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USE OF RADAR DATA FROM D/RADEX FOR OPERATIONAL HYDROLOGY

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1. INTRODUCTION

One of the most fruitful advances in river and flood forecasting will be achieved by acquiring improved precipitation inputs for streamflow synthesis. Precipitation data of sufficient temporal and spatial detail (as digitized radar data can provide) are required to accurately synthesize the temporal distribution and quantity of streamflow. The precipitation data must also be made available to the river forecaster in approximately real-time to ensure a "timely" forecast. The optimum spatial resolution of the precipitation inputs changes as a function of variability in time and space of the precipitation, the magnitude of the precipitation event, and the hydraulic and geometric characteristics of the watershed--especially the area of the watershed above the forecast point. The operational rain-gage network often fails to provide the spatial resolution required to adequately specify the rainfall inputs to a runoff model. This is particularly true for geographic regions which receive a significant portion of their rainfall from convective and thunderstorm activity.

The weather radar has been an important sensor for operational hydrology, since it provides the capability to record the distribution of precipitation almost continuously in time and space within the domain useful for hydrologic applications. Until recently, its operational use has been limited due to the laborious task of manually processing radar data. Now, after several years of effort, an automatic radar-signal processing and data communication system designed for National Weather Service (NWS) operations is complete and will be tested and evaluated as part of the "Digitized Radar Experiments" (D/RADEX). Each automatic system basically consists of a signal processor, an analog to digital converter, a mini-computer for editing and preprocessing, a dual magnetic-tape system, and communication equipment. Figure 1 is a block diagram illustrating the arrangement of the basic components of the data-processing system.

For D/RADEX, WSR-57 (10cm) radars located at Monnett, Mo., Kansas City, Mo., Oklahoma City, Okla., and Fort Worth, Tex., were implemented the Spring of 1972 with processing and communication hardware. Figure 2 illustrates the radar network for D/RADEX. The radii of the circles are 125 n mi., which is the maximum range that radar data are collected for D/RADEX. Also shown in figure 2 are areas of the River Forecast Centers (RFC's) which fall within the D/RADEX net. These three RFC's, located at Kansas City, Tulsa, and Fort Worth, are contributing to the objectives of D/RADEX by providing streamflow verifications and by furnishing evaluations of the benefits gained from operational use of radar precipitation data.

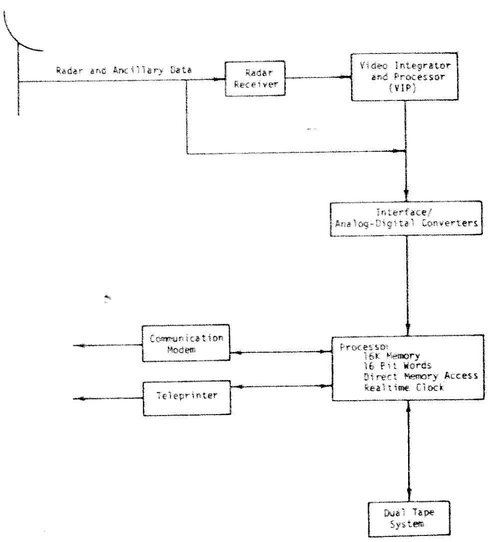

FIGURE 1. The D/RADEX Hardware Configuration.

The purpose of D/RADEX is to test and evaluate an automatic system for processing and transmitting radar data in real-time for operational applications. The purpose of this paper is to describe the operational experiments which comprise the radar hydrology subprogram of D/RADEX. Its scope is confined to the realm of radar hydrology as it applies to D/RADEX. Other authors have traced the history and considered the future of automatic radar systems which can provide real-time meteorological and hydrological services (e.g., see Flanders and Bigler (1971) and Kessler and Wilson (1971)). For additional information pertaining to D/RADEX, refer to other papers in this proceedings of the 15th Weather Radar Conference and see Bigler, McGrew, and St. Clair (1970) and McGrew (1970).

The exact configuration of the automated system probably will change with time as the system is updated to remain abreast of the "state of the art"--much will be learned from D/RADEX. Evaluation and feedback from the RFC's and the field radar units will be invaluable, since these evaluations will be based on the performance of the system under operational conditions.

