PDHonline Course C201 (4 PDH)

Stormwater Drainage Design for Parking Lots

2026

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Stormwater Drainage Design for Parking Lots

ACE Group, LLC

Course Outline

Parking lots can be seen almost everywhere, from shopping centers to office buildings to schools. Stormwater drainage design is an integral component in the design of parking lots. This course covers the basics of designing an adequate storm drainage system for a parking lot. Methods are presented for evaluating rainfall and runoff magnitude, pavement drainage, gutter flow, and drainage inlets. Concepts for the design of detention/retention facilities are also discussed. Several examples are presented to illustrate the detailed procedures for designing storm drainage system of a parking lot. The basic principles discussed in this course can be applied not only to parking lots, but to parking decks, paved streets, and highways as well. This course includes a multiple-choice quiz at the end, which is designed to enhance the understanding of course materials.

Learning Objective

At the conclusion of this course, the student will be able to:

- Understand the basic principles of storm drainage design;
- Perform simple storm runoff analysis for parking lots;
- Select appropriate types of inlets;
- Position inlets at proper locations;
- Understand the concept of stormwater detention/retention; and
- Utilize the rainfall data published by the federal, state and local governments.

A Parking Lot next to Office Buildings

Course Introduction

In addition to providing safe and efficient ingress and egress for vehicles, an engineer/architect should design parking lots in a way to prevent flooding and erosion damage to surrounding landscaping. This course provides basic guidance for the storm drainage design of paved or unpaved parking lots, and is intended for engineers and architects who are not very familiar with the subject.

Stormwater conveyance system includes storm drain piping, ditches and channels, pumps, and etc., and is beyond the scope of this course.

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Course Content

The stormwater drainage design for a parking lot includes data collection, regulatory considerations, preliminary concept development, concept refinement and design, and final design documentation. The surface drainage of a parking lot is a function of transverse and longitudinal pavement slopes, pavement roughness, inlet spacing, and inlet capacity. The content for this course includes the following aspects:

1. Regulatory Considerations
2. Drainage Terminologies
3. Stormwater Drainage System
4. Surface Drainage
5. Design Frequency
6. Rainfall Intensity
7. Sheet Flow
8. Gutter Flow
9. Peak Runoff
10. Time of Concentration
11. Runoff Coefficient
12. Flow Depth and Spread
13. Drainage Inlets
14. Inlet Locations
15. Stormwater Detention/Retention
16. Design Examples
17. Other Considerations

A Parking Lot with Curb-Opening Inlets

1. Regulatory Considerations

The stormwater drainage design for parking lots must meet federal, state, and local regulatory requirements. Typical regulatory authorities include the US Army Corps of Engineers, the US Environmental Protection Agency, State Departments of Environmental Regulation, and local governments.

Typical regulatory considerations at local levels include erosion control, best management practices, and stormwater detention. Many urban cities and county governments have developed erosion control and stormwater management manuals that provide guidance for meeting local requirements, and have implemented Best Management Practices (BMP) pertaining to the design, construction, and maintenance of stormwater management facilities. The primary objectives of the regulations are to minimize the impact of stormwater runoff rates and volumes, to prevent erosion, and to capture pollutants.

A detailed discussion of federal, state and local regulations related to drainage design is beyond the scope of this course.

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2. Drainage Terminologies

Storm water drainage design includes several technical aspects, from statistics to hydrology. In order to better understand the technical and regulatory aspects of storm drainage design, an engineer must be familiar with the relevant acronyms and glossary. Some of the terms listed below may not be used in this course. However, they are often encountered in the articles and discussions related to storm drainage design.

ACRONYMS

ASCE – American Society of Civil Engineers
BMP - Best Management Practices
DOT - Department of Transportation
EPA - Environmental Protection Agency
FHWA – Federal Highway Administration
IDF - Intensity-Duration-Frequency
NOAA - National Oceanic and Atmospheric Administration
NRCS - Natural Resources Conservation Service (formerly SCS under USDA)
NWS - National Weather Service (an agency under NOAA)
SCS - Soil Conservation Service (an agency under USDA)
USACE - United States Army Corps of Engineers
USDA - United States Department of Agriculture

GLOSSARY

Best Management Practices (BMP) – Policies, procedures, practices and criteria pertaining to the design, construction, and maintenance for stormwater facilities that minimize the impact of stormwater runoff rates and volumes, prevent erosion, and capture pollutants. Best Management Practices are categorized as structural or non-structural. A BMP policy may affect the limits on a development.

Catch Basin – A subsurface drainage structure with a grate on top to collect and convey surface runoff into the storm sewer system, usually built at the curb line of a street or parking lot. It is designed so that sediment falls to the bottom of the catch basin and not directly into the storm sewer.

Channel - A portion of a natural or man-made watercourse with a defined bed and banks.

Conveyance - A mechanism for transporting water from one point to another, including pipes, ditches, channels, culverts, gutters, manholes, weirs, man-made and natural channels, water quality filtration systems, dry wells, etc.

Conveyance System - The drainage facilities which collect, contain, and provide for the flow of surface and stormwater from points on the land down to a receiving water.

Design Storm - A selected storm event for the design of drainage or flood control in terms of the probability of occurring once within a given number of years.

Detention - Temporary holding of stormwater runoff to control peak discharge rates and to provide gravity settling of pollutants.

Detention Facility – A facility, such as a man-made pond, that temporarily stores stormwater runoff before discharging into a creek, lake or river.

Discharge - The rate of water flow in terms of cubic feet per second or millions of gallons

per day.

Ditch - A long narrow trench dug in the ground for the purpose of irrigation or drainage.

Drain - A slotted or perforated pipe buried in the ground (subsurface drain) or a ditch (open drain) for carrying off surplus groundwater or surface water.

Drainage - The removal of excess surface water or groundwater from land by means of gutters, ditches or subsurface drains.

Drainage Area - The watershed runoff area or surface runoff area in the case of a parking lot.

Drainage Inlets - The receptors for surface water collected in ditches and gutters to enter the storm drainage system. The openings to drainage inlets are typically covered by a grate or any other perforated surface to protect pedestrians.

Drainage Structure – A generic term which can be used to describe any of the following structures: a manhole, catch basin or drain inlet.

Drainage System - The combination of collection, conveyance, retention, detention, treatment of water on a project.

Duration - The time period of a rainfall event.

Erosion - The wearing away of the earth's surface by water, wind, ice, or other natural forces.

Flow Regime - The prevailing pattern of water flow over a given amount of time.

Gauge - A device for measuring precipitation, water level, pressure, temperature, etc.

Grate Inlet - Parallel and/or transverse bars arranged to form an inlet structure.

Gutter - A channel at the edge of a street or parking lot for carrying off surface runoff. Parking lots are typically curbed in urban settings. Curbs are typically installed in combination with gutters where runoff from the pavement surface would erode fill slopes.

Gutter Flow - Water which enters a gutter as sheet flow from the paved surface or as overland flow from adjacent land area until reaching some outlet.

Hydrograph - A plot of flow versus time.

Hydrologic Cycle - The cycle of evaporation and condensation that controls the distribution of the earth's water through various stages or processes, such as precipitation, runoff, infiltration, transpiration, and evaporation.

Hydrology - The scientific study of the properties, distribution, and effects of water on the earth's surface, underground, and atmosphere.

Impervious - Incapable of being penetrated or infiltrated.

Invert - The inside bottom of a culvert or other conduit.

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Longitudinal Slope - The rate of elevation change with respect to distance in the direction of travel or flow.

Manhole – A generic term referring to a subsurface structure for almost any utility.

Mean Velocity – The average velocity of a stream flowing in a channel or conduit at a given cross section.

Natural Drainage - The flow patterns of stormwater runoff over the land prior to development.

Open Channel - A natural or man-made structure that conveys water with the top surface in contact with the atmosphere.

Open Channel Flow - Gravitational flow in an open conduit or channel.

Open Drain - A natural watercourse or constructed open channel that conveys drainage water.

Orifice Flow – The flow of water controlled by pressure into an opening that is submerged.

Overland Flow – A combination of sheet flow, shallow concentrated flow, and/or open channel flow.

Rainfall Intensity - The rate of rainfall at any given time, usually expressed in inches per hour.

Rational Formula - A simple technique for estimating peak discharge rates for very small developments based on rainfall intensity, watershed time of concentration, and a runoff coefficient (Q= CIA).

Rational Method - A method of calculating storm peak discharge rates (Q) by use of the Rational Formula Q= CIA.

Retention - The temporary or permanent storage of stormwater.

Retention Facility – A facility designed to capture a specified amount of stormwater runoff from the watershed and use infiltration, evaporation, and emergency bypass to release water from the facility.

Return Period - A statistical term for the average time of expected interval that an event of some kind will equal or exceed given conditions (e.g., a storm water flow that occurs once every 10 years). Return period is also referred as design frequency or storm frequency.

Runoff - The excess portion of precipitation that does not infiltrate into the ground or evaporate into the air, but "runs off" on the land surface, in open channels, or in stormwater conveyance systems.

Sheet Flow – Water flow over the ground surface as a thin, even layer, not concentrated in a channel.

Slotted Inlets - A section of pipe cut along the longitudinal axis with transverse bars spaced to form slots.

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Slope - Degree of deviation of a surface from the horizontal, measured as a numerical ratio or percent.

Steady Flow - Flow that remains constant with respect to time.

Stochastic Methods - Frequency analysis used to evaluate peak flows where adequate gauged stream flow data exist.

Storm Drain - A particular storm drainage system component that receives runoff from inlets and conveys the runoff to some point. Storm drains are closed conduits or open channels connecting two or more inlets. Also referred as a storm sewer.

Storm Drainage System – A system which collects, conveys, and discharges stormwater runoff.

Storm Event - An estimate of the expected amount of precipitation within a given period of time.

Storm Frequency - The time interval between major storms of predetermined intensity and volumes of runoff – for instance, a 5-year, 10-year or 20-year storm. Also referred as design frequency or return period.

Storm Sewer - A sewer that carries stormwater, surface drainage, street wash, and other wash waters but excludes sewage and industrial wastes. Also referred as a storm drain.

Surface Runoff - Precipitation that flows onto the surfaces of roofs, streets, parking lots, the ground and etc., and is not absorbed or retained by that surface but collects and runs off.

Time of Concentration - The time for a raindrop to travel from the hydraulically most distant point in the watershed to a point of interest. This time is calculated by summing the individual travel times for consecutive components (e.g., gutters, storm sewers or drainage channels) of the drainage system.

Uniform Flow - A state of steady flow when the mean velocity and cross-sectional area remain constant in all sections of a reach.

Unit Hydrograph - The direct runoff hydrograph produced by a storm of given duration such that the volume of excess rainfall and direct runoff is 1 cm.

Watercourse - Any river, stream, creek, brook, branch, natural or man-made drainageway into which stormwater runoff or floodwaters flow either continuously or intermittently.

Watershed - The region drained by or contributing water to a specific point that could be along a stream, lake or other stormwater facilities.

Weir - A channel-spanning structure for measuring or regulating the flow of water.

Weir Flow - Flow over a horizontal obstruction controlled by gravity.

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3. Stormwater Drainage Systems

Stormwater drainage systems can be classified into major systems and minor systems. A major system provides overland relief for stormwater flows exceeding the capacity of the minor system, and is generally not conveyed by storm sewers per se, but rather over the land surface in roadways and in natural or man-made receiving channels such as streams, creeks, rivers, lakes, or wetlands.

A minor system consists of the components of the storm drainage system that are normally designed to carry runoff from the more frequent storm events. These components include: curbs, gutters, ditches, inlets, manholes, pipes and other conduits, open channels, pumps, detention/retention ponds, water quality control facilities, etc.

The primary drainage function of parking lots is to convey minor storms quickly and efficiently to the storm sewer or open channel drainage with minimal impact on the vehicle/ pedestrian traffic and the surrounding environment. In addition, removing water quickly from paved surfaces will prevent water from reaching the subgrade, minimize cracks due to the weakened subgrade, and prolong the life of the pavement in a parking lot.

Parking lot drainage requires consideration of surface drainage, gutter flow, inlet capacity, and inlet locations. The design of these elements is dependent on storm frequency and rainfall intensity.

A Parking Lot with Grate Inlets

4. Surface Drainage

When rain falls on a sloped pavement surface, part of it infiltrates into the ground, part of it evaporates into the air, and the remainder runs off from the high point to the low point as a result of gravity. The runoff water forms sheet flow - a thin film of water that increases in thickness as it flows to the edge of the pavement. Factors which influence the depth of water on the pavement are the length of flow path, surface texture, surface slope, and rainfall intensity.

Surface drainage for a parking lot consists of slopes, gutters and inlets. Desirable gutter grades should not be less than 0.5 percent (0.005 ft/ft) for curbed pavements with an absolute minimum of 0.3 percent.

Water is probably the greatest cause of distress in a paved structure. The efficient removal of a storm runoff from paved surfaces has a positive effect on parking lot maintenance and repair. A minimum slope of 0.4 percent (0.004 ft/ft) shall be used for the paved surfaces. Parking lots with grades flatter than 0.4 percent are subject to ponding and are candidates for installing underground storm sewers. To achieve adequate drainage, a slope between 1% and 5% is recommended for paved surfaces in a parking lot.

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5. Design Frequency

Design frequency is also called storm frequency or return period, which is a selected storm event frequency for the design of drainage or flood control in terms of the probability of occurring once within a given number of years. For example, a 10-year frequency, 24-hour duration storm event is a storm that has a 10% probability of occurring in any one year. The amount of precipitation is measured over a 24-hour period. If the design is for a 2-year storm event, there is a 50% probability that this design will be exceeded in any given one year.

Local governments normally specify the design criteria such as design frequency (return period) for the collection and conveyance of runoff water on different types of developments. A listing of typical design storm return period is presented in Table 1 below.

Table 1. Typical Return Periods for Stormwater Drainage Design (ASCE, 1992)

Drainage Type	Land Use	Return Period (year)
Minor drainage systems	Residential area	2 – 5
	High-value general commercial area	2 – 10
	Airports (terminals, roads, aprons)	2 – 10
	High-value downtown business area	5 – 10
Major drainage system elements		up to 100

A minimal design storm frequency for a parking lot is a 2-year event.

A Parking Lot with Grate Inlets

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6. Rainfall Intensity

Rainfall intensity represents the rate of rainfall at any given instant, usually expressed in inches per hour. Rainfall data in the United State have been collected and published by the federal, state and local governments. The National Weather Service (NWS) under the National Oceanic and Atmospheric Administration (NOAA) is the primary source of weather data, forecasts and warnings for the United States.

The Office of Hydrology (HYDRO) of NWS has published a series of technical memoranda to facilitate the dissemination of scientific and technical materials related to river and water supply forecasts, including the rainfall data. NOAA Technical Memorandum NWS HYDRO-35, published in 1977, contains precipitation-frequency values for durations of 5-, 15-, and 60-minutes at return periods of 2 and 100 years for 37 states from North Dakota to Texas and eastward (see Figure 1 below for sample precipitation map). **You may find NOAA Technical Memorandum NWS HYDRO-35 at the end of this handout.** For the 11 western states, rainfall data is available in the NOAA Atlas 2, published in 1973.

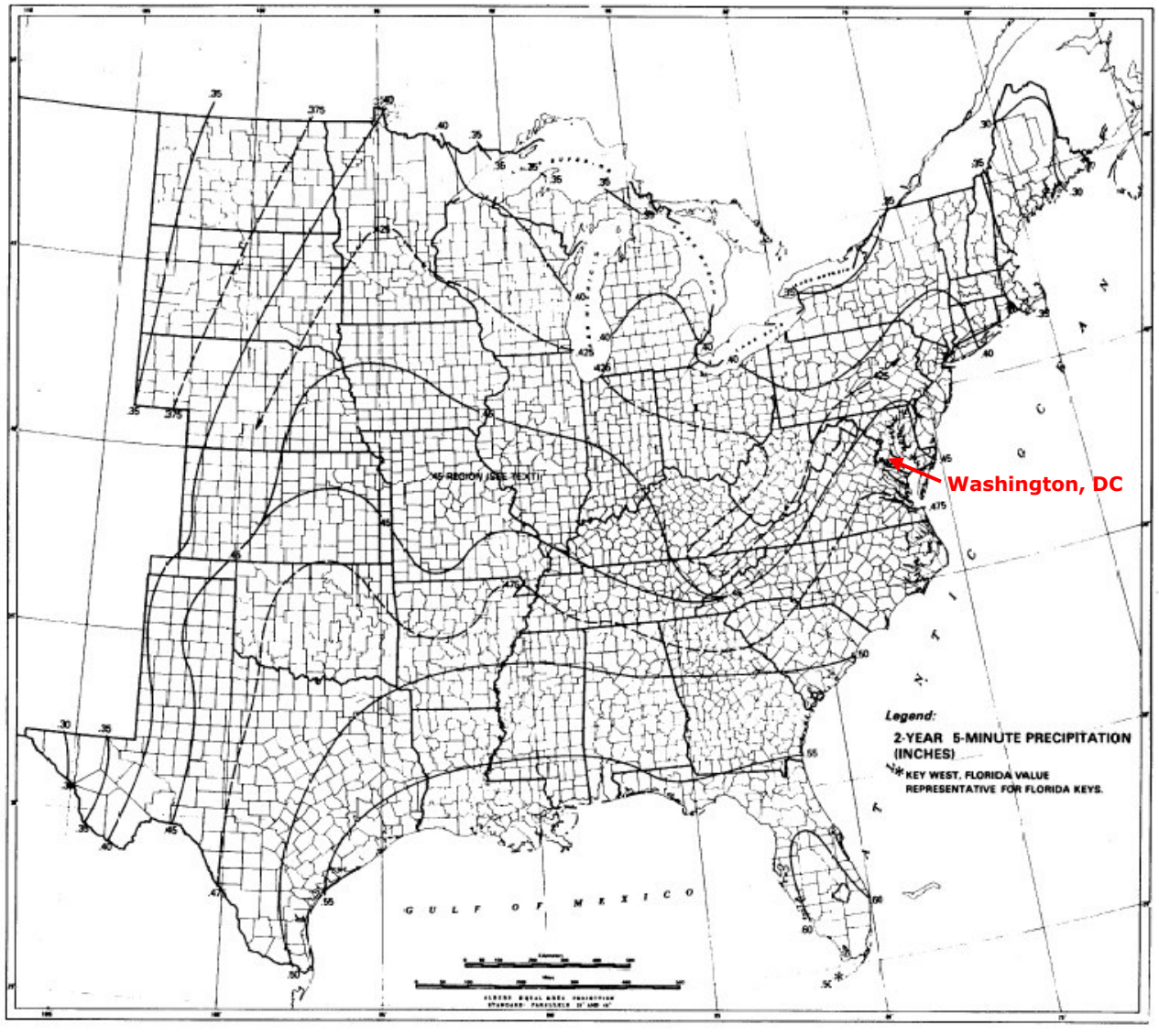

Figure 1. 2-Year, 5-Minute Precipitation (inches) – Adjusted to Partial-Duration Series
(Source: NOAA Technical Memorandum NWS HYDRO-35)

