International Seminar on Hydrology of Extremes
1-3 December, 1988
Roorkee (India)

FLOOD FORECASTING USING RADAR RAINFALL ESTIMATES

J. R. Donald E. D. Soulis N. Kouwen
E. A. McBean

Department of Civil Engineering, University of Waterloo, Waterloo
Ontario, N2L 3G1, Canada

SYNOPSIS

The ability of radar-rainfall estimates to improve real-time flood forecasting is currently under research at the University of Waterloo. Visual assessment of the input radar-rainfall field is an important task in the flood forecasting procedure. In this study, radar-rainfall images are displayed in order to examine the impact of clutter errors and a clutter removal technique on the estimate of the rainfall field and the subsequent flood forecast.

1. INTRODUCTION

Hydrologic simulation models are useful tools for the planning, design and operation of hydrologic systems. For example, simulation of the hydrologic system can aid in the planning for emergency response to flooding; the regulation of reservoirs; and the estimation of availability of adequate water supply.

The capabilities of a particular hydrologic model are determined by its structure and the quality of data input to the model [Link, 1983]. In his paper, Link divides the structure of a hydrologic model and its associated inputs into 3 categories:

1) meteorology;
2) physical watershed parameters; and,
3) hydrological processes.

In the hydrologic model, the physical watershed parameters are combined with the knowledge of the hydrologic processes to evaluate the response of the watershed to the meteorological inputs.

Historically, our knowledge of the behaviour of hydrologic processes and our ability to model the hydrologic response of a basin has evolved through parallel developments in concept, measurement capability and computational capability [Link, 1983]. In other words, as our ability to accurately define the hydrologic input parameters increases, so does our ability to evaluate the physical processes that are associated with the hydrological response of the watershed.

The emergence of relatively inexpensive computer technology has virtually eliminated the problem of computational power, and remotely sensed data, from satellite, airborne, and ground-based sensors, promises to provide greater definition of the meteorological and physical basin input parameters than there has been in the past.

The objective of this paper is to examine the use of ground-based microwave radar for the estimation of the major meteorological input, rainfall, and its subsequent application to flood flow forecasting. The spatial distribution of the rainfall field can be estimated from radar information and calibrated to point rain gauge rainfall values to yield a "continuous" rainfall field. It is the ability of the radar-rain gauge rainfall estimates to improve the real-time flow forecasting in large river basins that is currently under research at the University of Waterloo.

In the first part of the paper the basic radar rainfall estimation theory and the forecasting system structure are reviewed. In the second part of the paper, the visual inspection of the radar field used in the University of Waterloo research is carried out using image display software.

The objective of the viewing is three-fold. Firstly, the viewing of the rainfall fields serves as a visual verification of the input radar rainfall fields. Second, the radar rainfall fields are viewed after sequential application of the radar rainfall corrections. This provides insight into the impact of the various correction factors on the radar rainfall field. Finally, visual assessment of the radar rainfall field is utilized as a tool to interpret the flood forecasting results.

2.0 RADAR RAINFALL ESTIMATION

2.1 Theory

The concept of ground-based radar rainfall estimation is simple; an active radar installation emits a microwave beam and the beam interacts with raindrops. The resulting beam scatter and reflectance are measured and then interpreted to estimate the rainfall field. The estimated rainfall is then used as input to a flood forecasting model. A schematic of such a flood forecasting system is shown in Figure 1.

The two major characteristics of the radar signal that can be related to rainfall [Doviak, 1983] are:

1) reflectivity factor (Z); and,
2) attenuation rate (K).

The reflectivity factor is examined in this section as it is the only technique for measuring rainfall from the radar installations in operational use [Wilson and Brandes, 1979].

Backscatter radar power from precipitation is proportional to the summation of the sixth power of the raindrop diameters in a unit volume illuminated by a radar beam [Wilson and Brandes, 1979].

Wilson and Brandes [1979] point out that if the drop size distribution is known and vertical air motions are negligible there would be "no fundamental limitation to the accuracy of radar rainfall estimates". Thus, to estimate rainfall directly from radar then detailed estimates of the drop size distribution are required.

Doviak [1973] shows that drop size distributions tend to take an exponential form. If an exponential drop size distribution is assumed, the relationship between the reflectivity factor and rainfall intensity can be expressed as

$$Z = aR^b \tag{1}$$

where: a,b are parameters related to drop size distribution.

Equation (1) is known as the Z-R relationship.