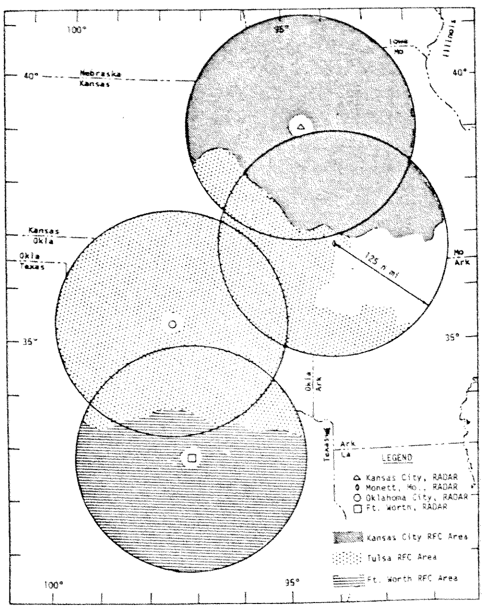

FIGURE 2. D/RADEX Network and RFC Coverages.

2. TREATMENT OF DIGITAL RADAR DATA

The executive software (EXEC) used with the 16K mini-computer illustrated in figure 1 receives and packs each sweep of digital radar data into core--making the data readily accessible for input to the hydrology subroutine (HYDRO). From the 256 levels (8 bits) which constitute the complete set of intensities available from the hardware system, EXEC extracts 10 threshold levels which are stored in core for use by HYDRO. All 256 levels or any portion thereof are available from the D/RADEX system, and the D/RADEX scientific program provides an option for routine archiving of all 256 levels for post analysis. However, for the real-time operational experiment in hydrology, 10 of the 256 levels are considered sufficient to define the rainfall regime. The 10 threshold levels are selected to give approximately 6 db steps beginning at the minimum detectable signal.

The radar video is digitized at a spatial resolution of 2 degrees in azimuth by 1 n mi in range. Two degrees is the beam width of the WSR-57 radar. One can consider the digital array to consist of data bins of size 2° x 1 n mi and each data bin contains an integer value between 0 and 9 (10 levels).

Through the use of the radar equations and an expression relating rainfall rate (R) to the reflectivity factor (Z), the digital intensity value can be transformed to an estimate for rainfall rate. Presently, $Z = 200R^{1.6}$ is used for the hydrologic calculations in D/RADEX, since this relationship is frequently cited as being representative of many rainfall situations. If future experience prescribes, the Z-R relationship may be altered to conform with the rainfall climatology of the D/RADEX area.

The rainfall rates derived from the procedure described in the preceding paragraph are used, unadjusted out to ranges of 70 n mi, for deriving mean-basin precipitations. Due to the likelihood of incomplete beam filling at ranges beyond 70 n mi, an empirical range-adjustment factor is applied to the digital values falling in those data bins beyond 70 n mi. The adjustment factor increases exponentially from 1.0 at 70 n mi to about 4.5 at 125 n mi.

As can be surmised from foregoing discussions, the crux of the operational hydrology experiment for D/RADEX consists of deriving time integrated and spatially averaged precipitation estimates from the radar data. The fundamental computational algorithm can best be illustrated with an example. Figure 3 shows the radar data bins which fall within a sub-watershed located in the Ft. Worth area. This is a drainage area for Clear Creek which lies north-north west of Ft. Worth, just outside the ground clutter pattern.

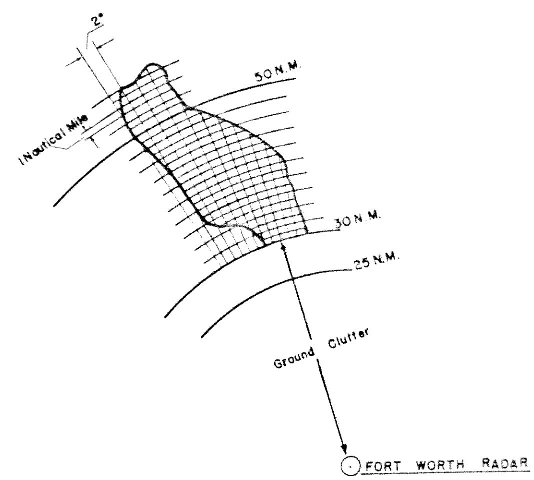

FIGURE 3. Illustration of the Radar Data Bins (2° x 1 n mi) Contained in the Clear Creek Watershed near Ft. Worth, Texas.

