Evaluation of NEXRAD precipitation data for rainfall monitoring in Eastern Ontario, Canada

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Abstract

The development of NEXRAD weather radar products has greatly advanced the capacity to forecast and provide warnings of severe weather conditions over large areas in a time-efficient manner. However, most studies in the literature are conducted within the U.S. This study evaluates the reliability of NEXRAD precipitation data and rain gauge measurements in Eastern Ontario, Canada, for potential flood monitoring and water budget analysis. Five-month daily rainfall data from NEXRAD and rain gauge measurements were collected and generated for two Eastern Ontario conservation authority regions. The NEXRAD data was evaluated using rain gauge measurements as the reference. A good correlation (0.78) exists between the daily NEXRAD precipitation data and rain gauge measurements, especially for heavier rainfalls. The result also shows that 62% of radar precipitation data underestimates the daily precipitation. This underestimate is more common when the rainfall is small. The evaluation of spatial patterns of rainfall suggests that radar precipitation shows a more continuous pattern than the interpolated surfaces from rain gauges. Considering that small rainfall events contribute a relatively small portion of the total precipitation, NEXRAD products can play an important role in real-time flood monitoring and water budget analysis during heavy rainfall events in Canadian regions within the working range distance of the NEXRAD system.

1. Introduction

Accurate precipitation data are important for flood forecasting and regional water management. Traditionally, rain precipitation has been monitored at ground rain gauges placed at different locations. However, this type of monitoring network cannot capture spatial variation and patterns of rainfall, especially for regions with complex terrain (Young et al. 1999; Morin et al. 2003; Vieux and Bedient 2004). The development of remotely sensed weather radar data has greatly advanced the forecast of spatial pattern and rainfall quantity over large areas in a time-efficient manner (Maddox et al. 2002; Bedient et al. 2003).

In order to better detect severe weather and improve the accuracy of precipitation forecast, the U.S. National Weather Service (NWS) began installing the Next Generation Weather Radar WSR-88D (NEXRAD) system in 1988. NEXRAD comprises 158 weather surveillance radar–1988 doppler (WSR-88D) radars across the United States. The WSR-88D radar sends out radar beams at several different altitudinal scanning angels using a 10 cm wavelength (S-band) and penetrates the atmosphere and rainfall with little attenuation over long distances. The ground-based radars then receive radar signals bouncing off of precipitation. Precipitation intensity is estimated by using information about the strength, velocity, and spectrum of the reflected beam (more details on how NEXRAD works can be found at www.wunderground.com/radar/). Under most conditions, its usefulness range is considered to be 180 km, even though it can produce precipitation estimates up to 230 km away (Vieux and Bedient 2004). The launch of the NEXRAD system has revolutionized the capability of the NWS to forecast and warn of severe weather conditions (Xie et al. 2006). Since the installation of NEXRAD system, NWS's precipitation products have been evaluated for their application to rainfall estimation (Johnson et al. 1999; Krajewski and Smith 2002; Morin et al. 2003; Xie et al. 2006), hydrologic modeling (Pereira Fo et al. 1999; Young et al. 2000; Vieux and Bedient 2004), and flood forecasting and validation (Vieux and Bedient 1998; Bedient et al. 2000; Bedient et al. 2003; Zhang and Smith 2003; Vieux and Bedient 2004).

NEXRAD precipitation products are categorized into four product levels according to the amount of preprocessing, calibration, and quality control performed (Reed and Maidment 1999). The lowest level NEXRAD product, Stage I, is the hourly digital precipitation (HDP) estimate directly derived from radar reflectivity. In Stage II, the HDP is calibrated by merging with surface rain gauge measurements with a mean field bias correction. The most commonly used is the NEXRAD Stage III data, in which, the Stage II data from multiple weather radars covering the entire NWS River Forecast Center is combined and corrected using the average of all available rain gauge measurement (Young et al. 2000, Xie et al. 2006). Another NEXRAD product is the mosaicked Stage III precipitation product covering the entire Continental United States.