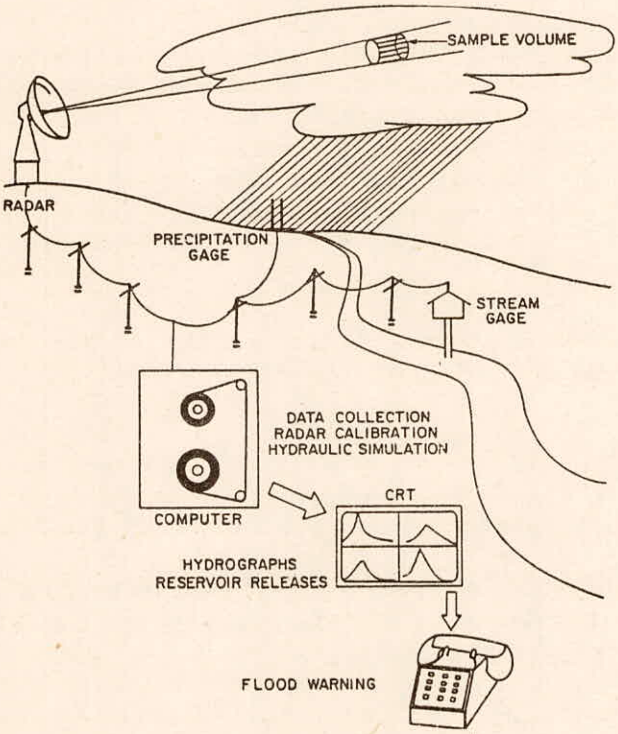

Figure 1 Schematic of Flood Forecasting System Structure (Kouwen, 1988)

Although the theory relating backscatter to rainfall rates is well-developed, the use of radar to directly measure rainfall has not been overly successful [Hildebrand, et al., 1979]. This is due to the difficulties in defining the parameters of the Z-R relationship in both time and space. There is no unique Z-R relationship, as drop size distributions are highly variable and can change dramatically from storm to storm as well as within the same storm.

Since there is no unique Z-R relationship, hydrologists must rely on average relationships derived theoretically; from drop size distributions; or, empirically [Hildebrand et al., 1979]. The high variability in the Z-R relationships has the unfortunate consequence that rainfall estimates derived from average Z-R relationships are only approximate, with errors on the order of a factor of two high or low [Wilson and Brandes, 1979]. Because of the difficulties in estimating rainfall directly from radar reflectivities, the radar rainfall estimates must be calibrated to rain gauge results. Calibration to rain gauges has proven to be the most effective way of improving radar data [Wilson and Brandes, 1979].

2.2 Errors

Radar reflectivity is also caused by targets other than raindrops, which results in errors which must be eliminated when estimating rainfall. The major factors which must be corrected prior to rainfall estimation are:

(1) beam blockage (occultation): the reflected signal is blocked from returning to the radar receiver after it has reflected from a target. This results in underestimation of rainfall.

(2) anomalous propagation: differential air densities can cause bending of the radar beam either away from or toward the earth. This results in erroneous interpretation of the rainfall field.

(3) attenuation: is the signal loss as the radar beam passes through rainfall particles. Attenuation affects shorter wavelengths to a greater degree than longer. A wavelength of 10 cm is recommended for rainfall radar.

(4) random error: the random error that can occur in reflectivity readings is reduced by averaging consecutive pulses in time (e.g. over a one hour period).

(5) bright-band detection: when the radar signal passes through a region of ice particles or hail, the reflected power is much higher than that of a rainfall field. This results in overestimation of the rainfall field.

(6) clutter: is reflectance of non-rainfall targets such as high hills, towers, buildings, airplanes, etc. If uncorrected, clutter will result in over-estimation of the rainfall field.

The work of Dalezios [1982] and Garland [1986] discuss the above errors in greater detail.

Another obvious limitation of radar rainfall estimation is that echo detection is rarely close to the ground [Doviak, 1973]. Thus, the measured rainfall field is subject to processes such as evaporation and wind before it reaches the ground, resulting in errors both in magnitude and in location of the rainfall field. Also, significant rainfall processes below the beam go undetected.

2.3 Calibration of Radar Rainfall to Rain Gauges

As discussed in Section 2.1, direct estimation of rainfall from radar reflectivity has not proved successful and hydrologists have turned to the use of multisensors; calibration of radar rainfall estimates to rain gauge measurements. This is a significant data management task for operational flood forecasting where estimates from the rain gauges and radar stations must be collected, coordinated and calibrated every hour. For example, in the radar-rain gauge flood forecasting system for the Grand River watershed approximately 6×10^8 data points must be processed each hour at the radar installation alone [Kouwen, 1988].

The technique presented by Brandes [1975], and minor variations of it, has been used in most radar-rain gauge calibration applications to date. The technique is described by Wilson and Brandes [1979] as a plane-fitting technique in which radar observations are "moulded to gauge observations ... while retaining the radar-indicated precipitation variance between gauges". The calibration technique reduces the impact of the Z-R relationship on the magnitude of the rainfall estimate, as rain gauge values are used to adjust the radar estimates [Brandes, 1975]. The mathematical details of the calibration technique are contained in the work of Brandes [1975].