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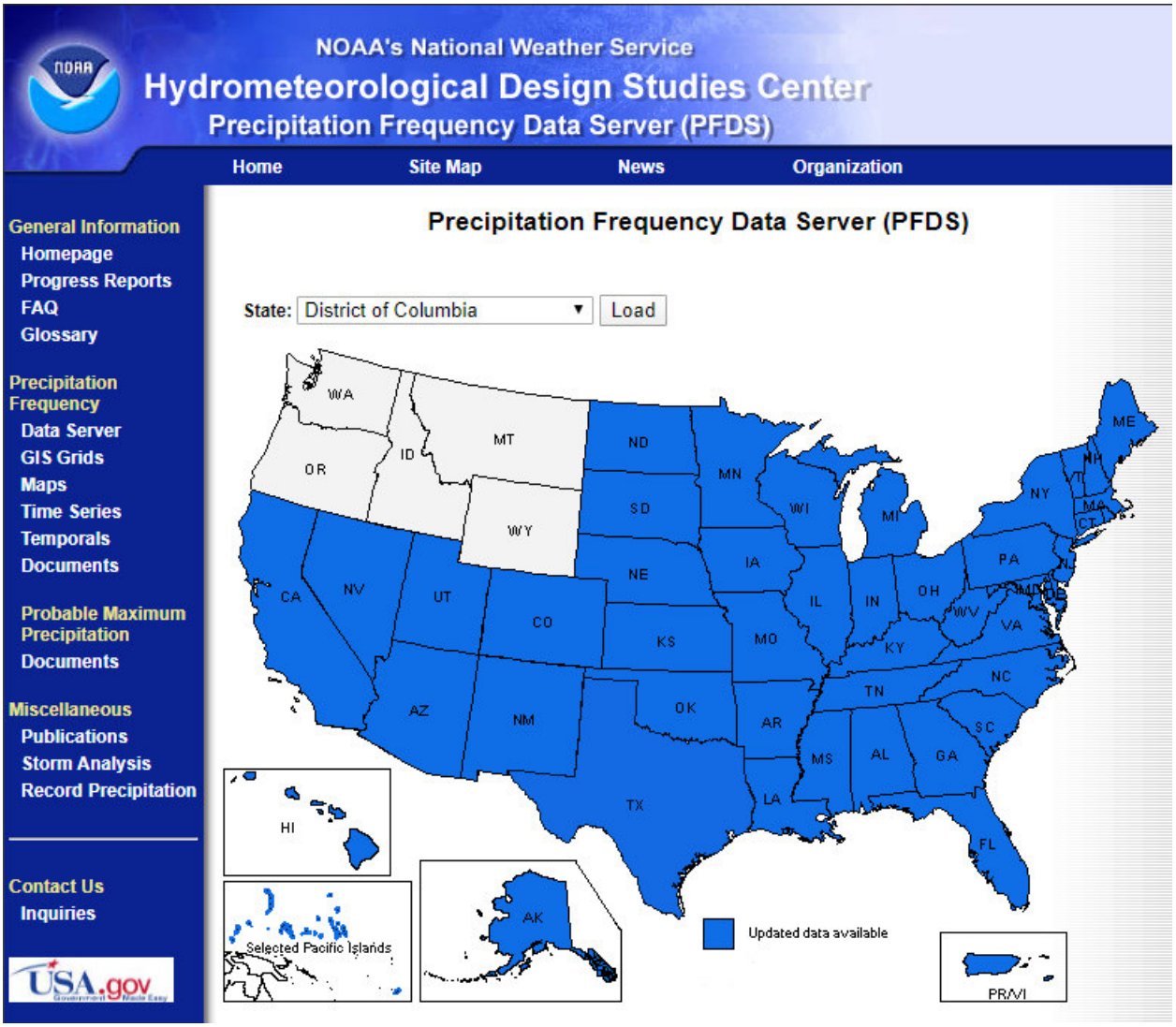
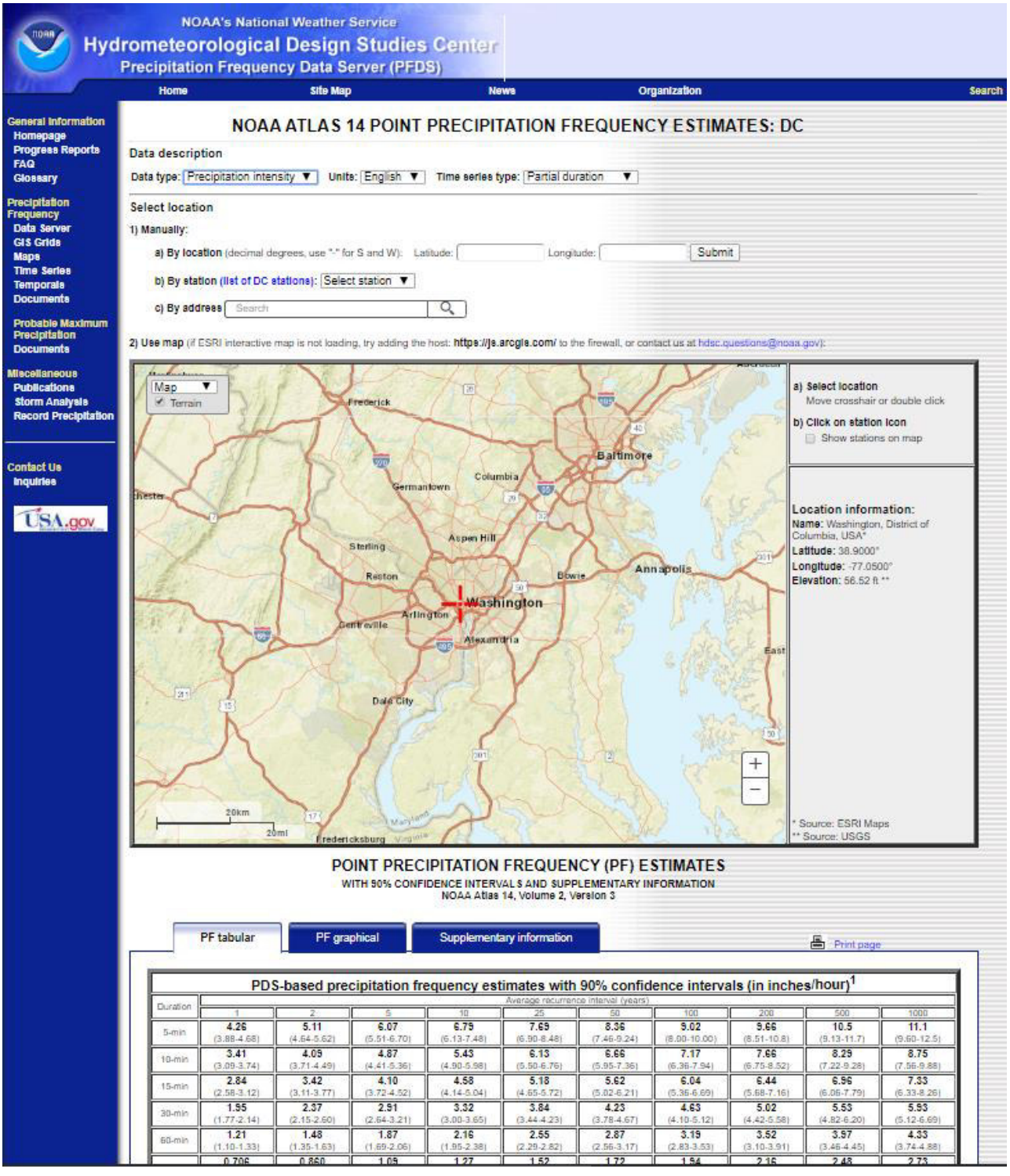
In the last two decades, the Hydrometeorological Design Studies Center (HDSC) within the Office of Water Prediction (OWP) of the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) has been updating precipitation frequency estimates for various parts of the United States and affiliated territories. Updated precipitation frequency estimates, accompanied by additional relevant information, are published as **NOAA Atlas 14** and are available for download from the Precipitation Frequency Data Server (PFDS).

NOAA Atlas 14 (Precipitation-Frequency Atlas of the United States) is a National Weather Service study of historical rainfall. The historical record for the previous rainfall study ended in 1994. Atlas 14 extends the rainfall data through 2017, and can be accessed through https://hdsc.nws.noaa.gov/hdsc/pfds/.

The Precipitation Frequency Data Server (PFDS) is a point-and-click interface developed to deliver NOAA Atlas 14 precipitation frequency estimates and associated information. Upon clicking a state on the map above or selecting a state name from the drop-down menu, an interactive map of that state will be displayed. From there, a user can identify a location for which precipitation frequency estimates are needed. See screen captures below for Washington, DC.



Estimates and their confidence intervals can be displayed directly as tables or graphs via separate tabs. Links to supplementary information (such as ASCII grids of estimates, associated temporal distributions of heavy rainfall, time series data at observation sites, cartographic maps, etc.) can also be found.



The followings are the tabulated and graphical rainfall intensity data for Washington, District of Columbia.

NOAA Atlas 14, Volume 2, Version 3
Location name: Washington, District of Columbia, USA*
Latitude: 38.9°, Longitude: -77.05°
Elevation: 56.52 ft**
* source: ESRI Maps
** source: USGS

POINT PRECIPITATION FREQUENCY ESTIMATES

G.M. Bonnin, D. Martin, B. Lin, T. Parzybok, M.Yekta, and D. Riley

NOAA, National Weather Service, Silver Spring, Maryland

PF tabular | PF graphical | Maps & aerials

PF tabular

PDS-based point precipitation frequency estimates with 90% confidence intervals (in inches/hour)[1]

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	4.26 (3.88-4.68)	5.11 (4.64-5.62)	6.07 (5.51-6.70)	6.79 (6.13-7.48)	7.69 (6.90-8.48)	8.36 (7.46-9.24)	9.02 (8.00-10.00)	9.66 (8.51-10.8)	10.5 (9.13-11.7)	11.1 (9.60-12.5)
10-min	3.41 (3.09-3.74)	4.09 (3.71-4.49)	4.87 (4.41-5.36)	5.43 (4.90-5.98)	6.13 (5.50-6.76)	6.66 (5.95-7.36)	7.17 (6.36-7.94)	7.66 (6.75-8.52)	8.29 (7.22-9.28)	8.75 (7.56-9.88)
15-min	2.84 (2.58-3.12)	3.42 (3.11-3.77)	4.10 (3.72-4.52)	4.58 (4.14-5.04)	5.18 (4.65-5.72)	5.62 (5.02-6.21)	6.04 (5.36-6.69)	6.44 (5.68-7.16)	6.96 (6.06-7.79)	7.33 (6.33-8.26)
30-min	1.95 (1.77-2.14)	2.37 (2.15-2.60)	2.91 (2.64-3.21)	3.32 (3.00-3.65)	3.84 (3.44-4.23)	4.23 (3.78-4.67)	4.63 (4.10-5.12)	5.02 (4.42-5.58)	5.53 (4.82-6.20)	5.93 (5.12-6.69)
60-min	1.21 (1.10-1.33)	1.48 (1.35-1.63)	1.87 (1.69-2.06)	2.16 (1.95-2.38)	2.55 (2.29-2.82)	2.87 (2.56-3.17)	3.19 (2.83-3.53)	3.52 (3.10-3.91)	3.97 (3.46-4.45)	4.33 (3.74-4.88)
2-hr	0.706 (0.641-0.778)	0.860 (0.782-0.948)	1.09 (0.989-1.20)	1.27 (1.15-1.39)	1.52 (1.36-1.67)	1.72 (1.54-1.90)	1.94 (1.72-2.14)	2.16 (1.90-2.39)	2.48 (2.15-2.77)	2.73 (2.35-3.07)
3-hr	0.503 (0.458-0.556)	0.611 (0.556-0.676)	0.775 (0.701-0.855)	0.905 (0.817-0.998)	1.09 (0.977-1.20)	1.24 (1.11-1.37)	1.41 (1.24-1.55)	1.58 (1.38-1.75)	1.83 (1.57-2.04)	2.03 (1.73-2.28)
6-hr	0.309 (0.281-0.342)	0.374 (0.340-0.413)	0.472 (0.428-0.522)	0.553 (0.498-0.611)	0.673 (0.601-0.743)	0.775 (0.685-0.856)	0.885 (0.775-0.980)	1.00 (0.870-1.12)	1.18 (1.00-1.32)	1.33 (1.11-1.50)
12-hr	0.186 (0.167-0.208)	0.224 (0.202-0.251)	0.285 (0.256-0.319)	0.337 (0.301-0.376)	0.416 (0.368-0.465)	0.486 (0.424-0.543)	0.563 (0.486-0.631)	0.649 (0.552-0.731)	0.781 (0.650-0.885)	0.895 (0.732-1.02)
24-hr	0.108 (0.098-0.121)	0.131 (0.119-0.146)	0.168 (0.153-0.187)	0.201 (0.182-0.223)	0.251 (0.225-0.277)	0.296 (0.263-0.325)	0.347 (0.306-0.379)	0.405 (0.353-0.441)	0.493 (0.423-0.536)	0.571 (0.483-0.619)
2-day	0.063 (0.057-0.070)	0.076 (0.069-0.084)	0.097 (0.088-0.108)	0.116 (0.105-0.128)	0.143 (0.129-0.158)	0.167 (0.150-0.184)	0.194 (0.172-0.213)	0.224 (0.197-0.246)	0.269 (0.233-0.295)	0.308 (0.263-0.338)
3-day	0.044 (0.040-0.049)	0.053 (0.049-0.059)	0.068 (0.062-0.076)	0.081 (0.074-0.090)	0.101 (0.091-0.111)	0.117 (0.105-0.129)	0.136 (0.121-0.149)	0.157 (0.138-0.172)	0.188 (0.163-0.207)	0.215 (0.184-0.237)
4-day	0.035 (0.032-0.039)	0.042 (0.039-0.047)	0.054 (0.049-0.060)	0.064 (0.058-0.071)	0.079 (0.071-0.087)	0.092 (0.083-0.102)	0.107 (0.095-0.118)	0.123 (0.109-0.136)	0.148 (0.128-0.163)	0.169 (0.145-0.186)
7-day	0.023 (0.021-0.025)	0.028 (0.026-0.031)	0.035 (0.032-0.039)	0.042 (0.038-0.046)	0.051 (0.046-0.056)	0.059 (0.053-0.065)	0.068 (0.061-0.074)	0.078 (0.069-0.085)	0.093 (0.081-0.102)	0.105 (0.091-0.116)
10-day	0.019 (0.017-0.020)	0.022 (0.020-0.024)	0.028 (0.025-0.030)	0.032 (0.030-0.036)	0.039 (0.036-0.043)	0.045 (0.041-0.049)	0.051 (0.046-0.056)	0.057 (0.051-0.063)	0.067 (0.059-0.074)	0.075 (0.066-0.082)
20-day	0.012 (0.012-0.014)	0.015 (0.014-0.016)	0.018 (0.017-0.019)	0.020 (0.019-0.022)	0.024 (0.022-0.026)	0.027 (0.025-0.029)	0.030 (0.027-0.032)	0.033 (0.030-0.035)	0.037 (0.033-0.040)	0.040 (0.036-0.044)
30-day	0.010 (0.010-0.011)	0.012 (0.011-0.013)	0.014 (0.013-0.016)	0.016 (0.015-0.017)	0.019 (0.017-0.020)	0.021 (0.019-0.022)	0.023 (0.021-0.025)	0.025 (0.023-0.027)	0.028 (0.025-0.030)	0.030 (0.027-0.033)
45-day	0.009 (0.008-0.009)	0.010 (0.009-0.011)	0.012 (0.011-0.013)	0.013 (0.012-0.014)	0.015 (0.014-0.016)	0.016 (0.015-0.017)	0.017 (0.016-0.019)	0.019 (0.017-0.020)	0.020 (0.019-0.022)	0.022 (0.020-0.023)
60-day	0.008 (0.007-0.008)	0.009 (0.008-0.010)	0.010 (0.010-0.011)	0.011 (0.011-0.012)	0.013 (0.012-0.014)	0.014 (0.013-0.015)	0.015 (0.014-0.016)	0.016 (0.015-0.017)	0.017 (0.016-0.018)	0.018 (0.016-0.019)

[1] Precipitation frequency (PF) estimates in this table are based on frequency analysis of partial duration series (PDS).

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 average recurrence interval) 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.

