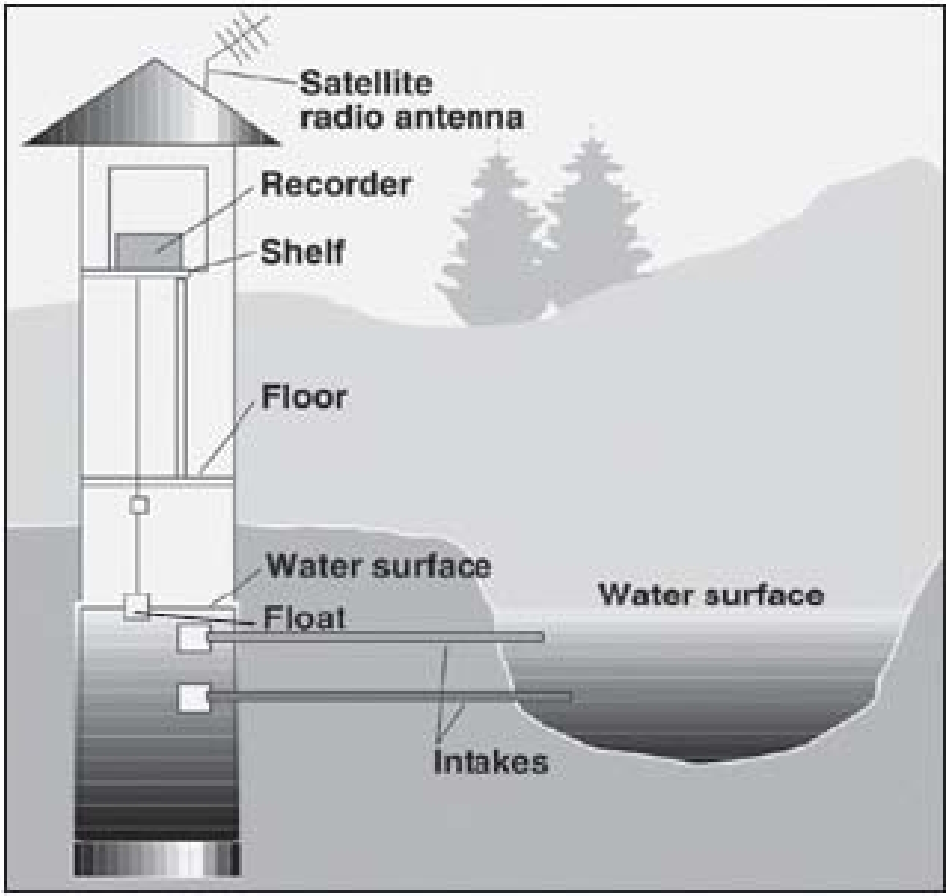


FIG. 2-9 Price current meter and 30-lb C-type sounding weight. (U.S. Geological Survey.

Current-meter discharge measurements are made by determining the discharge in each subsection of a channel cross section and summing the subsection discharges to obtain a total discharge.

How do Stream Gages Work?



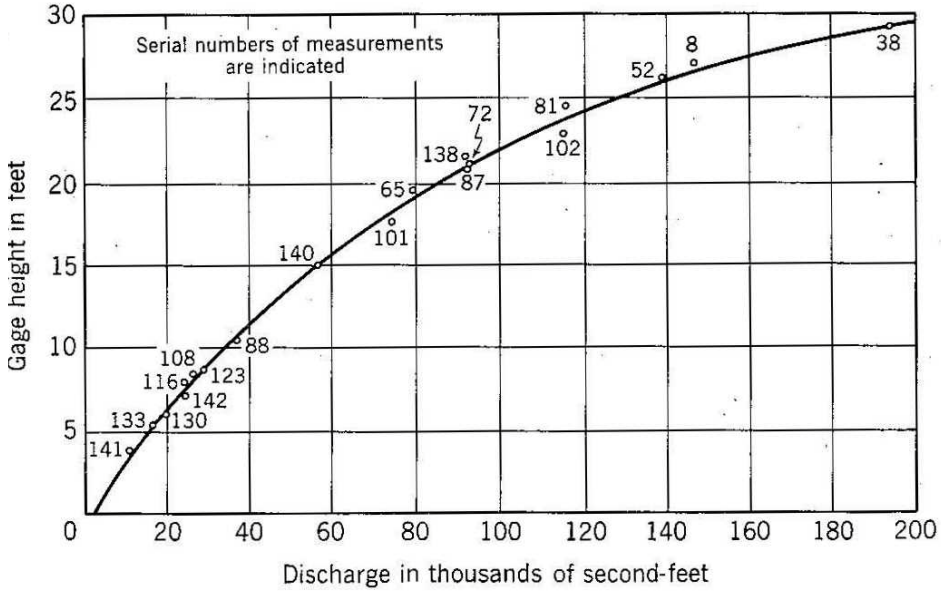
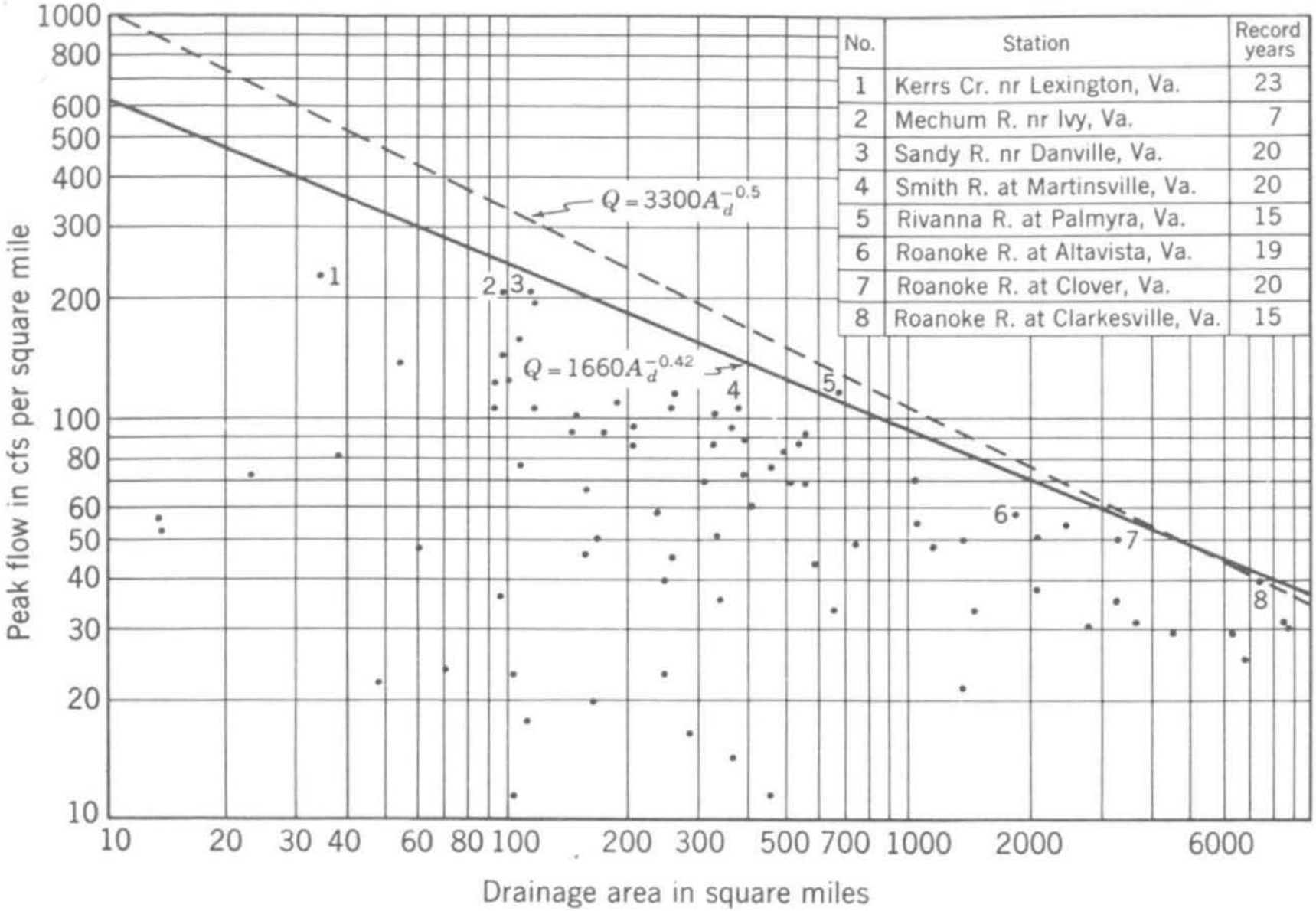


FIG. 2-8 Stage-discharge relation for the Willamette River at Albany, Oregon. (Data from the U.S. Geological Survey)

Flow/sq mile VS Drainage Area



No.	Station	Record years
1	Kerrs Cr. nr Lexington, Va.	23
2	Mechum R. nr Ivy, Va.	7
3	Sandy R. nr Danville, Va.	20
4	Smith R. at Martinsville, Va.	20
5	Rivanna R. at Palmyra, Va.	15
6	Roanoke R. at Altavista, Va.	19
7	Roanoke R. at Clover, Va.	20
8	Roanoke R. at Clarkesville, Va.	15

FIG. 5-6 Record floods on coastal streams of Virginia prior to 1949.

Flow Duration Curve

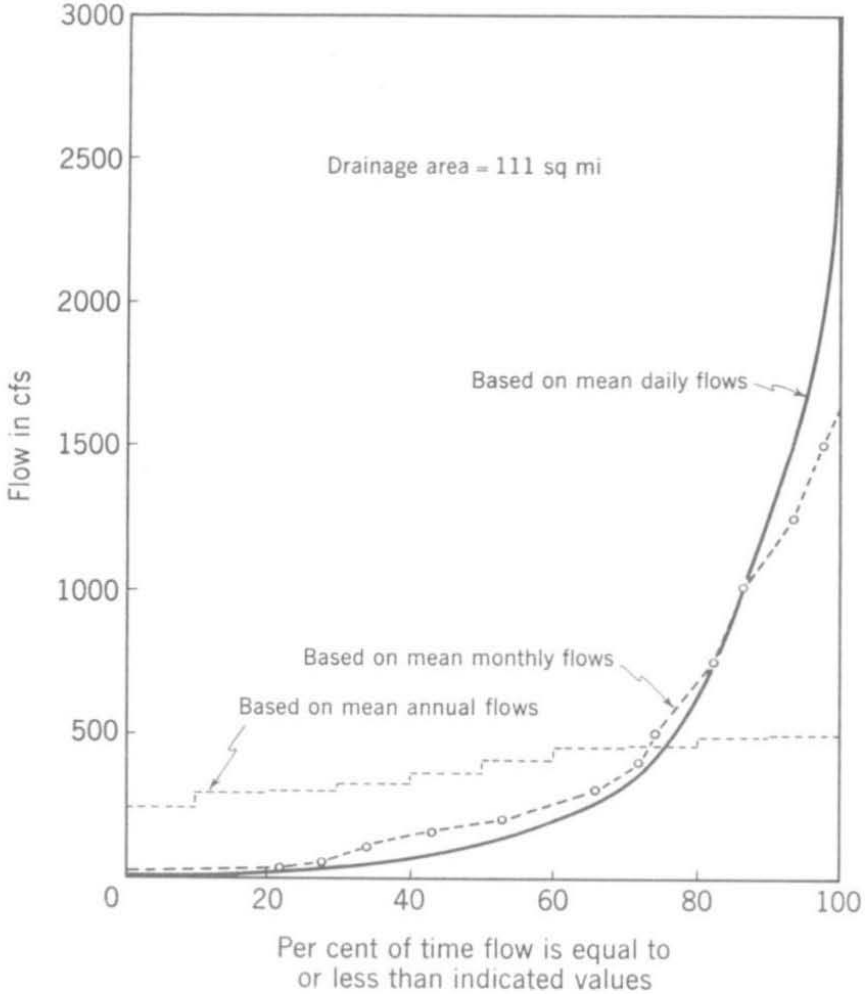
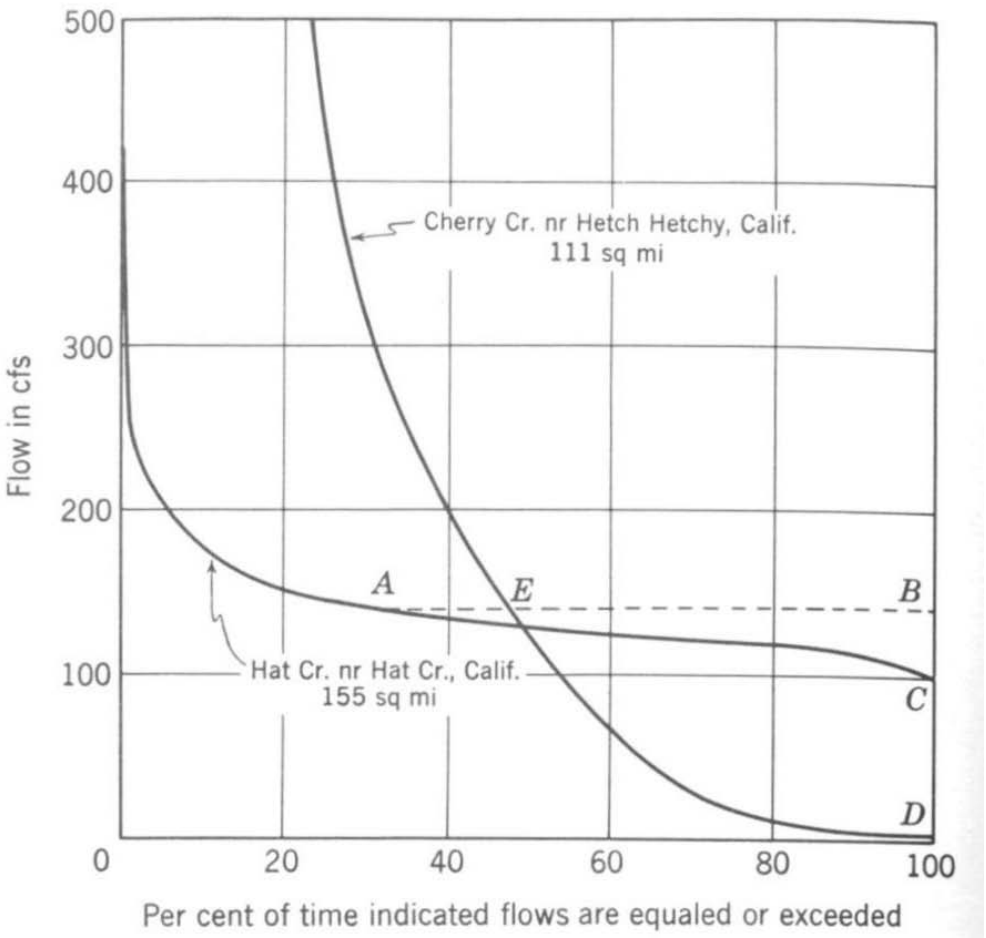


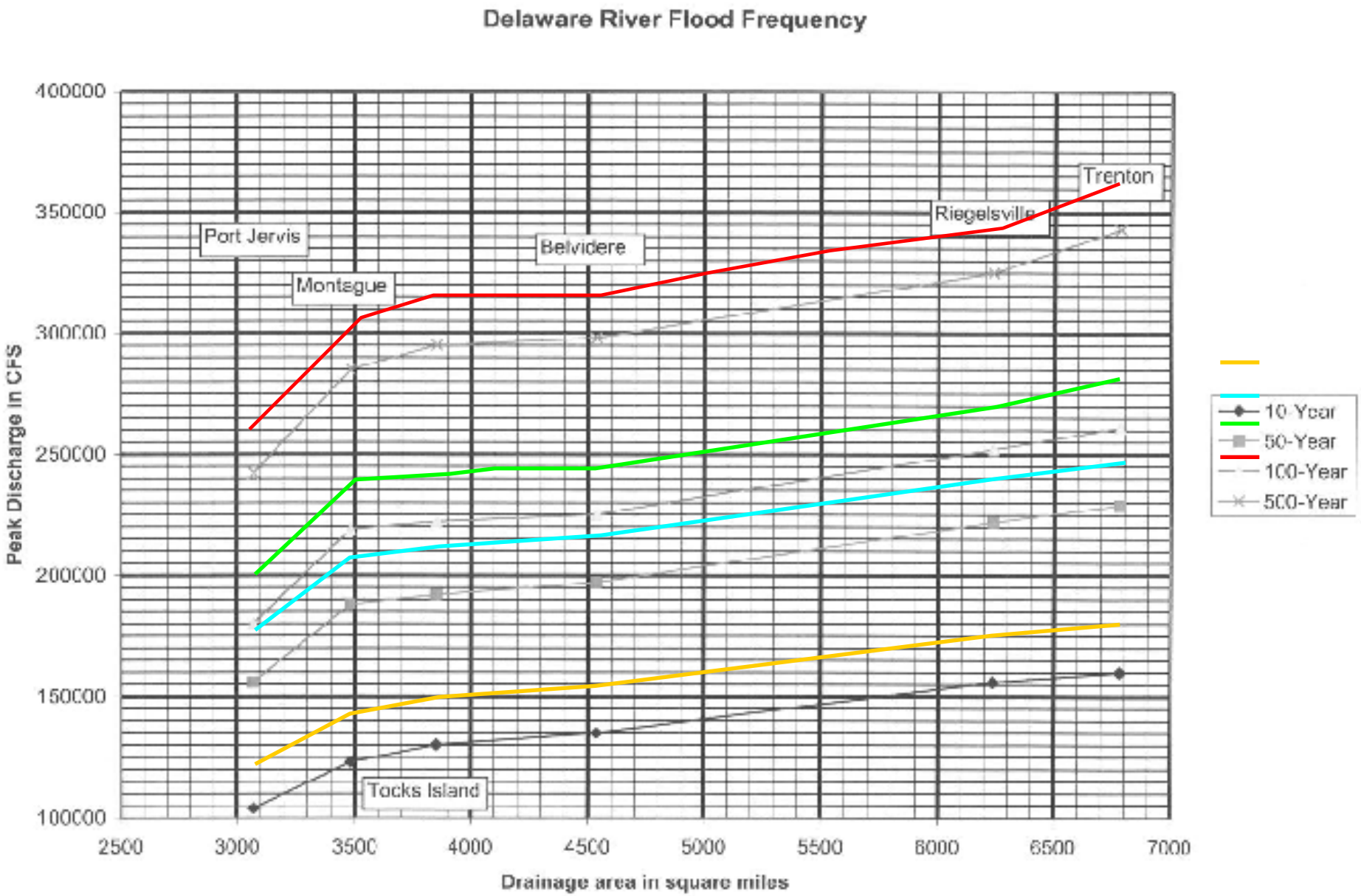
FIG. 5-12 Flow-duration curves for Cherry Creek near Hetch Hetchy, California (1941–1950).