Despite the wide use of NEXRAD data, a key concern about these products is their accuracy and uncertainty (Anagnostou et al. 1999; Ciach 1999; Seo et al. 1999; Habib 2002; McCollum et al 2002). Because NEXRAD precipitation data are increasingly used as inputs for hydrological models of flood forecasting and warning, the accuracy of and uncertainty about this data needs to be evaluated. Many studies have compared the NEXRAD precipitation data with ground measurements at rain gauges in different regions of the U.S. (Johnson et al. 1999; Young et al. 1999; McCollum et al. 2002; Stellman et al. 2000; Krajewski et al. 2003; Xie, et al. 2006). The most common approach to evaluating accuracy is to compare the differences between radar estimates and rain gauge measurements through standard statistics, although the gauge measurements do not reflect the spatial scale of a NEXRAD pixel (Xie et al. 2006).

Since all NEXRAD radar stations are located within U.S., all previous studies related to NEXRAD precipitation data have focused on their application within the U.S. Although many populated regions of Canada are within 250 km of the border, within the usefulness range of radar located in the border areas of U.S., no studies have tested the reliability of NEXRAD data in Canada.

Since 2004, the Ontario government has adopted the Source Water Protection Act. This act requires all conservation authorities in Ontario to maintain detailed catchment-scale water budgets. Due to the low density of weather stations in Ontario, it is almost impossible for a conservation authority to declare a regional drought or a flood alert, because the precipitation varies so widely over the large, lake-influenced areas of Eastern Ontario. Several conservation authorities have been interested in using free NEXRAD precipitation data to track how much rainfall has fallen in their areas. They contacted us to conduct an evaluation study to determine the usability of free NEXRAD data for estimating rain fall in their areas.

The purpose of this study is to evaluate the usefulness of NEXRAD Stage III precipitation data to map the spatial distribution of rainfall for flood monitoring and water management in the area of Eastern Ontario, Canada, near the U.S. border.

2. Methods

2.1 Study area

Figure 1 shows the two conservation authorities used in this study: the Quinte Conservation Authority and the Cataraqui Conservation Authority, both located in Eastern Ontario, Canada. The study area belongs to the ecozone of the mixedwood plains. The total area is about 8400 km^2. Elevation of the study area ranges from 58 m to 457 m. Most of the areas are relatively flat, with slopes of less than 30 degrees. The north part of the region is mainly covered by forest, while agriculture dominates the south area. Largely influenced by the Great Lakes, the climate in the study area is highly changeable.

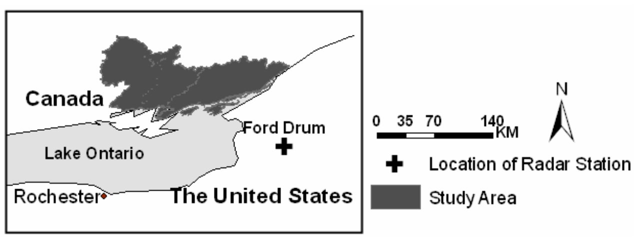

Fig. 1. The study area

Within the 8400 km^2 study area, there are only ten meteorological stations that have continuous daily precipitation records from Environment Canada (Figure 2 and Table 1). Instruments at each station continuously record precipitation and other climate variables, such as air temperature, relative humidity, and wind speed and direction, on an hourly basis. Most rain gauges use the Geonor T-200B accumulating precipitation gauge. However, hourly precipitation data are not always available for all stations at the National Climate Data and Information Archive (www.climate.weatheroffice.ec.gc.ca) of Environment Canada.

Rates of rainfall can change dramatically over space and time, particular during convective events due to lake effect. The mean annual precipitation within the study area ranges from 892 mm at Belleville to 1027 mm at Glenburnie (Table 1). For the conservation authorities to declare a regional drought or flood alert using the rainfall data from the limited rain gauges is almost meaningless. For that reason, spatial distribution of the rainfall is needed. Conservation authorities have expressed a need for more precipitation gauges all over the region. However, that is financially impossible.