NOAA Atlas 14, Volume 2, Version 3
Location name: Washington, District of Columbia, USA*
Latitude: 38.9°, Longitude: -77.05°
Elevation: 56.52 ft**
* source: ESRI Maps
** source: USGS

POINT PRECIPITATION FREQUENCY ESTIMATES

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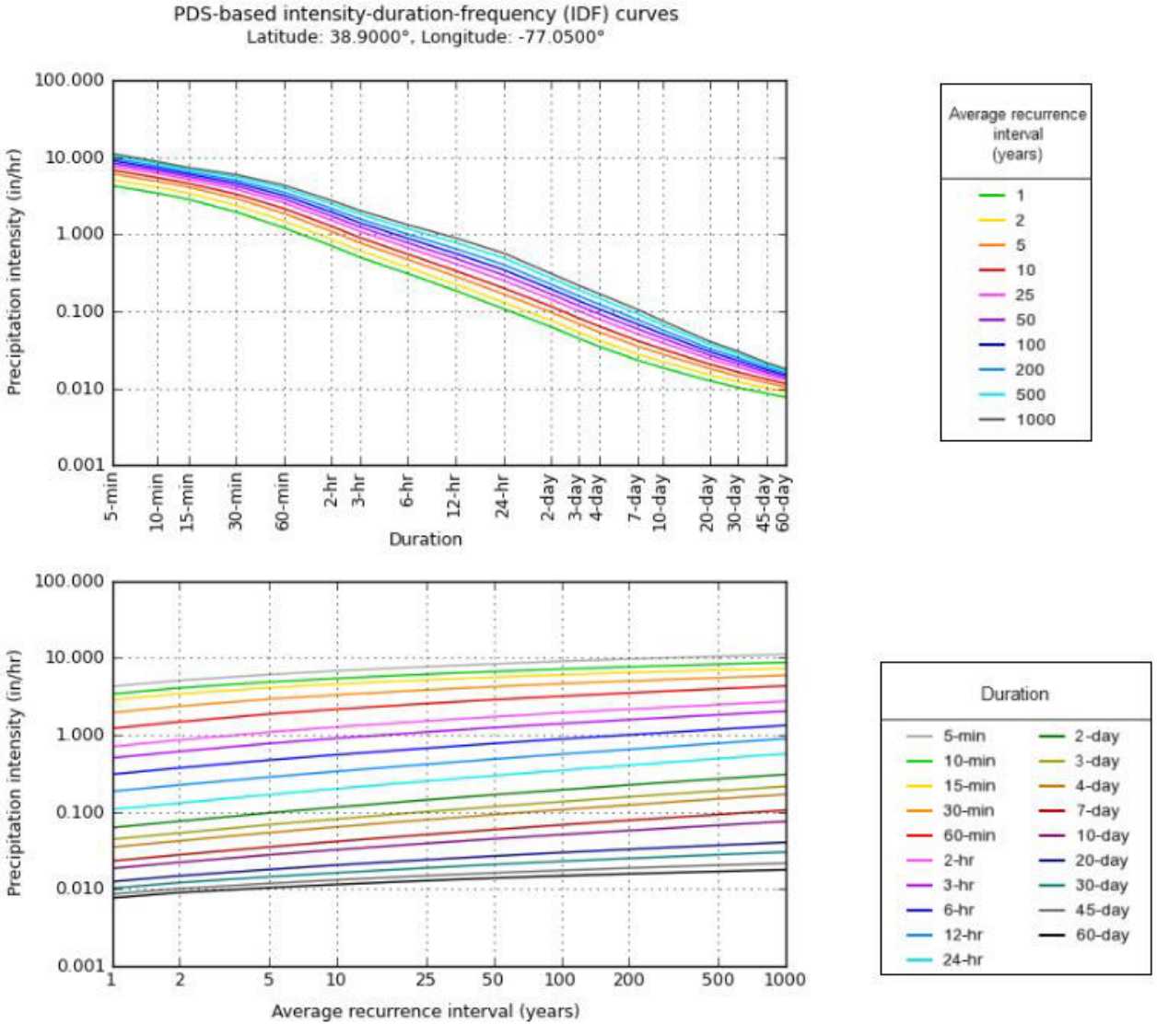
NOAA, National Weather Service, Silver Spring, Maryland

PF_tabular | PF_graphical | Maps_&_aerials

PF graphical



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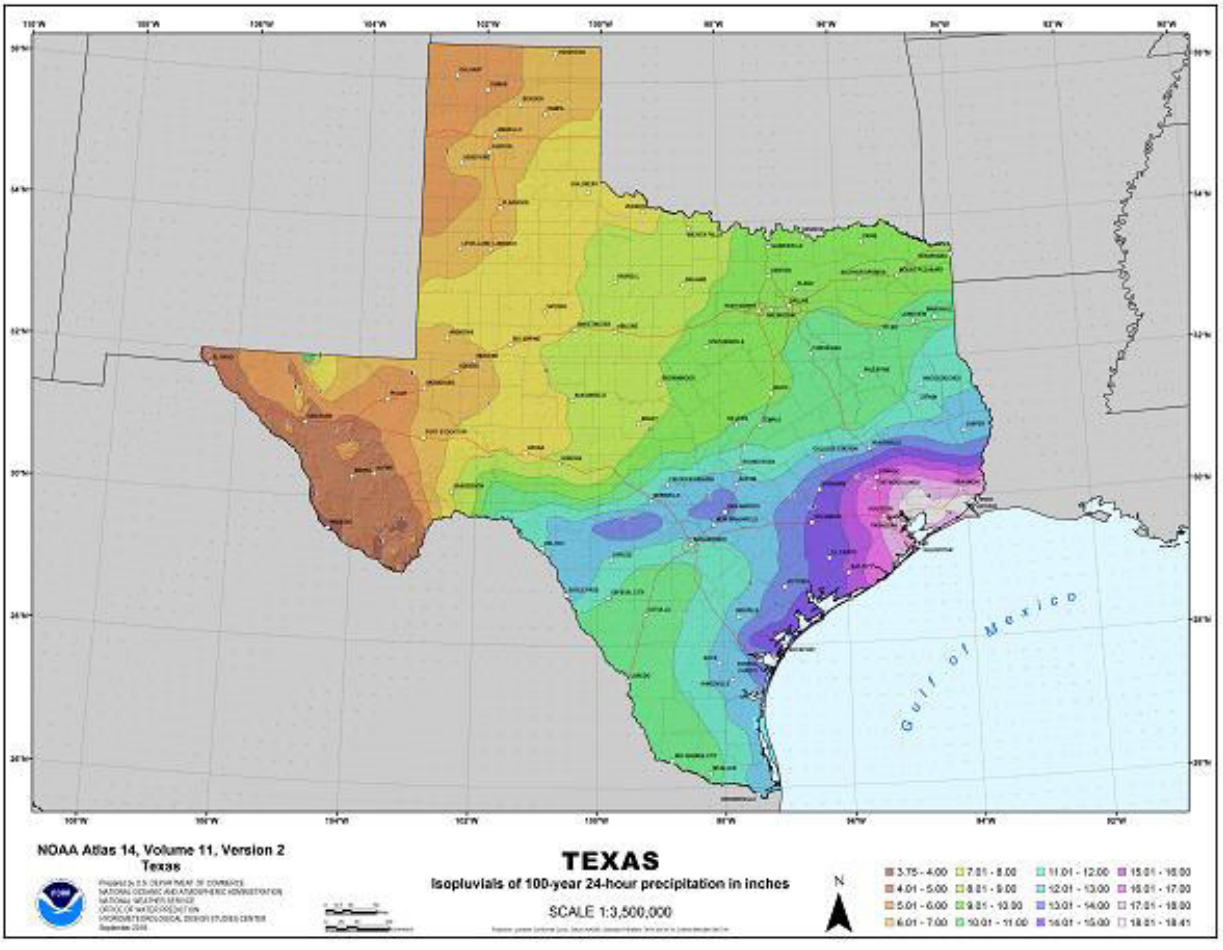
Based on the data provided by NOAA's Precipitation Frequency Data Server (PFDS) in the screen captures above, the amount of rainfall in 60 minutes for the DC area is 3.19 inches for a 100-year storm event (1% of probability of Occurrence in any given year). This estimate is very close to what is shown in Figure 5 of NOAA Technical Memorandum NWS HYDRO-35.

To get the total amount of rainfall in 24 hours for the DC area for a 100-year storm event, we need to multiple the precipitation intensity from the table (0.347 in./hr.) by 24 hours, which results in a total of 8.33 inches in 24 hours.

The NDSC website also provides access to NOAA Atlas 14 cartographic maps of precipitation frequency estimates in the PDF format for selected average recurrence intervals (ARIs) and durations (shown in the table below). They recommend that these maps are used as visual aids only. Precipitation frequency estimates can be obtained from the high resolution grids available from the PFDS interface.



NOAA Atlas 14 Cartographic Maps of Precipitation Frequency Estimates for Selected Frequencies and Durations

Using the data and maps provided by NOAA Atlas 14, engineers will be able to predict future rainfall intensity based on historical rainfall data and to better manage the flood risk for the public.

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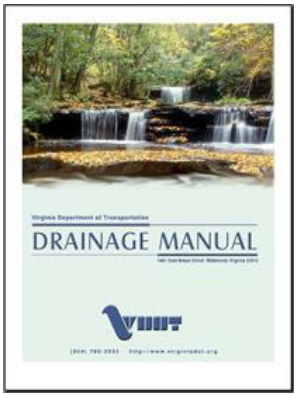
Many state and local governments have compiled rainfall data according to their local conditions. Regional Intensity-Duration-Frequency (IDF) curves have been developed for many jurisdictions throughout the United States through frequency analysis of rainfall events from thousands of rainfall gauges. IDF curves are available in most highway agency drainage manuals or in local storm water management manuals (see Figure 2 below for sample IDF curve). If the local rainfall data are not available, a designer may utilize the rainfall data published by the US governments.

For storm drainage design of parking lots, rainfall intensities for short durations (60-minutes or less) are of primary interest to the designer.



VDOT Drainage Manual

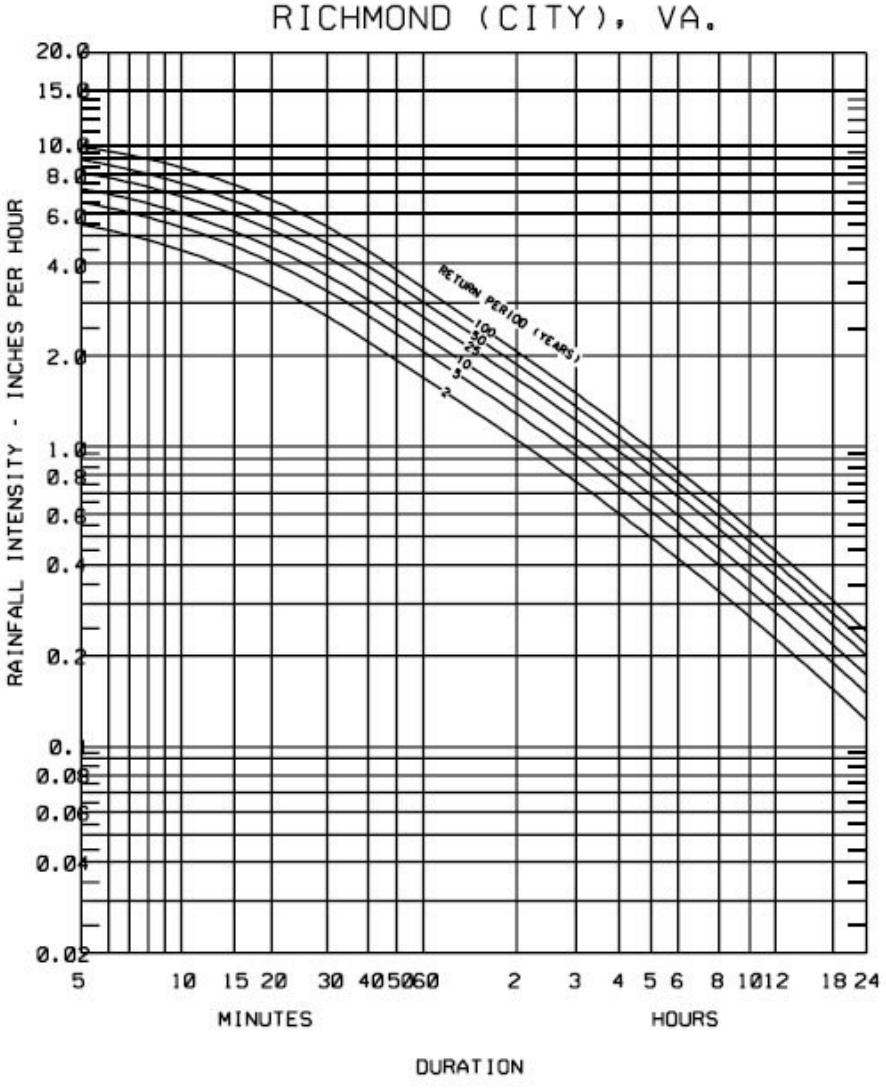


Figure 2 - Rainfall Intensity-Duration-Frequency (IDF) Curve for Richmond, Virginia (Source: VDOT Drainage Manual)

IDF curves may be presented in different formats (see Figure 3 to the right for another type of IDF curve). The rainfall intensity for a 2-year, 20 minute duration storm event is approximately 3.5 and 4.0 inches per hour based on Figures 2 and 3, respectively.

When the duration is less than 5 minutes, it is generally acceptable to use the rainfall intensity equal to a 5-minute event for the purpose of calculating peak runoff.

Equations for these IDF curves are often available in the design manuals and can be utilized in the computerized calculation of peak runoff.

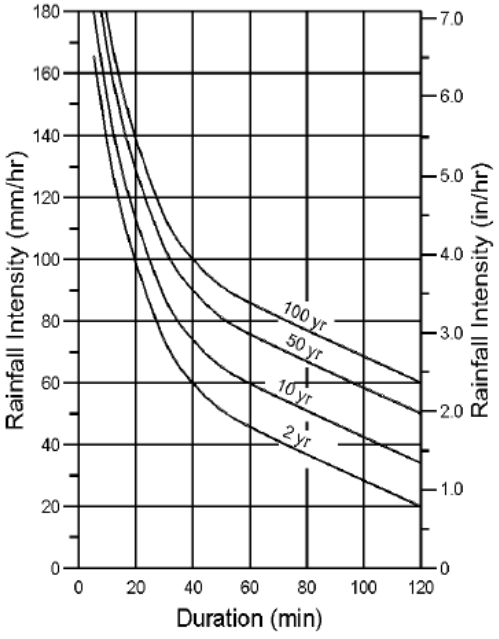


Figure 3 - Sample IDF Curve
Source: FHWA HEC-22

7. Sheet Flow

Sheet flow is the water flow over the ground surface as a thin, even layer. It usually occurs in the upper reaches of a drainage area. Surface runoff in a parking lot before it reaches a gutter is an example of sheet flow.

8. Gutter Flow

Gutter flow is the water which enters a gutter as sheet flow from the paved surface or as overland flow from adjacent land area. Gutter flow is sometimes called curb flow if a curb exists along the edge of a street or parking lot.

Concrete Curb/Gutter in a Parking Lot

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9. Peak Runoff

Peak runoff for a parking lot is the maximum water flow as a result of surface runoff. Storm drainage systems for parking lots usually rely on gravity. There are several acceptable methods for performing hydrologic calculations used in determination of peak stormwater flow rates and runoff volumes:

1) The stochastic methods or frequency analysis;
2) The Soil Conservation Service (SCS, now known as NRCS) Unit Hydrography Method;
3) The Rational Method.

Stochastic methods are not commonly used in urban drainage design due to the lack of adequate streamflow data. The NRCS Unit Hydrograph Method is normally used for sites with contributing drainage area greater than 10 acres. Among the three methods listed above, the Rational Method is most often used in determination of the peak flow from an urbanized area, such as a parking lot. The equation used in the Rational Method is called the Rational Formula, which can be expressed in English units as follows:

$$Q = C_f\, CIA \qquad \text{Eq. (1)}$$

where:

Q = Peak runoff in cubic feet per second (cfs).
C_f = Runoff coefficient adjustment factor (see Table 1a).
C = Runoff coefficient (see Table 2).
I = Average intensity of rainfall in inches per hour for a duration equal to the time of concentration, Tc, for a selected rainfall frequency.
A = Size of drainage area in acres.

The following assumptions are used in deriving the Rational Formula:

- Rainfall intensity is the same over the entire drainage area;
- Rainfall intensity is uniform over a duration equal to the time of concentration, Tc;
- Peak runoff occurs when the entire parking lot is contributing to the flow;
- Frequency of the computed peak runoff is the same as that of the rainfall intensity;
- Coefficient of runoff is the same for all recurring rain storms.

Because of these assumptions, the Rational Formula should only be applied to drainage areas smaller than 200 acres (or 80 hectares for SI units).

Table 1a. Runoff Coefficient Adjustment Factor

Return Period	C_f
1, 2, 5, 10	1.0
25	1.1
50	1.2
100	1.25

So for storm events with average recurrence intervals of 10 years or less, Eq. (1) can be simplified as:

$$Q = CIA \qquad \text{Eq. (2)}$$

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10. Runoff Coefficient

Runoff coefficient C represents the characteristics of the drainage area. In essence, runoff coefficient corresponds to the amount of the rainfall that runs off rather than infiltrates into the ground or evaporates into the air. Its value may range from 0 to 1 depending on the type of drainage surface.

Table 2 below lists the published runoff coefficients by FHWA (HEC-22 "Urban Drainage Design Manual", 2001):

Table 2. Runoff Coefficients for the Rational Formula

Type of Drainage Area		Runoff Coefficient, C
Business	Downtown areas	0.70 - 0.95
	Neighborhood areas	0.50 - 0.70
Residential	Single-family areas	0.30 - 0.50
	Apartment dwelling areas	0.50 - 0.70
Lawn	Sandy soil, flat, <2%	0.05 - 0.10
	Heavy soil, flat, <2%	0.13 - 0.17
	Heavy soil, steep, >7%	0.25 - 0.35
Streets	Asphalt	0.70 - 0.95
	Concrete	0.80 - 0.95
	Brick	0.70 - 0.85
Others	Drives and walks	0.75 - 0.85
	Roofs	0.75 - 0.95

For parking lots, it is reasonable to assume C=0.9 and 0.2 for asphalt paved areas and flat lawn areas, respectively, when calculating storm runoff.

If the drainage area consists of several different surfaces, a weighted average can be calculated as follows:

$$C_{weighted} = \Sigma (C_x \times A_x)/\Sigma A_x \qquad \text{Eq. (3)}$$

For instance, the weighted average runoff coefficient for a parking lot with 30% lawns and 70% asphalt pavement can be calculated using Eq. (3):

$C_{weighted} = (0.9 \times 0.7 + 0.2 \times 0.3)/(1.0) = 0.69$

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11. Time of Concentration

Time of concentration, or T_c, is the time in minutes, for a raindrop to travel from the hydraulically most distant point in a parking lot to a concentration point (an inlet) after the beginning of rainfall. T_c for sheet flow in impervious areas such as parking lots can be estimated with a version of the kinematic wave equation derived from Manning's equation, as follows:

$$T_{ti} = \frac{0.933}{I^{0.4}} \left(\frac{nL}{\sqrt{S}} \right)^{0.6} \qquad \text{Eq. (4)}$$

where:

T_{ti} = sheet flow travel time in minutes
I = rainfall intensity in inch/hour
n = roughness coefficient (see Table 3)
L = flow length in feet
S = surface slope in foot/foot

If the runoff consists of several flow segments, the time of concentration, T_c, can be calculated as the sum of the travel times as follows:

$$T_c = \sum T_{ti} \qquad \text{Eq. (5)}$$

Because rainfall intensity "I" depends on T_c and T_c is not initially known, the computation of T_c is an iterative process. For a small parking lot, one may start with I corresponding to the 5-minute precipitation, and use I based on the calculated T_c in the successive computations. It may take a few rounds of iterations for the solution to converge.