Flow Duration Comparison
Why are they Different?

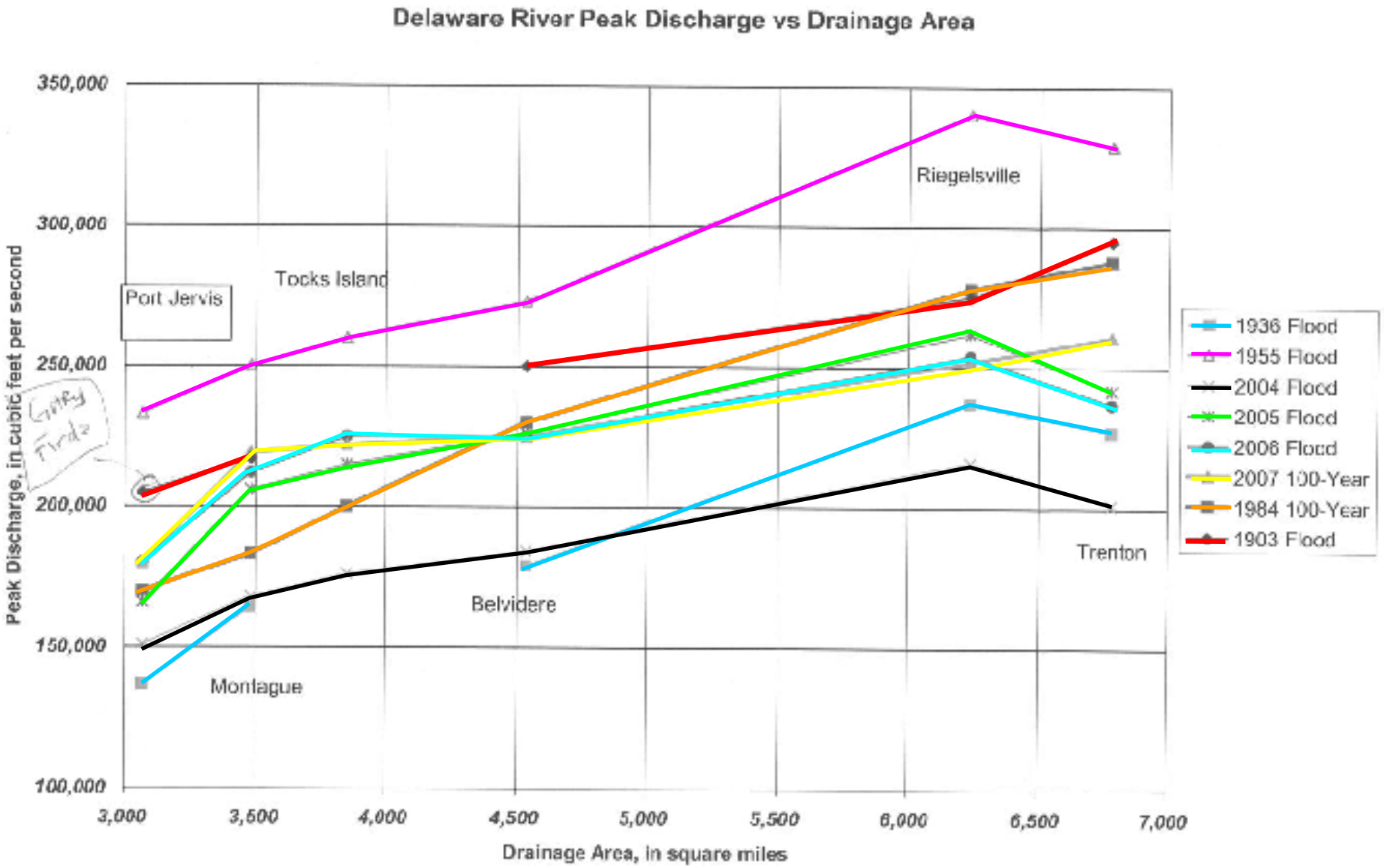


Hat Cr is in Limestone
Cherry Cr is not

Frequency Flow with Drainage Area



Historic Flood Change with Drainage Area



Volume Units

- gallon

7.48 Gallons = 1 cubic foot

43,560 Cubic Feet = acre-foot

1cfs-day ~ 2 acre-feet

CFS-Day Example

- land area = 1000 acre
- water depth to remove = 0.5 ft in 1 day (i.e., 24 hour)
- volume to remove = 500 acre-ft in 1 day
- since 1cfs-day ~ 2 acre-ft,

then, 250 cfs-day ~ 500 acre-ft

so, an averge discharge of 250 cfs will remove the volume of 500 acre feet in one day

Water Flow

volumetric flow rate

- gallon / minute (gpm)

- cubic feet / second (cfs

$$Vol = QT$$

Vol = volume

Q = volumetric flow rate

T = time

Watershed:

all points on earth's surface contributing runoff to a given point on a stream

FACTORS AFFECTING RUNOFF

-Slope

-soils

-cover

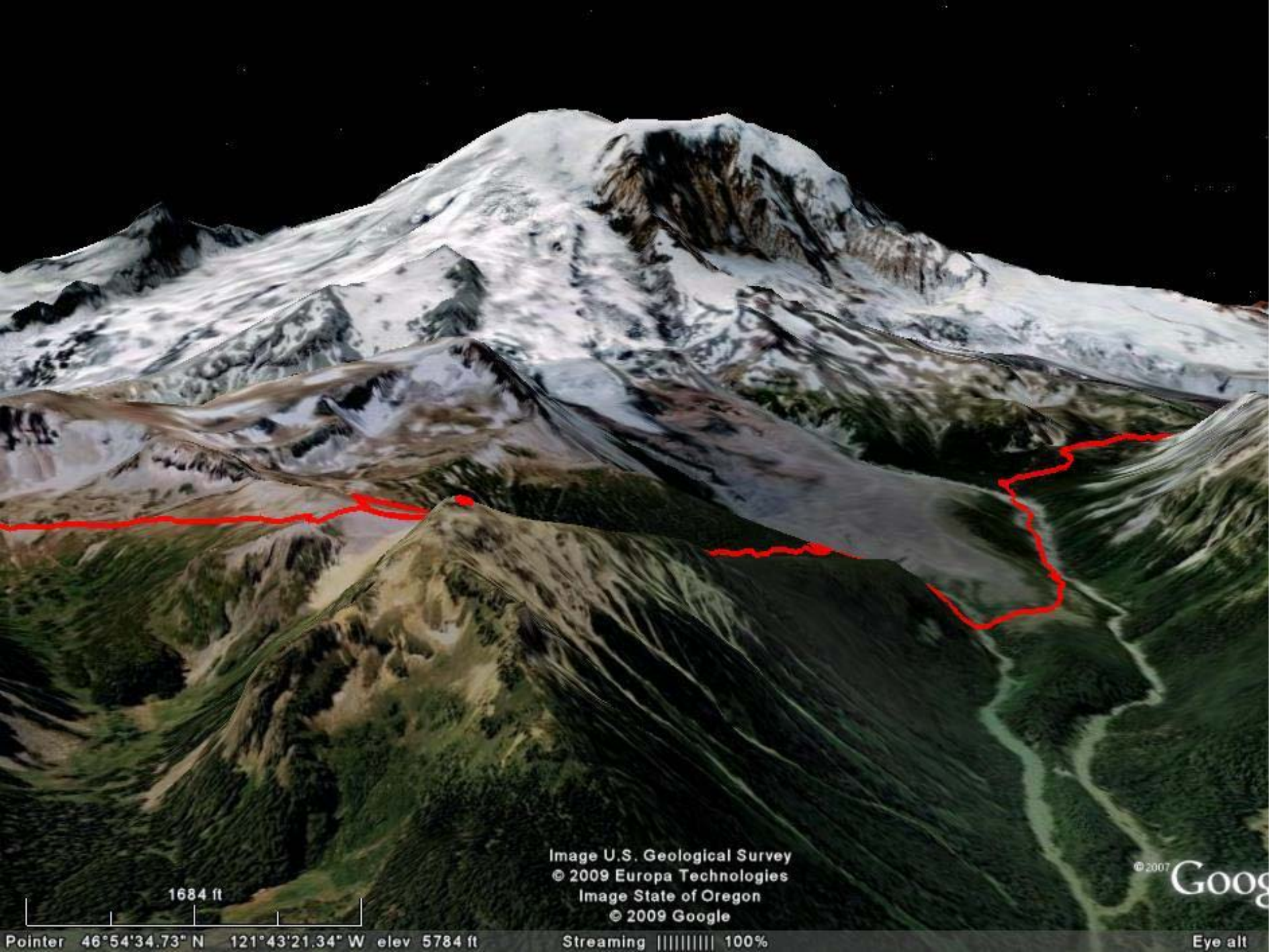
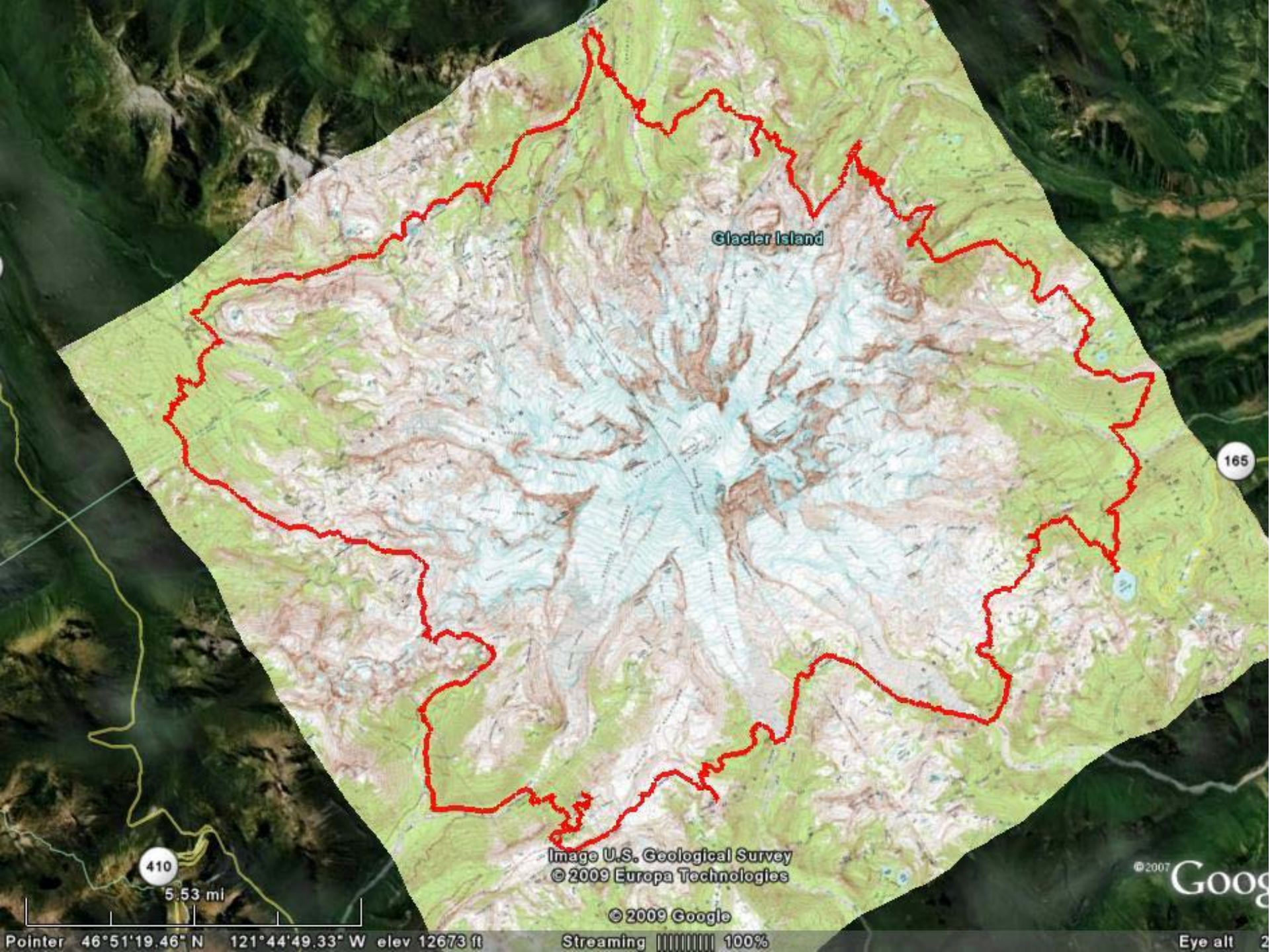


Image U.S. Geological Survey
© 2009 Europa Technologies
Image State of Oregon
© 2009 Google
1684 ft
©2007 Goog
Pointer 46°54'34.73" N 121°43'21.34" W elev 5784 ft
Streaming |||||||||| 100%
Eye alt

Image U.S. Geological Survey
© 2009 Europa Technologies
Image State of Oregon
© 2009 Google
1684 ft
Pointer 46°54'34.73" N 121°43'21.34" W elev 5784 ft
Streaming 100%
Eye alt


Glacier Island
165
410
5.53 mi
Image U.S. Geological Survey
© 2009 Europa Technologies
© 2009 Google
©2007 Goog
Pointer 46°51'19.46" N 121°44'49.33" W elev 12673 ft
Streaming 100%
Eye alt

Glacier Island
165
123
410
5.53 mi
Image U.S. Geological Survey
© 2009 Europa Technologies
© 2009 Google
©2007 Goo
Pointer 46°51'19.46" N 121°44'49.33" W elev 12673 ft
Streaming |||||||||| 100%
Eye alt

