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Radar Rainfall Data Estimation and Use

Prepared by the
Radar Rainfall Data and Application Task Committee of the
Surface Water Hydrology Technical Committee of the
Watershed Council of the Environmental and Water Resources
Institute of the American Society of Civil Engineers

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PREFACE

This manual on radar rainfall data estimation was developed as one of the several tasks that was undertaken by the Radar Rainfall Data and Application Task Committee, under the Surface Water Hydrology Technical Committee within the Watershed Council of Environmental and Water Resources Institute's (EWRI), American Society of Civil Engineers (ASCE).

This manual was developed primarily for use by the practicing water resources engineers in the industry. This manual has nine chapters and their titles and authors are shown as follows.

Chapter 1: Radar Rainfall Estimation, Chandra S. Pathak (US Army Corps of Engineers);

Chapter 2: Radar Rainfall Data: Temporal and Spatial Characteristics, Chandra S. Pathak (US Army Corps of Engineers) and David C. Curtis (WEST Consultants);

Chapter 3: Radar Rainfall Data Processing, David Kitzmiller (National Weather Service);

Chapter 4: Evaluation and Improvement of Radar Rainfall Data, Ramesh S.V. Teegavarapu (Florida Atlantic University);

Chapter 5: Use of Radar Rainfall Data in Hydrologic Modeling, David C. Curtis (WEST Consultants);

Chapter 6: Examples in Radar Rainfall Data, Analyses, and Applications, Chandra S. Pathak (US Army Corps of Engineers);

Chapter 7: Advanced Topic: Framework for Bias Analysis of Radar Data, Ramesh S.V. Teegavarapu (Florida Atlantic University);

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Chapter 8: Advanced Topic: Rain-Gauge Rainfall Data Augmentation and Radar Rainfall Data Analysis, Ramesh S.V. Teegavarapu (Florida Atlantic University);

Chapter 9: Advanced Topic: Design of Rainfall Monitoring Networks, Ramesh S.V. Teegavarapu (Florida Atlantic University).

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The Blue-Ribbon Panel of reviewers was established by the Watershed Council of EWRI and approved by the Technical Executive Committee of EWRI. The Blue-Ribbon Panel Review members were Dr. Scott Huebner, P.E. (South Florida Water Management District); Mr. Michael DelCharco, P.E. (Taylor Engineering, Inc.); and Mr. David Preusch, P.E. (WEST Consultants, Inc.). The drafts of the manual were reviewed by individuals chosen for their diverse perspective and technical expertise in accordance with the procedures approved for ASCE's *Manual of Practice*. The purpose of this independent review was to provide candid and critical comments that assist EWRI in making this publication as sound as possible and to ensure that the manual meets ASCE institutional standards in science and engineering and usability by the practicing engineers.

The authors wish to thank the following individuals for their reviews of this manual: Dr. Scott Huebner, P.E. (South Florida Water Management District); Mr. Michael DelCharco, P.E. (Taylor Engineering, Inc.); Mr. David Preusch, P.E. (WSP USA and formerly with WEST Consultants, Inc.); Dr. Thomas Evans (US Army Corps of Engineers); and Dr. Daniel Wright (University of Wisconsin—Madison and formerly with Princeton University).

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CHAPTER 1

RADAR RAINFALL ESTIMATION

1.1 INTRODUCTION

Radar-derived rainfall estimation is clearly one of the most significant recent advances in hydrologic engineering and practice. There is a trade-off in hydrologic modeling between using rainfall data collected by rain gauges and those collected by radar. Rain gauges provide point values of rainfall depth and intensity, but they are not cost-effective in providing information about the spatial distribution of rainfall. Although rain gauges might suffice for widespread rain events, a gauge network can miss localized convective rainfall events altogether. Radar-derived rainfall data provide a density of measurements that are not obtainable by rain gauges alone. Combining these two sensor systems produces better rainfall estimates that more accurately characterize rainfall over a watershed. Using rain-gauge–adjusted radar rainfall data, hydrologists have more information about rainfall rates at high resolution in space and time over large areas. Understanding radar rainfall estimation and estimation errors within a hydrologic modeling context have important advantages.

