JP3.11 USING RADAR DATA WITH THE WATFLOOD HYDROLOGICAL MODEL TO ESTIMATE STREAMFLOW

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1 INTRODUCTION

Since the availability of digital radar data over 25 years ago, the routine operational and research use of these data sets by the meteorological and hydrological community has been hampered by the need of a proper interpretation. Radar data are seriously affected by various factors, including: the broadening of the radar beam with range, beam blocking, the contamination by melting snow, “clutter” (non-hydrological returns), and anomalous propagation (AP) (Doviak and Zrnic, 1993). These errors can be partially removed through signal processing filters, but residual error remains. This paper presents preliminary results of newly developed algorithms to automatically convert raw radar data into a quantitative hydrological product (precipitation).

The capability of radar to diagnose severe weather and extreme events of precipitation has been well documented throughout the years (e.g. Doviak and Zrnic, 1993; Seo and Smith, 1992). The radar reflectivity is converted to rainfall estimates through the Marshall-Palmer (1948) Z-R relationship, using various coefficients according to the precipitation type. It has also been recognized that radar is useful for hydrologic purposes (e.g. Gorrie, 1976; Kouwen and Garland, 1989; Moore, 1987). A hydrological model such as WATFLOOD (Kouwen, *et al.*, 1993) allows for prediction of river flows, which may be used for flood forecasting purposes and also as an independent verification of the precipitation estimates. Unlike rain gauge networks, which provide only rainfall estimates at single points, streamflow data represent an “integration” of the precipitation over the drainage area. Therefore, the ability of the radar data to reproduce streamflow hydrographs (through an hydrological model) represents the ability of the radar to estimate the volume of precipitation across an area. One example of this technique is the work of Innes (2001), which applied range correction factors to radar precipitation based on the response of the streamflow hydrograph. In this paper, the data were used to calculate streamflow hydrographs in order to compare the different algorithms that clean the radar data.

This research used a distributed hydrological model called WATFLOOD that subdivides the watershed into grids. Therefore, it is ideally suited for use with gridded data sets, such as radar data. WATFLOOD uses the Grouped Response Unit (GRU) methodology to account for land cover in-homogeneity. The model has been used for a wide variety of watersheds.

The writers have used WATFLOOD with radar data to predict streamflow hydrographs for watersheds in Ontario, Quebec, and the northern United States. The work was begun with the King City Radar near Toronto, Ontario in 1993, which provided radar data for southern Ontario (Innes, 2001). Results from this analysis indicated that it was worthwhile to pursue the proper interpretation of radar data for hydrological purposes. As a result, a more indepth analysis with the McGill Radar in Montreal, Quebec was begun to test the effectiveness of various correction algorithms. The hydrological model has been used to predict streamflow hydrographs, which are then compared to observed hydrographs as a validation tool. The McGill Radar provides coverage for several basins in Ontario, Quebec, and the northern United States. This study is ongoing and therefore this paper presents preliminary results only.

The remainder of this paper is organized as follows. First, the two radars and their respective study areas will be presented. Secondly, the WATFLOOD hydrological model will be described briefly. Finally, the preliminary results will be presented, and preliminary conclusions presented.

2 STUDY AREAS

2.1 King City Radar

The King City radar is located about 60 km north of Toronto, Ontario, on a high east-west moraine. It is operated by Environment Canada. The radar covers an area with a radius of 240 km at a resolution of 2 km by 2 km. The radar covers

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most of southern Ontario, bounded by Lakes Huron, Erie, and Ontario.

Hourly accumulations of precipitation calculated from the radar data have been collected since 1993. In this almost 10-year time span, there have been numerous, often undocumented changes to the hardware and software used to process the radar data. It has been difficult to obtain a consistent long-term radar record for hydrologic study.

The radar data often contain errors due to ground clutter and anomalous propagation (AP). These errors were not removed automatically, and hence may affect the calculation of the streamflow hydrograph. In Southern Ontario, the ground clutter usually results from the City of Toronto (south of the radar) and the Niagara Escarpment (about 40-50 km west of the radar). The radar beam is also partly blocked by the Niagara Escarpment, and therefore the precipitation data to the west of the escarpment is less accurate. In this analysis, clutter and anomalous propagation were removed (by removing the radar image from the database) on clear days. On days when there was a precipitation event, however, the radar image was left in the database, and it may therefore affect the streamflow hydrographs (Innes, 2001).