Watersheds or Drainage Basins

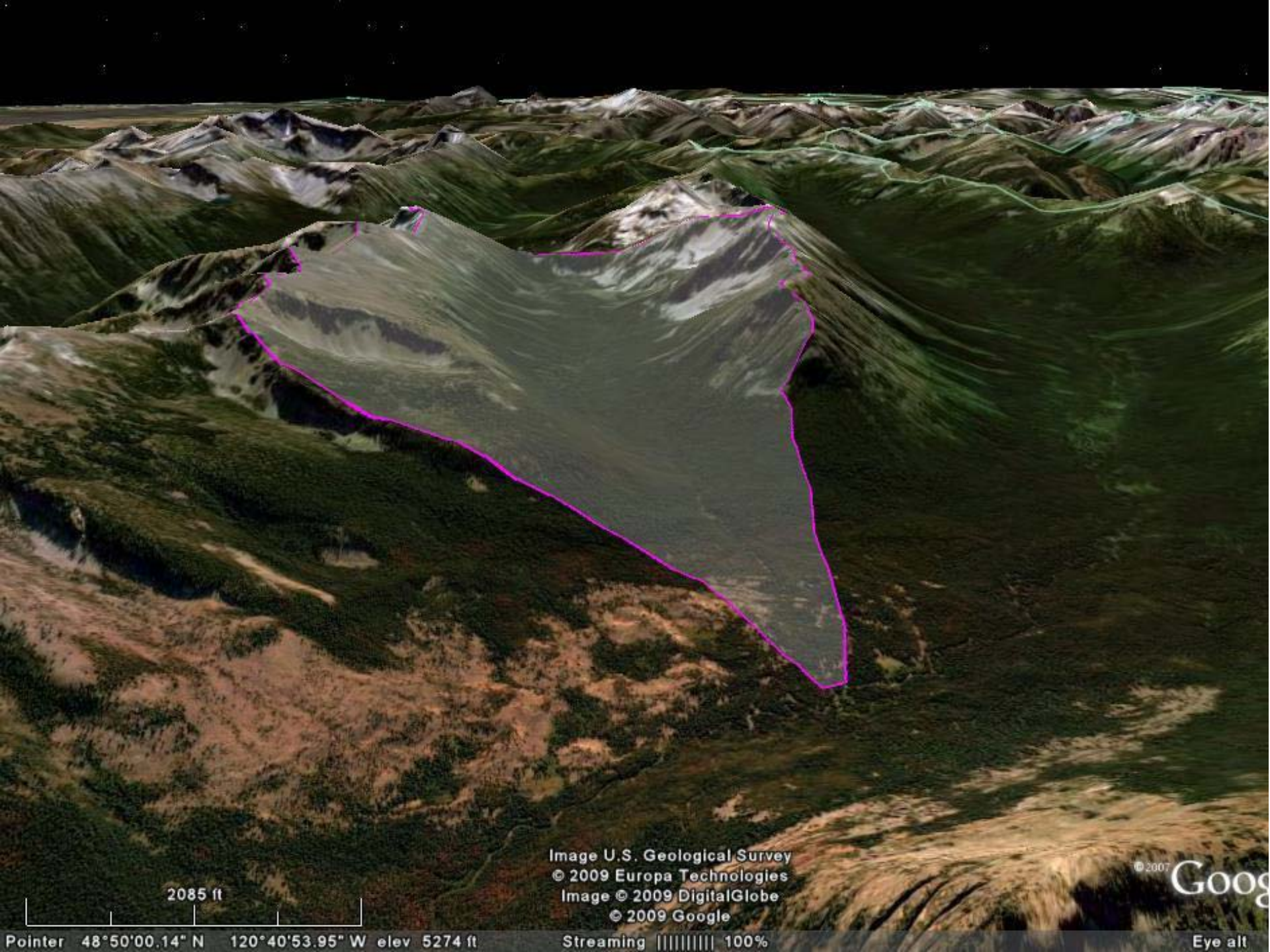
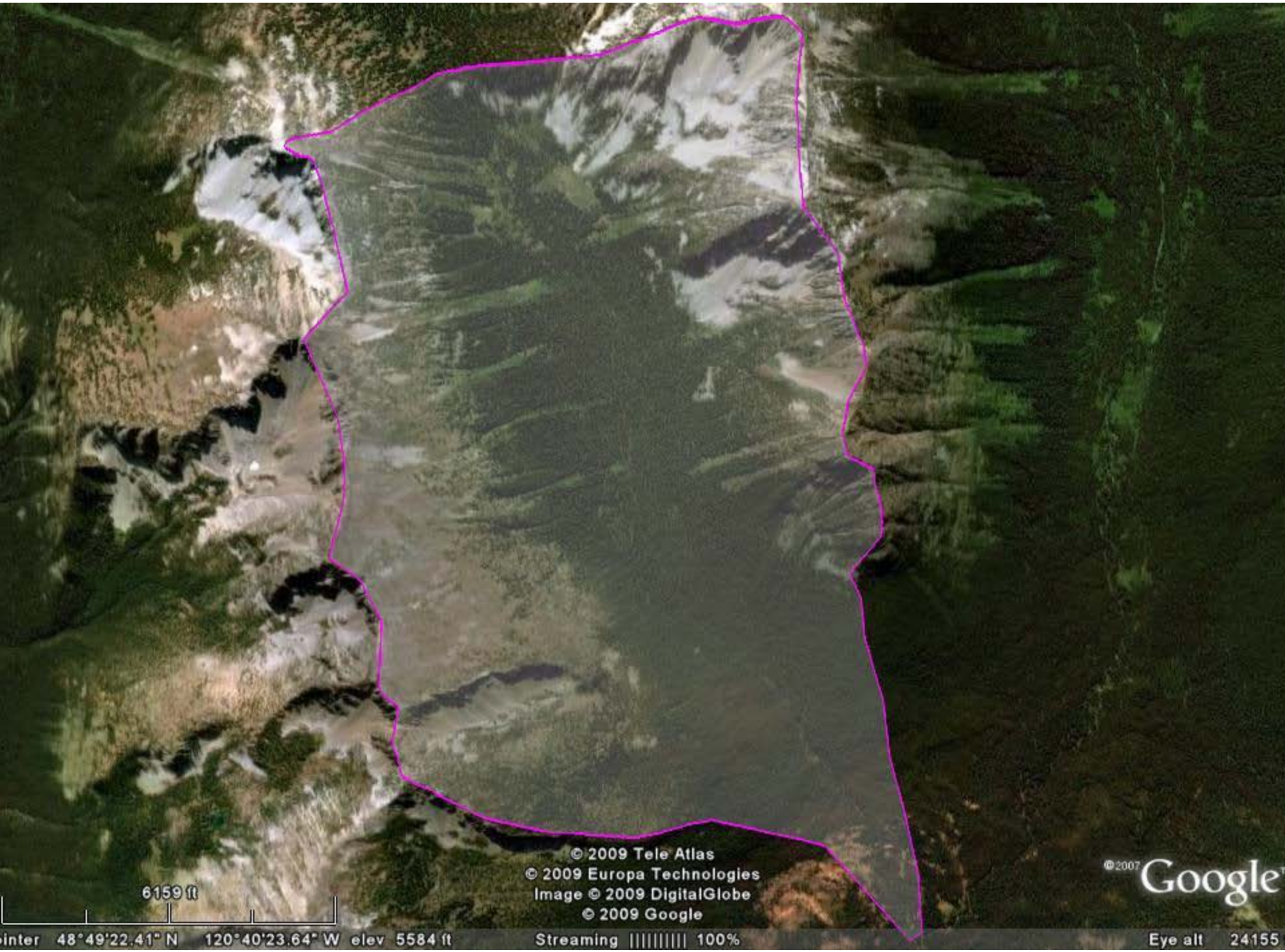


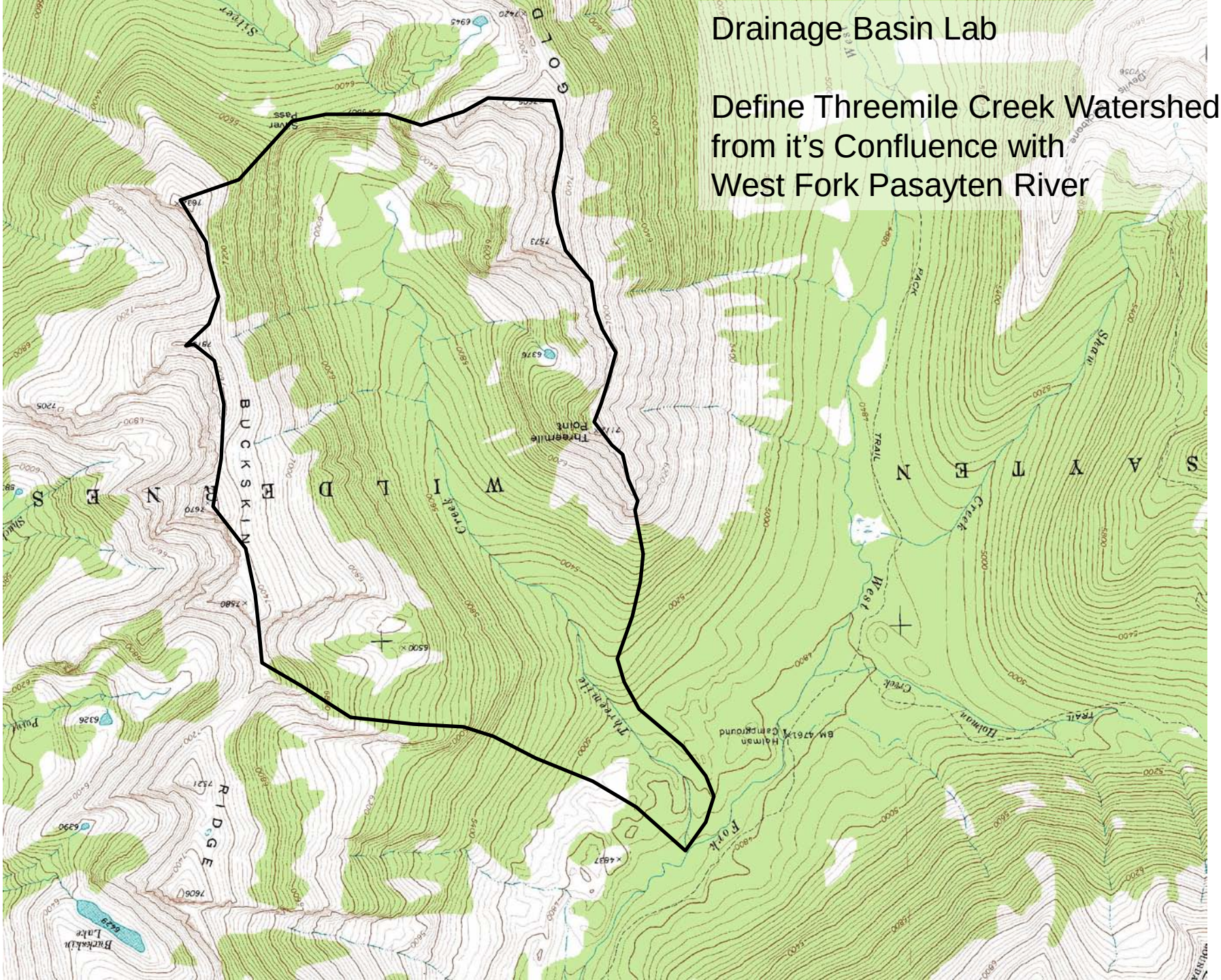
Image U.S. Geological Survey
© 2009 Europa Technologies
Image © 2009 DigitalGlobe
© 2009 Google
2085 ft
Pointer 48°50'00.14" N 120°40'53.95" W elev 5274 ft
Streaming |||||||||| 100%
Eye alt

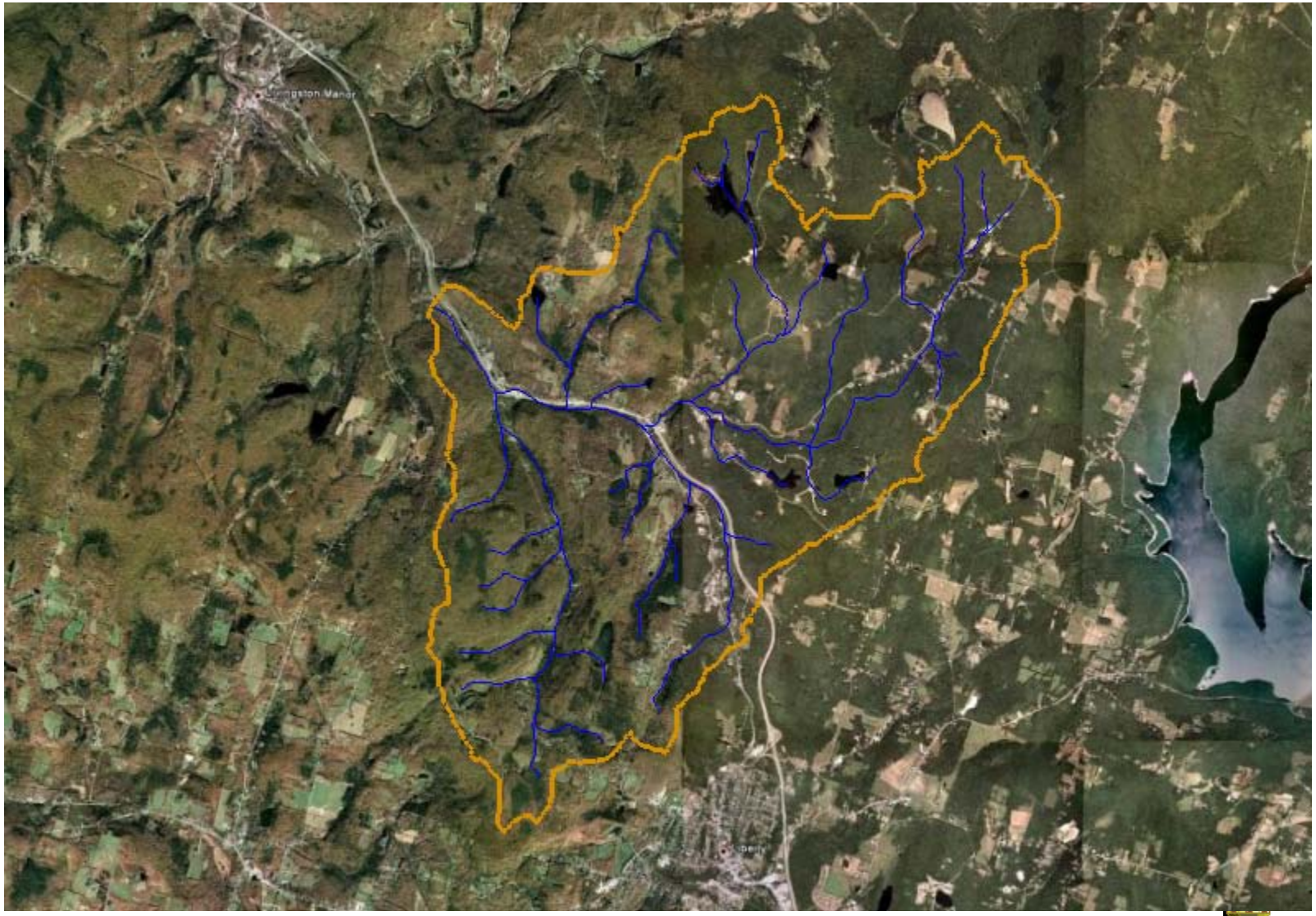

© 2009 Tele Atlas
© 2009 Europa Technologies
Image © 2009 DigitalGlobe
© 2009 Google
6159 ft
©2007 Google
inter 48°49'22.41" N 120°40'23.64" W elev 5584 ft
Streaming |||||||||| 100%
Eye alt 24155

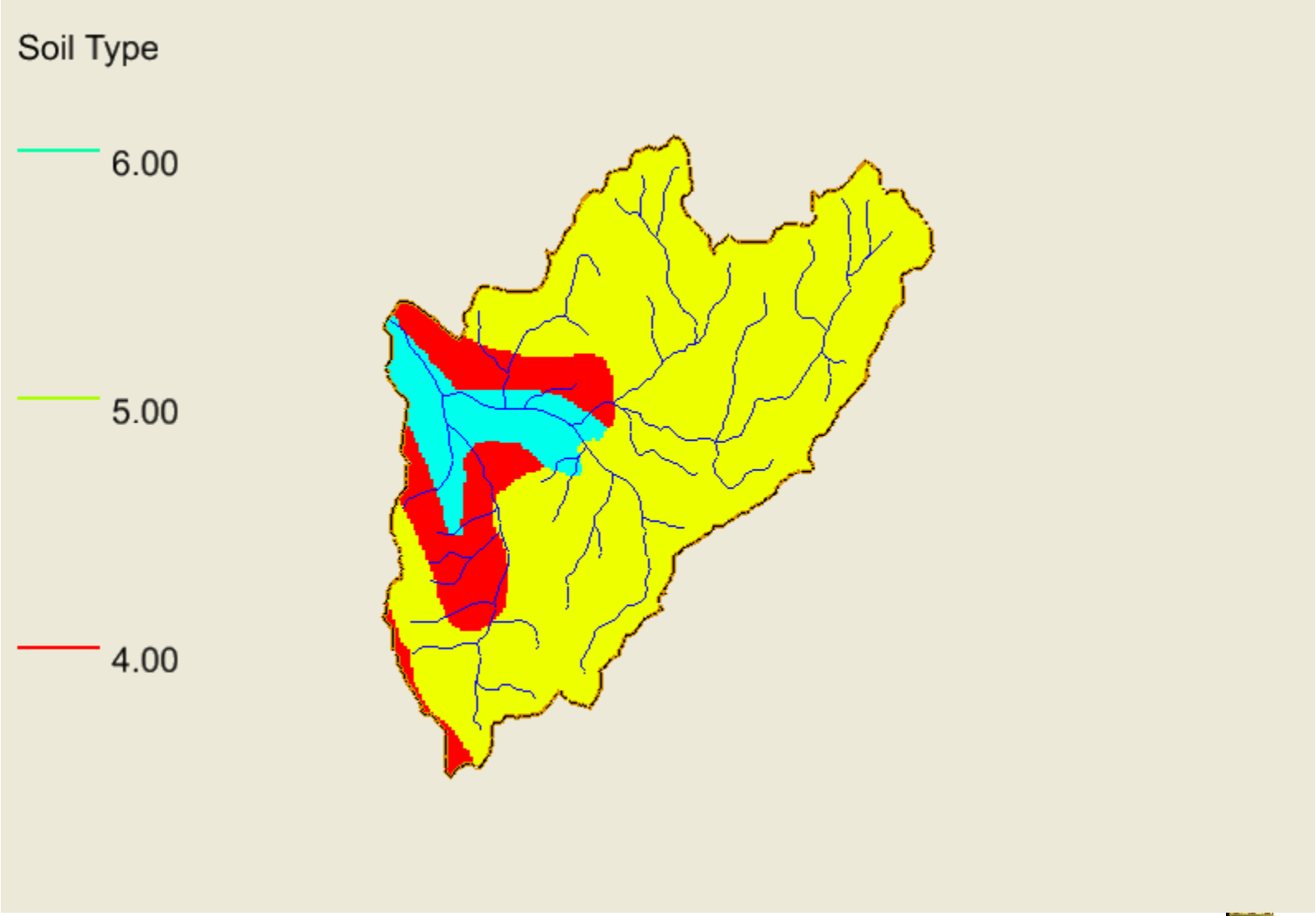
© 2009 Tele Atlas
© 2009 Europa Technologies
Image © 2009 DigitalGlobe
© 2009 Google
6159 ft
©2007 Goog
Pointer 48°49'22.41" N 120°40'23.64" W elev 5584 ft
Streaming |||||||||| 100%
Eye alt

Drainage Basin Lab

Define Threemile Creek Watershed from it's Confluence with West Fork Pasayten River

