Chapter 16

Weather Radar and Flood Forecasting

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For accurate flood forecasts, or any distributed hydrological modelling exercise, distributed rainfall data are required as the basic input. Smoothing of the rainfall data reduces peak flows due to the averaging of the rainfall-runoff process. Errors in rainfall sampling will reduce confidence in the optimized parameters. Locally intense rainfall might be missed entirely by rain gages or an intense rainfall in the immediate vicinity of a rain gage might lead to an over estimation of rainfall on a watershed. These problems all lead to the conclusion that rainfall rates measured with weather radar could greatly improve hydrological modelling and, as a result, flood forecasts.

Digital data from weather radar has been available for approximately 20 years but to date has not been widely applied to hydrologic applications. However, recent developments have made radar rainfall data readily available for hydrological applications, especially flood forecasting, in Southern Ontario. The purpose of this chapter is to describe a prototype on-line weather radar data acquisition system developed by the Atmospheric Environment Service (AES), Canada, for the flood forecasting purposes.

16.1 Weather Radar

16.1.1 A Radar Primer

Usually, weather radars are justified because of their ability to detect and

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track severe weather. Weather radar is used to route aircraft and issue warnings and advisories to mariners. Already, flood forecasters have access to weather radar through private companies but from this source, only visual, qualitative data is available. Such data can be of great value to forecasters because it allows them to judge the extent, duration, intensity and movement of rainfall systems and help evaluate whether a storm system presents a threat to their jurisdiction. Digital radar data allows for automation of flood forecasting. However, weather radar is a remote sensor and is subject to a range of errors. These sources of errors have been described and discussed in detail in the literature on this topic but for the sake of completeness are summarized again here.

Wilson (1976) provides a good discussion of the problems, which include:

Radar errors:	calibration of the electronic and mechanical components of the radar installation;
Signal attenuation:	loss of signal with distance travelled;
Terrain echoes (clutter):	false readings;
Beam blocking:	interception of the beam by terrain, and subsequent diminishing return signal strength from points beyond;
Z-R relationship:	drop size influences the radar-to-rainfall conversion;
Effects of winds:	vertical and horizontal movement of the air mass can change the rate and location of the rainfall after its measurement at some distance above the earth;
Evaporation:	water may evaporate before reaching the ground;
Bright band:	high reflectivity due to the presence of melting ice crystals in the atmosphere, giving false readings;
Anomalous propagation:	bending of the beam caused by atmospheric conditions, causing false readings at long range when the radar beam intersects the ground; and
Skipping:	Discontinuous imagery due to rapid cell movement.

A complete volumetric scan of the atmosphere is made approximately every ten minutes. For presentation purposes, a 1 km. CAPPI (Constant Altitude Plan Precipitation Index) is constructed that gives a horizontal slice of the rain field at the 1 km level above the earth's surface. The radar data used in this study is from the AES weather radar located at King City, Ontario, Canada (WKR). All errors listed above exist in the King City data, as they do with all weather radars.

Judicious siting of the radar and an appropriate choice of wavelength can reduce but not eliminate the problems.

The return signal is converted to rainfall rate using the standard Marshall-Palmer (1948) Z - R relationship:

$$Z = a R^b \quad (1)$$

where Z is the returned power in dbz and R is the rainfall rate in mm/hr. The reflectivity is highly sensitive to drop size and the same rainfall intensity may give very different reflectivity values if the drop size distribution of the rain is different. For this reason, the a and b coefficients may have to be assigned different values for different events, although it often varies wildly during an event. In the UK, Collier (1987) reports that differentiating between widespread rainfall and showers is possible.

Applications of radar data to runoff events over southern Ontario have shown that values of $a = 295$ and $b = 1.43$ give good results in southern Ontario when the full amount is used for summer rain and a 1/2 scale is used for winter rain. The values of $a = 1780$ and $b = 2.21$ are used to convert reflectivity to snowfall in terms of mm of water equivalent per hour (Crozier, Personal Communication, 1992).

Experience with radar in the UK (Collier, 1987) has shown that, if all observations with bright band conditions are excluded, the average percentage difference between hourly radar and rain gage amounts in widespread frontal rain is 60%. Hourly adjustment of the data using rain gage information reduced the difference to 45%. For convective rainfall, the numbers were 37% and 21% respectively. Similar ratios, and often larger values have been found by the writers for the Grand River watershed area in southern Ontario. Such discrepancies result in errors in flood forecasts that are unacceptable.