For this example, the total number of bins contained within the boundary of the watershed is about 170. After converting the radar intensity digits into rainfall rates by the methods discussed previously, the average precipitation flux over the watershed is given by

$$\overline{R} = \sum_{i=1}^{170} R_i/170 \quad , \qquad (1)$$

where R_i is the rainfall rate for the ith radar data bin. Equation (1) gives the spatially averaged rainfall rate for an instant in time. To obtain the total amount of precipitation deposited during an interval of time, trapezoidal integration is applied, giving

$$\overline{P} = \frac{(\overline{R}_1 + \overline{R}_2)\Delta T}{2} \quad , \qquad (2)$$

where $\overline{P}$ is the accumulative precipitation deposited from Time 1 to Time 2 over the watershed, $\overline{R}_1$ and $\overline{R}_2$ the average rainfall rates for Time 1 and Time 2 respectively; and ΔT = Time 2 minus Time 1.

The validity of applying equation 2 depends on the magnitude of ΔT. It is assumed that equation (2) will provide useable results for up to 60 minutes for the size watersheds normally used in D/RADEX. However, it must be realized that the error due to an inadequate sampling rate can increase significantly once ΔT exceeds about 15 minutes (see Wilson, 1970). For normal operations in D/RADEX, ΔT will be set for 15 minutes. If due to equipment failure or other system interruption ΔT exceeds 60 minutes, no attempt will be made at deriving $\overline{P}$ values deposited during the missing period. For time gaps larger than one hour, linear interpolation and trapezoidal integration can result in such large errors that the numbers become invalid.

Actually, the software algorithm is designed to process the digital radar data one radial at a time and performs an accounting of the digits entering the solution of equation (1) for all watersheds intersecting the radial. The algorithm assigns the radar data to the appropriate watershed by comparing the location of the radar data bins to the polar-coordinate data defining the watershed boundaries which are stored on magnetic tape.

The computer program for the radar hydrology experiment was first written in Fortran IV language and was then converted to the machine language of the D/RADEX mini-computer. Figure 4 is a generalized flow chart illustrating the basic computational routine for the hydrology (HYDRO) program. The HYDRO program is called into action by the system executive (EXEC) program.

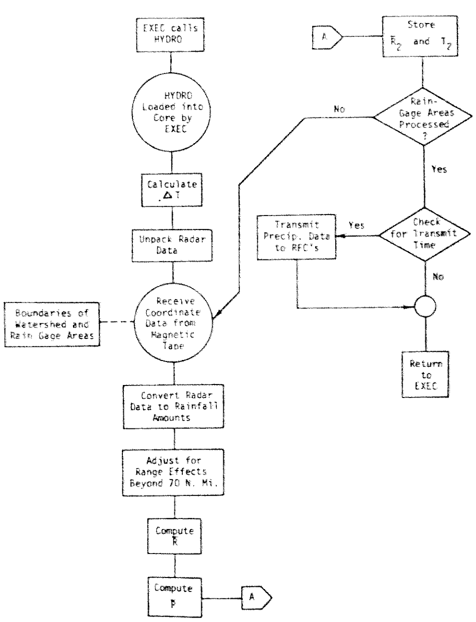

FIGURE 4. Abbreviated Flow Chart for the HYDRO Software - EXEC = Executive Routine.

Integral precipitation values can be derived for any subarea within the radar umbrella by simply providing the perimeter of the subarea in polar coordinates to the computer program. Although the watershed has been the fundamental area considered thus far, precipitation estimates can be derived with identical procedures for any geometric pattern. For example, it is planned to subjectively compare rain-gage data for a point to radar data averaged over a small circle (4 n mi radius) centered on the rain gage. The procedures employed for deriving the rainfall amounts deposited within the circular areas are identical to the ones presented above for watershed areas.

