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14. ABSTRACT
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radar-rainfall, radar-rainfall calibration, rainfall-runoff simulation, RADAP-II, real-time water control

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THE ESTIMATION OF RAINFALL FOR FLOOD FORECASTING USING RADAR AND RAIN GAGE DATA

William J. Charley*

Abstract

An inadequate knowledge of the magnitude and spatial distribution of precipitation is often a major limitation in developing accurate river-flow forecasts for use in reservoir operations. Digitized weather radar data can provide useful information regarding the spatial distribution of rainfall, although radar-based estimates of rainfall may be in error due to several factors. The use of radar-rainfall data in combination with rain gage measurements may improve rainfall estimates over those based on either form of measurement alone. This improvement is accomplished by adjusting, or "calibrating", radar-rainfall data with data from rain gages situated within the radar "boundary". A set of rainfall analysis software that incorporates this methodology has been developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center to aid hydrologists in making real-time water control decisions.

The rainfall-analysis software retrieves real-time radar-rainfall data from a National Weather Service RADAP II (Radar Data Processor), and rain gage measurements from data collection platforms via the Geostationary Operational Environmental Satellite (GOES). The radar data from the RADAP II is "calibrated" with the rain gage data using a simple Kriging technique. Subbasin-average rainfall is then computed from the calibrated data and stored in a data base file for subsequent use by a river-flow forecast model. Graphics programs aid in the evaluation of the data. This software system has been implemented for a few pilot watersheds in Oklahoma.

Introduction

A typical rain gage network usually does not provide adequate definition of the spatial distribution of rainfall over a watershed. During a precipitation analysis for river-flow forecasting, a frequent assumption is that averaging or interpolating rain gage data will provide an adequate representation of the average rainfall over a watershed. In many cases this may not be true.

Digitized weather radar data can provide useful information regarding the spatial distribution of rainfall, but this data may contain errors such as the following: 1) the relationship used to compute the rainfall rate from the radar reflectivity assumes standard conditions (e.g., drop size), which may or may not be representative of the actual conditions (Battan, 1973); 2) different types of precipitation (e.g., rain, hail, or snow) have different reflectivities and cannot be represented with the same relationship; 3) atmospheric conditions may cause anomalous propagation of the radar beam and indicate rainfall where there is none; and 4) the radar measures rainfall rates in an elevated volume, not the rate at ground level; evaporation and air currents can significantly alter this rate.

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Research has shown that radar-rainfall data may be improved by adjusting, or "calibrating", the data with rain gage measurements situated within the radar boundary (e.g., Wilson, 1970). Several algorithms have been proposed to calibrate radar data with rain gage measurements (e.g., Brandes, 1975; Cain and Smith, 1976). However, the rainfall data and the calibration of the data must be carefully evaluated, because improperly calibrated radar data can produce results that are less accurate than would be obtained from either the gage data or radar data alone.

Accumulated digitized radar-rainfall data can be obtained from the National Weather Service's RADAP II radar sites on a real-time basis (Green, et al., 1983; Saffle, 1976). This data is on a grid-cell basis, for which a cell is 3 by 5 nautical miles. The U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) has developed a set of computer software* for rainfall analysis that can be used to acquire and analyze this data in an attempt to improve estimates of the rainfall over a watershed. No forecasting of rainfall is attempted.

Calibration

The calibration of radar-rainfall data with rain gage measurements proceeds in the following manner. Three hourly accumulated radar-rainfall data for the watershed is automatically retrieved from the NWS RADAP II. This data is decoded and stored in an HEC Data Storage System data base file (HEC, 1985). Concurrently, hourly rain gage measurements are obtained from data collection platforms throughout the watershed via the GOES satellite, and are stored in a similar data base file.

The radar-rainfall data is calibrated by the software component called RADRAN according to the following procedure. The rain gage locations reporting valid data within or near the watershed boundary are identified. The rainfall measured by each gage is compared to the amount measured by the radar at that gage location. If the measured rainfall exceeds a minimum amount (typically 0.1 inch), the ratio of the gage value to the radar value (G/R ratio) is computed. If the ratio is "reasonable" (within user-specified limits), it is used for that site. Otherwise, the algebraic difference between the rainfall measured by the gage and the radar is computed and used for that location.

The radar-measured rainfall for each radar grid cell is adjusted by the G/R ratios and G-R differences from the surrounding gage locations. The area surrounding each cell is divided into quadrants, and the closest two gages within each quadrant are selected. A simplified (linear) Kriging algorithm is applied in order to generate weighting factors, based upon distance, for each of these gage locations. The radar measured rainfall amount for the grid cell is adjusted according to the weighted ratios and differences computed at the selected gages (Charley, 1986).