The data have been used to estimate streamflow in the Grand River watershed, (35 km to 105 km from the radar), and parts of the Saugeen watershed (65 to 145 km) and the Maitland watershed (95 to 175 km) (Innes, 2001). Only the results for the Grand River watershed were presented in this paper.

Initial results, although subject to the errors listed above, indicate that radar data may be used to improve flood forecasts. As a result, a more detailed analysis with the McGill Radar was initiated.

2.2 McGill Radar

The McGill radar is located at the J.S. Marshall Observatory on the McGill University campus in Montreal, Quebec (west of downtown Montreal). It is operated by McGill University. The radar covers an area with a radius of 240 km at a resolution of 2km by 2km. The area includes parts of southern Quebec, eastern Ontario, New York, Vermont, and New Hampshire.

There are several "typical" problems with the radar data. The first results from obstructions in the way of the radar beam. There are two hills to the northwest of the radar that block the radar and therefore there is an underestimation of the precipitation beyond the hills. In Figure 1, the double V-shaped shadows of the hills may be seen in a precipitation band as areas of lower (or zero) precipitation. The tall buildings of Montreal (south and east of the radar) can also partially block the radar beam. The Green Mountains in Vermont also obstruct the radar beam, and are located southeast of the radar. Occasionally, the mountains cause "bright spots" (clutter) during rainfall events that are not completely removed by the automatic algorithms (Figure 2). These are typically a problem for the low-level scans. The second typical problem involves AP, mainly in the area to the south and southwest of the radar. AP is often caused by a nighttime temperature inversion that bends the radar beam towards the earth, and can be particularly strong in the summer. Figure 3 shows a case of AP that was not completely removed by the automatic algorithm and a line with zero precipitation beyond the AP. In all of these images, the light blue colour corresponds to a small amount of precipitation, with precipitation increasing as the colours change from blue to green to yellow to red. Although there are algorithms to remove these effects, it is difficult to account for missed precipitation behind hills or due to abnormal beam bending, and the algorithms cannot always removed all of the error. Therefore, precipitation estimates in these areas are often poor.

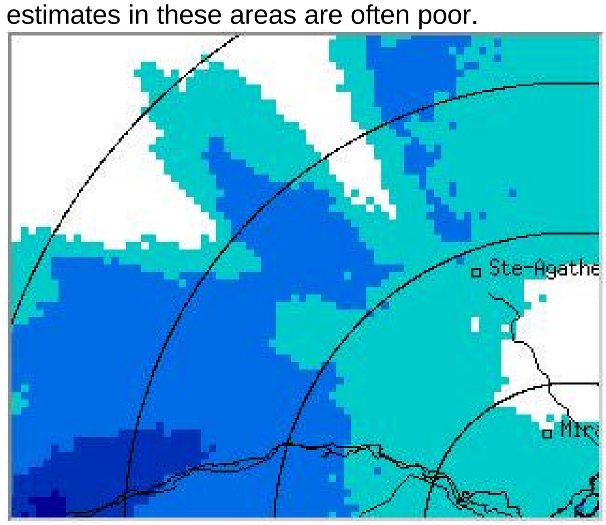

Figure 1 - Northwest portion of McGill Radar coverage showing the V-shaped shadows of the two hills northwest of the radar, which is located in the lower right corner (February 1, 2002, 11:00 UTC)

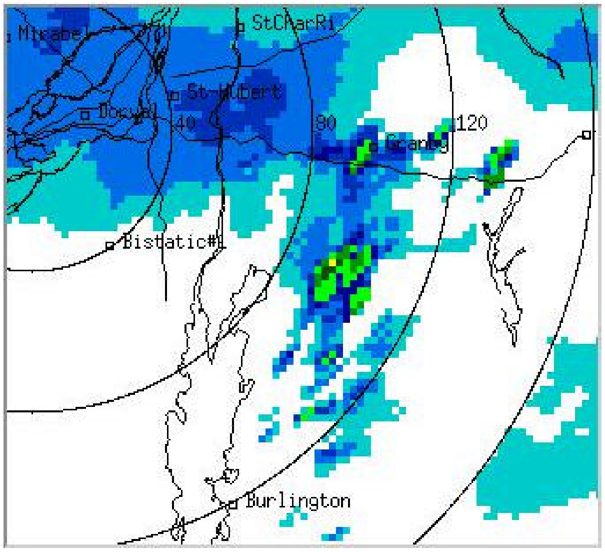

Figure 2 - Southeast portion of McGill Radar coverage showing bright spots associated with Green Mountains (radar is located in upper left corner) (February 20, 2002, 21:00 UTC)