While the appearance of radar imagery is very reassuring, that is, the spatial characteristics of rainfall appear to be well represented, its application to flood forecasting has often been disappointing in the past. There are times when radar rainfall data yields flow predictions that are very good. Figure 16.1 is such an example. This event occurred on January 3 and 4, 1993 over Southern Ontario. There was some snow on the ground but snowmelt did not contribute substantially to the flows. Figure 16.1 compares flows computed with the WATFLOOD/SIMPLE flood forecasting system to the flow recorded at Cambridge/Galt, Ontario. The WATFLOOD/SIMPLE flood forecasting system is fully described elsewhere (Kouwen et al., 1993; Kouwen and Soulis, 1993). A brief summary follows in section 16.2.1.

The watershed above this point is 3520 km² and is covered by the King City radar. The radar data was collected in real-time with the data acquisition system described below. The winter Z - R relationship was used and the data was not adjusted by raingauges nor was the model re-calibrated for the event. The fit

Figure 16.1
Comparison of computed hydrograph to the measured hydrograph at Cambridge (Galt), January 3-10, 1993 (based on radar measurements of rainfall).

of the computed hydrograph is considered to be very good.

At other times, hydrographs calculated by the same method can exhibit large errors, pointing to the need for methods that can flag data that may be suspect due to one or other of the errors listed above having a dominant effect at a particular time: radar can not be blindly applied to flood forecasting.

16.1.2 Real-time Radar Data Acquisition System

Personnel at the AES Radar Observatory WKR in King City, Ontario Canada, have developed a low cost method of providing radar data to outside users. The minimum requirements at the radar station are a 386-based computer with a 200 Mb drive and a text-only monitor. In addition, a 9600 baud modem and dedicated telephone data line are required to give access to the data. Minimum requirements for accessing the data is another 386 with VGA colour graphics and a compatible 9600 baud modem.

The radar data acquisition system depends on four computer programs: 1) sender, 2) dialup, 3) replay and 4) data conversion. CAPPI (Constant Altitude Plan Precipitation Index) and RFA (Rainfall Accumulation) maps (or images)

are retained on the hard disk for eight days and a provision has been made to receive and replay maps in an archive directory. This feature allows study of past events that are available from the archive optical disks at WKR.

Once the radar data has been downloaded to the computer there are two utility programs that can replay the RFA maps in hourly time steps and create additional ASCII files or reconstruct ASCII files that may have been deleted. The replay program also has a zoom feature that allows closer inspection of rainfall rates at user specified locations. The ASCII files can then be used directly as input to a hydrologic model that can utilize rainfall data on a 2 km grid or the user can average the 2 km data over a watershed or a larger grid size.

Radar CAPPI's are provided in seven pixel levels on a logarithmic scale. The scale provides for 1 to 64 mm/hr for summer rain, 1 to 32 mm/hr for winter rain and for snow. On the other hand, RFA maps are provided in 29 levels of rainfall on a linear scale. The sender determines the highest rainfall intensity in the radar picture and adjusts the maximum scale to suit: 0.5 to 14.4, 1 to 29, 2 to 58, or 4 to 89 mm/hr. Any rainfall rate higher than 89 mm/hr is reported as 89 mm/hr. Figure 16.2 is an example of an RFA map for the area covered by the WKR radar.

Figure 16.2
Example of a one hour rainfall accumulation (RFA) map for southern Ontario.

Of special interest to hydrologists is the very textured nature of the map. This indicates that the rainfall accumulations vary greatly. Images such as these are the norm and one is left to wonder if ground-based rainfall gages are of any use for real-time flow forecasting or for that matter, for distributed hydrologic modelling.

The above method of reporting rainfall intensities is based on research conducted at the University of Waterloo that was aimed at determining the time and space requirements of rainfall data for flood forecasting in intermediately sized watersheds (say 100 to 10,000 km²) (Kouwen and Garland, 1988; Gorrie and Kouwen, 1977).

16.2 Hydrology

16.2.1 WATFLOOD Flood Forecasting System

The WATFLOOD/SIMPLE flood forecasting system is a set of computer programs that can integrate radar and raingauge rainfall data, streamflow and reservoir release data, and watershed land cover and topographic data to produce a flood forecast. A snow redistribution and melt component has also been included. The heart of the system is a hydrologic model called SIMPLE. The emphasis is on: real-time data acquisition; data checking, correction, and adjustment; reservoir operation; fast turn around and robustness with respect to missing data; and forecasts of flow and stage at damage locations.

The components of the hydrological model are as follows:

Interception - Interception of precipitation by vegetation is calculated in SIMPLE using an exponential relationship with accumulated precipitation (Linsley et al., 1949).

Surface Storage - The ASCE Manual of Engineering Practice No. 37 for the design of sanitary and storm sewers (ASCE, 1969) gives typical values of retention for various surface types.