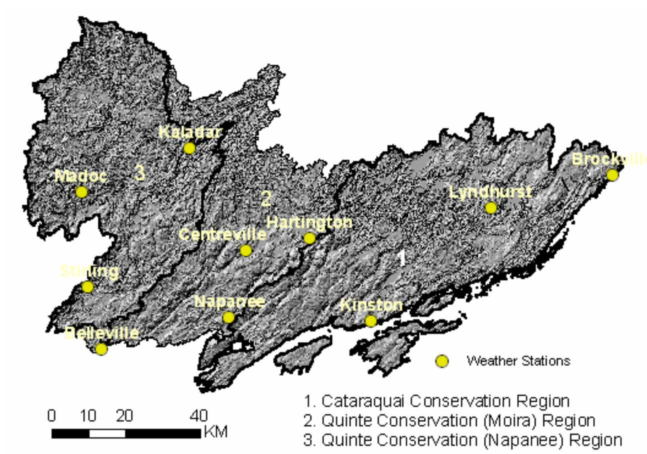

Fig. 2. Location of weather stations. The background image is a shaded relief DEM of the study area.

Table 1. Weather station information

Climate ID	Station Name	Elevation (m)	Average annual rainfall (mm)	Average annual precipitation (mm)
6104146	Kingston	93	795	968
6150689	Belleville	76.2	736	892
6100971	Brockville	96	784	983
6103367	Hartington	160	796	967
6104725	Lyndhurst	86.9	801	977
6152555	Centreville	114.3	778	901
6156533	Picton	76.2	759	964
6102808	Glenburnie	114.3	868	1027
6101265	Cararaqui	144.8	813	994

2.2 Radar data

The American radar station used in this study is located at Fort Drum, New York, and was chosen because of its proximity to the study area. The Fort Drum (FDX) station is situated at an altitude of 562 m above sea level and has been active since 1997. Fort Drum is within 70 km of the nearest border of the study area and within 200 km of the farthest border, which means both conservation areas are within the working range of the radar.

The altitude of the Fort Drum station is higher than the highest elevation in the study area. An elevation check shows that no mountains block the radar beams to the study area. NEXRAD precipitation products typically use data from the lowest of the four radar tilts with no significant beam blockage (Morin et al. 2003). Therefore, the first four tilts (0.5, 1.5, 2.4, and 3.4 degrees) of the radar beam from the FDX should be useful for the study area.

The initial intent of this study was to obtain the most recent rainfall data; however, due to the lack of rainfall prior to the start of our study, a different time period had to be selected. To find time periods with a relatively high number of rainfall dates, we searched the Environment Canada database. Five months (May 2002, July 2002, May 2003, June 2003, May 2004) with a high percentage of consecutive days with large amount of rainfall were selected to compare the radar precipitation data with rain gauge measurements.

The most time-intensive aspect of the analysis involved the preprocessing the radar data extracted from the NOAA website. The radar data used in this study had to be accessed through the NOAA archives, given that the NOAA website posts only records for the two most recent days. The variable examined was THP, the three-hour total precipitation. Once downloaded via ftp, the data were viewed and exported into ArcGIS shapefile using the “NEXRAD viewer” program.

The radar precipitation data exported using the NEXRAD viewer was displayed in a polygon shapefile in ArcGIS. We added up all THPs for each rainfall day to generate the radar rainfall layer for the study area. Then we extracted the daily radar precipitation for each station from the summarized radar rainfall layer for all days in ArcGIS and compared that data with the daily rainfall records from rain gauges, which were imported to point shapefiles in ArcGIS. All these processes were conducted by a Model built by Model Builder in ArcGIS.

2.3 Comparison of radar precipitation and rain gauge data

The comparison of radar precipitation and rain gauge data was conducted using two approaches. One was standard statistical analysis: comparing the mean, standard deviation, and the correlation coefficient of individual stations. A bias factor is also calculated by the ratio of radar precipitation and rain gauge measurement. Dates without rainfall were excluded from the analysis. If both radar precipitation and rain gauge measurements were zero for a particular station, that pair was excluded. In total, 177 pairs of NEXRAD precipitation and rain gauge measurement were used in the analysis.

The second comparison method used involved checking the spatial pattern of radar precipitation surface and interpolated surface from rain gauge measurements. The latter approach is commonly used to generate the rainfall surface. Three types of interpolation methods were tested: inversed distance weighting (IDW), kriging, and spline interpolation. Kriging is a geostatistical method that considers the spatial autocorrelation in the data, while IDW and spline interpolation are deterministic methods that use mathematical formula. IDW uses a linear combination of distance-based weights at known points to estimate values at unknown points. In spline interpolation, the interpolated surface is smoothed because the points do not have to pass through the original points of the data set (see Longley et al. (2003) for more details on each interpolation method). In order to generate a better interpolated surface, four additional weather stations outside but close to the study area were used together with the ten weather stations within the study area. The correlation coefficient (CV) between the interpolated surface and the radar rainfall surface was used to evaluate similarities and differences between the two data sets.