The *Journal of Hydrologic Engineering* has been publishing technical articles on radar rainfall since 1996. Through April 2013, it has published more than 150 technical papers, case studies, and technical notes on this subject. In February 2013, the *Journal of Hydrologic Engineering* published a special issue on “Radar Rainfall Data Analyses and Applications.” This publication includes the most significant advances in hydrologic engineering practice on the subject. This special issue (Pathak 2013) has 17 technical papers grouped into four categories: (a) two papers are of radar rainfall data development methods, (b) six papers are on radar rainfall data improvement and validation, (c) four papers are on application of radar rainfall data, and (d) five papers are on case studies. The reader is also directed to the special issue on radar rainfall and operational hydrology (Pathak et al. 2017) and a special issue on hydrologic applications of weather radar (Seo et al. 2015) for a compendium of papers on different issues ranging from radar estimation to applications for operational hydrology.

This manual is intended to provide a flexible framework within which both government agencies and private consulting firms can develop radar rainfall data sets and analyze them according to their varied goals and resources. The guidelines herein are not intended to provide a complete manual of all procedures available for estimating radar rainfall data and data analyses. The basic philosophy and principles are described in sufficient detail to promote a reasonable degree of consistency and uniformity among data developers and users to perform various tasks within the hydrologic engineering field.

We, the editors and the authors, sincerely hope that this manual on the topic of radar rainfall data analyses and applications is useful to researchers and practicing engineers alike as this discipline of hydrologic engineering progresses in the future. This manual was developed as a part of several tasks that were undertaken by the Radar Rainfall Data and Application Task Committee, under the Surface Water Hydrology Technical Committee within the Watershed Council of the Environmental and Water Resources Institute (EWRI) of ASCE.

1.2 BACKGROUND

1.2.1 Traditional Rainfall Estimation

Traditionally, rainfall has been and is measured by rain gauges—devices that record rainfall entering the gauge orifice. Gauge diameters generally range from 1 to 12 in. (2.54 to 30.48 cm) in diameter. Even the largest diameter gauge (12 in. or 30.48 cm) measures rainfall over only a tiny portion of a watershed (0.0000000282 mi^2 or 0.0000000730 km^2). With a relatively dense network density of one gauge per 10 mi^2 (26 km^2), rainfall is only measured in parts per billion.

Hydrologically, rainfall estimates at tiny points are not particularly valuable. By themselves, rain-gauge measurements represent very little volume. What is really needed are rainfall estimates over an entire watershed to accurately determine watershed volumetric inflow. To estimate rainfall over an area from point rain-gauge data, engineers and hydrologists use a variety of interpolation techniques to compute a rainfall "surface" over a watershed. The rainfall surface is then integrated over the watershed area during each time step to estimate the volumetric rate of inflow (Figure 1-1).

Figure 1-1. Example of an automated rain gauge.

Common rainfall interpolation techniques include Thiessen polygons (Viessman et al. 1972), inverse distance squared weighting (Chow et al. 1988), and kriging (Bras and Rodríquez-Iturbe 1985). Each interpolated method is some form of weighted averaging of individual rain-gauge observations to create an area averaged rainfall estimate.

Figure 1-2 shows a rainfall "surface" interpolated from rainfall observed at gauge locations using the Thiessen polygon technique. A polygon enclosing all points closest to a given rain gauge is a Thiessen polygon. Each point within a Thiessen polygon is assigned the same value as the enclosed rain-gauge observation. By comparison, Figure 1-3 shows a rainfall surface for the same event as represented by radar rainfall estimates.

As seen in Figure 1-3, the band of heavy rainfall to the east is missed by several of the rain gauges. As a result, the Thiessen polygon estimates underrepresent rainfall in the eastern portion of the watershed (the watershed boundary is shown in white) and overrepresent rainfall in the middle portion of the watershed.

1.2.2 Radar Rainfall Estimation

The use of radar to estimate rainfall began in the 1960s. During the early 1990s, the use of this technology proliferated as the NOAA (National Oceanic and Atmospheric Administration) installed radar stations across the United States as part of the Weather Surveillance Radar 88-Doppler (WSR-88D) and the NEXt Generation RADar (NEXRAD) program initiated by the NWS (National Weather Service). Currently, 160 WSR-88D radar

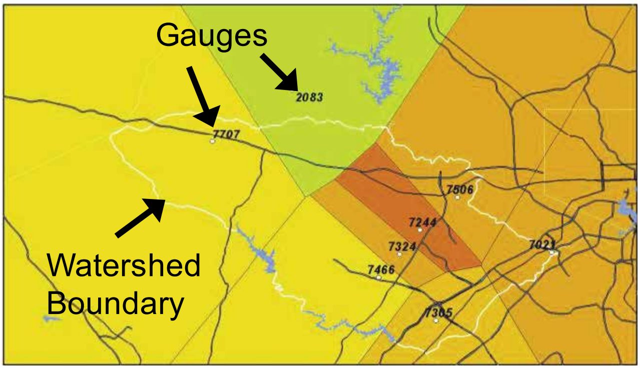

Figure 1-2. Thiessen polygon representation of rainfall.