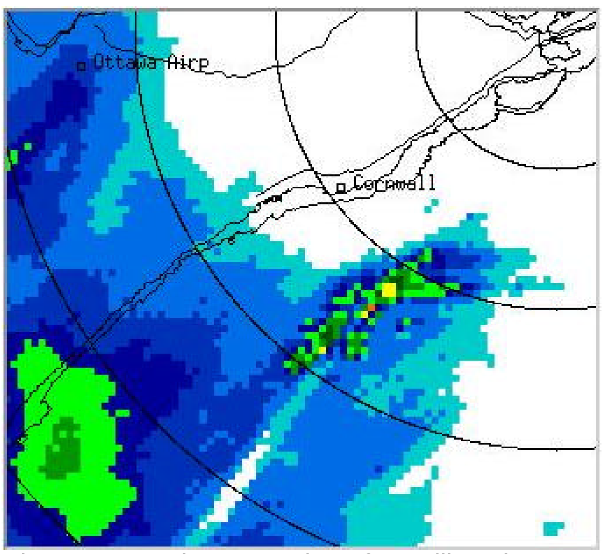

Figure 3 - Southwest portion of McGill Radar coverage showing bright spots and thin V-shaped shadow associated with anomalous propagation (radar is located in upper right corner) (February 21, 2002, 1:00 UTC)

The hourly accumulations of precipitation calculated from the radar data have been collected since December 2001. Various corrections have been applied to the data. The first correction level was clutter removal and anomalous propagation removal (this is called the “C0” correction). The second level of correction added the correction for the vertical profile of reflectivity (VPR) (this is called the “C2” correction). These two levels are provided at a scan height of 2 km. The final correction used multiple levels of data to derive an optimal surface rainfall at an equivalent height of 1.1 km (this is called the “C3” correction). However, this final correction level is only available for a radius of 120 km at a resolution of 1 km by 1 km. The third correction level attempts to go around obstructions by using high scan heights and extrapolating the precipitation down to the height of interest.

The data were interpolated to a 1.5 minute by 1.5 minute grid for use in WATFLOOD. The data have been used to estimate streamflow for watersheds in Ontario, Quebec, New York, New Hampshire, and Vermont.

3 DESCRIPTION OF WATFLOOD

The model WATFLOOD/SPL is a physically-based simulation model of the hydrologic budget of a watershed. As with all such models, it represents only a small part of the overall physical processes occurring in nature. The model is aimed at both short-term simulations for flood forecasting and long-term water balance simulation, using distributed precipitation data from radar or numerical weather models. The processes modeled include interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, baseflow, and overland and channel routing (Kouwen, *et al.*, 1993).

To account for the spatial variability of the hydrological variables, WATFLOOD/SPL uses the Grouped Response Unit (GRU) method to group hydrologically similar response units (Tao and Kouwen, 1989; Kouwen, *et al.*, 1993). A GRU is a hydrologic computational unit that consists of a grouping of areas that can be expected to react similarly to the same meteorological conditions. Satellite imagery is used to determine the landcover types. In the GRU method, all similarly vegetated areas (not necessarily contiguous) within a sub-basin element (either a grid or sub-basin area) are grouped into one response unit and called a GRU. Experience to date has shown that five to eight classes are usually sufficient to represent the variability of land cover. The hydrologic response of each class is computed as if that class covered the whole element but its response (e.g. streamflow) is then weighted according to its percent cover of that element or sub-basin. The size of the element is chosen to properly reflect meteorological variations and the streamflow system as well as computational requirements.