3. THE RADAR RAINFALL IMAGE

3.1 Background

The use of radar rainfall estimates for real-time flood flow forecasting is currently under research at the University of Waterloo [Kouwen, 1988]. The study area is the Grand River watershed, upstream from Galt, Ontario, and is shown in Figure 2. Radar rainfall reflectance data is available for this area from the Woodbridge radar installation, located 40 kilometers east of the watershed. Images from selected hours of a 36-hour storm event that occurred in May, 1976 are examined to show the impact that the various correction and calibration techniques have on the radar rainfall field.

3.2 Preprocessing

The raw radar data are in the form of reflected power for radar scans over a range of elevation angles, azimuths and distances from the radar installation. Programs have been developed to convert the reflectance values into rainfall intensities for use in flood flow forecasting. The raw radar data are extracted for the azimuths and ranges that encompass the Grand River watershed for the lowest radar elevation angle, 0.5 degrees above the horizon [Kouwen, 1988; Garland, 1986]. The lowest scanning angle is hypothesized to provide the best information regarding the rain which reaches the ground.

The radar data are then converted from polar to cartesian coordinates. From this cartesian grid radar rainfall intensities were calculated at a resolution of 2 km by 2 km. This results in 40x50 pixel grid (80x100 km) over the Grand River watershed, with mercator eastings ranging from 500 to 580 km; and northings from 4800 to 4900 km. In order to see the radar rainfall detail on the video screen, the 40x50 grid was expanded five-fold. Bilinear interpolation was used to assign values to each of the pixels in the expanded image. To assist in the interpretation of the radar images, the watershed outline as well as a 20 by 20 kilometer grid is displayed over each image. The radar data are not filtered before Brandes' calibration technique is applied. This is consistent with the rainfall fields used in the radar rainfall flood forecasting research at the University of Waterloo.

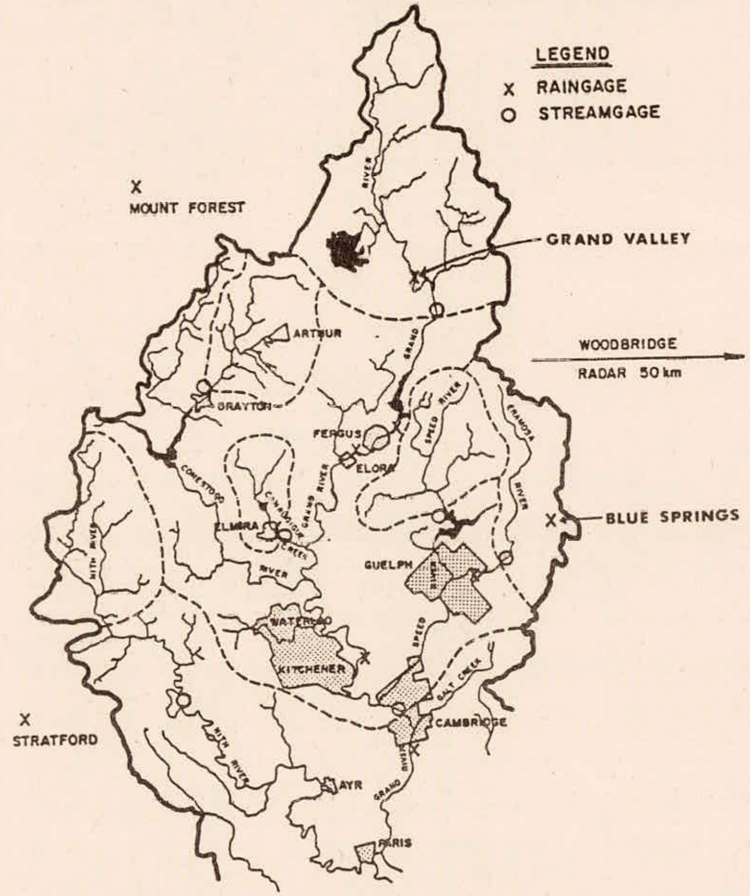

Figure 2 The Grand River Watershed (Kouwen, 1988)