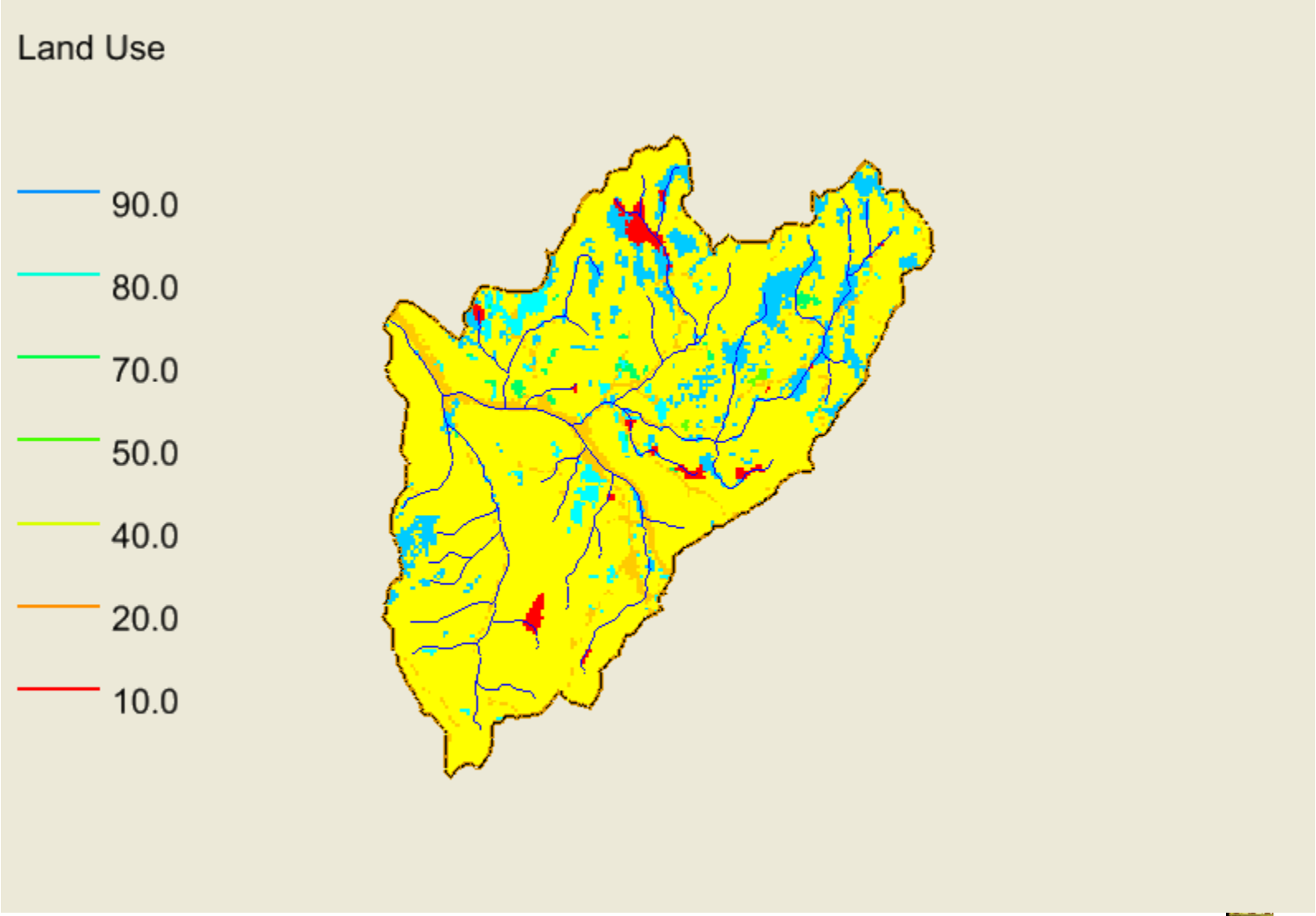



Livingston Manor


Soil Type
6.00
5.00
4.00

Soils

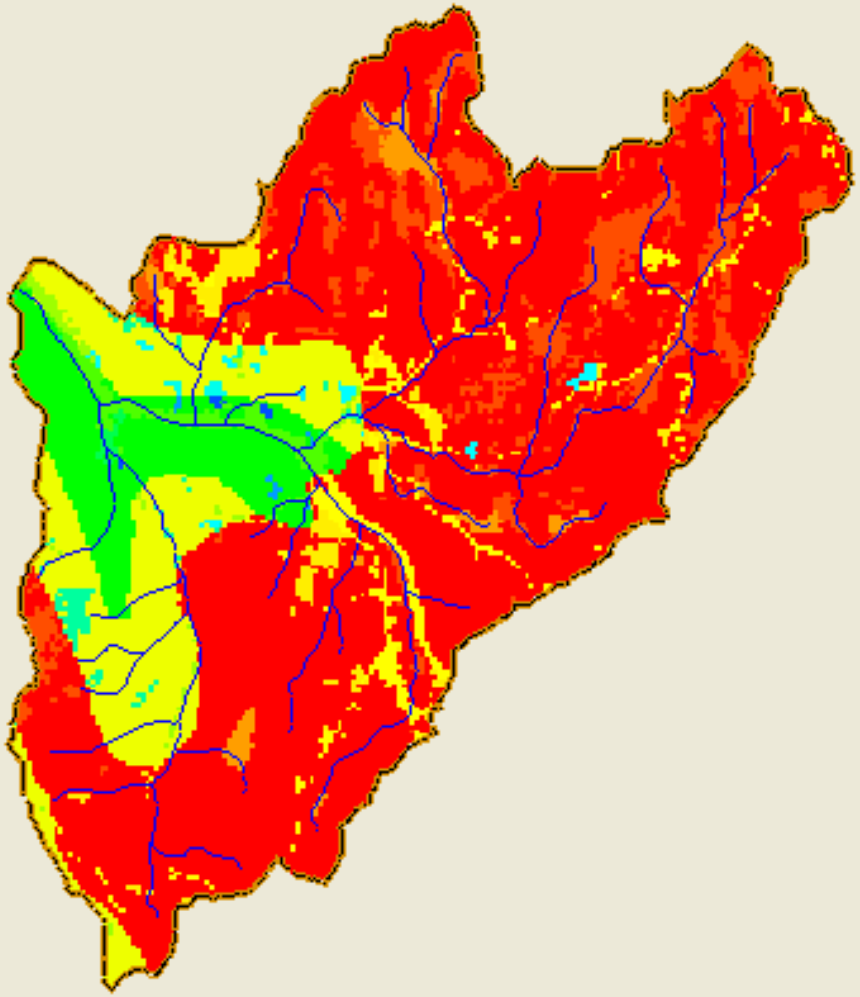
- classifications:
    - engineering
    - textural
    - soil series
- data:
    - borings
    - SCS/NRCS soil surveys


Land Use
90.0
80.0
70.0
50.0
40.0
20.0
10.0

Cover

- vegetation
  - species
  - stand
  - seasonality

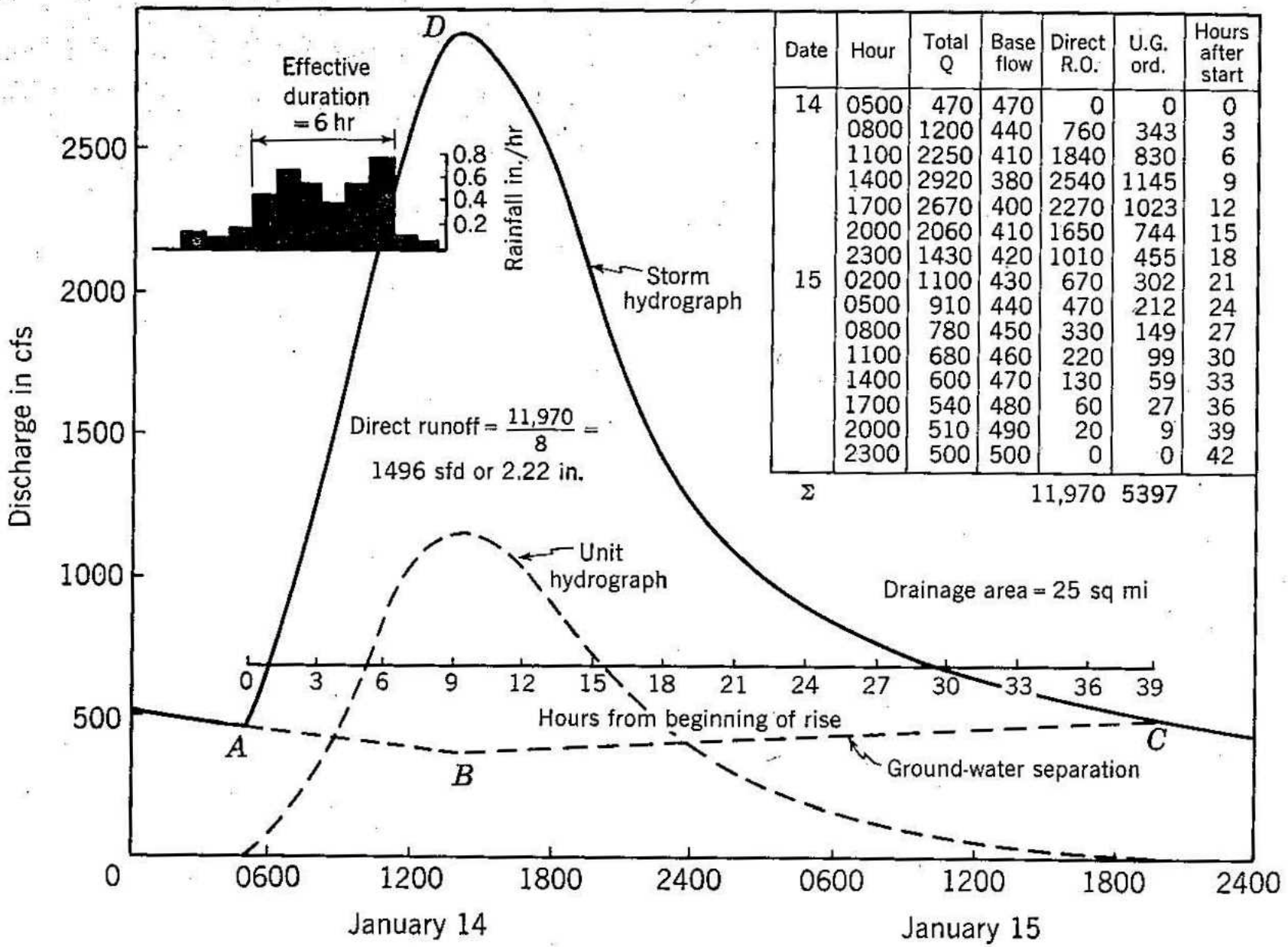
- developments
  - gravel
  - impervious



A Plot of Streamflow over time is call a Hydrograph

Factors affecting Hydrographs:

- Precipitation
  - Intensity
  - Storm Speed
  - Track
- Losses
  - ET
  - Depression Storage
  - Infiltration to Groundwater
- Runoff Speed
  - Vegetation
  - Slope
- Basin Shape



Date	Hour	Total Q	Base flow	Direct R.O.	U.G. ord.	Hours after start
14	0500	470	470	0	0	0
	0800	1200	440	760	343	3
	1100	2250	410	1840	830	6
	1400	2920	380	2540	1145	9
	1700	2670	400	2270	1023	12
	2000	2060	410	1650	744	15
	2300	1430	420	1010	455	18
15	0200	1100	430	670	302	21
	0500	910	440	470	212	24
	0800	780	450	330	149	27
	1100	680	460	220	99	30
	1400	600	470	130	59	33
	1700	540	480	60	27	36
	2000	510	490	20	9	39
	2300	500	500	0	0	42
Σ				11,970	5397	

FIG. 3-11 Derivation of a unit hydrograph.

Hydrograph Separation

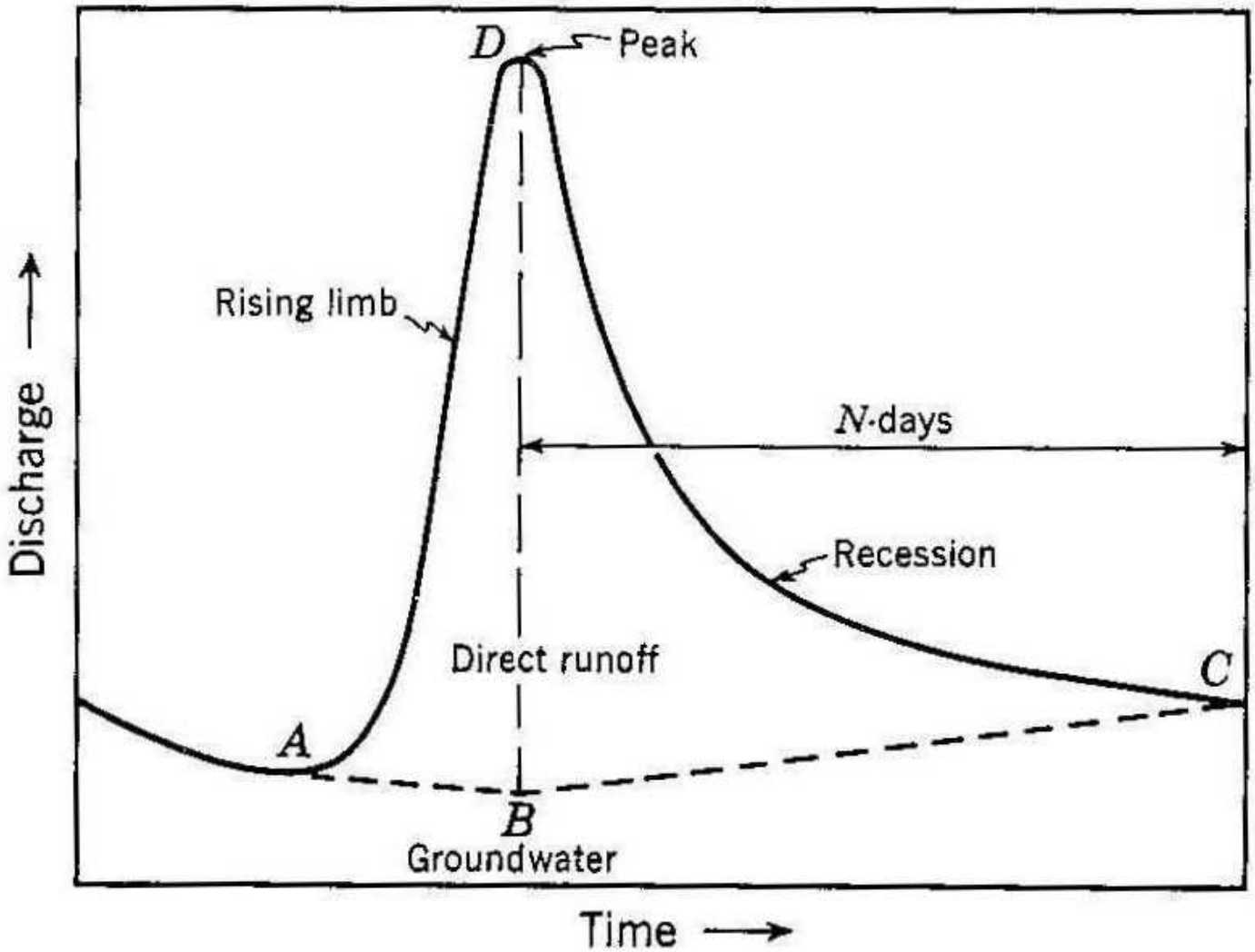
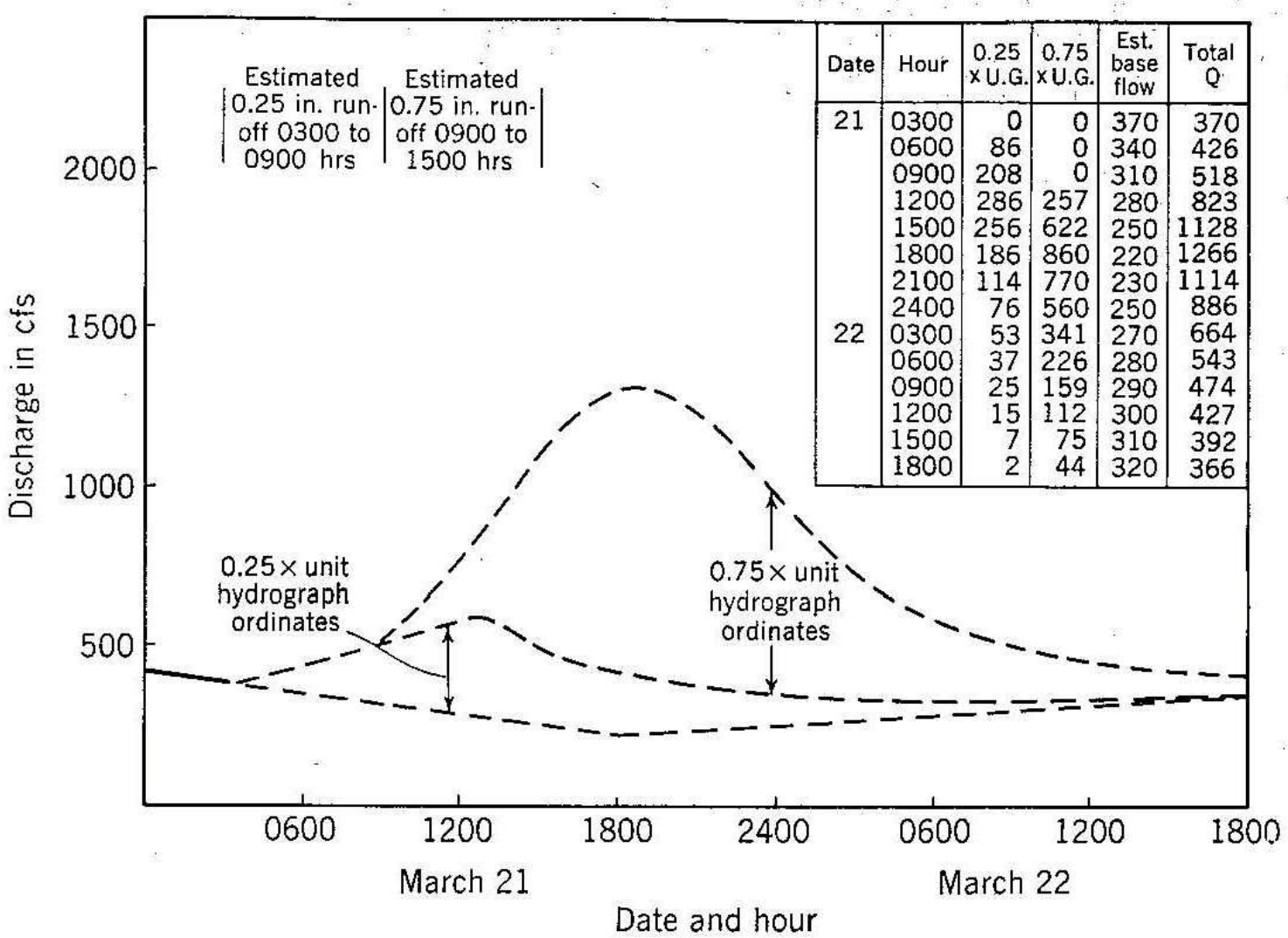