The meteorological forcing data can vary over the watershed, but are assumed to be uniform within a particular element. It is assumed that all pixels belonging to a land cover group respond in a similar way with respect to infiltration, surface and interflow, evaporation, snowmelt and drainage to ground water, regardless of their location within a grid. Therefore, model parameters are associated with each land cover class and are invariant over the modelled domain. In this way, there are very few "watershed specific parameters," only parameters pertaining to land cover that are readily transferred to other watersheds. Two parameters associated with the types of rivers in the modelled area and the underlying geology are watershed-specific, although in the future these parameters will be linked to geomorphological features.

The vertical water balance component of the WATFLOOD/SPL model is a conventional hydrological model. Where it differs is in the method that watersheds and regions are subdivided to preserve the hydrological responses of greatly differing surface areas, namely by employing the GRU or pixel grouping approach. Details of the hydrological abstractions in WATFLOOD/SPL are available in previous publications (Donald, *et al.*, 1995; Kouwen, *et al.*, 1993; Tao and Kouwen, 1989, and others).

4 RESULTS

4.1 King City Radar results

The King City radar data were used in WATFLOOD to produce streamflow hydrographs for the Grand River watershed. The hydrographs were generated for the period of 1993 to 1995 (a longer period is available, but three years is sufficient for the purposes of this paper).

Figure 4 to Figure 6 show the comparison of observed and simulated streamflow for the Grand River at Galt streamflow station. The radar precipitation adjustment factors were: 1.0 for January to March, 0.67 for April, and 0.5 for the rest of the year (in general the precipitation was over-estimated). The simulated and observed hydrographs had different levels of agreement from year to year. The simulated hydrographs for 1993 and 1994 matched the observed hydrographs very closely, while the hydrograph for 1995 overestimated the observed hydrograph throughout most of the year. The spring melts for 1993 and 1994 are well predicted by the radar data, but poorly predicted in 1995. This difference in behavior was most likely due to the undocumented changes in the hardware and software at the radar. For instance, small changes in threshold values to record precipitation can result in substantial changes in reported precipitation. Given the non-linearity of the rainfall-runoff process, these small changes in precipitation may result in large changes in runoff. In all three years, the radar appears to overestimate the smaller events in the summer and fall months. However, in general, the observed and simulated hydrographs matched reasonably well.