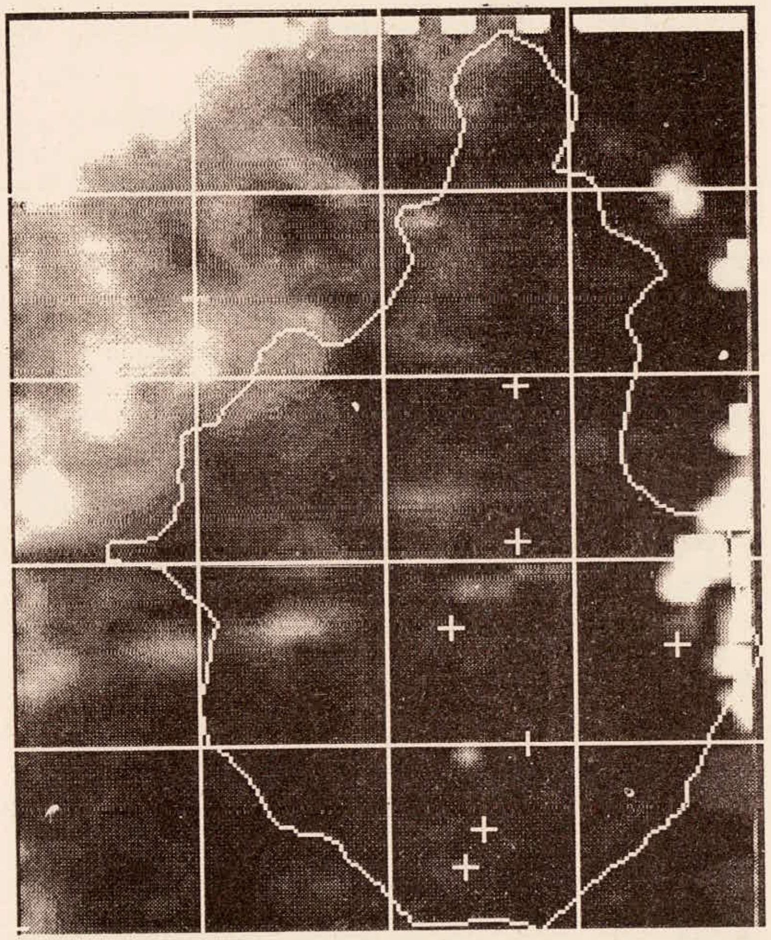

Figure 3 Raw Radar Rainfall Field May 5, 1976, 2200 hrs

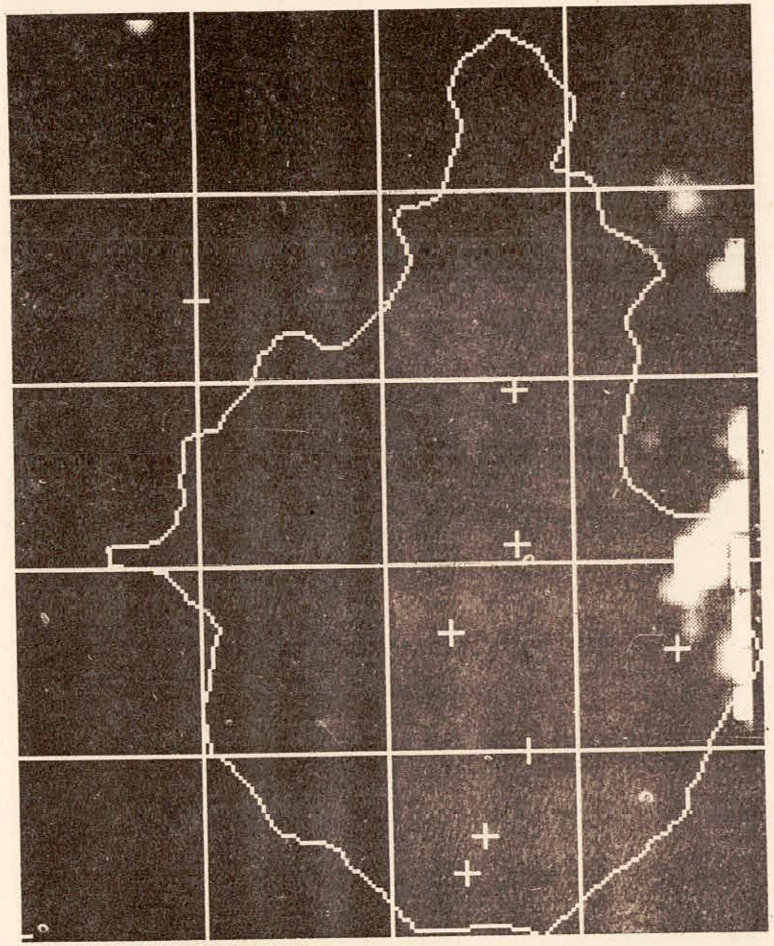

Figure 4 Clutter Field
May 7, 1976, 0600 hrs

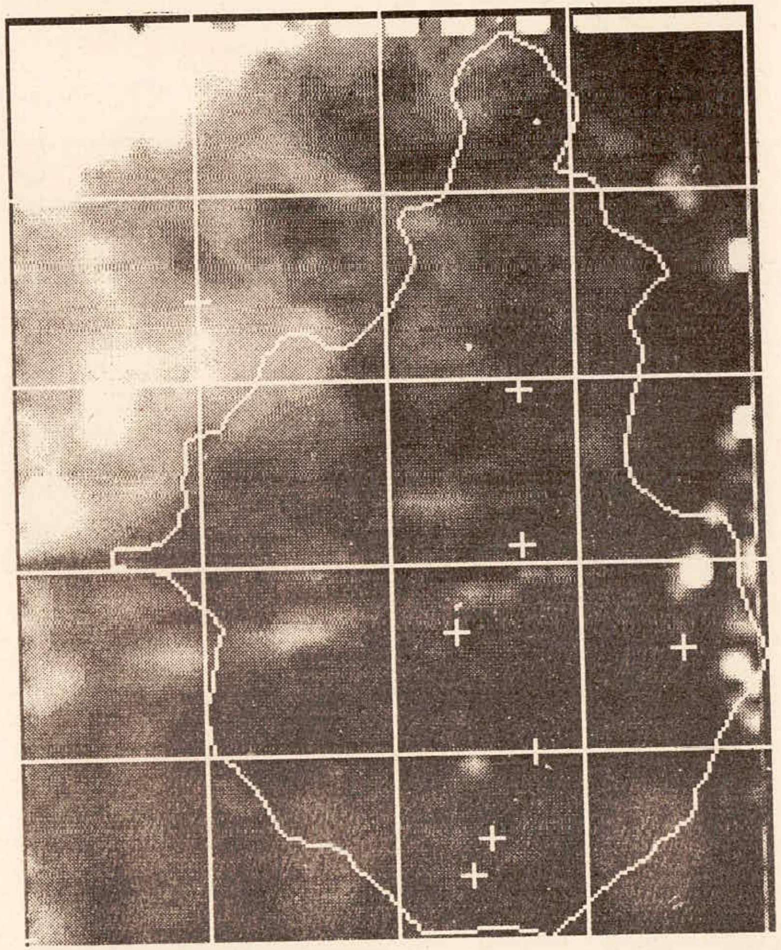

Figure 5 Clutter-Corrected Radar Rainfall Field
May 5, 1976, 2200 hrs

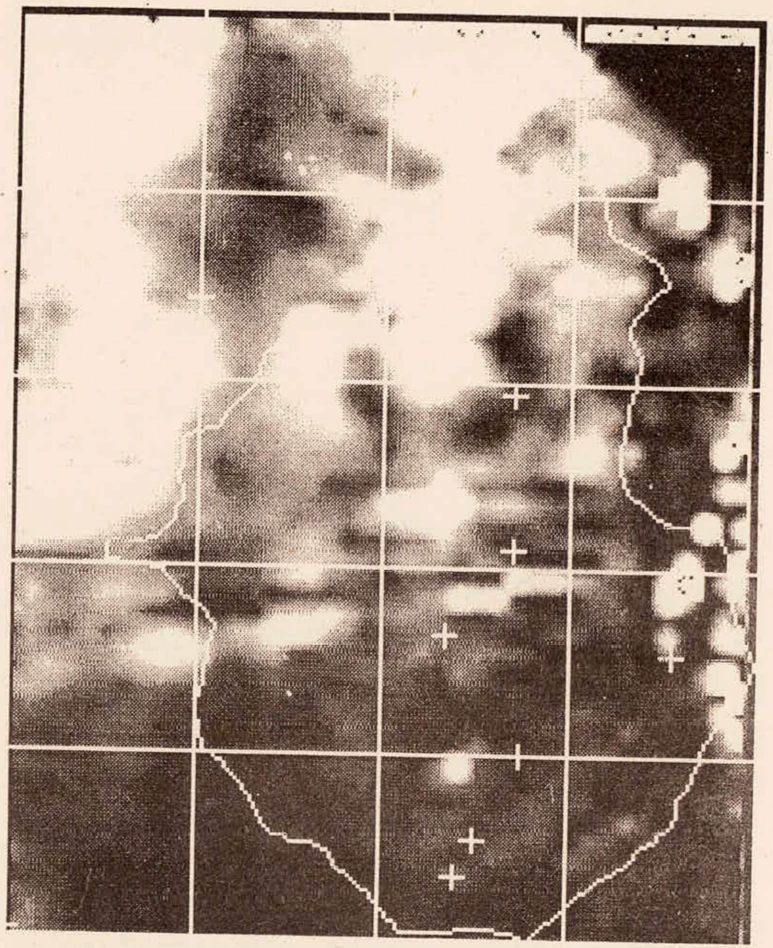

Figure 6 Calibrated Radar Rainfall Field
May 5, 1976, 2200 hrs

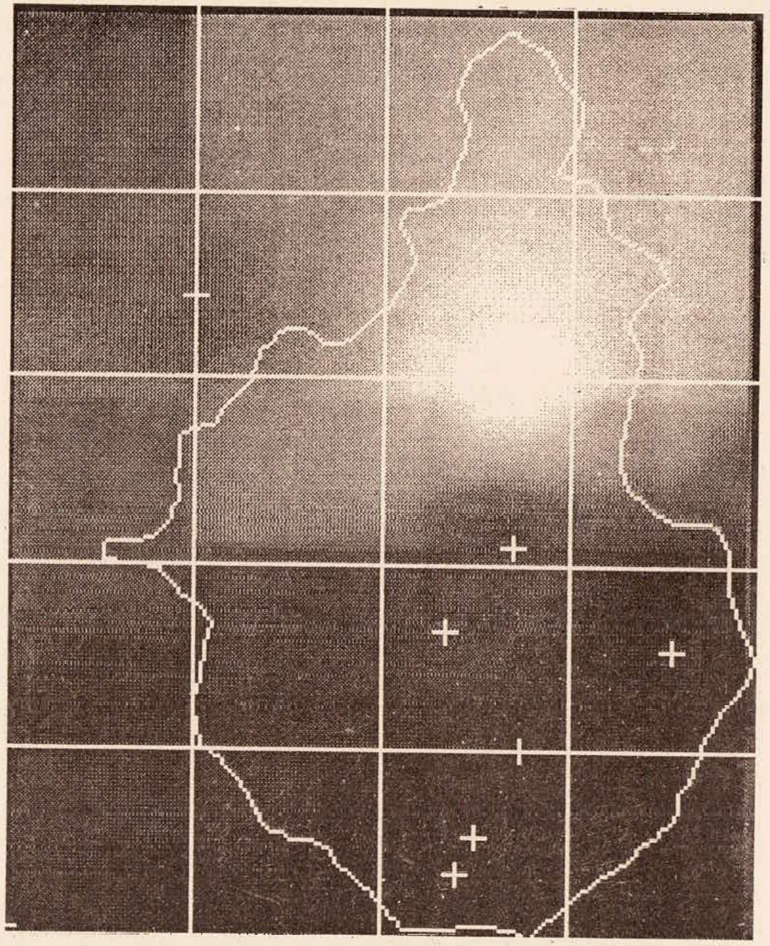

Figure 7 Gauge-Estimated Rainfall Field
May 5, 1976, 2200 hrs

3.3 Results

The sequence of images in Figures 3 through 6 show a progression of the corrections used in the processing of the radar rainfall field. The images are displayed in the following sequence:

(1) raw radar rainfall field (Figure 3)
(2) clutter removal (Figures 4 and 5)
(3) calibration to rain gauges (Figure 6)

In each of the images the outline of the portion of the Grand River watershed under study is shown as well as a 20x20 kilometer grid and the locations of the rain gauges used for calibration.

Figure 3 represents rainfall as estimated from the "raw" radar data. The Z-R relation for southern Ontario, with a=200 and b=1.43 [Kouwen, 1988], has been applied to the measured radar reflectivities to produce the radar rainfall field. The light and dark portions of the image correspond to high and low intensity radar-estimated rainfall respectively.