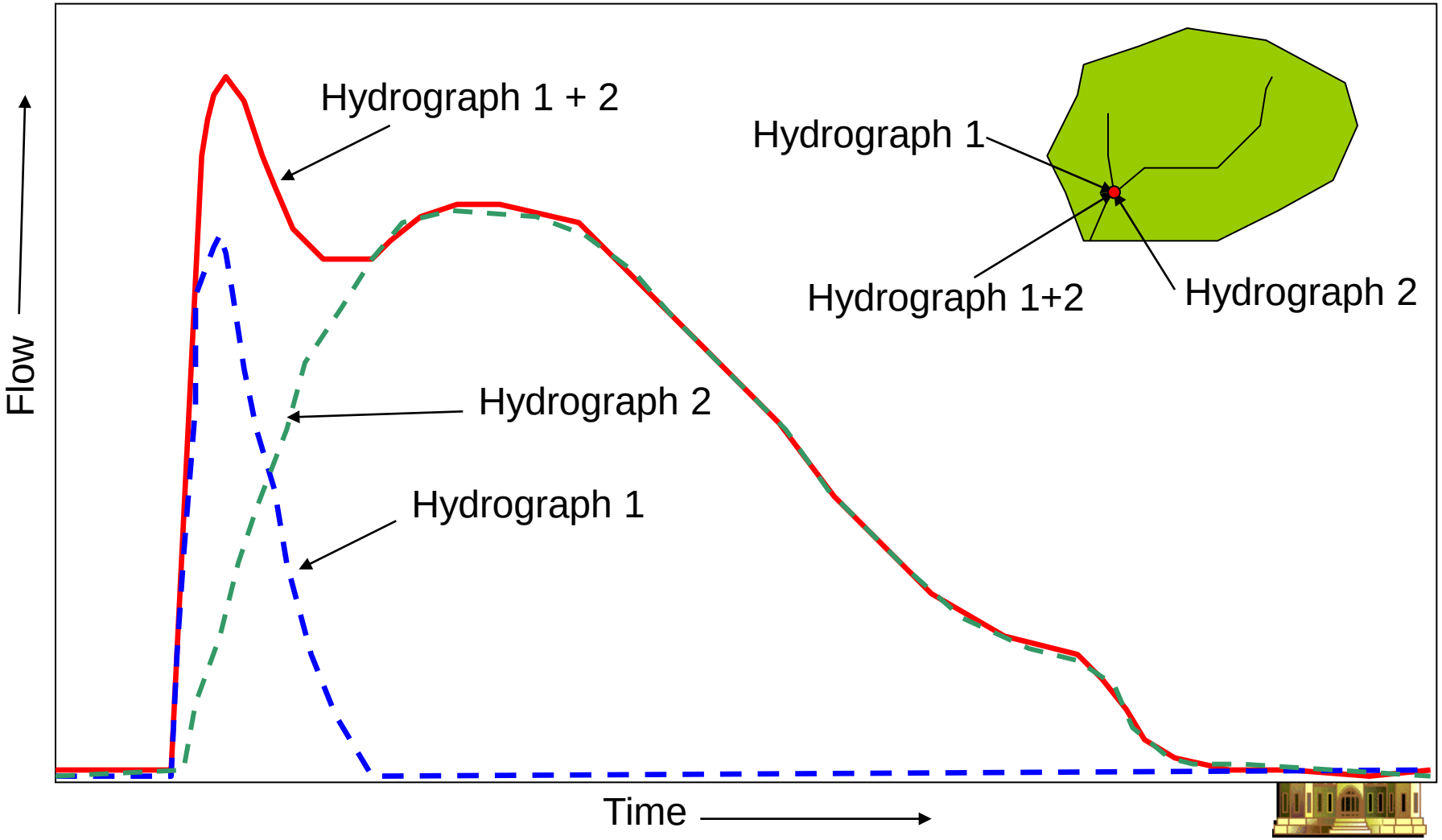
FIG. 3-1 Typical flood hydrograph showing method of separating direct and groundwater runoff.



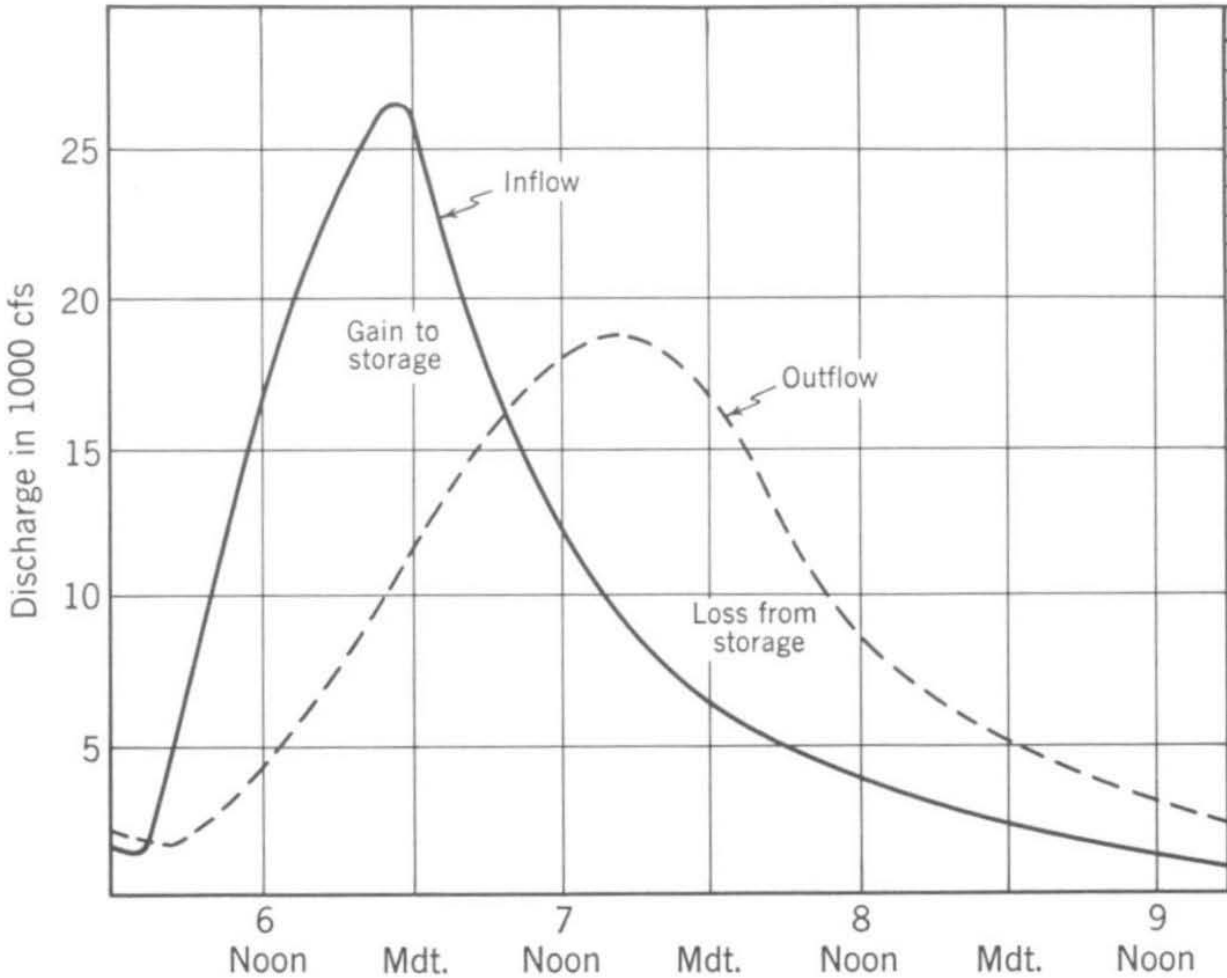
Date	Hour	0.25 x U.G.	0.75 x U.G.	Est. base flow	Total Q
21	0300	0	0	370	370
	0600	86	0	340	426
	0900	208	0	310	518
	1200	286	257	280	823
	1500	256	622	250	1128
	1800	186	860	220	1266
	2100	114	770	230	1114
	2400	76	560	250	886
22	0300	53	341	270	664
	0600	37	226	280	543
	0900	25	159	290	474
	1200	15	112	300	427
	1500	7	75	310	392
	1800	2	44	320	366

FIG. 3-13 Application of unit hydrograph to construction of a hydrograph resulting from two periods of rainfall.

How do you Add Hydrographs at Junctions?



River Routing – How a hydrograph moves downstream



Time	$\overline{I}$	$\overline{O}$	Δs	s
5/Mdt.				0
	3.5	2.0	1.5	
6/6 A.M.				1.5
	11.5	3.0	8.5	
Noon				10.0
	20.4	5.8	14.6	
6 P.M.				24.6
	25.2	9.0	16.2	
Mdt.				40.8
	21.4	13.4	8.0	
7/6 A.M.				48.4
	15.4	17.0	−1.6	
Noon				46.8
	10.0	18.5	−8.5	
6 P.M.				38.3
	7.3	17.7	−10.4	
Mdt.				27.9
	5.6	14.5	−8.9	
8/6 A.M.				19.0
	4.5	10.0	−5.5	
Noon				13.5
	3.5	7.5	−4.0	
6 P.M.				9.5
	2.8	5.8	−3.0	
Mdt.				6.5
	2.3	4.5	−2.2	
9/6 A.M.				4.3
	1.7	3.2	−1.5	
Noon				2.8

FIG. 3-19 Inflow and outflow hydrographs for a reach of river, showing method of calculating channel storage.

Control Volume Equation
Flow Units

[(Flow In) - (Flow Out)] (Time)
= (Change in Storage)

Routing Flows

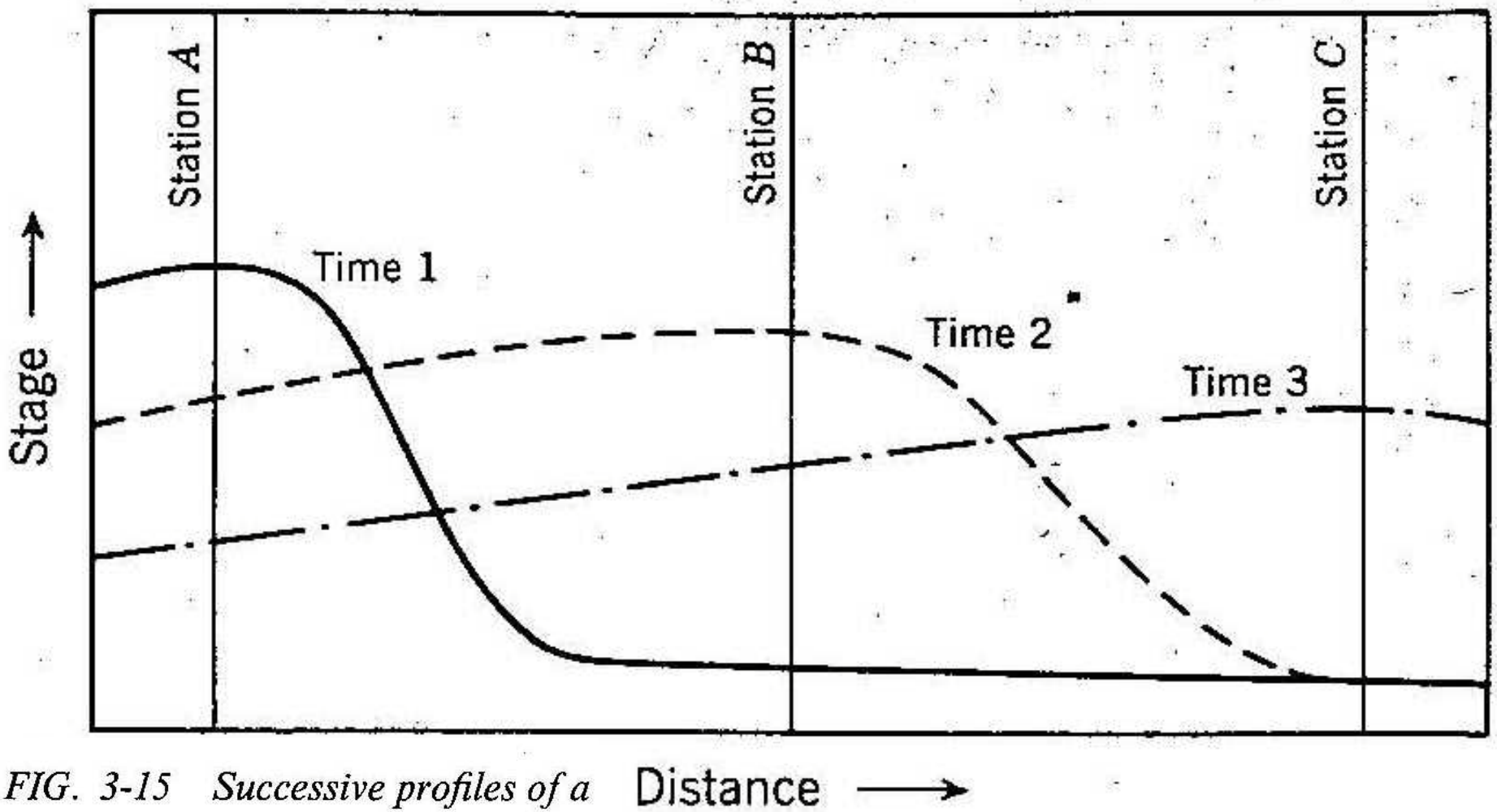


FIG. 3-15 Successive profiles of a flood wave, showing changes in shape.

Routing Concepts

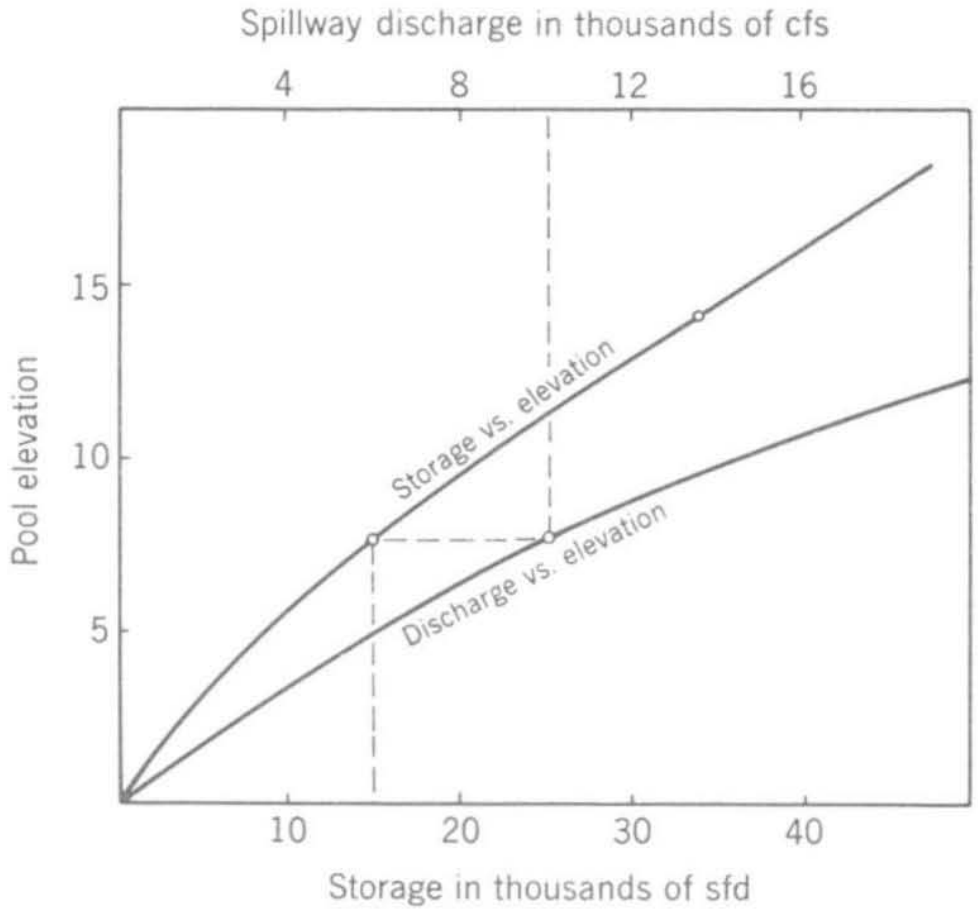


FIG. 3-16 Relation between reservoir surface elevation, storage, and spillway discharge for a reservoir with an ungated spillway.