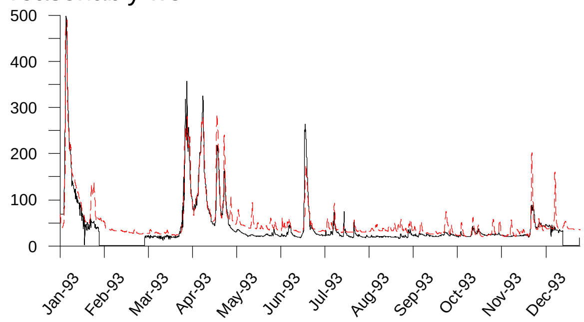

Figure 4 - Observed and Simulated Hydrographs for Grand River at Galt - 1993

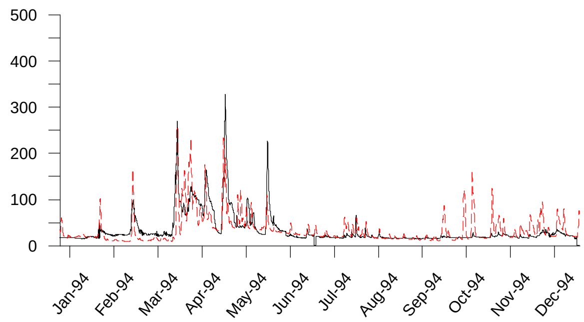

Figure 5 - Observed and Simulated Hydrographs for Grand River at Galt - 1994

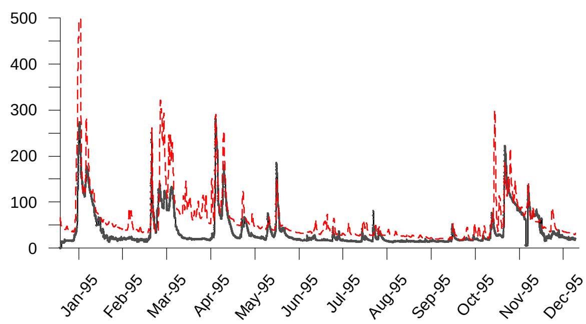

Figure 6 - Observed and Simulated Hydrographs for Grand River at Galt - 1995

The initial results with the Grand River showed that in general, the timing of the streamflow events was well matched, and the magnitudes of the events were reasonable in most cases. Therefore, radar precipitation data, although it contains error, is useful for calculating streamflow. These results are far from unique: many authors, working with different radars in different regions have also shown the usefulness of radar data for estimating streamflow hydrographs (e.g. Kouwen and Garland, 1989; Ogden and Julien, 1994; Pessoa, *et al.*, 1993). In addition, the WATFLOOD hydrological model is useful as a tool for converting the radar precipitation into streamflow.

It appears that the problem with the King City data is the lack of consistency from year to year in the radar data. It is necessary to develop a consistent long-term dataset to allow an in-depth examination of the use of radar data as a hydrologic tool. The current project was setup to investigate the different algorithms that are used to correct the radar data, to help develop a useful hydrological product.

4.2 McGill Radar results

The McGill radar data were used in WATFLOOD to produce streamflow hydrographs for multiple streamflow basins in Ontario, Quebec, New York, New Hampshire and Vermont. This paper presents results for the period December 2001 to August 2002. However, this project is ongoing, and further results may be viewed at the following website: http://www.civil.uwaterloo.ca/watflood/studies/nowcasting.htm. The results for only a few basins were included in this paper, in the interest of brevity. The website contains more detailed results for more basins.

The WATFLOOD model was calibrated for the "C2" correction level for the nine month period. This analysis used the same parameter set for all correction levels to allow comparisons to be made. Due to the relatively short simulation period and lack of variety of hydrologic conditions, the calibration of the WATFLOOD model is still incomplete. Calibration will improve as more data is collected.

During calibration, the authors found that, in general, the radar needed to be multiplied by a factor of 1.5 (summer) to 2.0 (winter) to match the observed precipitation. This was determined by comparing the observed and simulated runoff volumes. The underestimation factor appeared to vary in both space and time. This was most likely due to accumulated errors of underprediction for low-precipitation events (where the return is low or even below the detection limit). For large precipitation events, the precipitation volumes were more accurate. The accuracy of the radar in producing precipitation for low-precipitation events should be examined further, as low-precipitation events are important for setting antecedent conditions for runoff (e.g. depth of snowpack, soil moisture, etc.).

Figure 7 shows a plot of percent runoff volume error for the nine month period. The location of the radar is indicated with a red square in the center of the figure. This figure shows that, in general, the use of a constant scaling factor for the entire precipitation field results in over-estimation of runoff near the radar, and under-estimation of runoff far from the radar. The results may indicate the effect of radar attenuation and/or beam filling. The exception appears to be the area to the northwest of the radar. Although this area is near the radar, the error is negative, which illustrates the effect of the hills to the northwest of the radar that block the radar beam and cause underestimation of precipitation.

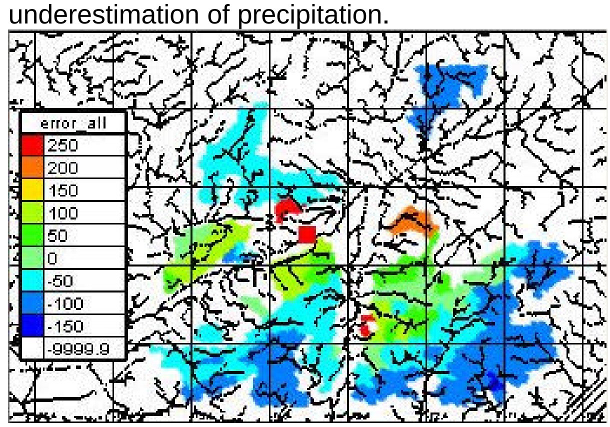

Figure 7 - Percent error in runoff for each watershed around the McGill radar

Despite these difficulties with the radar data, Figure 8 to Figure 10 show that the radar data are capable of producing reasonable streamflow hydrographs. Figure 8 to Figure 10 show several streamflow hydrographs for basins in Ontario, Quebec, and the northern United States. The radar appears to capture the majority of the rainfall events for all three stations. The Ontario basin is west of the radar, while the Quebec basin is northeast of the radar, and the Vermont basin is southeast of the radar. For the Vermont station, the radar measured a precipitation event in early July that did not appear in the observed streamflow data. These hydrographs show the C0 and C2 correction level hydrographs, with the observed hydrograph. Both simulated streamflow hydrographs match the observed hydrograph in terms of peak timing and hydrograph shapes reasonably well. This indicates that the radar captures the timing and spatial distribution of precipitation fairly well. However, some storms appear to have been "missed" by the radar, or the correction algorithms removed them. Other storms are overestimated. This varies according to region.