3. CHARACTERISTICS OF WATERSHED SUBAREAS

Figure 5, which depicts the boundaries of the Ft. Worth watersheds that lie under the radar "umbrella", provides an example of the manner in which the scope coverage is subdivided into areas according to hydrologic requirements. There are a total of 75 watersheds in the Ft. Worth radar area that are within the forecast network of the Ft. Worth RFC. The average size of the Ft. Worth watersheds is approximately 400 $(n\ mi)^2$ and they range in size from about 150 $(n\ mi)^2$ up to 1500 $(n\ mi)^2$.

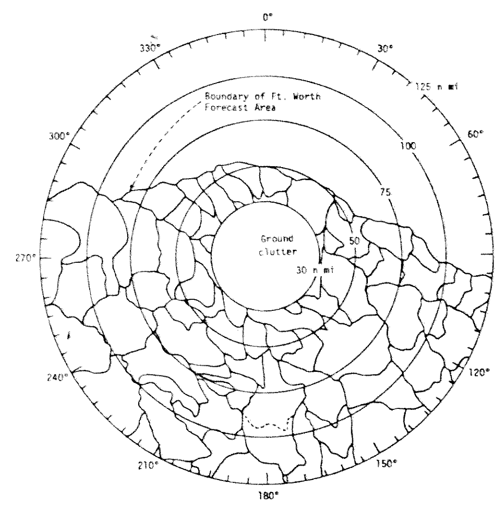

FIGURE 5. Map Illustrating the Boundaries of the 75 Watersheds (irregular lines) Which Lie Within the Ft. Worth RFC Network and the Ft. Worth Radar Umbrella.

In addition to the 75 watershed subareas shown in figure 5, there are approximately 625 watersheds or sub-zones of watersheds which are located within the portions of the Kansas City and Tulsa RFC forecast regions that lie inside the D/RADEX network (see figure 2). Thus, the subareas in the D/RADEX network (for which mean precipitation estimates are derived) total approximately 700 and the average size including all subareas is around 200 $(n\ mi)^2$. This translates to a total hydrologic coverage of about 140,000 $(n\ mi)^2$ for the entire D/RADEX network.

Many of the watersheds in the Tulsa RFC area are further subdivided into zones bounded by isochrones. The isochrones depict estimates of the times required for water on the surface at various locations in the catchment to reach the outflow point of the catchment. The isochronal subdivisions within a watershed allow for inclusion of greater spatial detail in the precipitation inputs to streamflow synthesis. This "distributive" approach as opposed to the unit-hydrograph concept can yield improved simulations provided the requisite precipitation inputs are available. Hudlow and Clark (1968) have demonstrated the value of radar inputs and distributive modeling for improving the "timing" of a streamflow forecast, when the rainfall is nonuniformly distributed over the catchment.

Due to the widely varying physiographic and geometric characteristics among the many watersheds in the D/RADEX network, valuable insight will be gained concerning the relationships between watershed characteristics and overall catchment response to rainfall inputs from radar. Also, by performing analyses for selected watersheds located at different ranges from the radar sites, it will be possible to evaluate the hydrologic efficiency of the radar as a function of range.

4. EXAMPLE OUTPUTS AND SYSTEM EVALUATION

In this section a radar-echo pattern which was selected for testing and "debugging" the HYDRO software is used to illustrate the type of outputs which are obtainable from the D/RADEX system. Examples of hydrologic D/RADEX products from the RFC's are also included.

Figure 6 is a matrix plot of digital radar data collected with the radar system located at Fort Worth. These data are from a moderately intense squall line which moved through the Fort Worth area on the night of December 14, 1971. The matrix of digital radar data shown in figure 6 was obtained by transforming the B-scan data (2° X 1 n mi bins) into a rectangular matrix of radar intensities. Each of the data bins in the rectangular format is 3 n mi X 3 n mi. The conversion from B-scan to rectangular format is accomplished with a software subroutine of EXEC. A radar operator can call for a B-scan or a rectangular matrix output at the end of the data collection cycle by simply keying the teletypewriter.