The adjusted values are averaged over each subbasin in order to compute subbasin average rainfall amounts. The subbasin averages are stored in the data base file for subsequent use by a rainfall-runoff model.

This calibration procedure makes two assumptions that may not always be true. These are that the the rain gage reports the correct amount of rainfall, and that this amount represents the average rainfall in the area corresponding to the radar grid cell. If these assumptions are not valid, the calibrated radar data may produce

*This software was developed on a Harris mini-computer, and contains machine dependent code.

results that are worse than those that would be obtained using rain gage data or radar data alone. Therefore, it is important to screen the gage data prior to use, and to evaluate the calibrations.

Several provisions are made to aid in this evaluation. The gage-radar relationship at each gage location is displayed in the output. If the values measured by the gage and the radar are very different, then the calibration may not provide acceptable results. Along with this information, the rainfall measured by each gage is compared to what would have been computed from the calibrated data at that location had that gage not been present. This is accomplished by temporarily removing the gage data from the analysis, then calibrating the radar data at that location. This is repeated for each gage location. The above information provides a quantitative evaluation of the data and the calibration.

The data and the calibration can be evaluated in a qualitative mode by graphical displays. The data can be plotted on a color graphics terminal with rainfall amounts color coded. Outlines of the watershed, rivers, gages and other information can be overlaid on the plot. A similar graphics product may be produced on a dot matrix printer with varying shades of grey.

Results

Models for the RADRAN program were prepared for a few watersheds in Oklahoma, and executed for several storm events. No systematic verification or evaluation procedure was attempted. For most of the events examined, hydrographs computed using rain gage data, and calibrated radar data, were similar. That is the volumes were within about 20 percent and there was little difference in the timing of the runoff peaks. In some of the events, the radar recorded a substantial amount of rainfall that was missed by the rain gages because of the positioning of the storm relative to the gages. An example is presented for the Waurika Lake Basin (located south of Oklahoma City) for the September-October 1986 storms. The subbasin average hyetographs computed for the calibrated radar data, and the gage data only, are presented in Figures 1(a) and 1(b), respectively. For the 30th of September, the calibrated radar hyetograph showed about one inch of rain that was not detected by the rain gages. The calibrated radar data indicates that the storm was situated over the watershed such that the rain gages were located only on the edges of the storm, as depicted in Figure 2(a). The same plot using rain gage data only, presented in Figure 2(b), shows little rainfall over the basin.

It is difficult to evaluate the hyetographs produced by the two procedures, based upon comparing hydrographs computed from these hyetographs against the observed hydrograph, because the basin loss rates necessary for computing the hydrographs are unknown, and cannot easily be determined without bias. However, a relative comparison can be made, as seen in the computed hydrographs depicted in Figure 3. The computed hydrographs were generated using typical loss rates for this area. Unfortunately, the observed hydrograph was computed from changes in reservoir elevation and does not provide an accurate definition of the inflow. The figure does show that, for this event, the hydrograph computed from the calibrated radar data is much closer to the observed hydrograph than that obtained using rain gage data only.

Conclusion

The use of accumulated rainfall data from the National Weather Service's RADAP II radar, adjusted with rain gage data, may give a better spatial estimation of rainfall over a watershed than would be obtained from gage data only. Because of the several

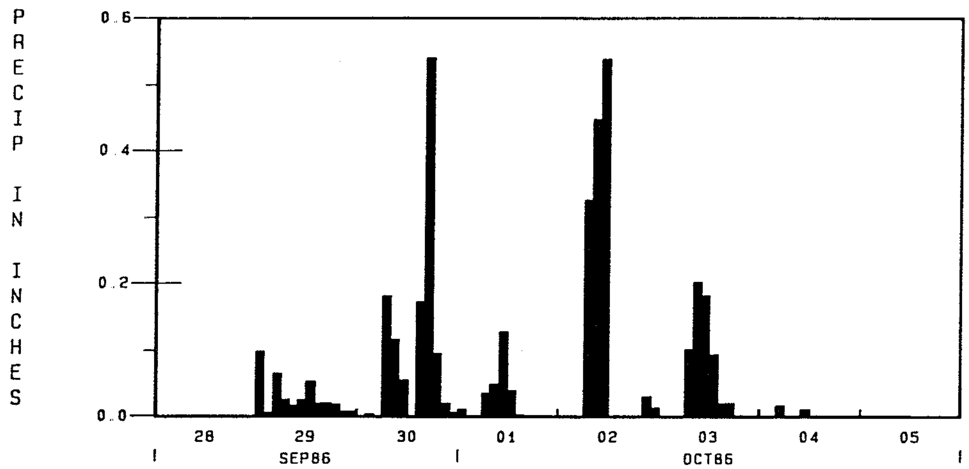


Figure 1(a). Waurika Lake Basin Hyetograph from Calibrated Radar Data (total volume: 3.79 inches).