The main differences between the two correction levels are in terms of magnitudes of the peak events. The C0 data appears to produce more winter precipitation, since the spring melts (mid March and early April) were often larger for the C0 simulated hydrographs. During the summer months, the two algorithms produce similar results. The various correction algorithms that modify the precipitation amounts where precipitation is detected cause these differences. In general, the C0 correction level has more precipitation than the C2 correction level. The C0 correction level precipitation data appear to be able to model the streamflow hydrographs better than the C2 correction level data. It can be inferred that the VPR correction over-corrects the precipitation, particularly in the winter.

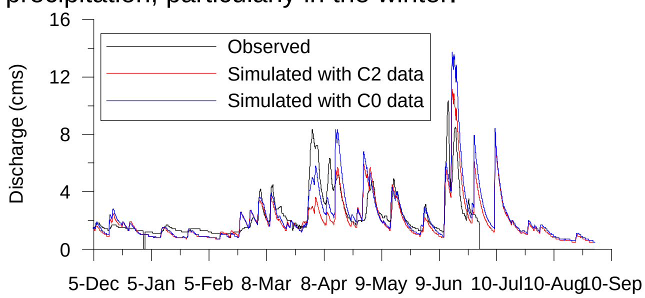

Figure 8 - Simulated and Observed Hydrographs for Rivière Delisle near Alexandria watershed (85.4 km^2) in Ontario

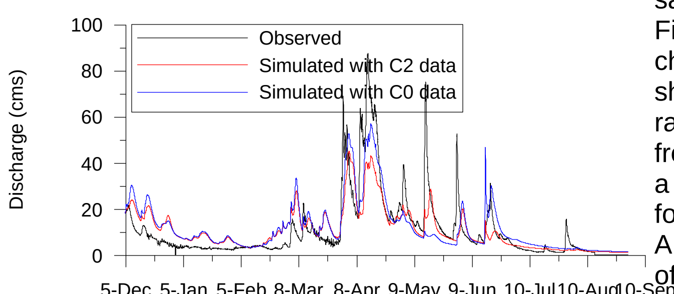

Figure 9 - Simulated and Observed Hydrographs for Rivière de l'Achigan (648 km2) in Quebec

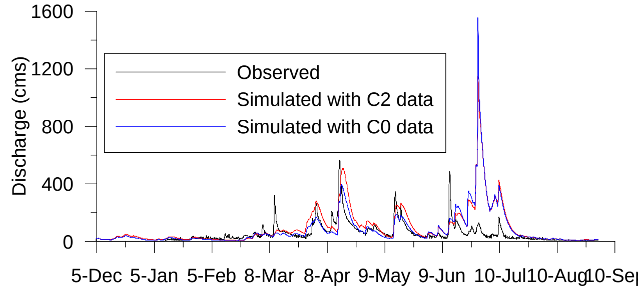

Figure 10 - Simulated and Observed Hydrographs for Winooski River near Essex Junction (2704 km^2) in Vermont

The correction level of most interest to this analysis is the C3 correction level. This level uses a new analysis technique to predict a low-level precipitation. This correction level is only available for the first 120 km from the radar. As a result, only watersheds that are close to the radar may be modeled with this correction level. The technique uses the lowest angle scan whenever possible (i.e. where the data is not affected by ground-level clutter, where the beam is not blocked, where the beam is not intersecting the “bright-band” of melting snow, etc.), in order to get precipitation as close to the ground as possible. Where it is not possible to use the lowest angle scan, a higher angle scan that is not affected will be used, and the precipitation extrapolated down to the height of the lower angle scan. This method tends to minimize the “typical” problems with the radar data that were shown in Figure 1 to Figure 3. The same three images are shown in Figure 11 to Figure 13 (note the scale has changed, due to the change in resolution). Figure 11 shows smaller V-shaped shadows due to the hills northwest of the radar. Figure 12 shows that much of the clutter from the Green Mountains has been removed, and a more reasonable estimate of precipitation was found. Finally, Figure 13 shows that some of the AP was removed (there still appears to be a “line” of precipitation pointing towards the radar that is not part of the system of precipitation), and the thin shadow was filled-in. In each case, the error was lessened with the optimum surface rainfall product.