Figure 4 is a raw radar image for a minimal-rainfall hour (as measured at the gauges) which occurred near the end of the storm. Even though little rainfall is present during this hour, high intensity regions are indicated in the same general areas as found in the image in Figure 3. These stationary high intensity areas, measured during non-rainfall hours, are clutter regions caused by permanent targets such as hills and towers. Clutter must be removed from the radar field before rainfall variability can be adequately estimated.

Figure 5 is the radar rainfall image with the clutter removed. The methodology currently used to remove clutter, is to define the clutter field from a non-rainfall hour prior to the storm (Figure 4) and subtract this field from each of the subsequent hourly rainfall fields during the storm event. The high intensity area in the east central portion of the image is of particular interest as it is located within the watershed (in the Eramosa River subbasin) and thus will have a large impact on the rainfall estimation.

Figure 6 shows the radar rainfall image of Figure 5 calibrated to rain gauges using Brandes' method. Figure 7 is the rainfall as interpolated from the rain gauge data alone.

3.4 Discussion of Results

3.4.1 Clutter

Most clutter can be seen as high intensity backscatter values that occur during non-rainfall hours. In Figure 4 the clutter field for the May 1976 storm is shown. The clutter removal technique simply subtracts this field from all subsequent fields in the storm event to obtain hourly rainfall fields with the clutter removed.

The radar rainfall image with the clutter removed is displayed in Figure 5. There are two areas in the images where clutter is not sufficiently removed. The first is along the northern boundary of the image. These clutter points are not critical as they do not impact the Grand River watershed or any of the gauges used in calibration.

The second clutter area occurs within the Grand River watershed, north of the Blue Springs rain gauge in the Eramosa River sub-basin and is caused by an escarpment which runs through the region. The impact of this clutter region on the Eramosa River food forecasts is examined in Section 3.4.2.

In the following paragraphs, an approach that might be used to eliminate the residual clutter is described. As a first pass, the simple clutter hour technique could be applied. As a second pass, residual clutter regions might then be identified using a statistical classification scheme. This could be based on gradients, as clutter regions tend to be sharply defined; on the actual reflectance values; or both (i.e. a two-parameter classification scheme).

Once the residual clutter areas have been identified, they then could be eliminated and replaced with estimates interpolated from surrounding radar values. For example, if local values have an extreme gradient, then these high gradient values would be assumed to result from clutter. The values would then be removed and replaced with values interpolated from the remaining points.