The data presented in figure 6 are unequally compressed in the x and y direction due to the characteristics of the teleprinter, i.e., 10 characters per inch in the horizontal versus 6 characters per inch in the vertical--thus producing the distorted presentation. Figure 6 is shown only for illustrative purposes. The HYDRO program uses the B-scan digital data for deriving the hydrologic products.

For a test case it is assumed that the pattern shown in figure 6 persists without translation for a 3-hour period. This is an unrealistic characterization of the manner in which the storm actually behaved during the 3-hour period. However, this assumption does provide a hypothetical 3-hour event which can be processed manually with relative ease, since solutions to the radar and rainfall equations are necessary for only one sweep of radar data. Thus, this hypothetical case is excellent for testing the HYDRO computer program.

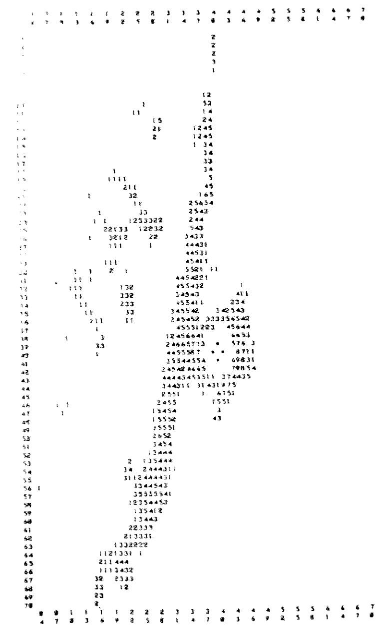

FIGURE 6. x-y Matrix Presentation (each character = 3 n mi square) of Radar Intensity Values for a Squall Line which Moved Through the Ft. Worth Area on the Night of December 14 and 15, 1971.

Figure 7 shows the teletype message containing the output from the test case described above and is an example of the standard message which is transmitted to the RFC's in real-time. This standard message may be amended to identify missing observations and periods of anomalous propagation. The rainfall amounts are in units, tenths, and hundredths of inches. There are 15 watershed subareas per line in the output, and the watersheds are listed sequentially according to a numbering identification scheme. If no watersheds on a given line received 0.005 inches of rain or more, the entire line is deleted. The lines are numbered line 1, line 2, etc., and, in the case of Fort Worth, all 75 watersheds can be contained on 5 lines (see figure 5).

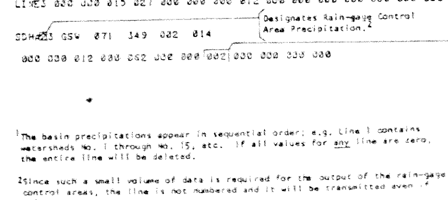

FIGURE 7. Example of Standard Message Output from HYDRO.

The existing HYDRO algorithm derives 3-hour accumulations of mean areal precipitation. Three-hour accumulations of rainfall provide acceptable time resolution for routine operational forecasting but are not entirely satisfactory for special phenomena such as the flash flood. The use of digital radar data for identification of potential flash floods is a subject which will be researched as a part of D/RADEX. An initial step toward acquiring the type of precipitation outputs required for prediction of flash floods will consist of including a provision in HYDRO which allows a radar operator to call for an output of the precipitation accumulators at any time. In this way, accumulations of areal precipitation for any ΔT down to about 15 minutes can be observed and intense, short-life events may be detected at the earliest possible stage.

The second portion of the message shown in figure 7 contains precipitation amounts derived from radar data for the rain-gage control areas described in Section 2.0. The radar rainfalls for the control circles are compared to point rain-gage data in a subjective manner by RFC personnel. Present evidence indicates that only in certain instances can quantitative adjustments based on these comparisons yield improved estimates of convective rainfall. Research is planned which will furnish additional knowledge, pertinent to the development of procedures for combining radar and rain-gage data. Hopefully, this research will lead to improved techniques for melding the two sources of data and acquiring the best overall precipitation product.