Table 3. Roughness Coefficients for Overland Sheet Flow

Surface Description		Roughness Coefficient, n
Pavement	Smooth asphalt	0.011
	Smooth concrete	0.012
Grass	Short grass prairie	0.15
	Dense grasses	0.24

After short distances of at most 400 ft, sheet flow tends to concentrate in rills and then gullies of increasing proportions. Such flow is usually referred to as shallow concentrated flow. The velocity of such flow can be estimated using the following equation:

$$V = 3.28\ k\ S_p^{0.5} \qquad \text{Eq. (6)}$$

where:

V = velocity in feet per second
k = intercept coefficient (see Table 4)
S_p = slope in percent

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Table 4. Intercept Coefficients for Shallow Concentrated Flow

Surface Description	Intercept Coefficients, k
Paved area	0.619
Unpaved	0.491
Grassed waterway	0.457

12. Flow Depth and Spread

Curbs are normally used at the outside edge of pavements in an urban parking lot to prevent erosion on fill slopes and to provide pavement delineation. Gutters formed in combination with curbs usually have a width of 12 to 36 inches and may have the same cross slope as that of the pavement or may be designed with a steeper cross slope. A curb and gutter combination forms a triangular channel that can convey runoff equal to or less than the design peak flow. When a design peak flow occurs in a parking lot, there is a spread or widening of the conveyed water surface. The water spreads to include not only the gutter width, but also portions of parking surface.

The spread of gutter flow (see Figure 4) can be determined by the following equation:

$$T = ((1.79Qn/(S_X^{1.67} S_L^{0.5}))^{0.375} \quad \text{Eq. (7)}$$

where:

T = width of flow (spread) in feet
Q = flow rate in cubic feet per second
n = Manning's roughness coefficient (see Table 3)
S_X = cross slope in ft/ft
S_L = longitudinal slope in ft/ft

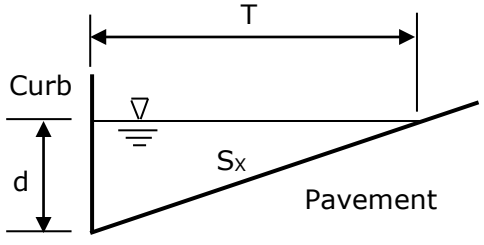

Figure 4 - Uniform Gutter Section

The depth of flow at the face of curb for a uniform gutter section can be expressed as:

$$d = T S_X \quad \text{Eq. (8)}$$

where:

d = depth of flow in feet

13. Drainage Inlets

Once collected in the gutter, storm runoff from a parking lot needs to enter the storm sewer through drainage inlets. Inadequate inlet capacity or poor inlet location may cause ponding on a parking lot, resulting in a hazard to the public.

There are several different types of inlets available for storm drainage application. This course will cover the following two types that are most common for parking lots:

1. Grate inlets
2. Curb-opening inlets

Grate inlets consist of an opening in the gutter or ditch covered by a grate. Curb-opening inlets are vertical openings in the curb covered by a top slab. Figures 5 and 6 below show samples of each inlet type.

Figure 5 – A Grate Inlet

Figure 6 – A Curb-Opening Inlet

The hydraulic capacity of a storm drain inlet in a parking lot depends upon its geometry as well as the characteristics of the gutter flow. Inlet capacity governs both the rate of water removal from the gutter and the amount of water that enters the storm drainage system.

Grate type selection should consider such factors as hydraulic efficiency, debris handling characteristics, and pedestrian and bicycle safety. In addition, grate loading conditions must also be considered when determining an appropriate grate type. Grates in traffic areas must be able to withstand heavy traffic loads.

The website (http://www.neenahfoundry.com/literature/index.html) of Neenah Foundry, a grate inlet manufacturer, provides information on the types of grate inlets and their capacities.

The efficiency of inlets in passing debris is critical in sag locations because all runoff which enters the sag must be passed through the inlet. Total or partial clogging of inlets in these locations can result in hazardous ponded conditions. Curb-opening inlets are recommended for use at these locations.

Curb-opening inlets are usually preferred to grate inlets in most parking lots because of their superior debris handling capabilities.

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Inlet Efficiency on Continuous Grades

Inlet design depends on inlet interception capacity, Q_i, which the flow intercepted by an inlet under a given set of conditions. The efficiency of an inlet, E, is the percent of total flow that the inlet will intercept for those conditions, and can be expressed in mathematical form as:

$$E = Q_i/Q \quad \text{Eq. (9)}$$

where:

E = inlet efficiency
Q_i = intercepted flow in cubic feet per second (cfs)
Q = total gutter flow in cubic feet per second (cfs)

The efficiency of an inlet changes with changes in cross slope, longitudinal slope, total gutter flow, and to a lesser extent, pavement roughness.

Curb-Opening Inlets on Grade

Curb-opening inlets should not be too high for safety reasons. Typical curb opening heights are between 4 to 6 inches. The length of the curb-opening inlet required for total interception of gutter flow on a pavement section with a uniform cross slope can be expressed by the following equation:

$$L_T = 0.6\, Q^{0.42}\, S_L^{0.3}\, (1/(n\, S_X))^{0.6} \quad \text{Eq. (10)}$$

where:

L_T = curb opening length, in feet, required to intercept 100% of the gutter flow
Q = gutter flow in cubic feet per second
S_L = longitudinal slope in ft/ft
S_X = cross slope in ft/ft
n = Manning's roughness coefficient (see Table 3)

The efficiency of curb-opening inlets shorter than L_T is expressed as:

$$E = 1 - (1 - L/L_T)^{1.8} \quad \text{Eq. (11)}$$

where:

L = curb opening length in feet

Grate Inlets in Sag Locations

A grate inlet in a sag location operates as a weir to depths dependent on the size of the grate and as an orifice at greater depths. Grates of larger dimension will operate as weirs to greater depths than smaller grates.

The interception capacity of grate inlets operating as weirs is:

$$Q_i = C_w\, P\, d^{1.5} \quad \text{Eq. (12)}$$

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where:

Q_i = interception capacity in cubic feet per second
C_w = 3.0 (weir coefficient)
P = length of the perimeter of the grate in feet, disregarding the side against the curb
d = average flow depth in feet across the grate

The interception capacity of grate inlets operating as orifices is:

$$Q_i = C_o A_g (2 g d)^{0.5} \quad \text{Eq. (13)}$$

Where:

Q_i = interception capacity in cubic feet per second
C_o = 0.67 (orifice coefficient)
A_g = clear opening area of the grate in square feet
g = 32.16 ft/s^2 (gravitational constant)
d = average flow depth in feet across the grate

The clear opening area A_g of a grate can be calculated or obtained from the manufacturer's catalog.

Curb-Opening Inlets in Sag Locations

The interception capacity of a curb-opening inlet in a sag depends on water depth at the curb, the length of the curb opening, and the height of the curb opening. Curb-opening inlets in sag locations of a parking lot operate as weirs under low head conditions and as orifices at greater depths. Orifice flow begins at depths dependent on the curb opening height.

The weir location for a curb-opening inlet that is not depressed is at the lip of the curb opening, and its length is equal to that of the inlet. The equation for the interception capacity of a depressed curb-opening inlet operating as a weir is:

$$Q_i = C_w (L + 1.8 W) d^{1.5} \quad \text{Eq. (14)}$$

where:

Q_i = interception capacity in cubic feet per second
C_w = 2.3 (weir coefficient)
L = length of curb opening in feet
W = lateral width of depression in feet
d = flow depth at curb measured from the normal cross slope in feet

For a curb-opening inlet without depression, the weir equation can be simplified as

$$Q_i = C_w L d^{1.5} \quad \text{Eq. (15)}$$

where:

Q_i = interception capacity in cubic feet per second
C_w = 3.0 (weir coefficient)
L = length of curb opening in feet
d = flow depth at curb measured from the normal cross slope in feet

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Note: the weir coefficient C_w in Eq. (13) is greater than the one in Eq. (14). Eq. (15) should be used for all depressed cub-opening inlet with length greater than 12 feet.

Curb-opening inlets operate as orifices at depths greater than approximately 1.4 times the opening height. The interception capacity of depressed and un-depressed curb-opening inlets operating as orifices is:

$$Q_i = C_o\, h\, L\, (2\, g\, d_o)^{0.5} \qquad \text{Eq. (16)}$$

Where:

Q_i = interception capacity in cubic feet per second
C_o = 0.67 (orifice coefficient)
h = height of curb-opening orifice, in feet
L = length of orifice opening, in feet
g = 32.16 ft/s^2 (gravitational constant)
d_o = depth at lip of curb opening, in feet

14. Inlet Locations

The locations of inlets in a parking lot are relatively easy to determine on a layout plan if a site contour map is available. There are a number of locations where inlets may be necessary with little regard to contributing drainage area. Examples of such locations are all low points in the gutter grade or inlet spacing on continuous grades.

For a continuous slope, the designer may establish the uniform design spacing between inlets of a given design if the drainage area consists of pavement only or has reasonably uniform runoff characteristics and is rectangular in shape. In this case, the time of concentration is assumed to be the same for all inlets.

Two Curb-Opening Inlets at Low Spots

15. Stormwater Detention/Retention

Land development activities, including the construction of streets and parking lots, convert natural pervious areas to impervious and otherwise altered surfaces. These activities cause an increased volume of runoff because natural infiltration and depression storage are reduced. Many local governments have established specific design criteria for allowable quantity and quality of stormwater discharges for new developments. Some jurisdictions also require that flow volume be controlled to pre-development levels as well. To meet these regulatory requirements, storm drainage systems will usually require detention or retention basins, and/or other best management practices for the control of discharge quantity and quality.

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The temporary storage or detention/retention of excess stormwater runoff as a means of controlling the quantity and quality of stormwater releases is a fundamental principle in stormwater management and a necessary drainage element of a large parking lot. The storage of stormwater can reduce the downstream flooding, soil erosion, sedimentation, and water pollution. Detention/retention facilities also have been used to reduce the costs of large storm drainage systems by reducing the required size for downstream storm drain conveyance systems. The reduced post-development runoff hydrograph is typically designed so that the peak flow is equal to or less than the pre-developed runoff peak flow rate.

A Dry Pond with Storm Sewer

A detailed discussion of stormwater detention/retention facility design is beyond the scope of this course.

16. Design Examples

Example 1

Compute the rainfall intensity of a 2-year, 5-minute storm event for a parking lot in Washington, DC, based on the NOAA Technical Memorandum No. 35.

Solution:

Step 1. Find the rainfall amount for the 2-year, 5 minute precipitation in Figure 6 of the reference.
Rainfall amount in 5-minutes = 0.46 inches

Step 2: Calculate the rainfall intensity, which is equal to the hourly rainfall amount.
$I = 0.46 \times (60/5) = 5.5$ *inch/hour*

Example 2

Compute the time of concentration for an asphalt parking lot of a size 200 feet (length) x 150 feet (width). The longitudinal slope along the length is 2% and the transverse slope 1%. A continuous gutter is built along the length of the parking lot and feeds into a curb-opening inlet at the end. Assume a rainfall intensity of 2 inches per hour.

Solution:

Step 1. Compute the sheet flow travel time using Eq. (4).
$T_{t1} = (0.933/2^{0.4})(0.011 \times 150/0.01^{0.5})^{0.6}$
$= 3.8$ *minutes*

Step 2. Computer the shallow concentrated flow travel time using Eq. (6).
$V = 3.28 \times 0.619 \times 2.0^{0.5}$
$= 2.871$ *feet/second*

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T_{t2} = L/V = 200/2.871
= 70 seconds
= 1.2 minutes

Step 3. Compute the time of concentration using Eq. (5).
$T_c = \sum T_{ti}$ = 3.8 + 1.2 = 5 minutes

Example 3

Compute the peak runoff for the problem in Example 2 assuming that the rainfall intensity used is based on a 2-year, 5-minute storm event.

Solution:

Step 1. Determine the runoff coefficient using Table 2.
C = 0.9 for paved parking lots

Step 2. Compute the rainfall intensity.
Because the assumed duration for the rainfall intensity is equal to the time of concentration calculated for the selected storm event, the rainfall intensity based on the assumed duration can be directly used in Eq. (1) (no iteration is needed).

Step 3. Calculate the drainage area.

A = 200' x 150'/ 43,560
= 0.69 ac.

Step 4. Compute the peak runoff using Eq. (1).

Q = CIA
= 0.9x2.0x0.69
= 1.24 cfs

Example 4

Compute the peak runoff for a concrete parking lot of a size 200 feet (length) x 100 feet (width) in Richmond, Virginia, using the IDF curve given in Figure 2. The longitudinal slope is 1% (along the length) and the transverse slope 2%. A continuous concrete gutter is built along the width of the parking lot and feeds into a curb-opening inlet at the end. Assuming that the local regulation requires the design for a 10-year storm event.

Solution:

Step 1. An iterative approach has to be used for the solution of this problem because the rainfall intensity I depends on the time of concentration. First, try a time of concentration of 10 minutes and read from the IDF curve in Figure 2 an approximate intensity of 6.0 in/hr.

Step 2. Now use Eq. (4) to see how good the 10 minute estimate was.
$T_{t1} = (0.933/6.0^{0.4})(0.012x200/0.02^{0.5})^{0.6}$
= 2.5 minutes

Step 3. Determine the new I from the IDF curve.
I = 7.0 in/hr for a duration less than 5 minutes

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Step 4. Re-calculate the time of concentration.

$T_{t1} = (0.933/7.0^{0.4})(0.011x200/0.02^{0.5})^{0.6}$
$= 2.3$ *minutes*

Step 5. Use I = 7.0 in/hr because the time of concentration is less than 5 minutes in two consecutive iterations.

Step 6. Determine the runoff coefficient using Table 2.

C = 0.9 for paved parking lots

Step 7. Calculate the drainage area.

$A = 200' \times 100' / 43,560$
$= 0.49$ *ac.*

Step 8. Compute the peak runoff using Eq. 1.

$Q = CIA$
$= 0.9x7.0x0.49$
$= 2.9$ *cfs*

Example 5

Compute the flow depth for Example 4 assuming a uniform gutter section.

Solution:

Step 1. Based on the data given in Example 4:

$S_X = 0.01$
$S_L = 0.02$
$Q = 2.9$ *cfs*
$n = 0.012$

Step 2. Calculate spread using Eq.(7).

$T = ((1.79Qn/(S_X^{1.67} S_L^{0.5}))^{0.375}$
$= ((1.79x2.9x0.012/(0.01^{1.67} \times 0.02^{0.5}))^{0.375}$
$= 13.2$ *feet*

Step 3. Calculate flow depth using Eq.(8).

$d = T S_X$
$= 13.2 \times 0.01$
$= 0.132$ *feet*

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Example 6

Find the interception capacity for a 10' long curb opening inlet on grade with the following characteristics:

$S_X = 0.02$
$S_L = 0.01$
$Q = 2.9$ cfs
$n = 0.012$

Solution:

Step 1. Determine the length of curb opening required for total interception of gutter flow using Eq. (10).

$L_T = 0.6\ Q^{0.42}\ S_L^{0.3}\ (1/(n\ S_X))^{0.6}$
$= 0.6x2.9^{0.42} \times 0.01^{0.3}\ (1/(0.012x0.02))^{0.6}$
$= 35$ feet

Step 2. Calculate the curb opening efficiency using Eq. (11).

$L/L_T = 10/35 = 0.29$

$E = 1 - (1 - L/L_T)^{1.8}$
$= 1 - (1 - 0.29)^{1.8}$
$=0.46$

Step 3. Calculate the interception capacity using Eq. (9).

$Q_i = EQ = 0.46 \times 2.9 = 1.334$ cfs

Example 7

Find the interception capacity for a 10' long x 6" high un-depressed curb opening inlet in a sag with the following characteristics:

$S_X = 0.02$
$S_L = 0.01$
$T = 9.7$ feet

Solution:

Step 1. Calculate flow depth using Eq. (8).

$d = T\ S_X$
$= 9.7 \times 0.02$
$= 0.194$ feet
$= 2.3$ inches < 6 inches → Inlet operates as a weir.

Step 2. Calculate the interception capacity of the curb opening inlet using Eq. (15).

$Q_i = C_w\ L\ d^{1.5}$
$= 3.0 \times 10 \times 0.194^{1.5}$
$= 2.56$ cfs

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17. Other Considerations

To prevent stormwater from becoming a hazard to the public and causing water damage to the surrounding properties, a designer should also consider the following aspects of the drainage design for parking lots:

A. Drainage connection and path. If adjacent to a street, a parking lot drainage system can connect to the street drainage system using man-made ditches for the economic reason. Where an island prevents the natural drainage, it is recommended to split the island to create a path for water passage.

Connecting Two Drainage Systems

B. Maximum depth of standing water in a parking lot. It is recommended that the depth of standing water be less than 12" at any point in a parking lot, and that no more than 25% of the entire number of parking spaces be inundated by a parking lot pond during the design storm. Top of structures designed to contain the ponding should be at least 4" above the maximum water level.

C. Locations of parking lot ponds. It is recommended that no ponding occur within the primary ingress/egress portions of a site, and that a minimum 20-foot wide emergency vehicle lane to the buildings remain unflooded at maximum water level for the design storm. No parking lot ponding should occur for parking spaces under buildings.

Splitting an Island for Water Passage

D. Slopes in a parking lot. In general, a 2% cross slope is a desirable practical slope. Slopes of more than 5% are not recommended for the purpose of vehicle movement. Where ponding can occur, pavement slope should not be less than 1%.

Terminating an Island next to a Curb

Course Summary

State regulations often require that all storm drains and facilities be designed by a licensed professional engineer. Therefore, it is imperative for all professionals who are involved in building and road construction projects to have a basic understanding of the fundamental principles of stormwater drainage design.

- End -

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NOAA Technical Memorandum NWS HYDRO-35

FIVE- TO 60-MINUTE PRECIPITATION FREQUENCY FOR THE EASTERN AND CENTRAL UNITED STATES

Silver Spring, Md.
June 1977

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / National Weather Service

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NOAA Technical Memoranda

NWS HYDRO 12 Direct Search Optimization in Mathematical Modeling and a Watershed Model Application. John C. Monro, April 1971. (COM-71-00616)

NWS HYDRO 13 Time Distribution of Precipitation in 4- to 10-Day Storms--Ohio River Basin. John F. Miller and Ralph H. Frederick, May 1972. (COM-72-11139)

NWS HYDRO 14 National Weather Service River Forecast System Forecast Procedures. December, 1972. COM-73-10517)

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FIVE-TO 60-MINUTE PRECIPITATION FREQUENCY FOR THE EASTERN AND CENTRAL UNITED STATES

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ABSTRACT. Precipitation-frequency values for durations of 5, 15, and 60 minutes at return periods of 2 and 100 years are presented in map form for 37 states from North Dakota to Texas and eastward. Equations are given to derive 10- and 30-min values from the maps. Equations are also given to compute values for selected return periods between 2 and 100 years.