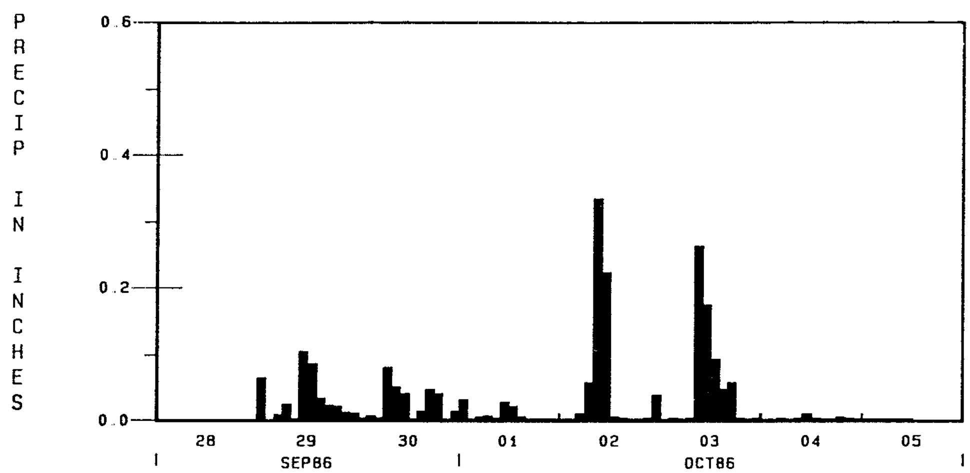
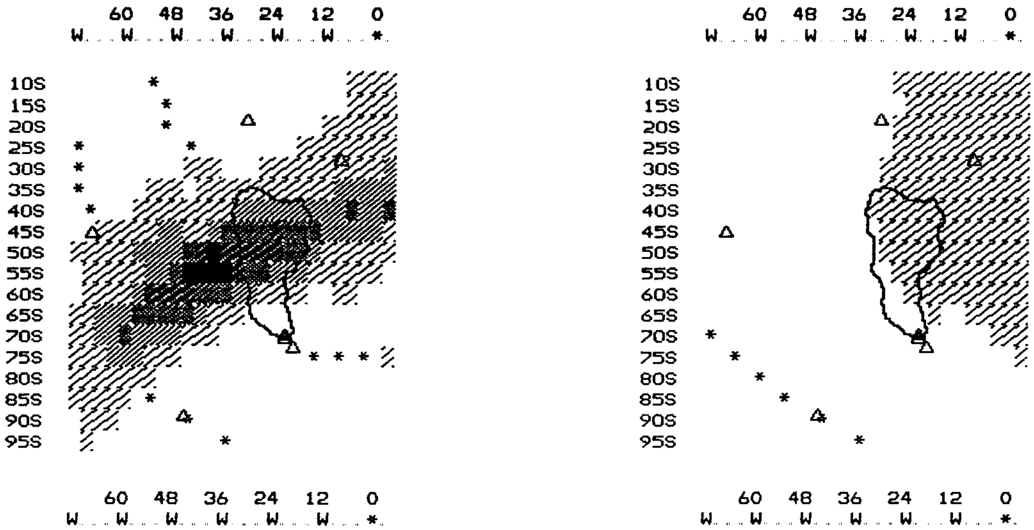


Figure 1(b). Waurika Lake Basin Hyetograph from Rain Gage Data (total volume: 2.19 inches).