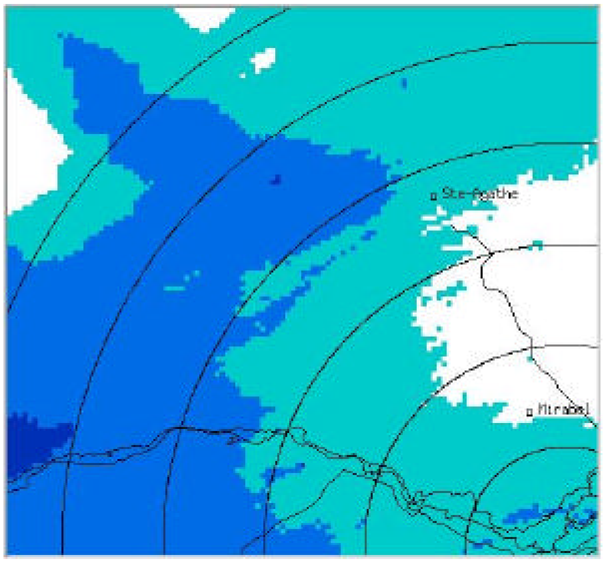

Figure 11 - Northwest portion of McGill radar coverage with C3 correction level showing a lower degree of shadowing by the two hills northwest of the radar, which is located in the lower right corner (February 1, 2002, 11:00 UTC)

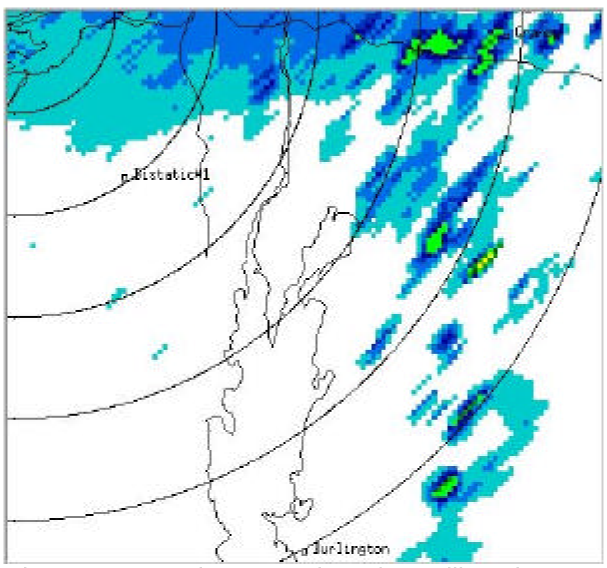

Figure 12 - Southeast portion of McGill Radar coverage with C3 correction level showing that the “bright spots” of the Green Mountains were decreased (radar is located in the upper left corner) (February 20, 2002, 21:00 UTC)

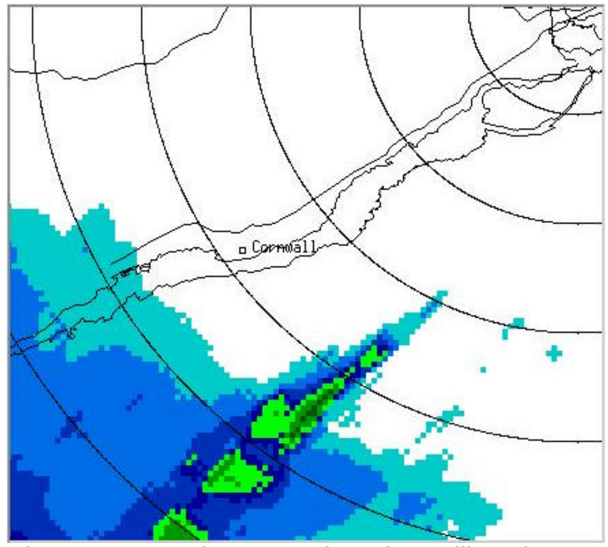

Figure 13 - Southwest portion of McGill Radar coverage with C3 correction level showing that the bright spots associated with anomalous propagation were decreased and the thin V-shaped shadow was filled in (radar is located in upper right corner) (February 21, 2002, 1:00 UTC)