In the opinion of the author, it is unlikely that consistently meaningful adjustments can be applied to radar-rainfall estimates for time periods as short as 3 hours by "anchoring" to a few isolated rain gages, unless an objective analysis scheme can be developed which makes use of co-spectra between the temporal distribution of rain-gage data and the spatial distribution of radar data. A suitable objective analysis scheme for this application does not presently exist. The development of objective analysis procedures is an important ongoing part of D/RADEX, since ultimately it is expected that telemetered rain-gage data can be feed directly into the mini-computer located at the radar site where analysis could be performed in real-time.

Operationally, only a limited number of gages can be handled automatically within the D/RADEX system (probably no more than about 20 gages/radar). Therefore, it becomes quite important to deploy the available gages according to a network design which allows optimum benefit to be gained from integration of the radar and rain-gage data. For example, concentrated clusters of gages and fewer control areas may be preferable to a network design consisting of isolated and widely scattered rain gages.

An essential ingredient of any experiment is evaluation of the performance of the experimental software and/or hardware system. For the hydrology subprogram of D/RADEX, invaluable evaluation and feedback will come from the RFC's and the field radar units. To date, evaluations have been limited to a few cases. It is planned that the evaluations will include comparisons of areal rainfall estimates derived from radar data to those derived from rain-gage data. Also, streamflow synthesis for selected watersheds will be derived from: (1) rainfall inputs from operational rain-gage networks and (2) rainfall inputs from radar. Both will be compared to observed streamflow.

As part of D/RADEX, radar and rain-gage data will be compared over a dense rain-gage network in Oklahoma. Another approach, which can provide valuable insight into the relationships between radar and rain-gage data for areas in the D/RADEX network, consists of comparing daily totals of areal rainfall from the operational rain-gage nets to those derived from the radar data. An example of this type of comparison which was made at the Tulsa RFC for the watershed on the Clear Boggy Creek near Caney, Oklahoma, is shown in figure 8. In figure 8, the small numbers are 24-hour rain-gage totals for the stations marked by dots and the larger numbers, in the zones A through E, represent mean-zone accumulations of rainfall estimated from radar data during the same 24-hour period. The dashed lines are isochrones of equal travel time (see Section 3.).

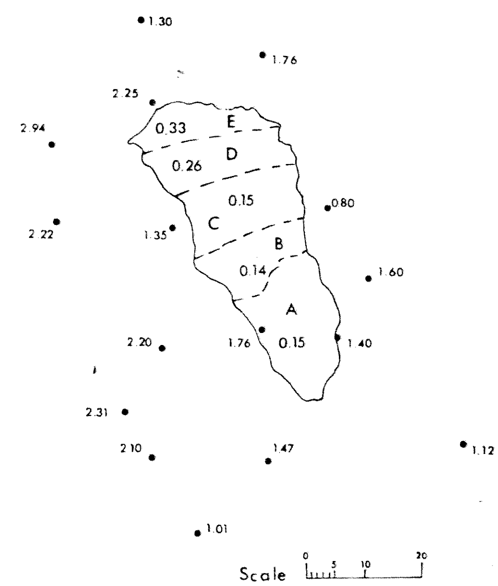

FIGURE 8. Plot of Rain-Gage Totals (small numbers) and Mean-Zone Precipitations derived from Oklahoma City Radar Data (large numbers) for a 24-Hour Period on May 11 and 12, 1972, on Clear Boggy Creek near Caney, Oklahoma.

Although not conclusive due to an inadequate number of gages inside the watershed, it is very probable that the radar estimates are substantially low. In fact, most cases considered in the limited number of comparisons made to date indicate that the magnitudes of the radar-rainfall estimates are noticeably smaller than those derived from rain-gage networks. The case presented in figure 8 illustrates one of the worst disagreements observed thus far. The apparent underestimates are not surprising. As pointed out by Jones and Bigler (1966, pp. 11-14), many previous investigators have observed the tendency for radar to underestimate the magnitudes of rainfall unless the theoretical radar equation is adjusted by a factor derived from an experimental comparison with independent data (e.g., with a rain-gage network). This vividly accents the need for combining radar and rain-gage data in order to acquire the best features from both sources of data. Examination of figure 8 illustrates that the radar is quite efficient in defining the spatial distribution of rainfall.