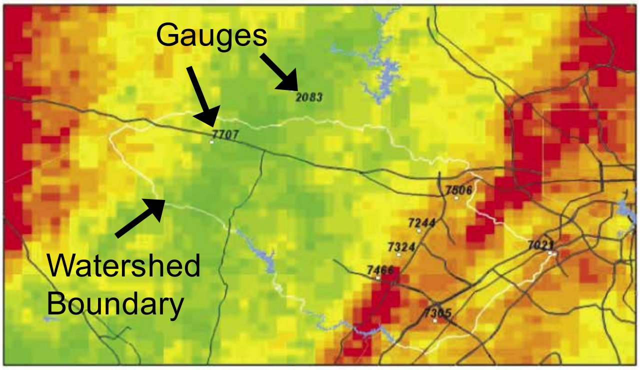

Figure 1-3. Gauge-adjusted radar rainfall.

stations are in operation as part of the NEXRAD network, providing estimates of rainfall and snowfall intensity with nearly complete spatial coverage across most of the United States.

Doppler (WSR-88D) radar operates by emitting short pulses of microwave energy. When a target such as a building, airplane, bird, snowflake, or rain droplet is encountered, the emitted energy is scattered in all directions. Small amounts of energy, known as backscatter, are returned to the radar antenna, where they are detected and recorded, known as radar reflectivity. The intensity of the returned radar reflectivity signal is then related to the size of the object and analyzed according to the time required for the pulse to reach the target and return to the antenna. This provides information regarding the range and Doppler velocity of the target relative to the radar. The WSR-88D radar is a 10 cm-wavelength (S-band) radar. It is designed for long-distance surveillance because its wavelength penetrates rainfall with little reduction in the strength of the signal (minimal attenuation). However, European radar systems predominantly use shorter- (less than 5 cm) wavelength (C-band) radar. Shorter-wavelength radars have relatively greater attenuation caused by absorption and scattering of the electromagnetic radiation that degrades performance as the distance from the radar increases, thus requiring an increased density of radar systems. Under most conditions, the useful range of a 10 cm-wavelength (S-band) radar is considered to be close to 180 km, even though the WSR-88D system produces rainfall estimates up to 230 km. As distance increases, the beam becomes increasingly higher above average ground level because the radar's lowest elevation angle is 0.5°, the earth is curved, and there is atmospheric refraction. X-band weather radars are also used for precipitation estimates and have even shorter wavelengths (2.5 to 4 cm). The range of X-band radar is much shorter than those of C- and S-band radars. Rainfall estimates from the C-, S-, and X-band radars are processed to correct the effects of (1) ground echoes, (2) beam blockage, and (3) attenuation of the radar beam.

Radar data that provide rainfall amount products can be created at any spatial resolution. However, three primary spatial resolutions, 4 km × 4 km (2.49 mi × 2.49 mi), 2 km × 2 km (1.24 mi × 1.24 mi), and 1 km × 1 km (0.39 mi × 0.39 mi), are commonly used in the industry. The radar rainfall data are limited by the measurement of raindrop reflectivity, which is affected by factors such as raindrop size and signal reflection by other objects. Because the reflected signal measured by the radar is proportional to the sum of the sixth power of the diameter of the raindrops in a given volume covered, small changes in the size of raindrops can have a dramatic effect on the radar's estimate of rainfall (Pathak 2013). For this reason, and owing to overshooting beams and poor radar calibration, radar-derived rainfall data are scaled to match the volume measured at coincident rain gauges using bias adjustment techniques.

Radar rainfall outputs are generally in the native polar coordinate system of the radar or resampled to a grid in Cartesian coordinates. Aggregation or disaggregation of gridded radar rainfall data is often necessary with grid-based distributed models because the model grid is not at the same resolution as the radar rainfall data input or it has a different geographic projection. Besides file-format manipulation, the link between radar rainfall data and hydrologic models requires spatial aggregation from one grid to another or to subbasin areas. Aggregation from polar coordinates to basins or to rectangular grids is usually accomplished with the help of a geographic information system (GIS) or special-purpose spatial analysis tools that can handle spatial data in geographic projections.