The basic input data to the study are the maximum annual precipitation values for 5, 10, 15, 30, and 60 minutes at about 200 stations and the maximum annual 1-hr events at about 1900 stations with recording rain gages. Computer space-averaging techniques were used for interstation interpolation.

INTRODUCTION

The growing environmental awareness of the past few years has increased the demand for hydrologic planning and design for small area drainages having very short times of concentration. Examples of such drainage areas are cattle feedlots and urban shopping and parking areas. Hydrologic design practice and legal standards are generally expressed in terms of control of storm flow of specified frequency of recurrence. Precipitation frequencies for short durations are an essential input to evaluating the runoff frequencies from small drainage areas.

Since 1961, U. S. Weather Bureau Technical Paper No. 40 (Hershfield 1961), abbreviated TP-40, has been the standard for precipitation-frequency values for durations from 5 minutes to 24 hours over the Eastern United States. For durations of less than 1 hour, the TP-40 values are derived by using nationwide, return-period independent ratios of shorter duration values to 1-hr values. While these average ratios are valid in many specific sections of the country, they have an observed, describable geographic pattern. It has also been found that the ratios vary with return period.

The present publication analyzes the above variations and derives new 5- to 60-min precipitation frequencies for the 37 states, North Dakota to Texas and eastward. These are presented in the form of maps for the 5-, 15- and 60-min durations at the 2- and 100-yr return periods, together with equations and nomograms for intraduration and intrareturn period interpolations.

This report is the latest in the precipitation-frequency literature for the United States that began in the 1930's when David L. Yarnell (1935) first published generalized precipitation-frequency maps for durations of 5 minutes to 24 hours at return periods of 2 to 100 years. Since 1955, the National Weather Service (NWS, then the Weather Bureau) and the Soil Conservation Service, U. S. Department of Agriculture, have been engaged in a cooperative effort to define the depth-area-duration precipitation-frequency regime of the entire United States. This effort is reviewed in the introduction to the several volumes of NOAA Atlas 2, "Precipitation-Frequency Atlas of the Western United States" (Miller et al. 1973).

BASIC DATA

N-MINUTE DATA

The data for durations from 5 to 60 minutes are from recording rain gages at nearly 200 first-order NWS stations (fig. 1). The period of record averages nearly 60 years. The measurements are mostly from tipping bucket gages of 12-in. (305-mm) diameter which mark each 0.01 in. (0.25 mm) of rainfall as a step on a recording strip chart (Weather Bureau 1963). Rainfalls for 5, 10, 15, 30 and 60 minutes that exceed certain intensity thresholds have been tabulated for these stations since 1936 (1943 for 15-min durations). These data are published in U. S. Meteorological Yearbook (Weather Bureau 1936-49) and Climatological Data, National Summary, Annual (Environmental Data Service 1950-72). For the present study, annual maxima for each duration at each station were abstracted from these sources. For the period prior to 1936 (1943 for 15-min values), maximum annual values for the selected durations were transcribed manually several years ago from station records at each field station (or repository for stations closed), in response to a request from the office of the authors.

HOURLY DATA

A network of recording rain gages has been maintained by the NWS, with cooperation from many agencies, since the early 1940s. Data from about 1,900 of these stations in the study area were analyzed for this project, (fig. 1). The basic rain gage was originally an 8-in. (203-mm) diameter weighing rain gage in which the weight of precipitation collected in a bucket guides a pen arm recording on a clock-driven strip chart. During recent years, some of these gages have been replaced by the newer Fischer & Porter gage which records the accumulated precipitation by 0.10 in. (2.5 mm) increments at 15-min intervals on punched paper tape.

Hourly precipitation for clock hours (1:00 a.m. to 2:00 a.m., 2:00 a.m. to 3:00 a.m., etc.) is abstracted from the charts of these gages and published in the Hydrologic Bulletin (Weather Bureau 1940-48), Climatological Data (Weather Bureau 1948-51), and Hourly Precipitation Data (Environmental Data Service 1951-72). The National Climatic Center, Environmental Data Service, NOAA, which is responsible for abstracting and publishing the data, began current punching of the data on cards in 1948 and later transferred the information to magentic tape. This clock-hour data for 1948-72 is available on magnetic tape. Maximum annual clock-hour precipitation magnitudes

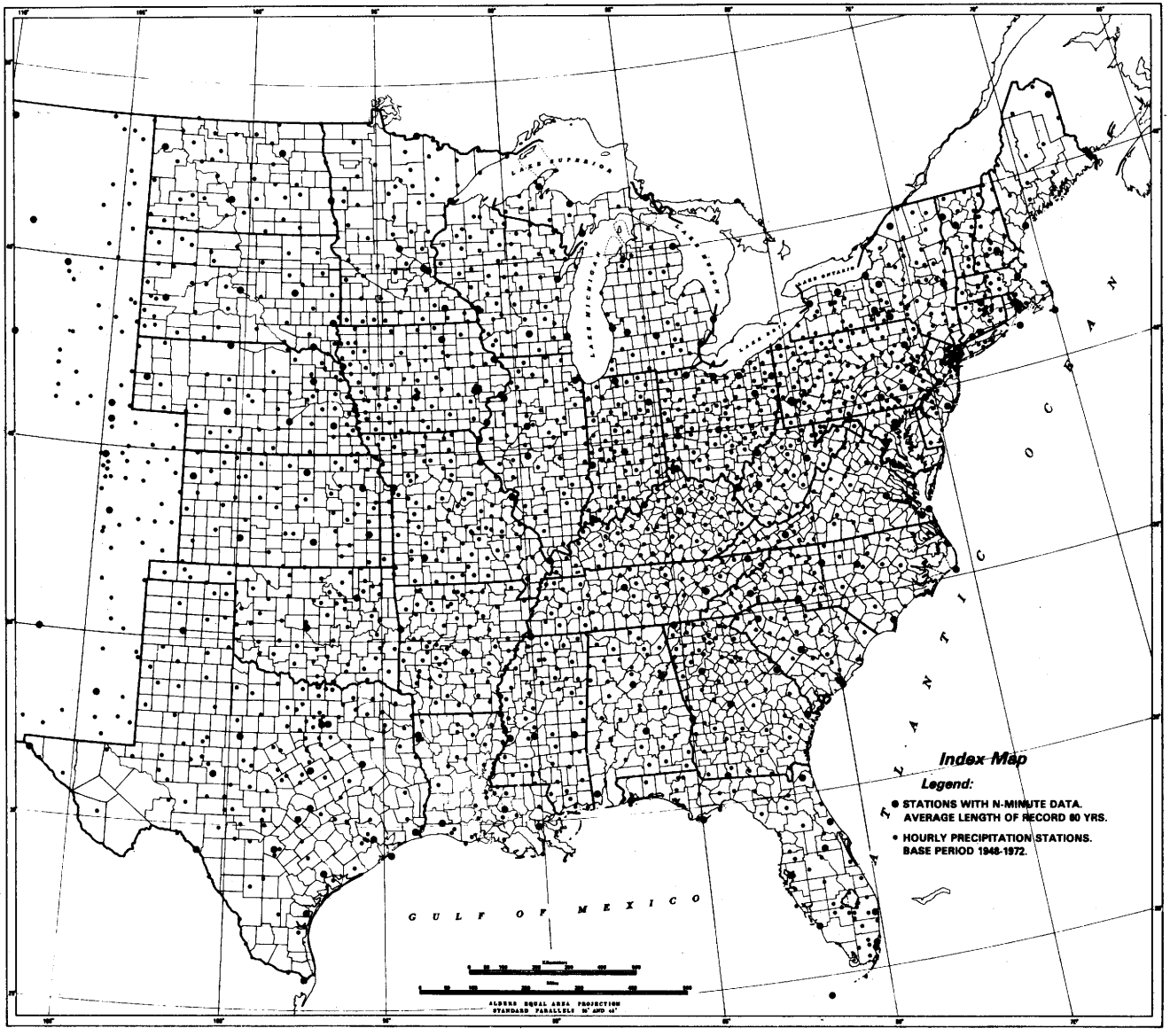

Figure 1.--Station index map.

extracted from this data set differ from, and may be smaller than, maximum 60-min magnitudes from the preceding data set. Statistical conversion of clock-hour precipitation frequencies to 60-min frequencies is discussed later. Stations with 15 or more years of data during the 1948-72 25-year period were processed. Many stations had a complete 25-yr record, most had more than 20 years and only a few as little as 15 years.

Canadian Data

The Canadian Atmospheric Environment Service (AES) recently prepared frequency distributions of short-duration precipitation (Atmospheric Environment Service, Canada, 1974). AES methods are similar to those used in this study. There are about 20 Canadian stations within about 100 miles of the United States border with frequency distributions of 5- to 60-min rainfalls based on records of 15 years or longer, and many additional stations with frequencies based on shorter records. The Canadian frequency values were used in the analysis without additional testing or investigation, giving the most weight to the longer record stations.

DATA PROCESSING AND TESTING

Computer Processing of Data Tapes

The data tapes containing hourly precipitation values for the period 1948 through 1972 were computer analyzed to select the maximum hourly value for each month for each station/year. From these monthly values, the computer selected the largest as the maximum hourly value for each year. During processing, the computer also tabulated the number of hours each month listed as missing and the number which contained accumulated amounts. All data (maximum monthly and annual values and number of missing or accumulated values) were listed on the computer output and checked by technicians. Errors sought included: (1) mispunched data still on the tapes and (2) a maximum value chosen from an incomplete station year. The inspected data sets used in the analysis are believed to be as reasonable and correct as can be expected when dealing with data sets of this magnitude.

Frequency Analysis

There are two methods of selecting data for analysis of extreme values. The first method selects the largest single event that occurred within each year of record. For this annual series, the year may be calendar year, water year, or any other consecutive 12-mo period. The second method recognizes that large amounts are not calendar bound and that more than one large event may occur within the time unit used as a year. In the latter, the partial-duration series, all values above a base (frequently the smallest maximum annual event) are used regardless of how many occur in the same year; the only restriction is that independence of individual events be maintained. The partial-duration series is not a complete series (Chow 1950) and thus is difficult to handle mathematically.

One requirement in the preparation of this publication is that the results be expressed in terms of partial-duration frequencies. To avoid the complexities of handling the partial-duration series, the annual series data for calendar years were collected and analyzed; and the resulting statistics were transformed to partial-duration statistics.

Conversion Factors Between Annual and Partial-Duration Series

Table 1 gives the empirical factors used to multiply annual series values to obtain the equivalent partial-duration series values. It is based on a sample of about 200 geographically well-distributed first-order NWS stations (Hershfield 1961). The factors shown in table 1 are reciprocals of the factors in table 2 of TP-40.

Table 1.--Factors for converting annual series to equivalent partial-duration series

Return period (yr)	Factor
2	1.13
5	1.04
10	1.01
25	1.00
50	1.00
100	1.00

The rainfall frequency maps in this publication are for partial duration occurrences, and are based on analysis of station annual series, adjusted by factors from table 1.

Frequency Distribution

The Fisher-Tippett Type I frequency distribution is used in this study. The fitting procedure is that developed by Gumbel (1958). This distribution and fitting procedure were used by the NWS in previous studies of short-duration precipitation values (U. S. Weather Bureau 1953, 1954a, 1954b, 1955a, 1955b, 1956, 1957-60, Hershfield 1961, and Miller et al. 1973). Studies by Hershfield and Kohler (1960) and Hershfield (1962) have demonstrated the applicability of this distribution to precipitation extremes. Recently, in conjunction with another study (Miller et al. 1973), a comparison of the values obtained by the Gumbel technique, the Lieblein fitting of the Fisher-Tippett Type I, the Pearson Type III, and the Log Pearson Type III distributions was performed. The data were for durations of 1, 6, and 24 hours. Several thousand station years of data were examined by determining the percent of observations that equaled or exceeded the calculated values for certain return periods. Results of the four computation procedures did not differ significantly. Therefore, there is no reason to use another technique; and by continuing the Gumbel fitting procedure, the study is compatable with previous studies.

The Gumbel procedure uses the method of moments. The 2-yr value measures the first moment, or central tendency. The relation of the 2-yr to the 100-yr value is a measure of the second moment, or dispersion. Values for other return periods can be derived mathematically from the 2- and 100-yr rainfalls.

DATA TESTING

Test for Climatological Trend

The aim of this study is to depict the frequency of N-min precipitation values in a population extending over a long period of time. A large share of the data is from a 25-yr record, but longer records are also used. To test the hypothesis that there was no recent climatological trend that would make different record lengths incompatible, 68 geographically well-distributed first-order NWS stations within the study area were selected. These stations had complete and concurrent records of maximum annual 5- and 60-min rainfalls for the 50-yr period 1923-72.

For the 68 stations, the data sample was divided into two 25-yr segments, 1923-47 and 1948-72, and means and standard deviation for the 2- and 100-yr 5- and 60-min values were computed. For each duration a t-test of the two

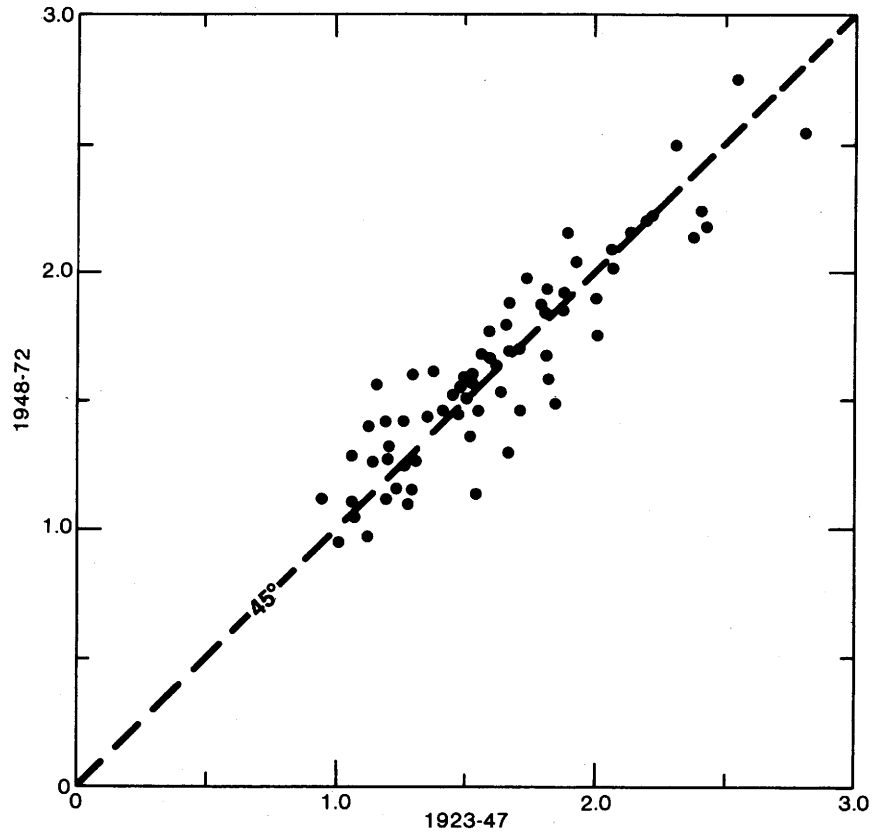

Figure 2.--Comparison of 2-yr 60-min precipitation values for 1923-47 and 1948-72, at 68 stations.

sample means (one mean for each data period) indicated a probability greater than 0.90 that samples from the two periods were from the same populations at the 5- and 60-min durations. Figure 2 is a plot of the 2-yr 60-min values from the two different record periods.

Adjustment of Clock-Hour Data to 60-Min Values

A factor to adjust statistical 1-hr values to 60-min values was determined empirically by NWS several years ago (Weather Bureau 1953, 1954a). It was found that, on the average, the N-yr 60-min value derived from the series of annual maximum 60-min events is 1.13 as great as the N-yr clock-hour value estimated from the series of annual maximum clock-hour values. This does not say that an annual maximum clock-hour event multiplied by 1.13 will give the maximum annual 60-min event in a particular case. This adjustment applies only to the results of a statistical analysis of a series of events.

Using probability theory, Weiss (1964) confirmed this adjustment. Nonetheless, an investigation was undertaken to insure that the adjustment of clock-hour to 60-min data, as previously used, was applicable to the present data set. Thirty first-order NWS stations, geographically well distributed over the study area and possessing complete and concurrent records of both maximum clock-hour and maximum 60-min precipitation for the period 1948-72, were chosen as a data sample. The series of annual maxima of the two types for each station was analyzed using the Gumbel fitting of the Fisher-Tippett Type I distribution. The ratios of the 60-min/1-hr values at the 2- and 100-yr return periods both confirmed the 1.13 factor.

The geographical variability of the adjustment factor, if any, was also investigated. A plot of the individual station ratios of the 2- and 100-yr return period clock-hour to 60-min values showed no discernible pattern. The 1.13 factor to adjust clock-hour values to comparable 60-min values was therefore adopted and used throughout this study.

ISOPLUVIAL MAPS

METHODOLOGY

The project objective is to define 2- to 100-yr precipitation at durations from 5 to 60 minutes. The usual approach to such a task is to draw maps for the enveloping durations and return periods and mathematically compute values for intermediate durations and return periods (e.g., Miller et al. 1973). For the present study, this would have meant drawing 5- and 60-min maps for the 2- and 100-yr return periods and developing equations to estimate 10-, 15- and 30-min values. To investigate the feasibility of this, data for the stations having N-min data were grouped geographically. Duration formulas for each such group for return periods of 2 and 100 years were computed in the following form:

$$R_n = C_n\ (R_{m2}) + (1-C_n)\ (R_{m1}) \qquad (1)$$

where R_n is the required frequency value for N minutes, R_{m1} and R_{m2} are mapped values for a lesser and longer duration, and C_n is the interpolation

constant. C_n was found to vary both geographically and by return period when the 10-, 15- and 30-min values were related to the 5- and 60-min values. For instance, interpolating the 15-min values between 5 and 60 minutes showed C_n ranging from 0.35 to 0.43 in different regions and for different return periods. 15-min values computed using an average C_n and analyzed 5- and 60-min values differed by over 10 percent from values obtained by statistical analysis of the station data. However, by interpolating 10-min between 5- and 15-min and 30-min between 15- and 60-min values, C_n stabilized with negligible geographic and return period differences. Thus, the decision was made to prepare the six maps named in the introduction.