Figure 9 illustrates a comparison between a predicted hydrograph for a 48-hour period based on rainfall inputs from the Ft. Worth radar and one from an operational rain-gage network. These predicted hydrographs are for a gaging station on the Navasota River near Bryan, Texas. The hydrographs were derived at the Ft. Worth RFC by applying the estimates of surface runoff to the characteristic unit-hydrograph for the watershed. The area of the drainage above the forecast point is several hundred square miles.

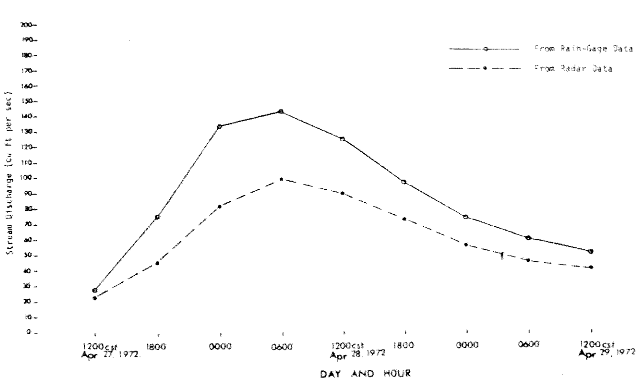

FIGURE 9. Comparison of Predicted Hydrographs for a Gaging Station on the Navasota River near Bryan, Texas, as Derived from Rain-Gage and Radar Inputs.

The example of the "radar hydrograph" shown in figure 9 demonstrates that real-time streamflow forecasts can be derived operationally from radar inputs. The closeness with which the hydrograph prediction matches the true streamflow can be assessed only by comparing to the observed streamflow data which were not available at the time of preparation of this paper. Comparisons with observed streamflow data, furnished by the U.S. Geological Survey for selected headwater areas, are planned as a future part of D/RADEX. The comparisons will be limited primarily to headwater areas to minimize the uncertainties of routing and because the radar data are most useful in headwater areas.

The rainfall inputs from radar and rain-gages, which were used in the derivation of the hydrographs shown in figure 9, are in much closer agreement than those for the previous example shown in figure 8. Figure 10 provides a comparison between rain-gage totals (small numbers) and the mean-basin precipitation estimated from radar data (0.56 inches) for a 24-hour period, lasting from 0600 CST on April 27, 1972, to 0600 CST on April 28, 1972. While the mean-basin precipitation from radar is somewhat lower than that given by the rain gages, agreement is to within a factor of 2.

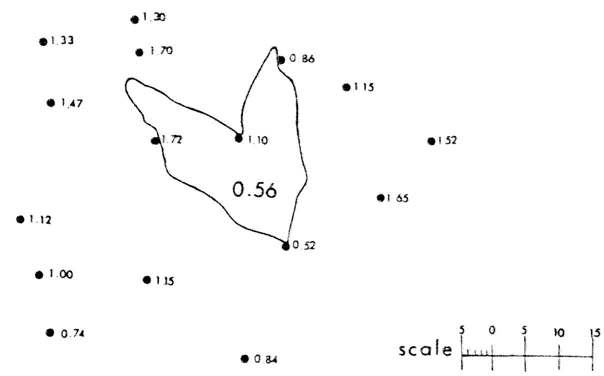

FIGURE 10. Plot of Rain-Gage Totals (small numbers) and the Mean-Watershed Precipitation Derived from Ft. Worth Radar Data (0.56 inches) for a 24-Hour Period on April 27 and 28, 1972, for a Watershed Located on the Navasota River near Bryan, Texas.

5. SUMMARY

Computer processing of digital radar data in real-time adds a new dimension of rainfall information for hydrologic applications. Figure 11 summarily illustrates how digital radar data are applied in the hydrology subprogram of D/RADEX.