Figure 14 and Figure 15 shows the observed and simulated with C3 data hydrographs for two streamflow stations that are within a 120 km radius of the radar station. A comparison of Figure 14 with Figure 8 shows that the C3 correction level predicts more winter precipitation (as evidenced by the spring melts in mid-March and early-April), and a slightly larger amount of precipitation in the summer months. Similarly, a comparison of Figure 15 with Figure 9 shows a similar pattern. There appears to be a greater amount of winter precipitation with the C3 correction level, and some of the summer precipitation events were also better matched with the C3 data. Therefore, it appears that the C3 correction level overcomes the over-correction of the VPR correction method (C2 correction level).

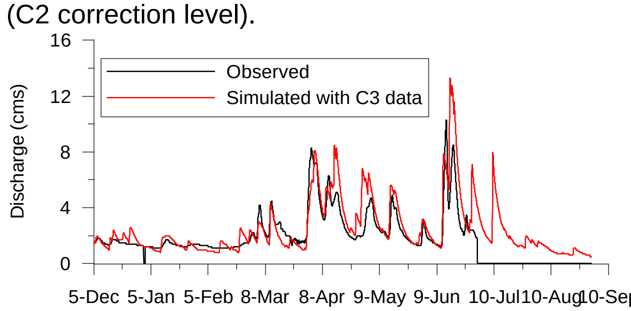

Figure 14 - Observed and Simulated (with C3 data) Hydrographs for Rivière Delisle near Alexandria (85.4 km^2) in Ontario

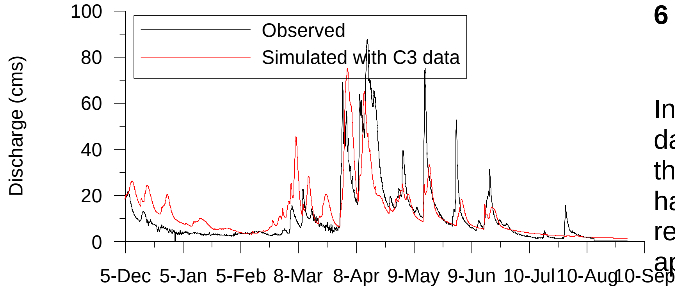

Figure 15 - Observed and Simulated (with C3 data) Hydrographs for Rivière de l'Achigan (648 km^2) in Quebec

5 CONCLUSIONS

This paper has presented preliminary results of the comparison between the different correction algorithms of the McGill Radar station in Montreal, Quebec. This analysis has focused on the use of streamflow hydrographs as a tool for verifying radar data. The hydrological model "integrates" the precipitation over the area of the watershed, and so allows for an areal validation of precipitation.

The radar data underestimated the true precipitation, and the radar data was multiplied by a factor of 1.5 to 2.0. The factor was modified until the observed and simulated runoff volumes were similar. The detection limit may be set too high, such that the radar missed smaller precipitation events (particularly in the winter).

The data also showed considerable attenuation in precipitation as distance from the radar increased.

The results indicated that the VPR correction removes too much precipitation from the radar data (as opposed to clutter and anomalous propagation removal only). There were several streamflow events that were underestimated by the VPR corrected data (C2 level).

In comparison, the optimal surface rainfall product (C3 level) appeared to fix the problems with VPR corrected data, and more precipitation was produced. The C3 data appeared to improve the estimates of the observed streamflow hydrograph, however, the data underestimated the true precipitation. The C3 data were only available for a radius of 120 km from the radar station, and therefore the attenuation in the data could not be evaluated.

This project is continuing, and up-to-date hydrographs and results may be viewed at the following website: http://www.civil.uwaterloo.ca/watflood/studies/nowcasting.htm

6 ACKNOWLEDGEMENTS

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