Infiltration - The Green and Ampt formula (Green and Ampt, 1911) is used in SIMPLE because it represents the important physical aspects of the infiltration process, including surface detention.

Interflow - Infiltrated water first enters what is commonly referred to as the Upper Zone Storage (UZS). Water within this layer percolates downward or is exfiltrated to nearby water courses and is called interflow. In the model, percolation downward is ignored because in most cases when dealing with single rainfall events, the path from the UZS to the stream via the ground water reservoir is too long in duration to contribute appreciably to streamflow during the event. Interflow is represented by a linear storage-discharge relation.

Overland flow - When the infiltration capacity is exceeded by the water

supply and the depression storage has been satisfied, water is discharged to the channel drainage system. The relationship employed is based on the Manning formula.

Base flow - The base flow in SIMPLE is determined from a measured hydrograph at the basin outlet. The baseflow contributed by each basin sub-element is found simply by prorating it to the total basin area. A recession constant is used to gradually diminish the baseflow over the duration of the event being modeled.

Total runoff and routing - The total inflow to the river system is found by adding the surface runoff and the interflow from each of the six land cover classes to the base flow and inflow from upstream elements. This total flow is added to the element's channel storage for routing to the next element. The routing of water through the channel system is accomplished using a storage routing technique.

16.2.2 Grouped Response Units (GRU's)

In SIMPLE, runoff is calculated separately for areas having different land covers. A detailed land cover inventory is required for use as a basic input to the model. This data is readily obtained from remotely sensed data such as LANDSAT MSS or TM imagery.

A watershed is subdivided into computational elements, which function as sub-watersheds, and the per cent of each land cover class is used to weight the runoff produced in each element. Modelling parameters are associated with land cover and these parameters are fixed for a large geographic area. Other watershed characteristics such as topographic relief, channel slope, drainage pattern and drainage density are explicitly considered in the overland and channel routing algorithms. These characteristics are obtained from standard topographic mapping.

The computational element in SIMPLE is called the Grouped Response Unit (GRU). The element can be arranged in a grid format, as is done in SIMPLE or can be applied to sub-watersheds as was done for the Kootenay River in British Columbia, Canada (Kite and Kouwen, 1992). The GRU is derived from urban drainage practice, where runoff is calculated separately for pervious and impervious areas, then is summed and routed together.

16.3 Applying Radar - Case Studies

16.3.1 Hurricane Andrew Remnants

In this section, the results of applying radar data from the radar data acquisition system will be presented and discussed. The first event was the passing of the remnants of Hurricane Andrew through southern Ontario during

late August 1992 and the other was the entire month of November 1992, when three or four substantial rainfall events occurred with in the WKR radar coverage.

The hurricane Andrew event illustrates some of the difficulties associated with hydrologic modelling in the summer as opposed to modelling during the rest of the year, when vegetation is dormant and the soil is often saturated or frozen. The January 1993 event shown in Figure 16.1 shows an almost perfect agreement between computed (heavy line) and measured (lighter line) hydrographs. Figure 16.3 shows the measured and computed hydrographs at nine streamflow gauging stations in the Grand River Watershed for hurricane Andrew. The drainage areas represented in Figure 16.3 range from 125 to 3250 km² for Elmira and Galt respectively. This time, the fit at Galt, as well as at other stations, is not as good, probably due to the much greater variability of initial soil moisture, vegetation and channel roughness. In the model, channel roughness parameters are kept the same throughout the year but this topic needs further study.

Also, it appears that some rainfall was not detected, possibly due to variations in the Z - R relationship. The “bulge” in the rising limb of the measured hydrograph is not characteristic of the unit hydrograph for the Grand River at Galt so it could only have been caused by rainfall. It also appears on the hydrographs for West Montrose, Armstrong Mills and Elmira.

Figure 16.3
Grand River hydrographs for Hurricane Andrew.

An examination of hydrographs at other stations in the watershed indicates that variations in roughness may add to the problem because some of the computed hydrographs compare very well to the corresponding measured hydrographs while others do not. A good fit is obtained for watersheds where river routing is not a major factor because the channels are steep or not as vegetated.

16.3.2 Continuous Modelling

One of the most perplexing problems with event modelling deals with having to determine the initial values for the state variables such as the amount of water in transit in the river system, the amount of ground water storage and the soil moisture condition. For flood forecasting, a determination of initial soil moisture is very important for two reasons:

- 1) The wetness of the soil affects the total amount of surface runoff and the peak flow.
- 2) The time at which the hydrograph begins to rise and its initial rate of rise is very much dependent on initial soil moisture. This in turn directly affects the model's ability to carry out real-time adjustment of either soil moisture or radar rainfall.