The above methodology has the potential problem of eliminating intense localized storms. However, if the clutter regions are identified when the radar data are at fine resolution (i.e. grid sizes small with respect to typical storm cells) then this is not likely to be a problem. Also, if the storm occurs only over a very small portion of the watershed, the impact of the reduced rainfall estimate on the runoff forecast is not likely to be significant.

There is no doubt that the removal of clutter is a difficult problem in radar rainfall estimation. It is expected that the impact of clutter would decrease as the resolution of the radar grid is reduced. In this way, reflectance values are averaged over larger areas (say 10x10 km vs. 2x2 km). However, using large grid sizes is contrary to the concept of using radar in the first place. Radar is used to increase our spatial understanding of the rainfall input so that it can be used in distributed models. Without the detailed precipitation input it will be difficult to improve our understanding of the physical parameters related to watershed response.

3.4.2 Impact of Clutter on Flood Forecasts

The region of unresolved clutter occurs to the north of the Blue Springs rain gauge in the Eramosa River basin. Figure 8 is taken from Garland [1986] and shows the measured flows for the Eramosa River during storm events, as well as forecasted flows using radar-rain gauge calibrated data at grid resolutions of 2 and 5 kilometres.

Figure 8 shows the results for the May 1976 storm and the impact of the residual clutter on the flow forecast is evident. At a radar resolution of 2 kilometres the flood forecasting model greatly over-predicts the runoff due to high input rainfall intensities in the form of clutter. The impact of the averaging effect on the residual clutter can be seen in the 5 kilometre resolution as the forecast only slightly over-predicts the runoff. This over-estimation problem, due to clutter, is also apparent in other storm events.

3.4.3 Wind

As discussed in Section 2.2, wind is a process which has the potential to translate the rainfall field after it has been measured. Comparison of Figures 6 and 7 shows a marked displacement of rainfall between radar and rain gauge estimates. The gauge rainfall shows an intense rain field centred at the Grand Valley gauge in the northeast portion of the watershed, while the radar image shows the high rainfall to be centered in the northwest portion of the basin, approximately 40 kilometres to the west and 30 kilometers to the north of the gauge. This large displacement could be hypothesized due to wind or could be due to incorrect temporal synchronization of radar and rain gauge data.

The impact of the field displacement can be seen in the runoff forecast for the May 1976 event. Figure 9 [Garland, 1986] shows the flood forecast for the Conestoga River sub-basin. This basin is located just south of the centre of the storm as detected by radar. The forecasted flows are much greater than the measured flows for both the 2 and 5 kilometre radar resolutions. This over-estimation is likely due to the high rainfall estimates over the basin which have been translated east, out of the basin.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are made regarding the work carried out in this study:

1. Intense effort is required in the direction of rainfall field estimation. The extreme errors in the estimated radar rainfall field observed in this study, such as the residual clutter and field translation, indicate that flood forecasting cannot be expected to be improved without further refinement of the radar rainfall field. Further to this, without adequate input rainfall fields the improvement in our knowledge of the hydrologic process will be limited.

2. The radar images indicate that much error remains in the radar rainfall fields used in the radar rainfall flood forecasting models under research at the University of Waterloo. This can result in significant forecasting errors, as well as invalid parameter optimization in the forecasting model. For this reason, it is recommended that the radar rainfall field be "cleaned up" before it is calibrated to the rain gauges. For example, statistical classification techniques could be used to identify and eliminate residual clutter in the radar rainfall field before calibration to gauges is undertaken. At the very least, a spatial filter should be applied to the radar rainfall field, prior to the calibration stage, that removes some of the small scale fluctuations while leaving the general trends intact.

3. The radar rainfall field, once refined, should be used in conjunction with other remotely sensed basin parameters in order to increase the resolution of additional input parameters. In this way, true distributed