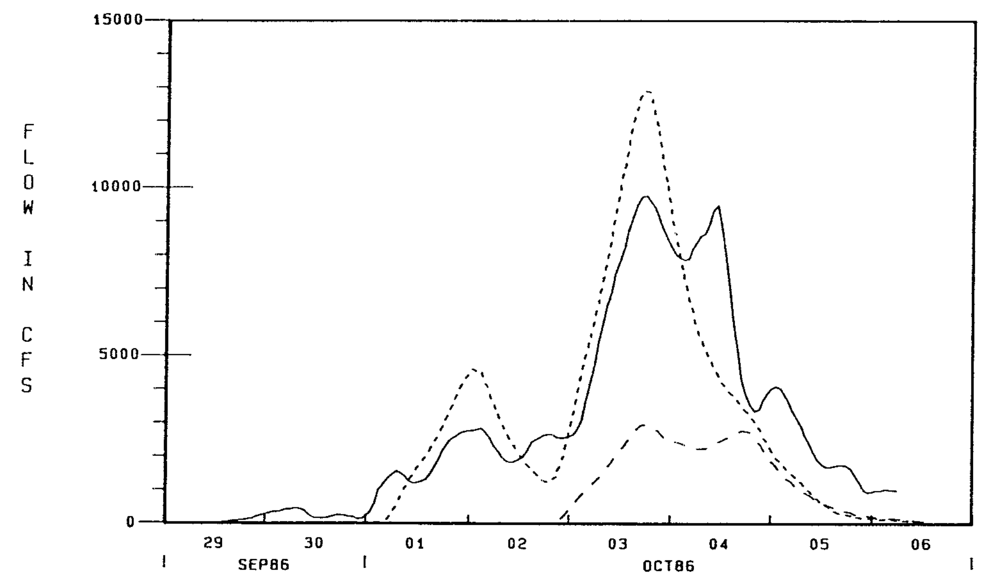
(a) Calibrated Radar

(b) Rain Gage Data Only

Legend

0.05 - 0.35 Inch
0.36 - 0.70 Inch
0.71 - 1.05 Inches
1.06 - 1.40 Inches
1.41 - 1.75 Inches
1.75 - 1.99 Inches

Figure 2. Rainfall Over the Waurika Lake Basin for 1500 to 1800 Hours on September 30, 1986 (distances in nautical miles west and south of the radar).



Inflow from Calibrated Radar Data
Inflow from Rain Gage Data
Observed Inflow (from Elevations)

Figure 3. Computed and Observed Inflows (observed inflow calculated from reservoir elevations).

possible errors in the radar-rainfall data, and assumptions made for the data calibration, the data and each calibration must be evaluated by an experienced analyst. Failure to properly evaluate the calibration could lead to erroneous results.

The National Weather Service is currently working on the NEXRAD program which will provide products similar to those obtained from RADAP II, but of superior quality. The NEXRAD program will use algorithms which will attempt to correct for radar errors, and will include a calibration procedure using rain gage information (Ahnert, et al., 1983; Hudlow, et al., 1983). This advancement should provide the hydrologist a valuable tool for river-flow forecasting.

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References

Ahnert, P., M. Hudlow, E. Johnson, and D. Green: Proposed "on-site" precipitation processing system for NEXRAD. Preprints, 21st Conference on Radar Meteorology, AMS, Boston, Mass., 1983, 378-384.

Battan, L.: Radar Observations of the Atmosphere. University of Chicago Press, 1973, 324 pp.

Brandes, E.: Optimizing rainfall estimates with the aid of radar. Journal of Applied Meteorology, 14, 1975, 1339-1345,

Cain, D., and P. Smith: Operational adjustment of radar estimated rainfall with rain gage data: A statistical evaluation. Preprints, 17th Conference on Radar Meteorology, AMS, Boston, Mass., 1976, 533-538.

Charley, W.: Weather Radar as an Aid to Real-Time Water Control. Masters of Science Thesis, University of California, Davis, Calif., 1986.

Greene, D., D. Nilsen, R. Saffle, D. Holmes, M. Hudlow, P. Ahnert: RADAP II, an interim radar data processor. Preprints, 21st Conference on Radar Meteorology, AMS, Boston, Mass., 1983, 404-408.

Hudlow, M., D. Greene, P. Ahnert, W. Krajewski, T. Sivaramakrishnan, and E. Johnson: Proposed off-site precipitation processing system for NEXRAD. Preprints, 21st Conference on Radar Meteorology, AMS, Boston, Mass., 1983, 394-403.

Hydrologic Engineering Center: HECDSS User's Guide and Utility Programs Manual. U.S. Army Corps of Engineers, Davis, California, 1985.

Saffle, R.: D/RADEX products and field operation. Preprints, 17th Conference on Radar Meteorology, AMS, Boston, Mass., 1976, 555-559.

Wilson, J.: Integration of radar and rain gage data for improved rainfall measurement. Journal of Applied Meteorology, 9, 1970, 489-497.

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