Frequency Analysis

Flow Frequency Concepts
Peak Flow Frequency
Low Flow Frequency
Risk
Terms to Know

Frequency Analysis
How Often Does it Happen?

- Rainfall Frequency
- Flow Frequency
  - Peak Flow
  - Low Flow

Data Ranking

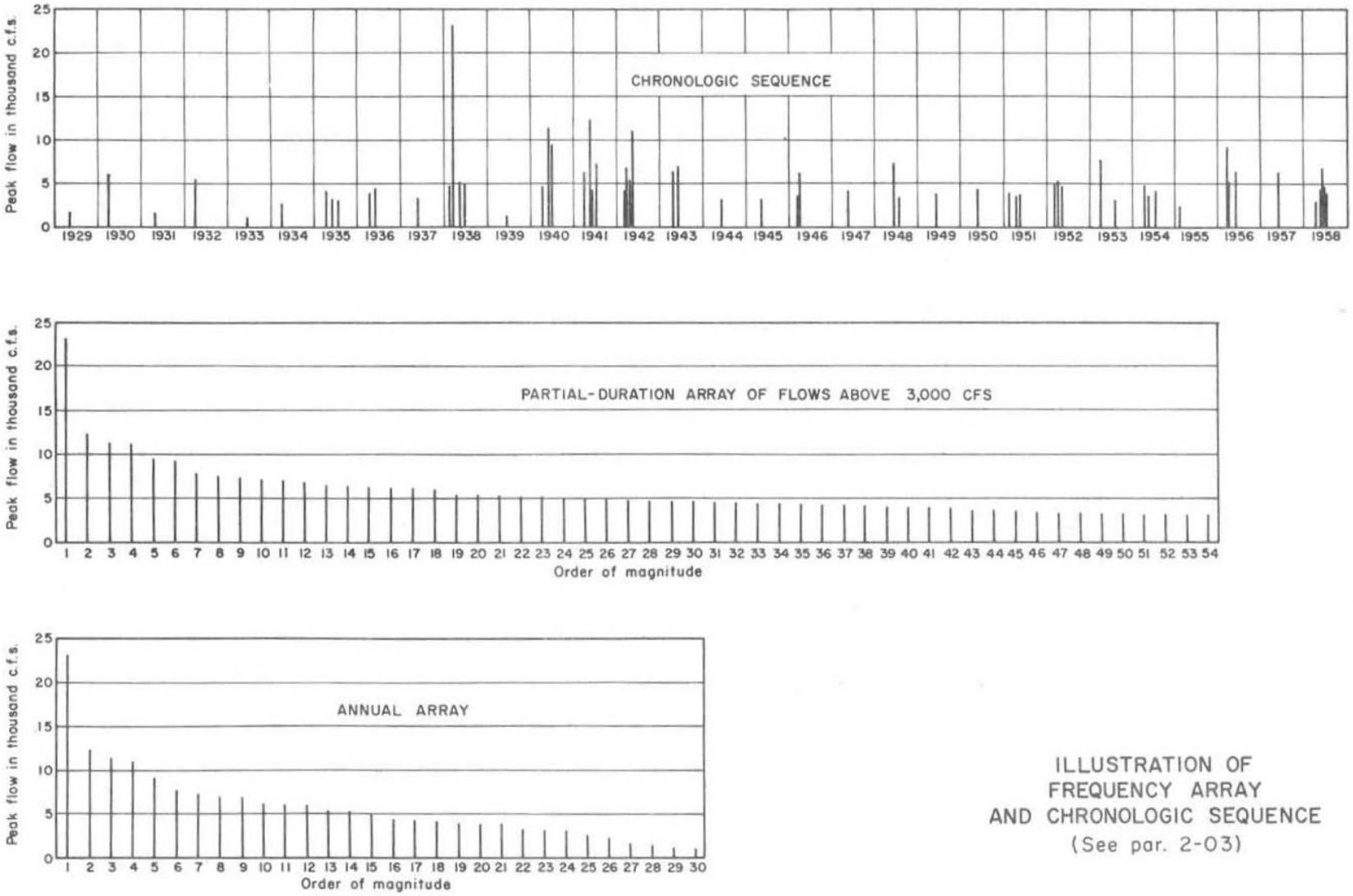


ILLUSTRATION OF
FREQUENCY ARRAY
AND CHRONOLOGIC SEQUENCE
(See par. 2-03)

Flood Frequency

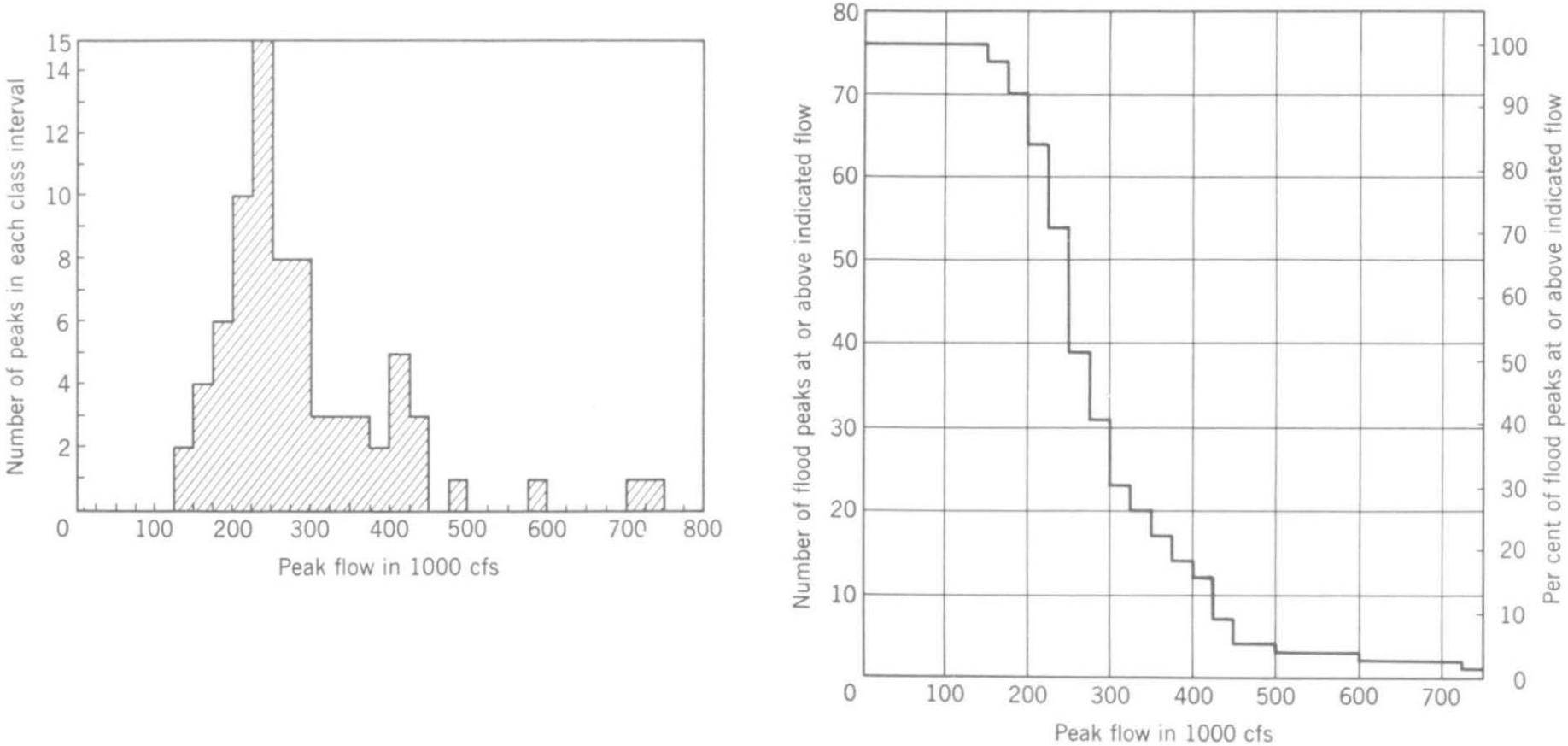
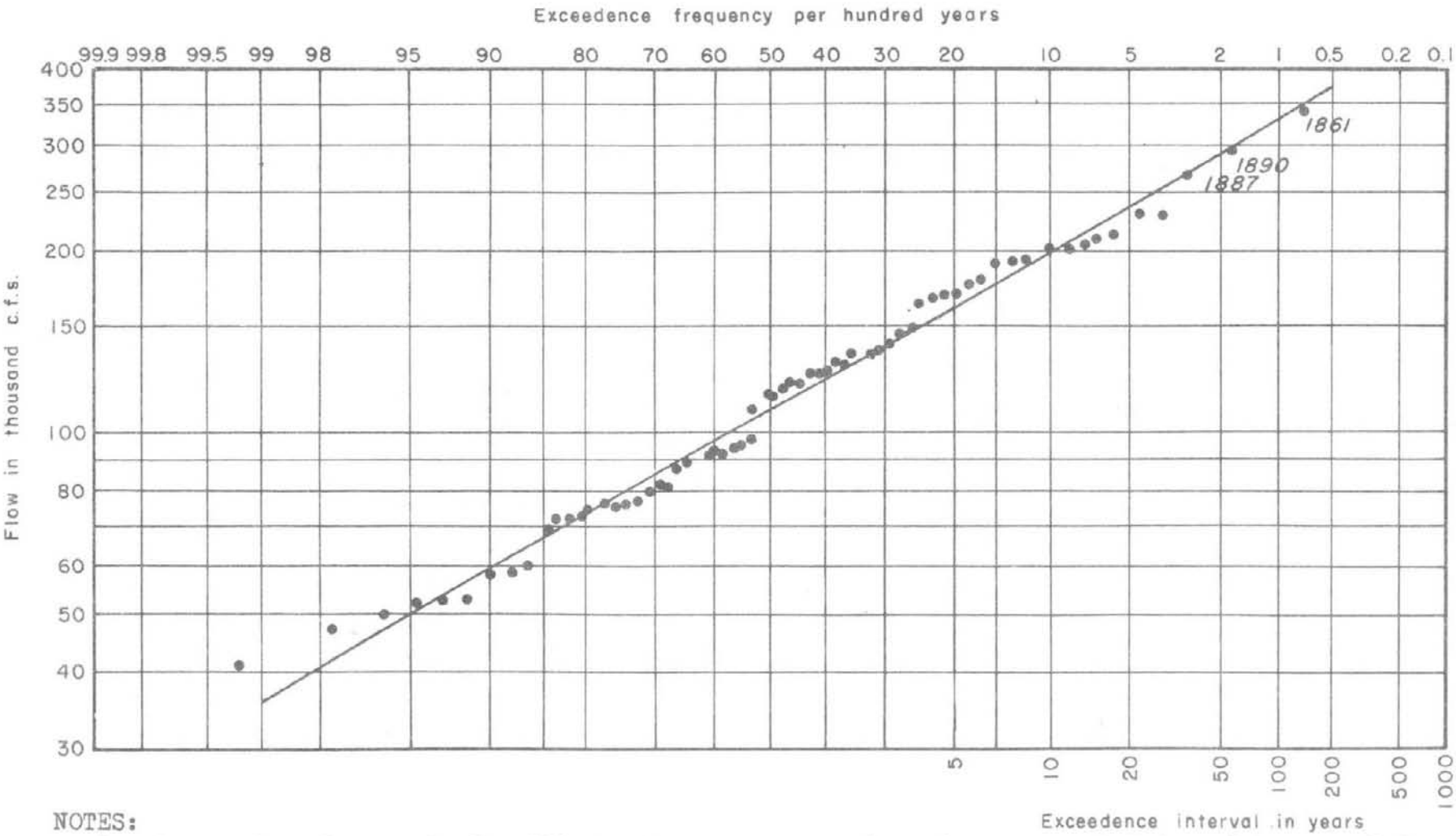


FIG. 5-2 Integrated histogram of flood peaks for the Susquehanna River at Harrisburg, Pennsylvania.



NOTES:

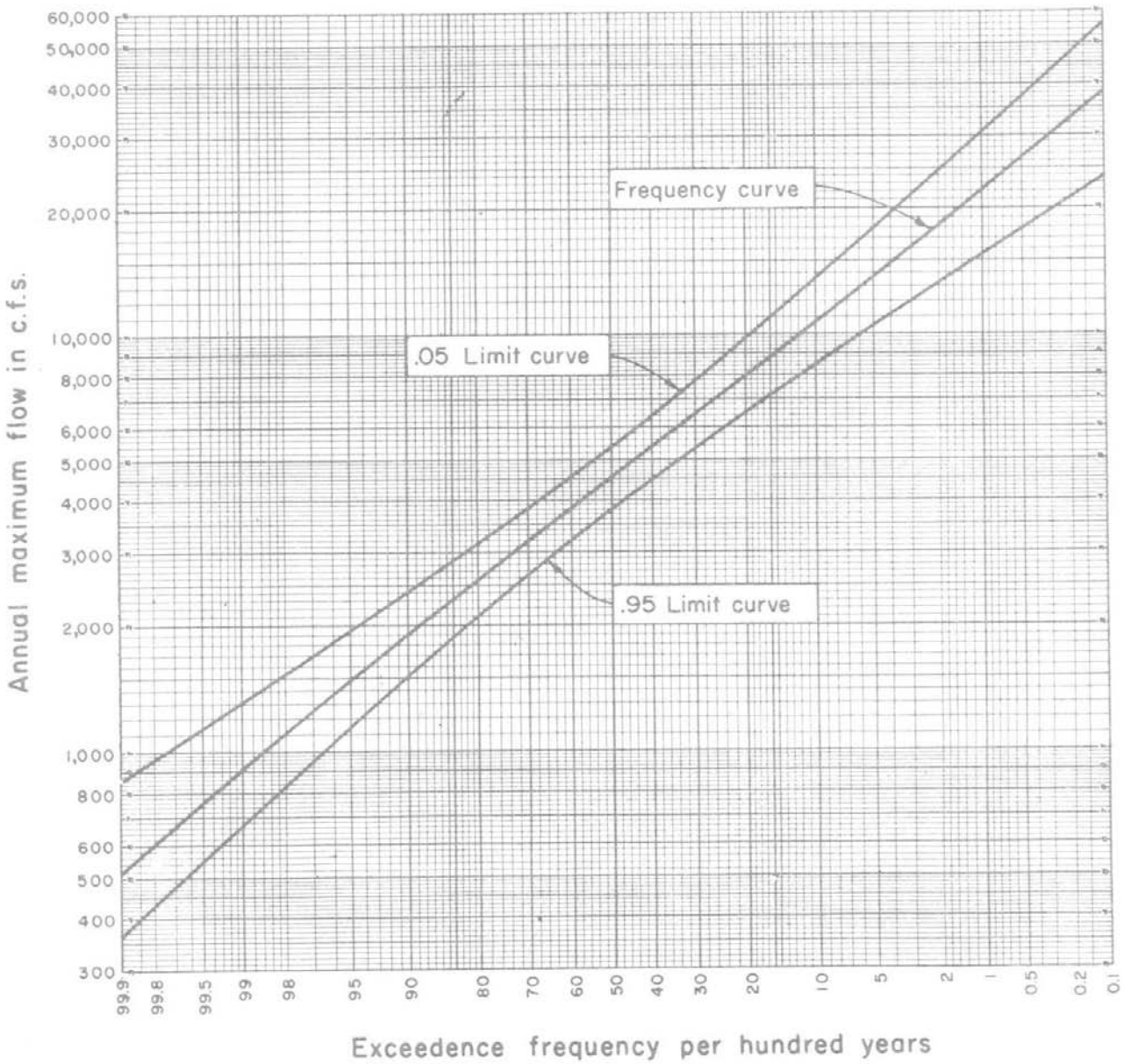
1. Curve shown hereon is for illustrative purposes only and was computed from data recorded from 1893 to 1958 and on estimates of three pre-record peak flows. Flows that were partly regulated (since 1941) were adjusted to natural conditions.