One method to circumvent these problems is to continuously model a watershed's hydrology for the purpose of tracking, keeping all important state variables up-to-date and calibrated. While this can be done using telemetered rain gauges, the use of radar provides much more detailed rainfall information than rain gauges can offer. In relatively dry periods, rain tends to be scattered and can easily be missed by rain gauges but this rain can substantially affect storm runoff because it affects soil moisture. With radar rainfall as input, the soil moisture can be tracked in a distributed fashion. This approach is now under development but preliminary results are encouraging.

Figure 16.4 compares computed hourly flows to measured flows for nine streamflow gauges on the Grand River. In the initial run, with parameters obtained from earlier, single events, the recession curves tended to be somewhat high. A modest re-calibration of the model parameters resulted in a very good fit generally, but there are some periods that do not fit. For instance, on all computed hydrographs shown in Figure 16.4, the third computed peak is not matched by any rise in the observed hydrograph. This could be due to a different $Z - R$ relationship for this event or it could be caused by bright band problems. In real-time, the forecaster would notice that the predicted flow seems out of line. In this case, the problem is widespread because it is noted for all streamflow gauges on the Grand River watershed. If telemetered raingauges are available,

Figure 16.4
Comparison of computed and measured hydrographs at nine streamflow stations in the Grand River watershed.

the rainfall amounts can be checked. In this case, a scaling factor must be found to adjust the radar rainfall amounts, but only if a threat of flooding exists. For small rainfall amounts, the radar could simply be ignored. Considering the size of the watershed, the variations in land cover that exist, and the use of identical parameters throughout, the fit in Figure 16.4 is considered to be good.

16.4 New Directions

With the new radar data downloading system described in section 16.2 and a data management system and hydrologic model that can incorporate this data in an appropriate format, flood forecasting can be entirely automated. While human intervention is always necessary to check, adjust and correct data, an automated process can have a preliminary forecast ready continuously. Real-time radar data can be used to calculate streamflows that can be compared to observed streamflow at any time. Once the forecaster is satisfied that the computed flows are reasonable, two options in WATFLOOD can provide direct graphical images of potential problems.

16.4.1 Stage Hydrographs with Damage Levels

Figure 16.5 is a stage plot at West Montrose. The vertical scale now represents the stage above a local datum and superimposed on the hydrograph are horizontal lines that show what problems arise at the indicated levels.

Stage hydrographs can be plotted at any desirable point on the river system because the data management system and simulation model is completely distributed. The grid size is initially chosen for considerations of computational efficiency, the need to represent the meteorological inputs and the need to properly represent the drainage system.

16.4.2 Two Dimensional Flood Flow Animation

Because of the distributed nature of the data system and model, flows are computed throughout the watershed. In fact, WATFLOOD has the capability to model the entire area covered by the radar in a single simulation. In the example below, only a part of the WKR radar coverage was modeled, namely, the Grand River above Galt, the Saugeen river and the Thames River above London, Ontario. Figure 16.6 shows a two dimensional grid representing 10 km by 10 km computational elements in south western Ontario. The names of the major cities are noted.

Figure 16.5
Stage hydrograph for Grand River at West Montrose showing critical levels, for the whole month of November, 1992.

Figure 16.6
Two dimensional image showing the percent of bank full flow in each computational grid for south-western Ontario.

The example shown in Figure 16.6 is one frame of an hourly animation that spans the entire flood hydrograph. Other information given on the screen but not shown in the figure, is a colour key to give the conditions associated with each colour and the date and time. The animation is scaled to suit whatever area is being modeled but it shows graphically where the flood wave is cresting. For instance, it clearly shows whether flooding is occurring in small tributaries or along the main rivers. The flood wave can be seen travelling downstream. In the future, the image could be changed from a schematic to a more realistic geometric representation. Roads and other critical locations can be marked and the images can be used by people without training in hydrology.

16.5 Summary and Conclusions

The foregoing discussion and examples show that from a hydrological perspective, weather radar has come of age. The modelling results are very good. For the modelling results presented in this chapter, radar data was used directly, without any adjustment whatsoever. It appears that most of the time radar data can be used without much adjustment but on occasions, it will have to be adjusted using either rain gauge or streamflow data, with the latter being preferred.

The radar applications presented in this chapter are based on radar data reported on a 2 km. grid. Considering that the computational grid of the model used can vary from 1 km to 10 km or more, the radar resolution is more than adequate. However, for applications involving urban drainage system, the standard weather radar formats used by Environment Canada will not be adequate. Specialized radars having smaller range and much greater resolution may be needed for these urban applications.

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