In this study, the ratio of number of stations providing hourly values to N-minute stations is about 10 to 1 and precipitation-frequency patterns can be most accurately defined at the 60-min duration. Similarly, the period of record is several multiples of two years, but only a fraction of 100 years. Frequency pattern depiction is most accurate at the 2-yr return period. The 2-yr 60-min isopluvial pattern therefore was constructed first and used as a guide in constructing maps for longer return periods and for shorter durations.

Space-Averaging of Precipitation-Frequency Values

Individual station frequency values are necessarily derived from a small sample of the entire precipitation population. In areas without strong orographic influences on precipitation, as in most of the study area, the occurrence of heavy rainfall has a random component and the computed frequencies at individual stations are variable due to sampling error. The random component is especially pronounced at the short durations with which this study is concerned. Some stations are expected to experience more extreme events during the data period than others in the same climatic regime. For these reasons, all precipitation-frequency maps are constructed through use of space-averaging techniques. The techniques may be either computationally explicit or implicit in the drawing of the isopluvials by an analyst.

In this project, computerized space-averaging (or smoothing) techniques were adapted from those used by the National Meteorological Center (NMC) of NWS for the objective analysis of a variety of weather maps, and from some experimental work in analyzing storm isohyets. The NMC methods described by Cressman (1959) are designed to eliminate erroneous values and to compute a smoothed data field closely fitting widely spaced observed data. Isohyetal analysis, using techniques similar to those described by Barnes (1963) and Greene (1971), is designed to produce a smoothed data field still retaining detailed features of individual storm cells. The problem of precipitation-frequency analysis in an area free of marked orographic influences is somewhat different from both these problems. The climatological precipitation-frequency field sought is smoother than individual storm isohyets and, compared with the NMC problem, is based on a greater density of data points. Both differences suggest stronger areal averaging.

The smoothing program employed the following steps to estimate precipitation-frequency values at grid points spaced at each half degree of latitude and longitude:

1. Precipitation-frequency values from all stations within a given latitude-longitude rectangle surrounding each grid point were averaged, weighted by a function of distance from the grid point, giving the first estimate of the grid point value, $GP_{N=1}$:

$$GP_{N=1} = \sum_{j=1}^{k} PF_j W_j \Big/ \sum_{j=1}^{k} W_j \tag{2}$$

where k is the number of stations within the chosen latitude-longitude rectangle, PF_j a station precipitation frequency value, and W_j a weight for that station derived from a distance weighting function.

2. The first estimates at the four grid points surrounding each station are in turn used in double linear interpolation to estimate a new value at each station, PF_{ADJ}:

$$PF_{ADJ} = \left[GP_{NW}(1 - DI) + GP_{NE}\ DI\right]\ (1 - DJ) + \left[GP_{SW}(1 - DI) + GP_{SE}\ DI\right]DJ \tag{3}$$

GP_{NW}, GP_{NE}, GP_{SW}, and GP_{SE} are the closest grid points northwest, northeast, southwest, and southeast of a station and DI and DJ delineate station location in fractional latitude and longitude grid intervals.

The difference is computed between the original station value and this interpolated value:

$$\Delta PF = PF - PF_{ADJ} \tag{4}$$

3. Each grid point first estimate from step 1 is adjusted by the average of the differences from step 2, weighted by the distance function, for all stations within a given distance (called the scan radius) of the grid point:

$$GP_N = GP_{N-1} + \sum_{j=1}^{k} \Delta PF_j\ W_j \Big/ \sum_{j=1}^{k} W_j \tag{5}$$

GP_N is the Nth grid point iteration and ΔPF_j and W_j are precipitation frequency difference from (4) and distance weighting factors for k number of stations within a given scan radius.

Steps 2 and 3 are repeated to progressively adjust the grid point estimates.

The degree of smoothing of a data field by this technique is a decision of the analyst exercised through the choice of constants and weighting functions and based on a combination of professional judgment and any independent statistical evidence, and is not inherent in the objective smoothing technique. The role of the objective technique is to carry out the subjectively determined degree of smoothing in a uniform, systematic and economical manner. The scan radius, number of iterations, and form of weighting function determine the degree of smoothing.

Using a test area in the midwest, the smoothing program was run on 60-min 2-yr data with various scan radii, number of repeats of steps 2 and 3, and linear and exponential weighting functions. In all cases the first grid point estimate (step 1) was the weighted average of the station values in a 2° latitude X 2° longitude box centered on the grid point. A 2° latitude and longitude scan radius (defining an ellipse with longest axis north-south) 3 iterations, and a linear weighting function ranging from a weight of 1.0 at zero distance to zero at the scan radius, produced the degree of smoothing illustrated in figure 3. This is judged appropriate to the 60-min data and the factors indicated were adopted. Additional iterations after the third in the test runs produced little additional change in the variance of differences between original station values and interpolated values.

Table 2 illustrates the frequency distribution of the number of stations which were used for estimation of the individual grid point values in step 3. The grid points with the fewest influencing stations are, naturally, located along the border of the study area and in such protrusions as the Florida peninsula, Maine and West Texas. Grid point values in such areas tend to be overly influenced by values inward of the grid field with no opportunity for influence from a gradient outside the grid field. In drawing lines in such areas, the analyst kept this in mind and made adjustments to compensate for it.

Table 2.--Frequency of number of station values used to estimate grid point values for 60 minutes.

No. stations	No. grid point	No. stations	No. grid point
0-9	38	100-109	189
10-19	132	110-119	136
20-29	218	120-129	93
30-39	283	130-139	43
40-49	334	140-149	57
50-59	220	150-159	43
60-69	131	160-169	30
70-79	161	170-179	23
80-89	187	180-189	5
90-99	196		

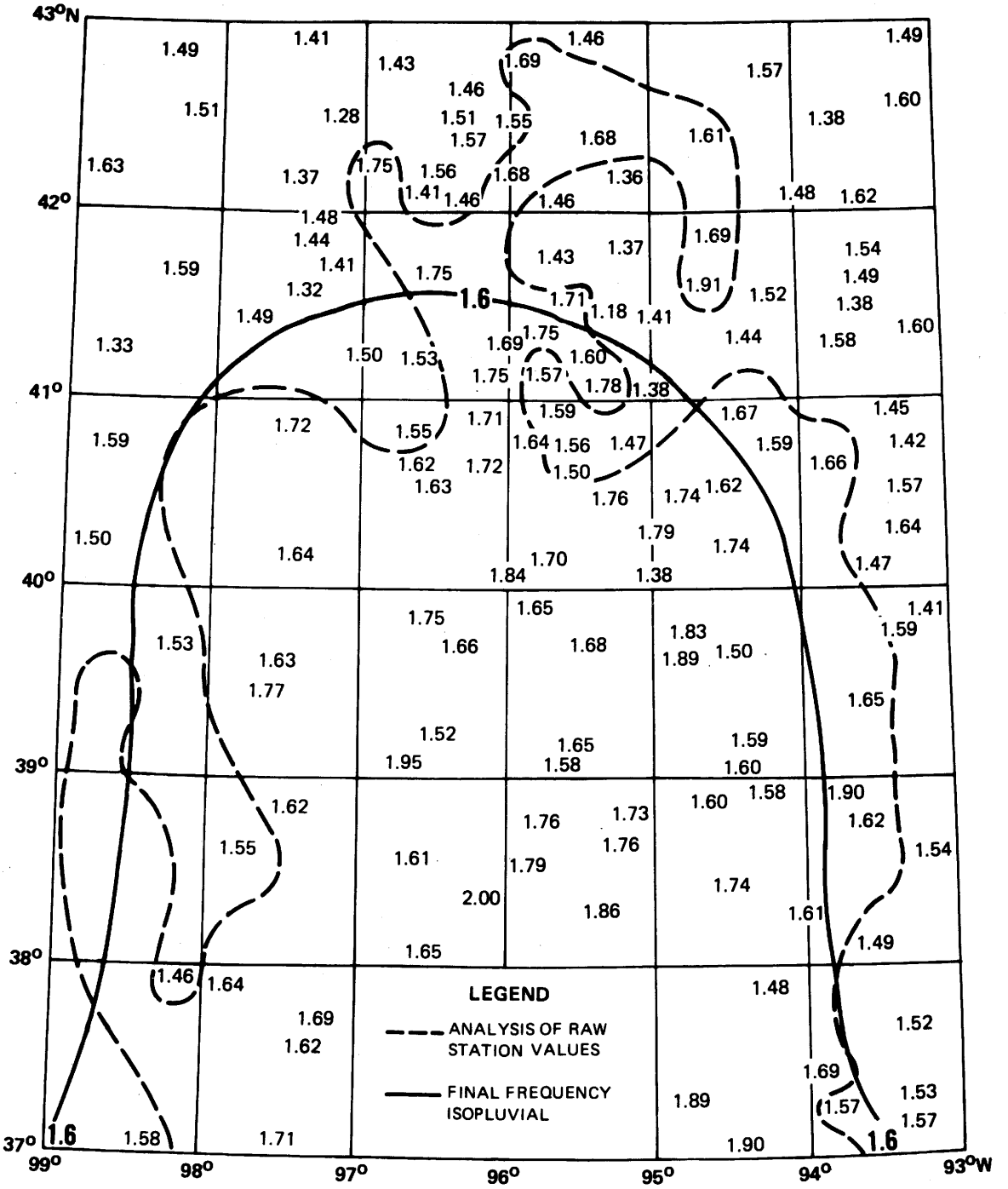

Figure 3.--Example of space-averaging of 2-yr 60-min precipitation values.

Because data for the 5- and 15-min durations are one tenth as dense as data for 60 minutes, the first estimate for these durations was made using all stations within 2° of latitude or longitude of the grid point and the adjustments using 4° scan radius. The first estimates plus three iterations was continued. In practice, this means that despite using a scan area four times as large as that used with 60-min data the number of stations bearing on a given data point is only about 40 percent of the number shown in table 2. This is not, however, a serious problem since areal variability decreases as duration decreases: i.e., the data field for the 5-min duration shows less variation than does the 60-min data field. To illustrate this point, four data sets consisting of all 2- and 100-yr 5-min values and 2- and 100-yr 60-min values in the area bounded by the Gulf Coast on the south, 45°N on the north, and 85°W and 95°W on the east and west sides were analyzed. At the 5-min duration the coefficient of variation of the 2-yr data set was 0.126 and at the 100-yr return period it was 0.121. The corresponding coefficients of variation for 60 minutes were 0.245 and 0.207.

Map Construction

2-Yr 60-Min (Fig. 4)

The individual station frequency values, calculated as previously described, were plotted on a map. Most of these are derived from maximum annual clock-hour values adjusted to 60 minutes by the 1.13 factor. Also plotted on the half-degree latitude-longitude grid system were the values obtained from the computer smoothing program. The final precipitation-frequency isopluvials were derived by small additional manual smoothing of the grid point values in areas with little or no orographic influence, with constant concurrent reference to the unsmoothed station data. In the vicinity of the Appalachian Mountains, there are believed to be substantial orographic influences on precipitation frequency at a scale finer than the station density available for this study. In NOAA Atlas 2 (Miller et al. 1973), this characteristic was recognized in the 11 Western States by developing statistical relations between precipitation-frequency and topographic parameters. The latter can be defined by elevations read from topographic maps in whatever detail is relevant. However, NOAA Atlas 2 was developed for longer durations (6 and 24 hours) than the present study and for 24 hours was able to use the more numerous data available from the NWS network of nonrecording rain gages to estimate isopluvial variations. The development of similar statistical relations for the Appalachians was beyond the scope of the present study. The precipitation-frequency isopluvials in the mountainous regions in the Eastern United States were shaped subjectively to the topography depicted on 1:1,000,000 scale World Aeronautical Charts with some guidance from valley vs. higher elevation data at a few places.

Isopluvial variations due to topographic influences are probably present in the Black Hills region and in the vicinity of the Ozark Mountains. The station precipitation-frequency data were closely scrutinized for such influences in these areas but no consistent, explainable variations could be detected and no nearby valley vs. mountain contrasts were found in the available station data. Thus, the final isopluvials in the Black Hills and Ozark Mountains are based on station data without regard to topography.

In addition, the isopluvials were tied into values calculated from or implied by the precipitation-frequency maps for Montana, Wyoming, Colorado, and New Mexico in NOAA Atlas 2 and the frequency values at nearby Canadian stations.

100-Yr 60-Min (Fig. 5)

No matter what distribution or fitting method is used in extreme value analysis, the sampling error at the 100-yr return period is greater than at the 2-yr return period. The general form of the equation for any return period is $Y_t = \overline{X} + KS$, where Y_t is the value for the return period, $\overline{X}$ is the annual series sample mean, and S its standard deviation. K is a factor that differs with distribution assumed and the fitting method used, but K values have a common trait no matter what the distribution or fitting method--they increase with increasing return period.

For example, using Gumbel's method on a data sample of 25 items, at the 2-yr return period, K = -0.1506; while at the 100-yr level, K = 3.7283--in absolute value the 100-yr K is about 25 times the 2-yr K. The noise component brought about by the difference between S and the population standard deviation, σ, is much greater at the 100-yr return period than at the shortest return periods.

Over the years, it has been found that the ratio of 100-yr to 2-yr precipitation-frequency values is conservative over large contiguous areas and varies less than the 100-yr values themselves. For example, the ratio of the 100- to 2-yr 60-min values gradually increases northward.

The construction of the 100-yr 60-min map used the following aids: 1) station data and smoothed grid point data developed from the station data by computer smoothing as previously described; 2) station 100-yr/2-yr ratios and smoothed grid point values of that ratio; and 3) the isopluvial pattern of the 2-yr 60-min map.

5-Min Maps (Figs. 6 and 7)

It was hypothesized that the maximum annual 5-min values at adjacent stations are mostly from different storms and may be treated as statistically independent. This hypothesis was examined by comparing data from all stations in a 240-mi (385-km) square centered on Iowa. The period of record was 1907-72, but not all stations had data for all years. There was a total of 264 station years at seven stations. About 11 percent of the 5-min annual maxima occurred on the same date as an annual maximum at another of the seven stations. However, only about a quarter of these equaled or exceeded the 2-yr return period value. Essential independence of the more significant maximum annual 5-min rainfalls was considered established.

In view of the above, new data series were constructed, consisting of all maximum annual 5-min events at all the stations within overlapping 4° latitude-longitude boxes. This new series was analyzed by the Gumbel fitting of the Fisher-Tippett Type I distribution, as previously discussed. The resulting 0.5 and 0.01 probability events (equivalent to 2-yr and 100-yr

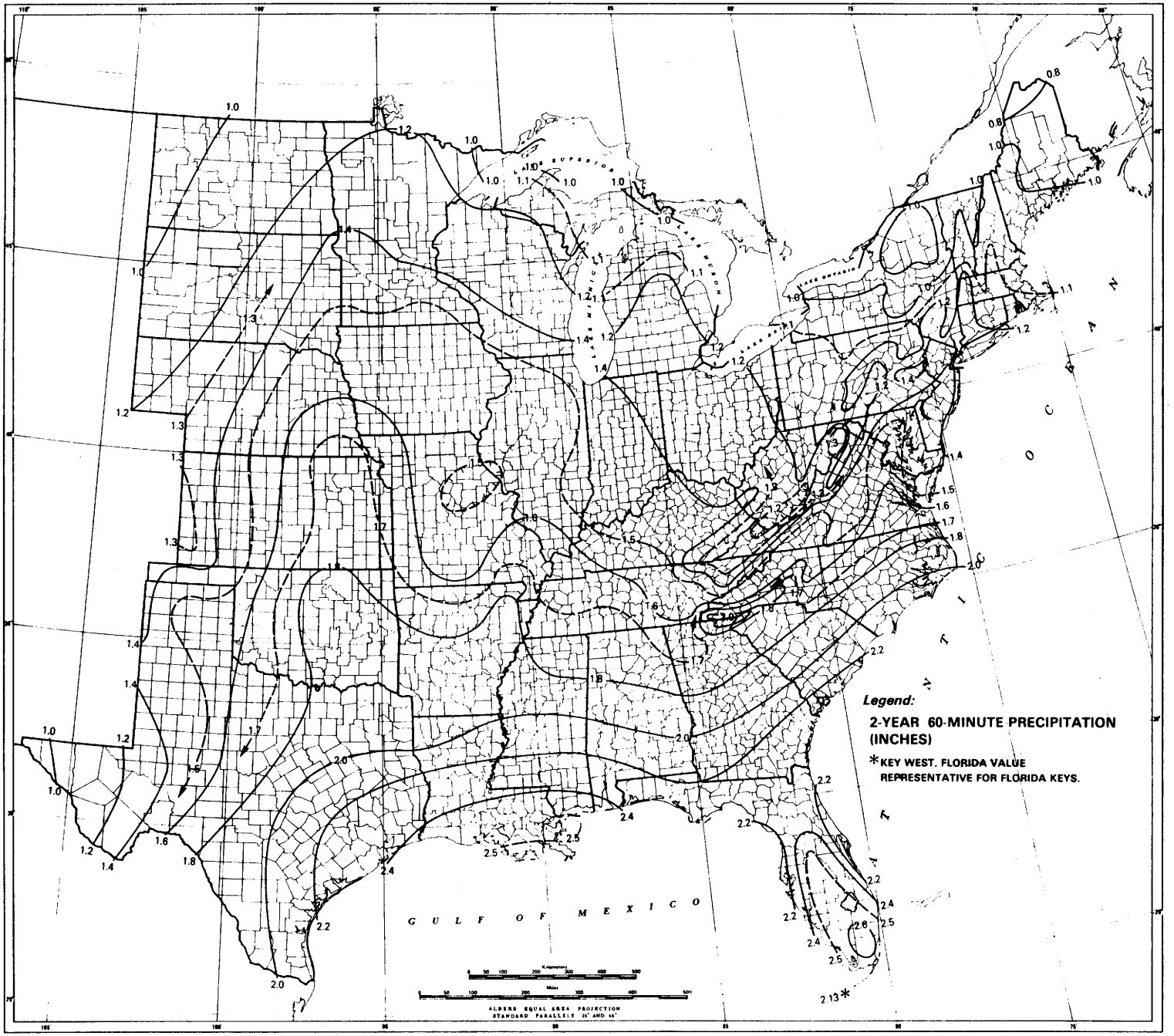

Figure 4.--2-year 60-min precipitation (inches)--adjusted to partial duration series.