2. See Exhibit 11 for computations.

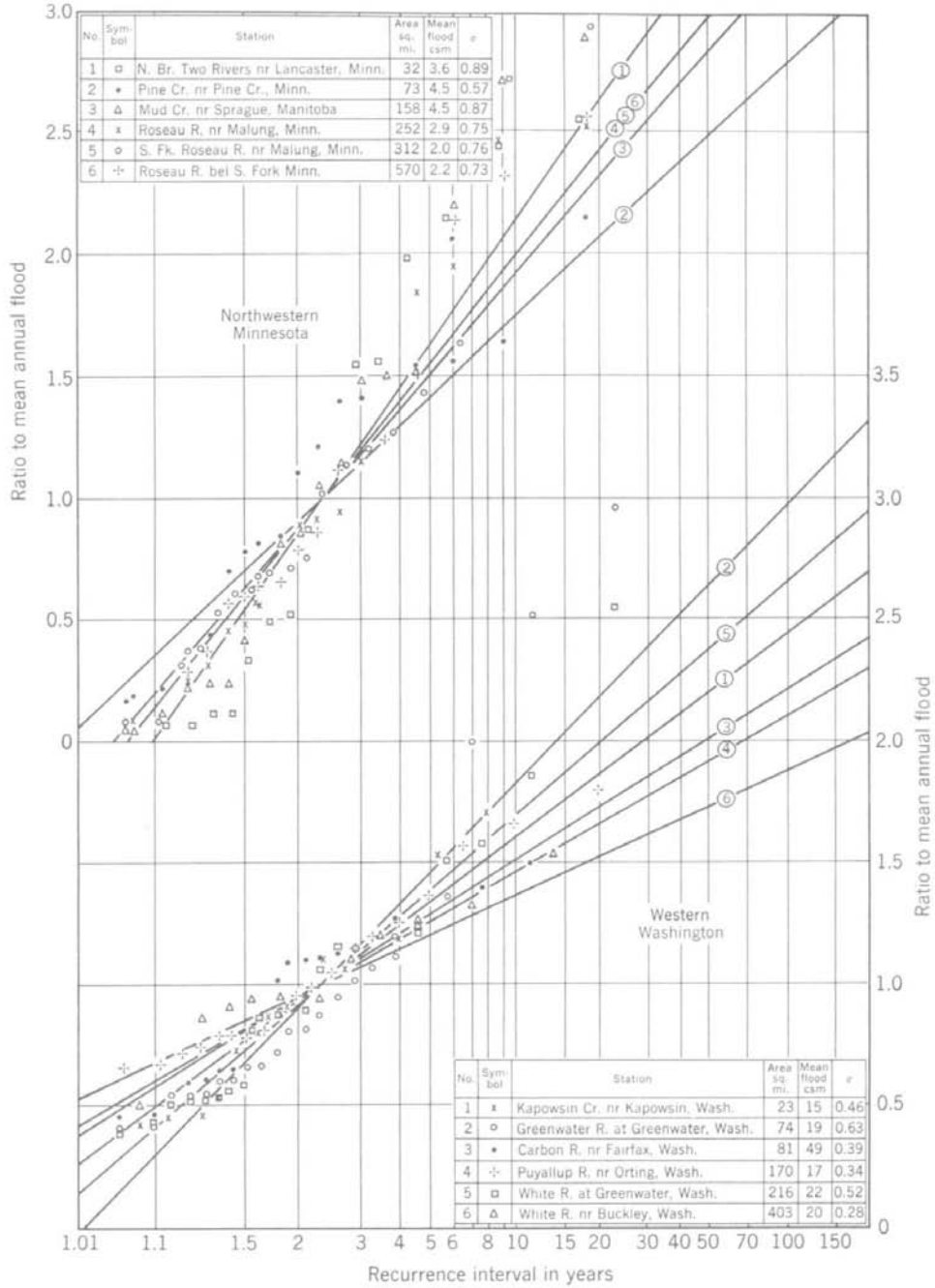
ILLUSTRATIVE EXAMPLE

ANALYTICAL FREQUENCY CURVE USING PRE-RECORD DATA
WILLAMETTE RIVER AT ALBANY, OREGON

Confidence Limits



Comparison of Flood Freq Curves

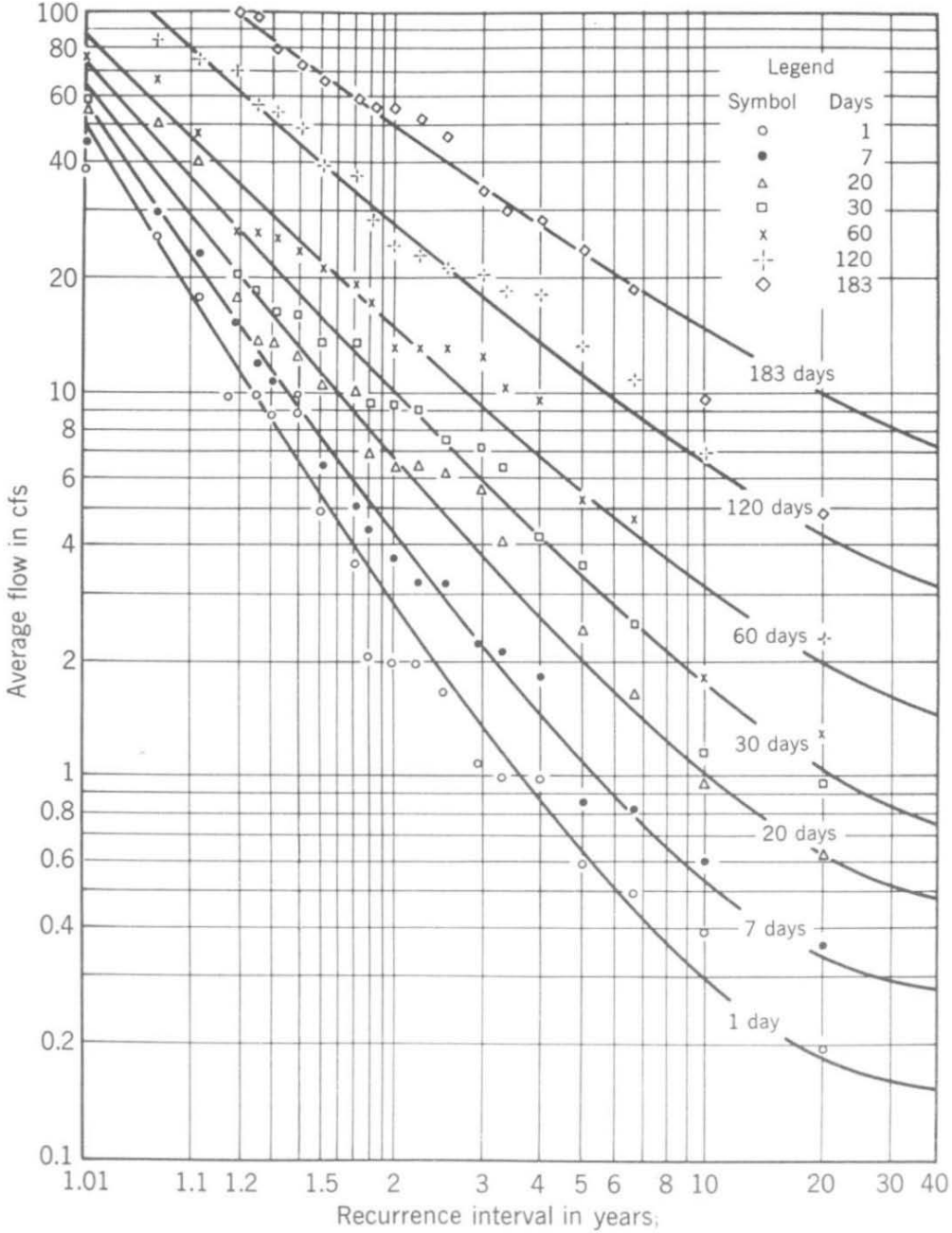


No.	Symbol	Station	Area sq. mi.	Mean flood csm	σ
1	□	N. Br. Two Rivers nr Lancaster, Minn.	32	3.6	0.89
2	•	Pine Cr. nr Pine Cr., Minn.	73	4.5	0.57
3	△	Mud Cr. nr Sprague, Manitoba	158	4.5	0.87
4	x	Roseau R. nr Malung, Minn.	252	2.9	0.75
5	○	S. Fk. Roseau R. nr Malung, Minn.	312	2.0	0.76
6	⊹	Roseau R. bel S. Fork Minn.	570	2.2	0.73

No.	Symbol	Station	Area sq. mi.	Mean flood csm	σ
1	x	Kapowsin Cr. nr Kapowsin, Wash.	23	15	0.46
2	○	Greenwater R. at Greenwater, Wash.	74	19	0.63
3	•	Carbon R. nr Fairfax, Wash.	81	49	0.39
4	⊹	Puyallup R. nr Orting, Wash.	170	17	0.34
5	□	White R. at Greenwater, Wash.	216	22	0.52
6	△	White R. nr Buckley, Wash.	403	20	0.28

FIG. 5-5 Comparison of flood-frequency curves for adjacent basins.

Low Flow Frequency



Frequency of minimum flows for Yellow Creek near Hammondsville, Ohio (1915–1935).

100 Year Flood

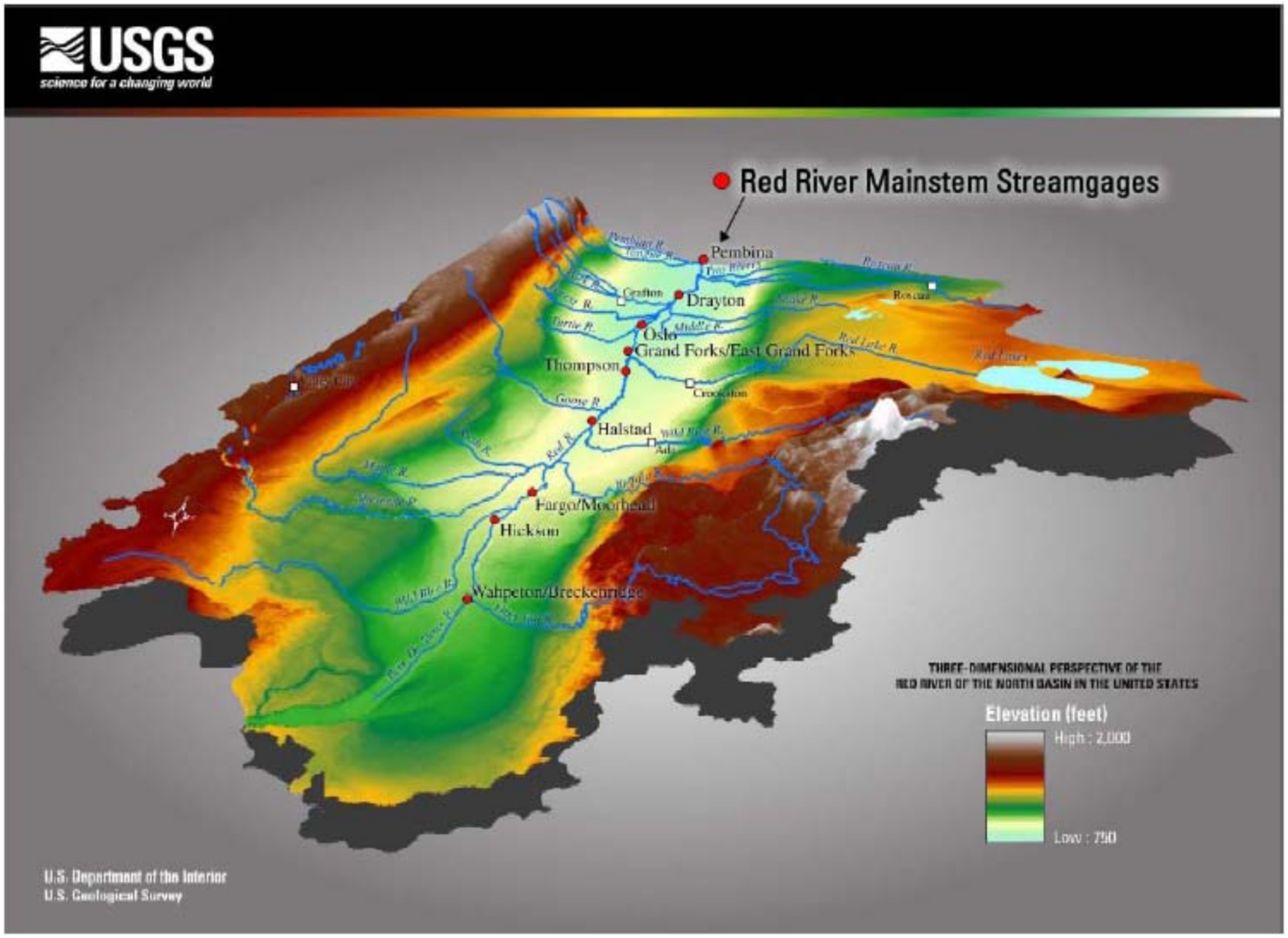
The flow for which there is a 1% chance, each and every year, that a flow of that magnitude or greater will occur at least once

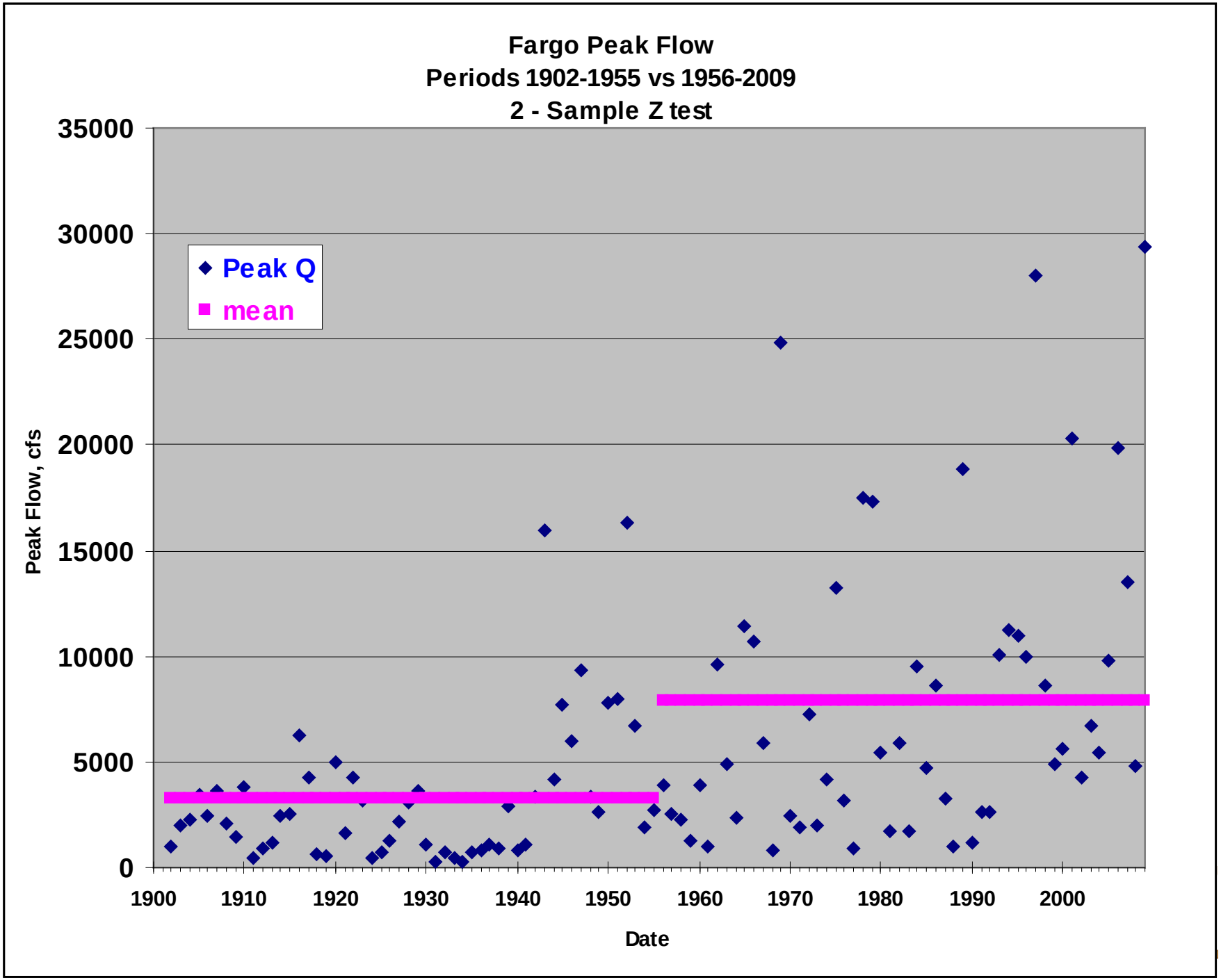
Risk

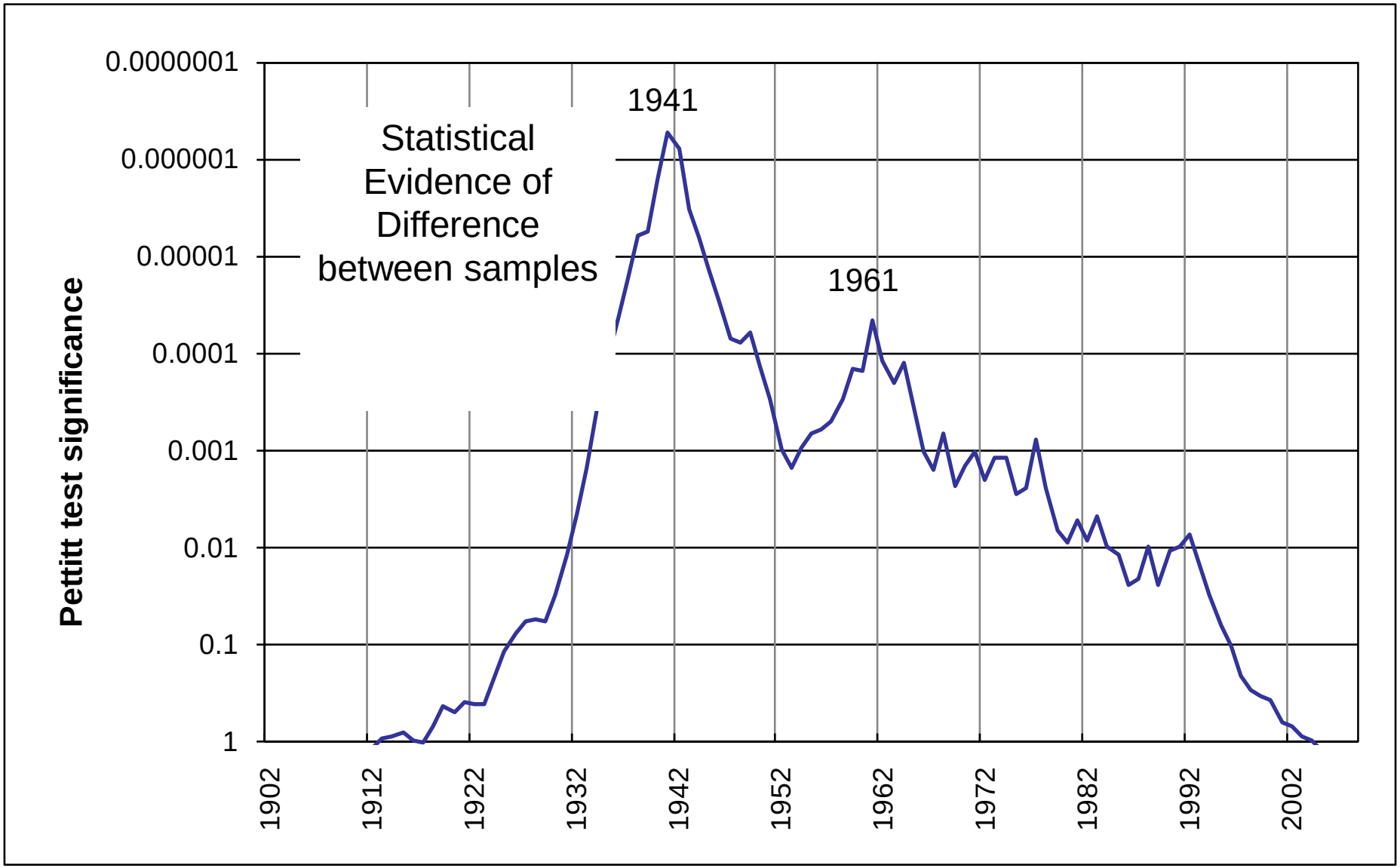
The probability that an event of a given magnitude or greater will occur at least once during a period of years