High-quality radar rainfall records in the United States have been kept only since the mid-1990s. Moreover, some significant changes in computation algorithms have been implemented during that period. Fifteen to twenty years of radar rainfall data have limited utility for rainfall frequency analyses or long-term statistical studies. However, short-term storm analyses can be performed using radar rainfall data for a specific, recent historical event, coupled with continuous hydrologic modeling. Although radar rainfall data are increasingly available over the World Wide Web, the data processing, quality assurance/quality control, and calibration using rain-gauge data all require certain skills that are not widely available in the engineering community. At present, those skill sets are limited to a small number of firms or organizations specializing in radar rainfall estimation for hydrologic applications. Use of governmental unadjusted radar data without the proper understanding or the application of tools for quality control and correcting for bias could lead to serious errors in hydrologic analysis. The methods of estimating rainfall from radar have changed appreciably since the original deployment of the weather radar network, and these methods will continue to evolve. For example, statistical biases can change over time as algorithms are refined. This poses a major challenge in the proper interpretation of radar-derived rainfall estimates in long time series.

Radar estimates of rainfall rates depend on assumptions about the number and sizes of raindrops in a representative volume of the atmosphere. Various radar reflectivity intensity (Z) and rainfall rate (R) relationships (commonly referred to as Z–R relationships) have been derived from a theoretical or empirical basis. Depending on storm type and the power of the radar, a range of Z–R relationships is possible. Once an appropriate Z–R relationship is selected, a comparison with rain-gauge accumulations is carried out to remove any systematic error, known as bias. After bias removal, differences between radar rainfall and gauge rainfall estimates remain as random error.

Understanding real-time and post-analysis quality control and post-processing yields improve radar rainfall data for hydrologic applications. Some errors tend to average out over a watershed area, although others may dramatically increase prediction errors. Dramatic progress has been made in the past decade toward achieving representative rainfall measurement through a variety of methods. More promising methods include dual-polarization and post-processing algorithms to account for attenuation and other artifacts in short-wavelength radars such as X- and S-band radars.

Distributed hydrologic models are particularly well suited to utilizing radar rainfall. Distributed models designed from the outset to utilize high-resolution rainfall rates from multiple sensors (radar, satellite, and rain gauge) allow detailed predictions at almost any location in a watershed characterized with geospatial data relating to topography, soils, and land cover. Besides hydrologic design, radar rainfall also provides timely inputs to operational decisions for water control structures and flood warning systems and guide emergency management personnel in taking proactive steps to protect life and property from flooding.

1.3 SCOPE

This manual contains nine chapters. Chapter 1 is an introduction to radar rainfall estimation. Chapter 2 provides temporal and spatial characteristics of radar rainfall data. Chapter 3 provides details on data processing as used by the NWS in estimating radar rainfall data. Chapter 4 provides a method for data quality evaluation and improvement of radar rainfall data. Chapter 5 discusses use of radar rainfall data in hydrologic modeling. Chapter 6 provides examples of estimating radar rainfall data, data analysis, and data applications. Chapters 7, 8, and 9 discuss advanced topics on a framework for bias analysis of radar data; rain-gauge rainfall data augmentation and radar rainfall data analysis; and design of rainfall monitoring networks.

1.4 AVAILABILITY OF RADAR RAINFALL DATA WITHIN THE UNITED STATES

Climate Data Online (CDO) provides access to the National Centers for Environmental Information (NCEI, formerly NCDC)'s archive of global historical weather and climate data in hourly, daily, monthly, seasonal, and yearly time steps. Other regional or state agencies may have their own data collection system and should be checked as well.

The PRISM (parameter-elevation regressions on independent slopes model) climate group gathers climate observations from a wide range of monitoring networks and develops a spatial climate data set that contains short- and long-term climate patterns that cover from 1985 to the present. Daily, monthly, and yearly precipitation and temperature grids for the entire United States are available for download. PRISM volumes can be combined with observed hourly rainfall gauges to disaggregate daily volumes into hourly grid cells.

RFC (River Forecast Center, NWS) offices can be contacted to obtain radar rainfall data [multisensor precipitation estimator (MPE)]. Figure 1-4 shows the RFC radar extent. This map can be used to identify the geographic location(s) covered by the RFC. MPE integrates precipitation information from rain gauges, radar, and satellites to generate gridded precipitation fields in the hydrologic rainfall analysis project (HRAP) grid format with a spatial resolution of 4 km × 4 km (2.49 mi × 2.49 mi). MPE data are used at the RFCs and WFCs (Weather Forecast Centers, NWS) throughout the nation. The advantage of using hourly MPE data is the flexibility of isolating a