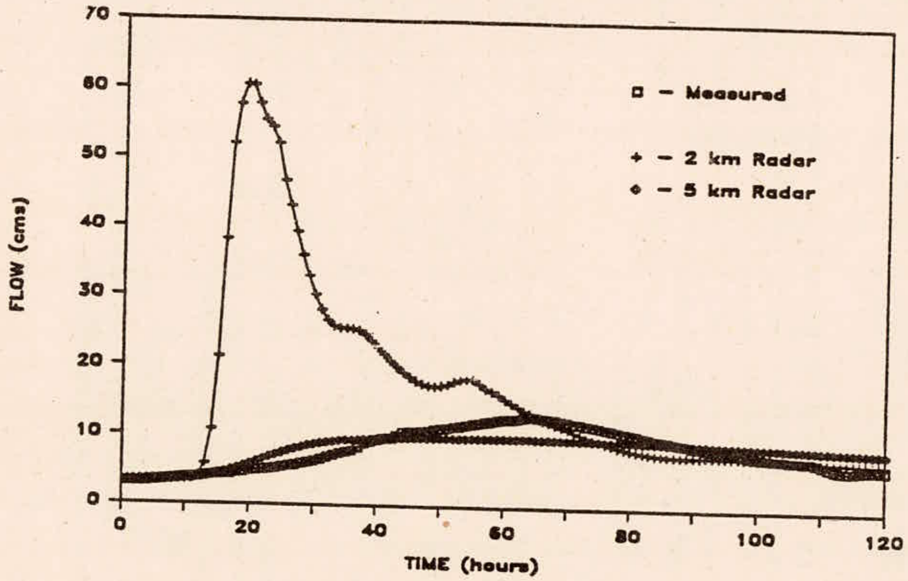

Figure 8 Eramosa River Flood Forecasting Results - May 1976 (Garland, 1986)

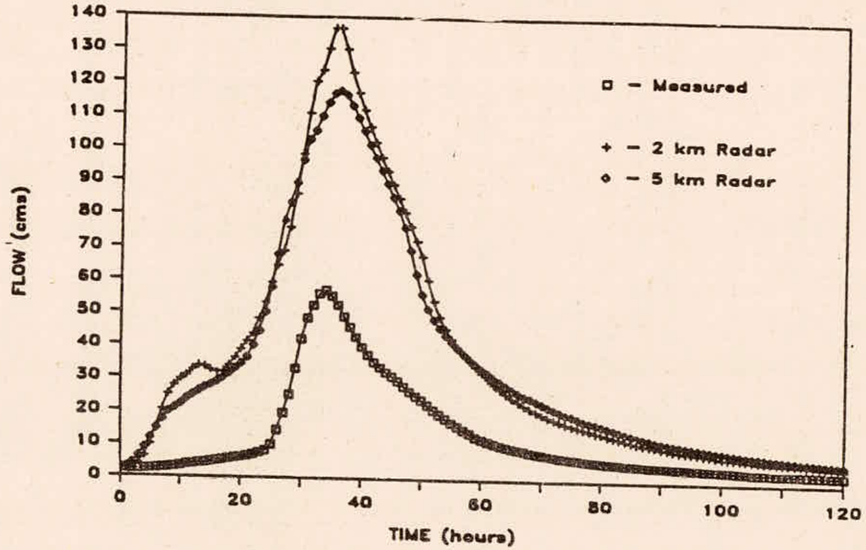

Figure 9 Conestoga River Flood Forecasting Results (Garland, 1986)

models can be developed. Examples of additional parameters that can or may be remotely sensed are land use/land cover, soil moisture and topography.

4. An interesting area for further application of image analysis would be to observe the spatial calibration field used in a rainfall event in order to examine the impact of clutter and other errors on the Brandes calibration technique.

5. An image processing procedure, that is not shown in this paper, is the plotting of image frequency histograms. Comparison of frequency histograms would show the character of the rainfall fields as well as reveal the potential for classification of residual clutter; high, medium and low intensity rainfall; as well as rainfall outliers.

6. The ultimate goal of the flood forecasting research at the University of Waterloo is to implement the radar-rainfall estimation/flood forecasting procedure on a real-time operational basis. This paper clearly shows the need for visual inspection of the radar rainfall field in interpreting the flood forecasts and recommends that the visual image processing procedure be included in any operational package.

5. REFERENCES

1. Brandes, E.A. (1975) "Optimizing Rainfall Estimates with the Aid of Radar", Journal of Applied Meteorology, Vol. 14, pp. 1339-1345.

2. Doviak, R.J. (1983) "Summary of Radar Rain Measurement Techniques", Journal of Climate and Applied Meteorology, Vol. 22, pp. 832-849.

3. Dalezios, N.R. (1982) "Real-Time Radar Rainfall Measurements for Hydrologic Modelling", Ph.D. Thesis, Dept. of Civil Engineering, University of Waterloo, Ontario.

4. Garland, G.A. (1986) "Resolution Considerations in Using Radar-Rainfall Data for Hydrological Modelling", M.A.Sc. Thesis, Dept. of Civil Engineering, University of Waterloo, Ontario.

5. Hildebrand, P.H., Tower, N. and Snell, M.R. (1979) "Measurement of Convective Mean Rainfall Over Small Areas Using High Density Raingauges and Radar", Journal of Applied Meteorology, 18, pp. 1316-1326.

6. Kouwen, N. (1988) "Watflood: A Micro-Computer Based Flood Forecasting System Based on Real-Time Weather Data", Canadian Water Resources Journal, Vol. 13, No. 1, pp. 62-77.

7. Link, L.E. (1983) "Compatibility of Present Hydrologic Models with Remotely Sensed Data", Seventeenth International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan.

8. Wilson, J.W. and E.A. Brandes(1979) "Radar Measurement of Rainfall - A Summary", Bulletin A.M.S., Vol. 60, No. 9, pp. 1048-1058.