In a 30 year period there is a 26% chance you'll see a 100 yr or GREATER event

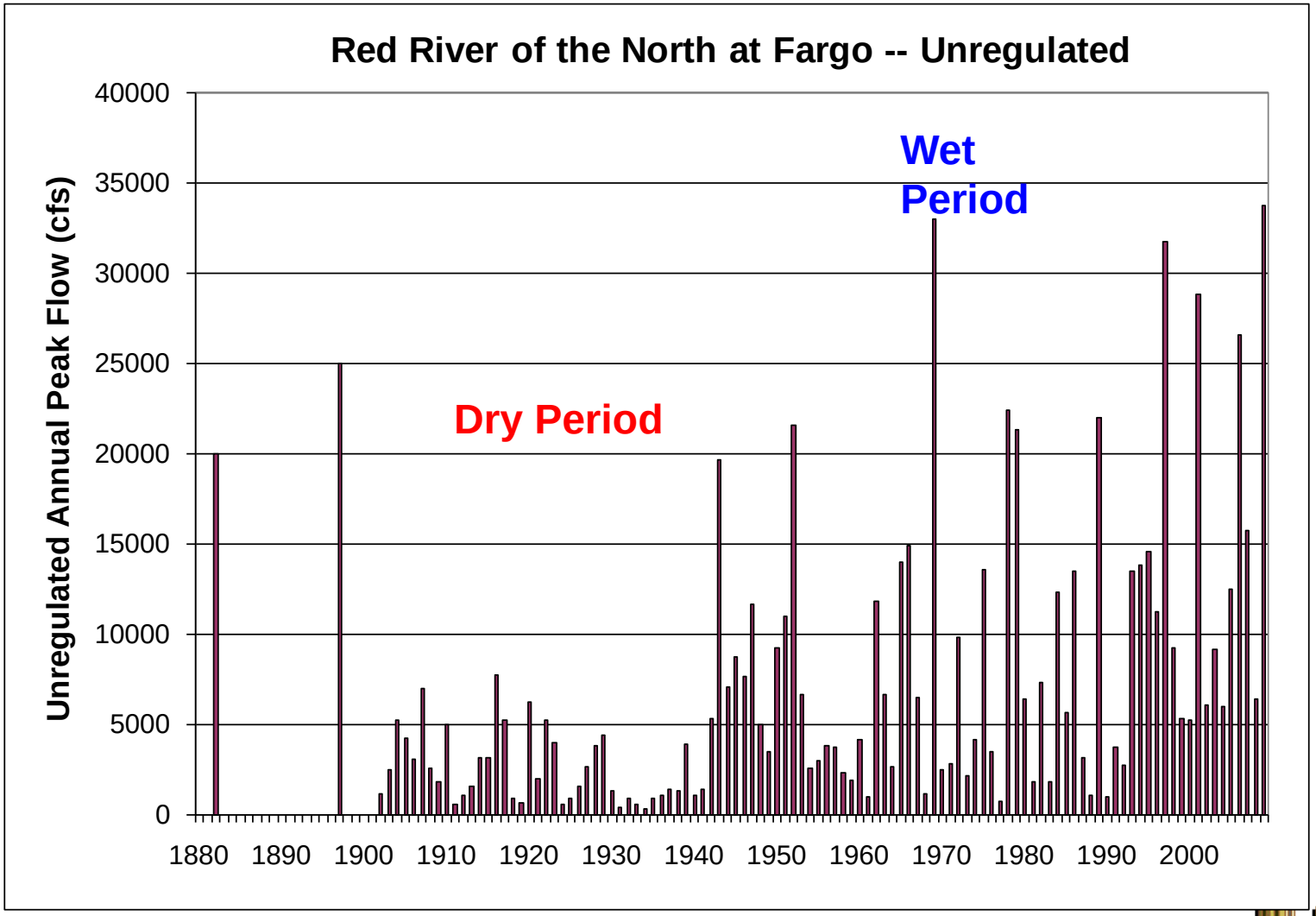
Climate Variability


USGS
science for a changing world
Red River Mainstem Streamgages
Pembina
Drayton
Oslo
Grand Forks/East Grand Forks
Thompson
Halstad
Fargo/Moorhead
Hickson
Wahpeton/Breckenridge
THREE-DIMENSIONAL PERSPECTIVE OF THE
RED RIVER OF THE NORTH BASIN IN THE UNITED STATES
Elevation (feet)
High : 2,000
Low : 750
U.S. Department of the Interior
U.S. Geological Survey


Fargo Peak Flow
Periods 1902-1955 vs 1956-2009
2 - Sample Z test
Peak Q
mean
Peak Flow, cfs
35000
30000
25000
20000
15000
10000
5000
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Date


Pettitt test significance
0.0000001
0.000001
0.00001
0.0001
0.001
0.01
0.1
1
1902
1912
1922
1932
1942
1952
1962
1972
1982
1992
2002
1941
1961
Statistical Evidence of Difference between samples

Annual Peak Flow Record



Suggestion of wet/dry cycle

Tree-ring evidence of historical flood peaks suggests a reoccurrence of wet and dry periods in the last few centuries

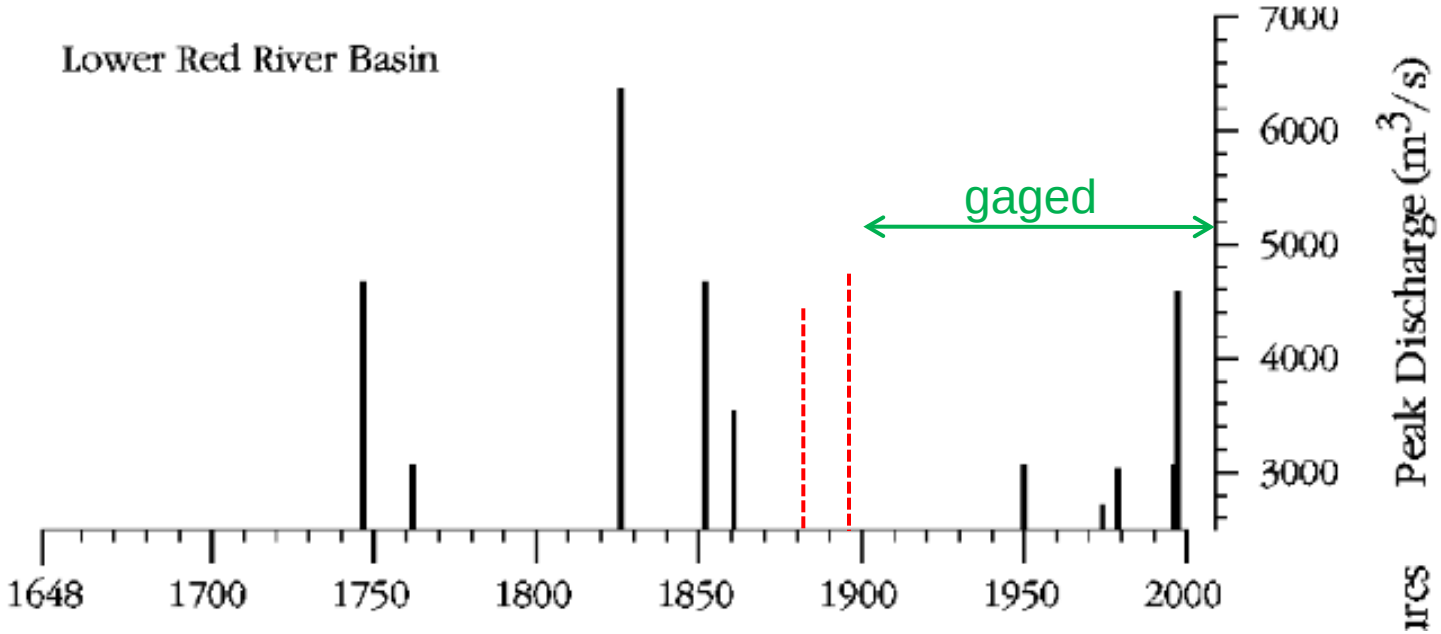
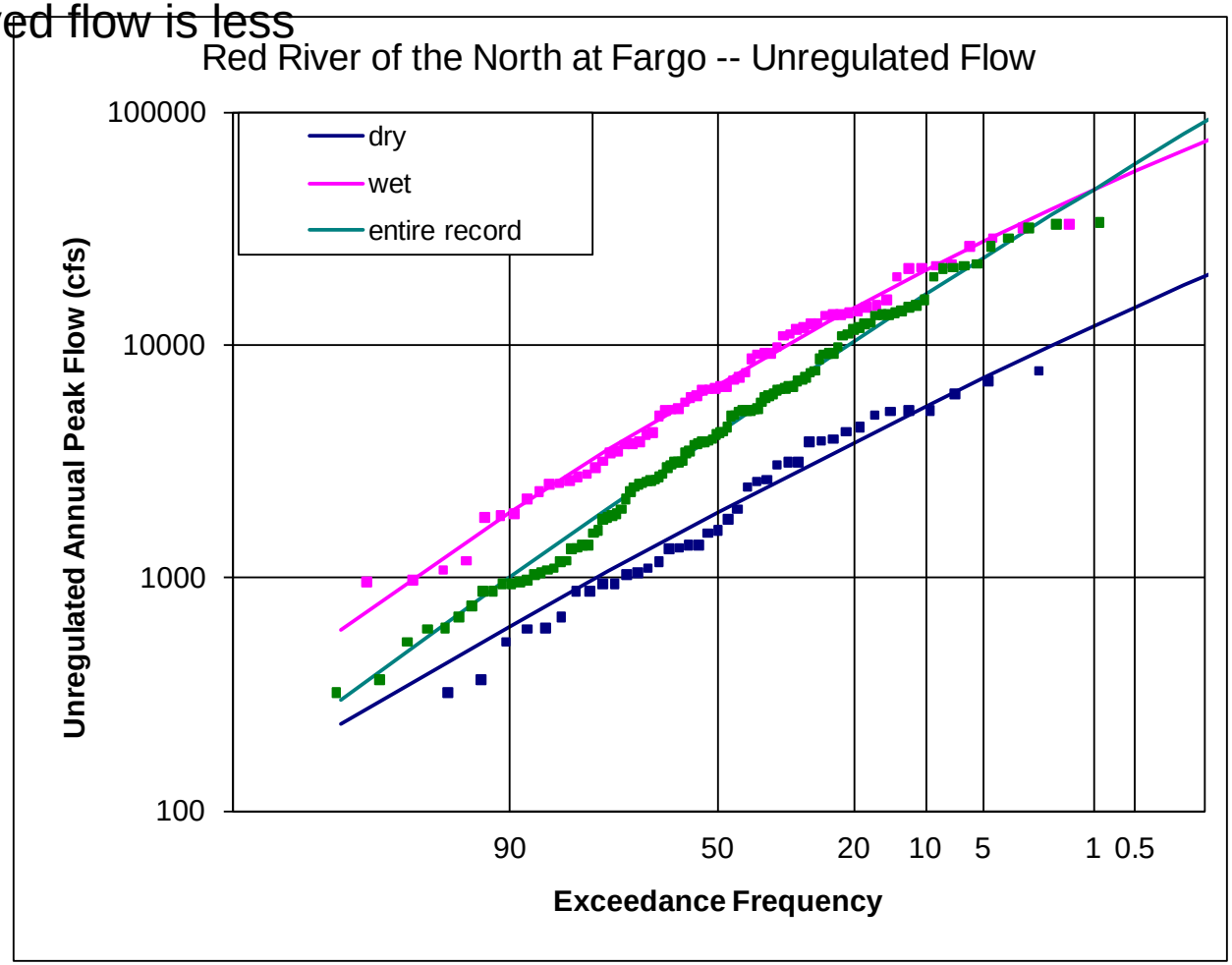


Figure 10 Estimated peak discharge for the Lower Red River basin at Winnipeg and flood signatures in the Upper Red River basin.

from: St. George, S. and Nielsen, E. "Palaeoflood records for the Red River, Manitoba, Canada, derived from anatomical tree-ring signatures," *The Holocene*, 13,4 (2003) pp. 547-555.

Frequency Analysis on Wet and Dry Records

The standard deviation (slope of curve) is much less for the wet and dry records than for the full record, because in either period, range of observed flow is less



Re-Combining the Wet and Dry Frequency Curves

Theorem of total probability:

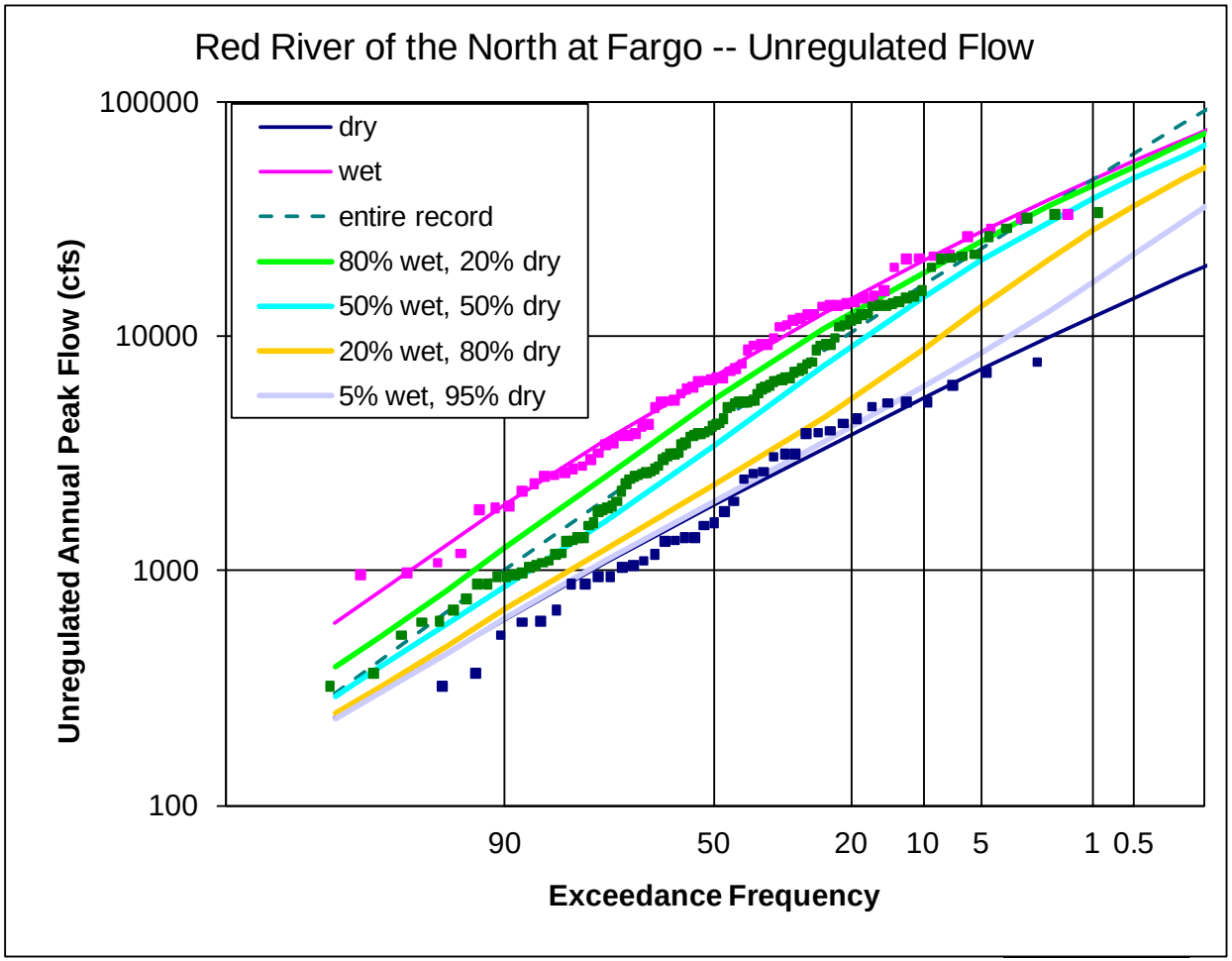
$$P(Q>q) = P(Q>q|wet) * P(wet) \quad + \quad P(Q>q|dry) * P(dry)$$

where:

P(Q>q) =
exceedance probability for a given flow, q

P(Q>q|wet) =
exceedance probability given that we're in the wet condition

P(wet) =
probability we're in the wet condition.



The End