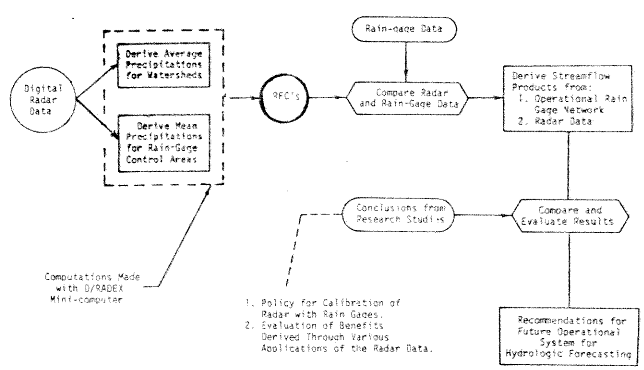

FIGURE 11. Block Diagram Summarizing the Operational Segment of the Hydrology Subprogram of D/RADEX.

Precipitation averaged over specified space and integrated for some time interval represents an essential ingredient for hydrologic forecasting. Radar is an excellent remote sensor for obtaining spatial definition and temporal integration since it provides the capability to sample almost continually in time and space. Now with the D/RADEX system, it becomes possible to process voluminous amounts of data in real-time with NWS radars; and thus, quantitative radar data can be effectively utilized in operational hydrology.

Briefly described, watershed precipitation products are derived from the D/RADEX system, and these products are input to the streamflow forecast models used by the RFC's located at Kansas City, Tulsa, and Ft. Worth. The streamflow results are compared to those derived from the conventional rain-gage inputs and, ultimately, to observed streamflow from selected watersheds. Also, radar-rainfall patterns are compared to those derived from rain-gage networks. D/RADEX provides a unique opportunity to benefit from evaluations and feedback from the RFC's and the field radar units, since these evaluations will be based on the performance of the system under operational conditions.

Even with limitations stemming from uncertainties in the absolute calibration, the use of radar as another tool for hydrologic forecasting undoubtedly will bring overall forecast improvements. Greater benefit could be realized from the radar data if a reliable independent source existed for calibrating the radar in an "absolute" manner. Accordingly, various possibilities will be examined, as an ongoing part of D/RADEX, for combining telemetered rain-gage and radar data. It is envisioned that as many as 20 rain gages per radar umbrella can be interrogated automatically by computer at the radar site. If reliable methodology can be developed to objectively adjust with computer the radar data for short-time spans (using telemetered rain gages), then hope exists for more accurately discerning small scale and intense flash-flood events.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Bigler, S. G., McGrew, R. G., and St. Clair, M., "An Experiment in Digitizing Weather Radar Data From A Four Station Network," Preprints for 14th Radar Meteorology Conference, American Meteorological Society, pp. 395-398, November 1970.

Flanders, A. F. and Bigler, S. G., "History and Development of Automatic Weather Radar Data Processing," Scientific Paper Presented at the Technical Conference of Hydrological and Meteorological Services, held from 28 September - 6 October 1970 in Geneva, contained in WMO publication No. 304, pp. 43-53, 1971.

Hudlow, Michael D. and Clark, Robert A., "The feasibility of Using Radar Measurements in the Synthesis of Flood Hydrographs," Preprints for 13th Radar Meteorology Conference, American Meteorological Society, pp. 412-415, August 1968.

Jones, R. F. and Bigler, S. G. (Chairmen) et al., "Use of Ground-Based Radar in Meteorology," World Meteorological Organization Technical Note No. 78, WMO No. 193. TP. 99, pp. 11-14, 1966.

Kessler E. and Wilson J. W., "Radar in An Automated National Weather System," Bulletin of the American Meteorological Society, pp. 1062-1069, November 1971.

McGrew, R. G., "Status of D/RADEX Planning - November 1, 1970," Internal Special Report No. 1, D/RADEX Project Office, National Weather Service - NOAA, Gramax Building, Silver Spring, Md., November 1970.

Wilson, J. W., "Operational Measurement of Rainfall with the WSR-57: Review and Recommendations," preprints for 14th Radar Meteorology Conference American Meteorological Society, pp. 257-263, November 1970.