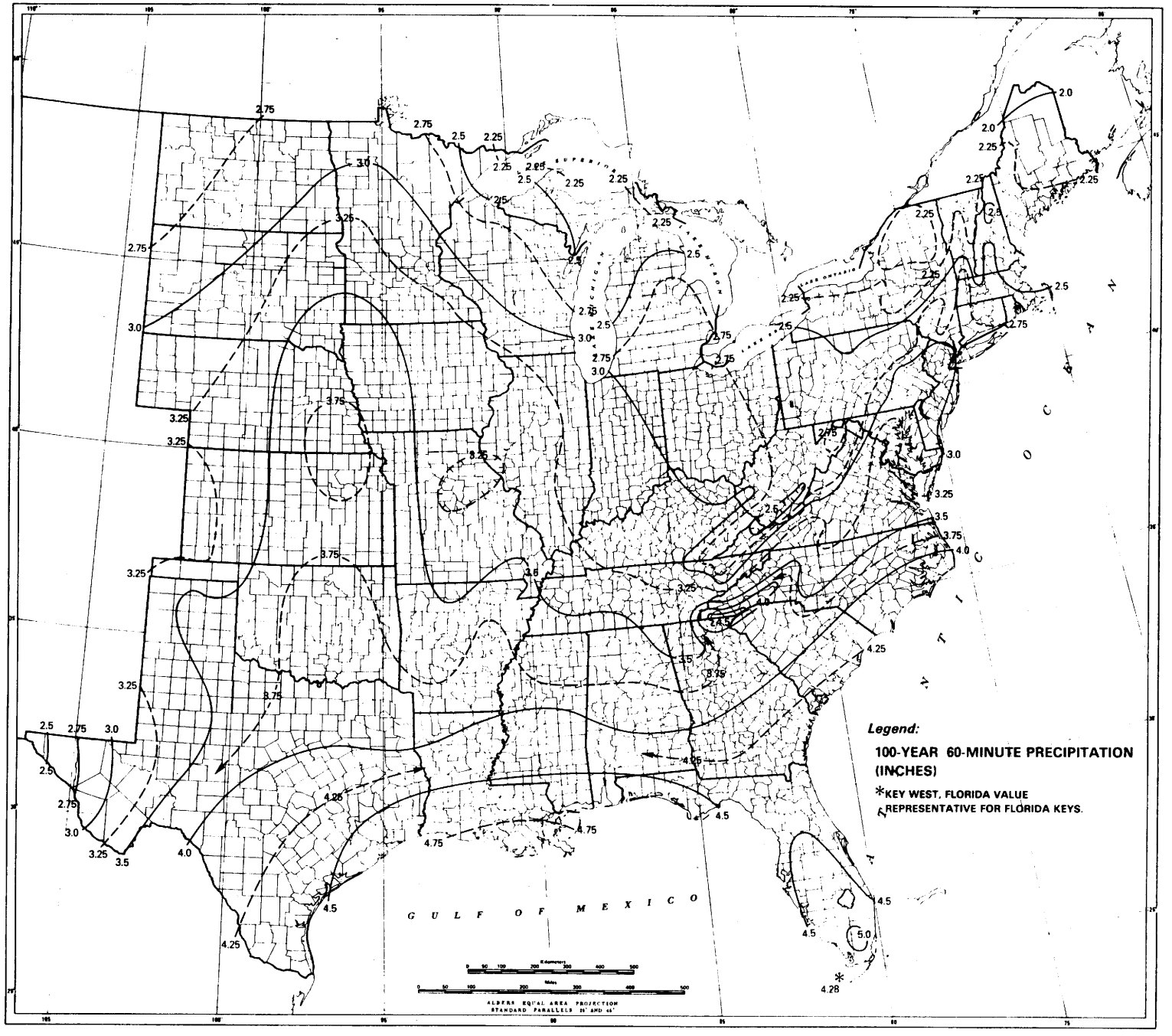

Figure 5.--100-year 60-minute precipitation (inches)--adjusted to partial duration series.

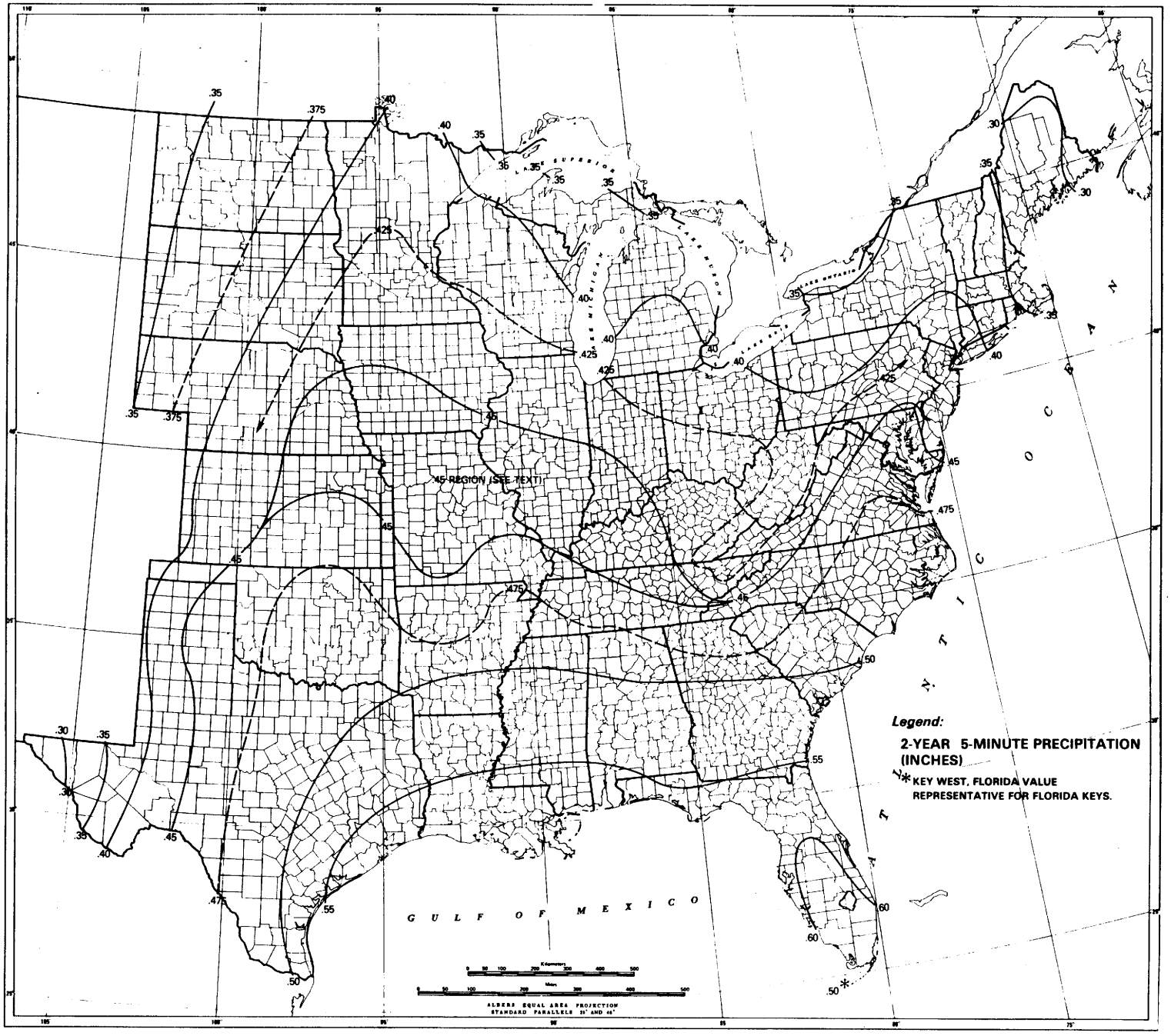

Figure 6.--2-year 5-minute precipitation (inches)--adjusted to partial-duration series.

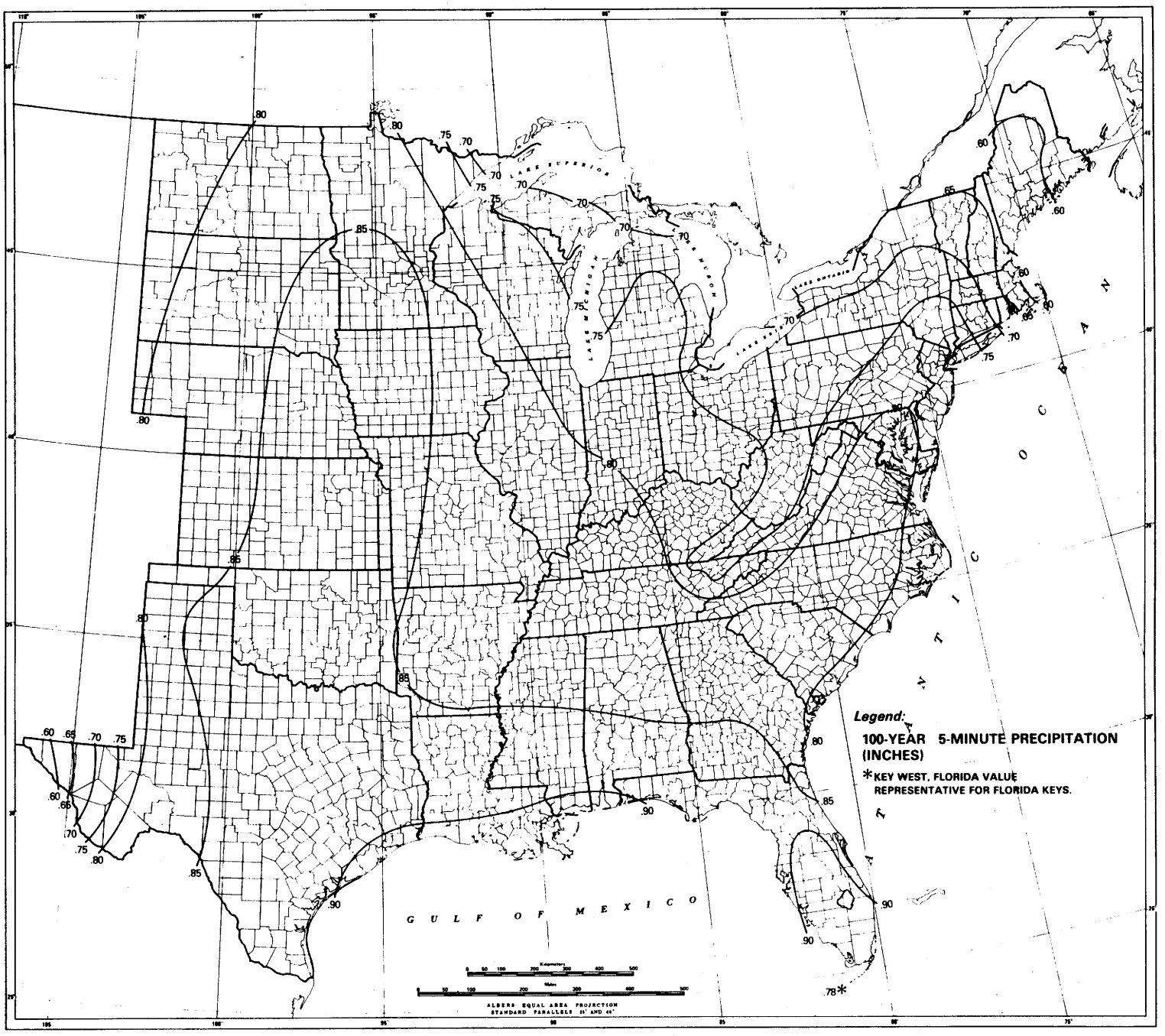

Figure 7.--100-year 5-minute precipitation (inches)--adjusted to partial-duration series.

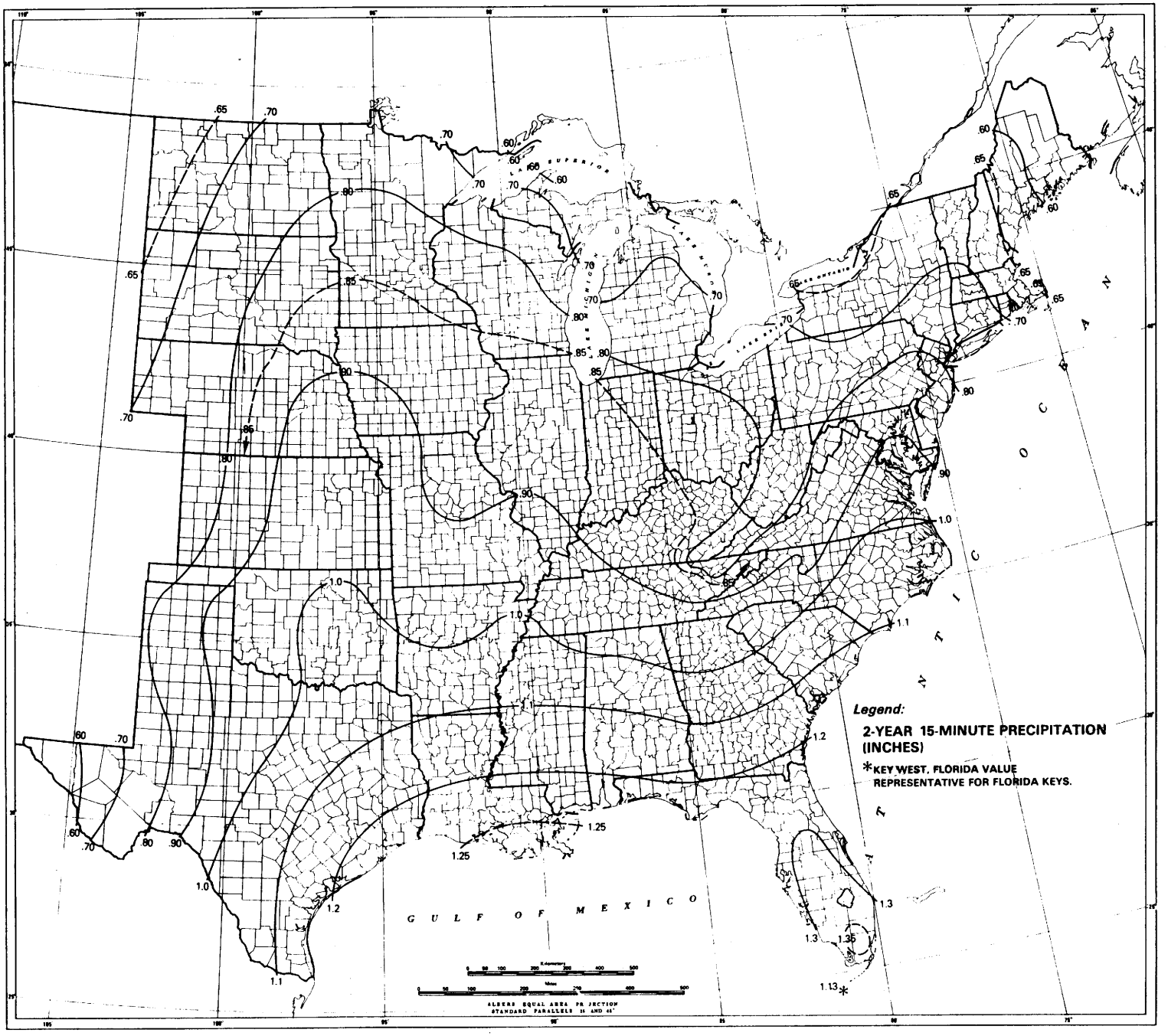

Figure 8.--2-year 15-min precipiatatation (inches)--adjusted to partial-duration series.

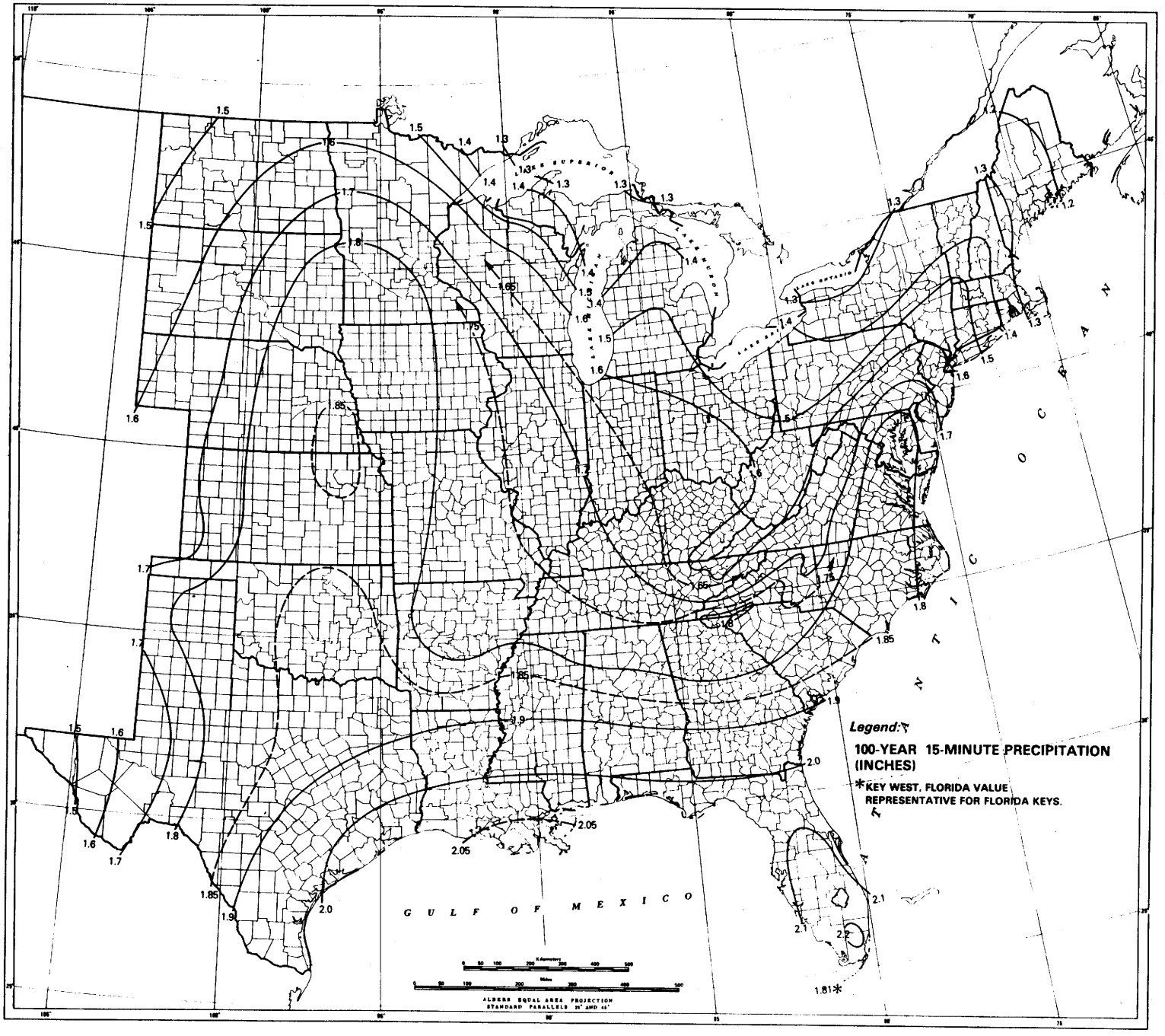

Figure 9.--100-year 15-minute precipitation (inches)--adjusted to partial-duration series.

return period) for each box were plotted at positions within the box determined by weighting the latitude and longitude of each contributing station by its length of record. In some regions of sparse data, only one station was available within a 4° box, but more generally the station years per box exceeded 100. The computer smoothing program was also run on the station 5-min values within the scan radius increased to 4°. Station ratios of 5- to 60-min values were similarly smoothed.

In summary, data used in construction of the 5-min maps included: 1) frequency values computed from all station data within each 4° latitude-longitude box and centered according to station location and length of record, 2) the computed frequency values and 5-min to 60-min ratio for the individual stations, 3) computer smoothed grid values for both frequency values and ratios, and 4) the isopluvial pattern developed for the 2-yr 60-min map.

The character of the 2-yr 5-min data (fig. 6) (and the climate) required an unorthodox analysis in the central part of the country, the shaded area labeled 0.45 region. All points within the area are to be considered to have a 2-yr 5-min frequency value of 0.45 in. (11.4 mm), with values gradually increasing southward and decreasing northward beyond this region. Considerable time and effort were spent attempting to define a precise location for the 0.45-in. isopluvial. The station data and the several forms of grid point data indicated that within this area values were equal to or within a few hundredths of an inch of 0.45, with no definable gradient. Since the placement of the line is a subjective judgment, the decision was made to treat the area as one broad line with all values equal to the value of the isoline.

15-Min Maps (Figs. 8 and 9)

As previously mentioned in the section "Methodology, Isopluvial Maps," the relationship between the 5-, 15- and 60-min precipitation frequencies was found to vary both geographically and by return period. Therefore, as an aid in the drawing of 15-min maps, the computer smoothing program was run on station values of the coefficient C_{15}:

$$R_{15} = C_{15} R_{60} + (1 - C_{15}) R_5 \qquad (6)$$

separately for the 2- and 100-yr return periods to obtain grid point values. Successive iterations of computer smoothing followed by manual adjustment were made to obtain consistent smooth fields of both C_{15} and R_{15}, holding R_{60} and R_5 fixed.

Maintenance of Internal Consistency

Once preliminary 5-, 15- and 60-min isopluvial frequency maps for the 2- and 100-yr durations were completed, values were read from the analyzed maps at 0.5° latitude-longitude grid points. These values were used to produce maps showing ratios at the grid points between the various durations and return periods. The ratio fields were then scanned for consistency and correspondence to ratios from the station data. The preliminary isopluvial maps were adjusted to remove any inconsistencies in the ratio fields. Next,

differences between adjacent grid points on the six maps were compared to discover any places where one map or set of maps showed increasing values where other maps or sets of maps were indicating decreasing values. This does not imply that values on all maps must move parallel to each other, but that nonparallel movement be examined to insure that the trends are intended by the analyst. A case of validated nonparallelism is illustrated in the Northern Plains States, where the ridge in the isopluvials shifts westward with increasing return period.

Intermediate Durations and Return Periods

10- and 30-Min Relations

The procedure discussed under "Methodology" was used to derive equations to estimate the 10-min values from 5- and 15-min, and 30-min values from 15- and 60-min values. The station data were first grouped geographically, and separate equations derived for each area and for the 2- and 100-yr return period. Neither geographical nor return period differences were significant, and one equation for the 10-min estimation and one equation for 30-min estimation were adopted. They are:

$$\text{10-min value} = 0.59\ (\text{15-min value}) + 0.41\ (\text{5-min value}) \quad (7)$$

$$\text{30-min value} = 0.49\ (\text{60-min value}) + 0.51\ (\text{15-min value}) \quad (8)$$

The graphical solution to these equations is shown in figure 10. The ordinate scale is linear. It is left unlabeled so that the user can label as appropriate for the range of data being used.

Intermediate Return Periods

A mathematical solution of the Gumbel equations for the partial duration series results in the following equations to compute values for selected return periods intermediate to the 2- and 100-yr values.

$$\text{5-yr} = 0.278\ (\text{100-yr}) + 0.674\ (\text{2-yr}) \quad (9)$$

$$\text{10-yr} = 0.449\ (\text{100-yr}) + 0.496\ (\text{2-yr}) \quad (10)$$

$$\text{25-yr} = 0.669\ (\text{100-yr}) + 0.293\ (\text{2-yr}) \quad (11)$$

$$\text{50-yr} = 0.835\ (\text{100-yr}) + 0.146\ (\text{2-yr}) \quad (12)$$

INTERPRETATION OF RESULTS

Physiographic and Meteorological Effects

The center of low precipitation frequencies depicted in Northern Missouri is validated by the fact that this is also a center of low frequency of tornadoes (Fujita 1976) compared to the surrounding regions. High-intensity, short-duration rainfalls and tornadoes are both associated with convective storms. We do not know whether this anomaly is a shadow effect of the

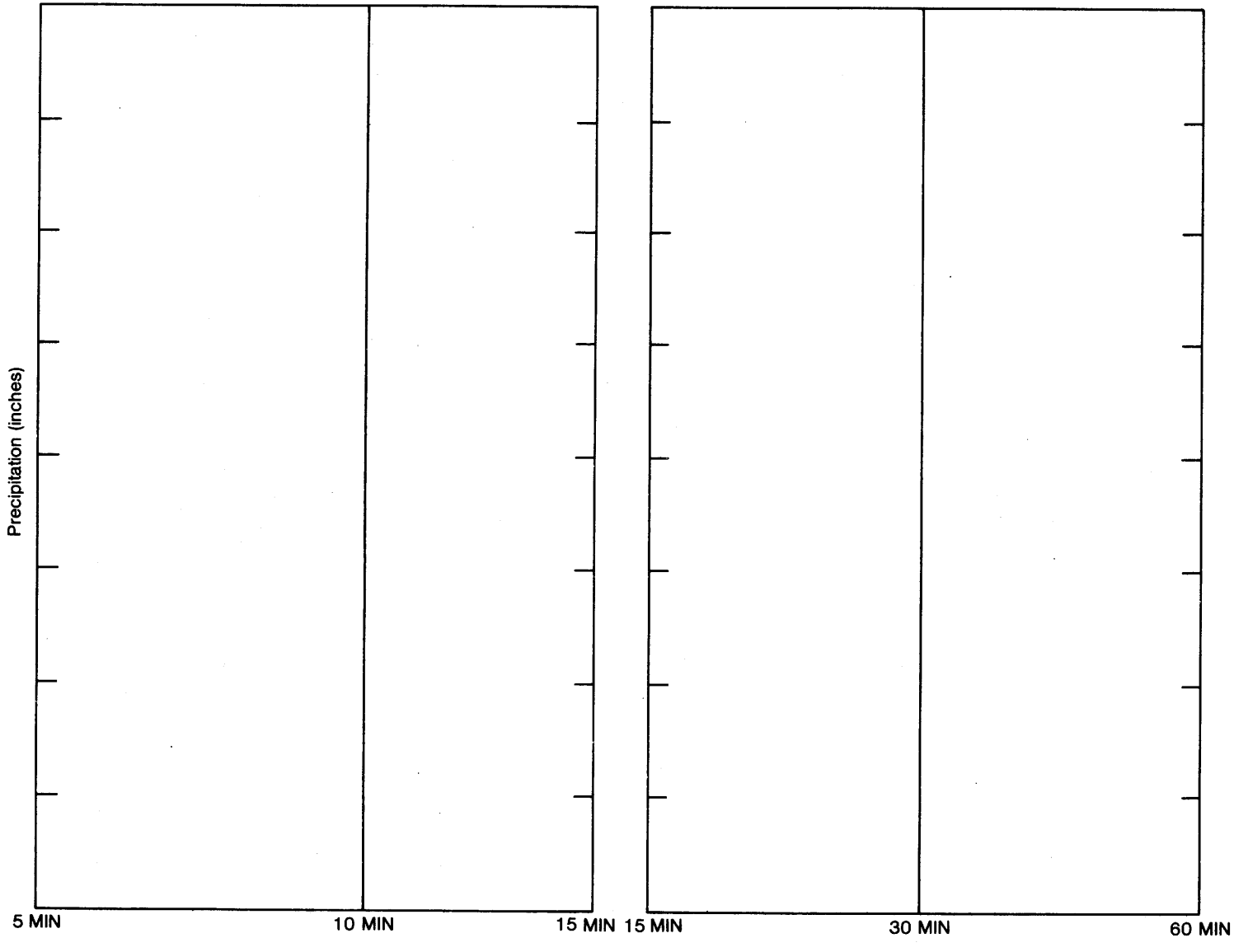

Figure 10.--Duration-interpolation diagram for 10- and 30-min estimates.

Ozark Mountains impeding the low-level moist inflow from the Gulf of Mexico or is due to some other cause.

The isopluvial discontinuities appearing across the Great Lakes occur because warm land surfaces to the windward enhance the development of summer thunderstorms, while the cool lake water surfaces tend to inhibit this type of weather. The data confirm this and suggest higher values on the upwind (west and south) shores of the Great Lakes than on the downwind (east and north) shores. A similar effect is noticeable in Florida, with the lowest values near the coast, especially the east coast in the summer easterlies, with higher values inland. Coastal effects are also noted along the middle Atlantic coast, being most prominent on the 5-min and 15-min 100-yr maps. The tongue of high values aligned north-south in the Western Plains coincides with the well-known nocturnal maximum of thunderstorms in the region, and with the frequent development of a band of strong winds from the south, called the low-level jet (Pitchford and London 1962). The trough of lower values paralleling, and northwest of, the Appalachians suggests that shielding by that mountain chain in a south to southwest flow has more impact on frequencies than does orographic simulation that might be expected with a west-southwest to west flow.

Comparison With Previous Studies

In both this study and TP-40, the 60-min map is the anchor map upon which precipitation-frequency values for shorter durations are based. Comparing the 60-min maps in the two reports at the 2-yr return period shows good correspondence with no overall trend to higher or lower values or pronounced regional differences.

The major difference is the greater detail with which the later map has been constructed, especially in the Appalachians. The largest increase in values, somewhat in excess of 20 percent, is at the triple point intersection of the borders of North Carolina, South Carolina, and Georgia, on the south-east flank of the Appalachians. An increase of less than 20 percent in northern Minnesota results from more northward penetration of the midwestern tongue of high values on the later analysis. Decreases of about 15 percent occur at points on the western shore of Chesapeake Bay, resulting from cutting back a tongue of high values east of the Appalachians. Most other changes are less than 10 percent and tend to average out over a given region. On the Florida peninsula, the general level of values is unchanged, but the later analysis gives more recognition to the stimulation of intense thunderstorms by solar heating of land (supported by the data) and places higher values in the interior of the peninsula than over the adjacent sea. For similar reasons, the north-south gradient is reduced in southern Louisiana.

Differences in the 60-min 100-yr maps are similar, with larger percentagewise changes in the Appalachians. This is expected, since more variation of both the mean of the annual series and its standard deviation have been introduced.

The largest differences between the new study and TP-40 exist at the 5-min duration. The present study shows values in Maine and parts of the northern plains 30 to 40 percent greater than values derived by use of the duration table in TP-40. Along the Gulf coast, on the other hand, the new values are about 20 percent less than those derived from TP-40 at the 2-yr return period and 30 percent less at the 100-yr return period. Values are also lowered along the Atlantic coast.

Yarnell (1935) published pioneering rainfall frequency maps for the United States based on data through 1933. He had available essentially the same network of first-order NWS stations available to this study for N minutes (fig. 1) but 40 years less record. The overall patterns and levels of values on Yarnell's charts and the maps of the present report are similar and are a testimony to the stability of the climate with respect to short-duration rainfalls. It has been possible to attain a finer scale of subregion detail in the later work, as well as provide the more detailed analysis in the Appalachians, which has been referred to. Values have been raised substantially in the Northeast in the present study compared to Yarnell. Identifying the reason for this would require repetition of Yarnell's analysis. Coastal patterns have been modified and the north-south axis of high values in the Plains States, prominent in all studies, is depicted farther to the west in the new study.

ILLUSTRATION OF THE USE OF PRECIPITATION-FREQUENCY MAPS, DIAGRAMS, AND EQUATIONS

1. Two-yr and 100-yr values for the duration of 5, 15, and 60 min are read from the six maps (figs. 4-9). Example: for the point at 37°N and 93°W, these values read by interpolation are entered in table 3.

2. Intermediate return period values are calculated using equations 9-12. The calculation for the 25-yr 15-min value (using eq. 11) is:

$$25\text{-yr } 15\text{-min} = 0.669\ (1.79) + 0.293\ (0.94) = 1.47$$

3. Values for intermediate durations are calculated using equation 7 or 8 or by plotting as in figure 11. The 100-yr 10-min value (using eq. 7) is:

$$100\text{-yr } 10\text{-min} = 0.59\ (1.79) + 0.41\ (0.85) = 1.40$$

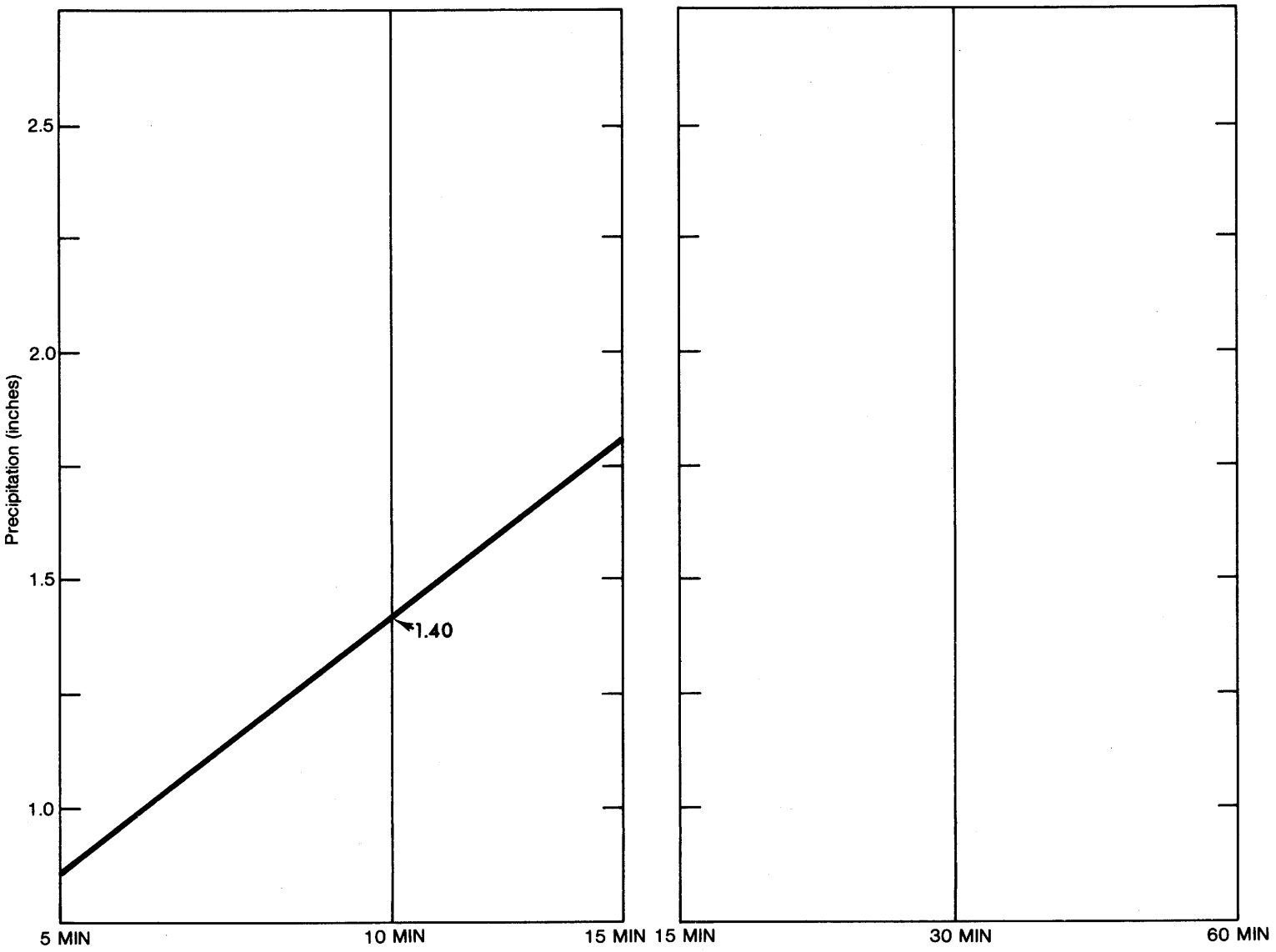

Figure 11.--Illustrative example using figure 10.

Table 3.--Precipitation frequency values (in.) for 93°00'W, 37°00'N)

	5-min	10-min	15-min	30-min	60-min
2-yr	0.45		0.94		1.59
5-yr					
10-yr					
25-yr			(1.47)		
50-yr					
100-yr	0.85	(1.40)	1.79		3.43

Note: Circled values are computed from the other values.

ACKNOWLEDGEMENTS

Sponsorship and financial support for this project were provided by Soil Conservation Service, U.S. Dept. of Agriculture. Coordination with the Soil Conservation Service was maintained through Robert E. Rallison, Chief, Hydrology Branch, Engineering Division.

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