3. Result analysis

Figure 4 shows the scatter plot of the NEXRAD daily precipitation and rain gauge measurements for all dates considered. Figure 4 shows that although there are differences between most of rain gauge measurements and radar precipitation values, the changes in the rain gauge measurements are proportional to the changes in the radar precipitation. The correlation coefficient between the radar precipitation and gauge measurements is 0.78, at the significance of 0.05. This correlation coefficient is much higher than those obtained in a similar study of a semi-arid region by Xie et al. (2006) and in other American studies. One reason for this high correlation is that only five months with consecutive daily rainfall were used in our study, while the other studies used several years of data. Also, Xie et al. used hourly precipitation, which fluctuates more than daily accumulation.

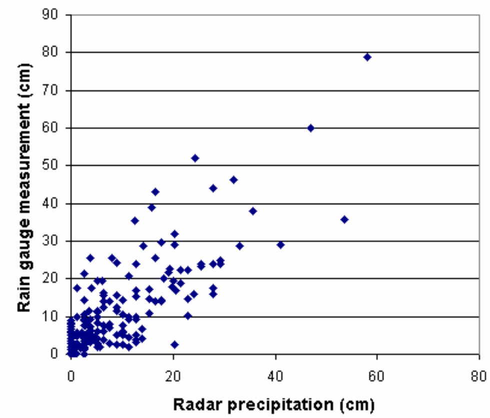

Fig. 4. The scatter plot of daily accumulated NEXRAD precipitation and rain gauge measurements for all stations and days.

Table 2 lists the basic statistics of radar precipitation and rain gauge measurements of weather stations for the study period. The average bias (the ratio of radar data and rain gauge data) is 1.16, showing, in average, the radar precipitation underestimates the actual rain fall. The worst underestimate case in this study is that radar estimate is 27.59 cm less than the rain gauge measurement in one day. However, the daily accumulated radar precipitation can also overestimate the actual rainfall as high as 18 cm. In this study, there are 62% of cases in which the radar precipitation value is smaller than the rain gauge measurement, indicating that NEXRAD precipitation underestimates the ground rainfall measurement, especially when the rainfall values are small.

Table 2. The basic statistics of radar precipitation and rain gauge measurements for weather stations

	Minimum	Maximum	Mean	Standard Deviation
Radar data	0.07	58.2	10.79	10.50
Rain gauge data	0.1	78.8	12.87	12.41
Difference between radar and rain gauge data (cm)	-27.59	18.06	-2.08	7.89
Ratio of radar and rain gauge data	0.07	10.16	1.16	1.29

Several previous studies (McCollum et al. 2002 and Xie et al. 2006) found that the 24-hour accumulation of NEXRAD precipitation is less than gauge measurements in the cold season, although, theoretically, the radar precipitation should be higher than the rain gauge measurements, due to radar's large detection area. There are two possible causes for this difference: an overshooting of the radar beam in stratified rainfall during cold seasons, or a truncation error in the NEXRAD processing. Our results seem consistent with the findings in these studies. Although June and June are considered the hot season in most of the U.S. region, the June-July temperature in Eastern Ontario is often only mild.

To further investigate the correlation between NEXRAD precipitation and rain gauge measurements, we also calculated the correlation coefficient for different rain gauge measurements of 0 to 5 cm, 5 to 15 cm, and over 15cm. The correlation coefficients at these different rainfall ranges are 0.33, 0.44, and 0.62, respectively, indicating that NEXRAD precipitation may be more appropriate for forecasting a heavy rainfall than a small rainfall.

Considering the high correlation between the radar precipitation and rain gauge measurement, we can use the spatial pattern shown in the NEXRAD data to evaluate which interpolation method can generate the best pattern. Table 3 lists the correlation coefficients of the radar precipitation surface and the interpolated surfaces using different methods, from twenty randomly selected daily rainfall data in the data set. To our surprise, the spline interpolation method, not the kriging, yielded the best interpolated rainfall surfaces, although the differences of the correlation coefficients were not significant.

Table 3. The correlation coefficient between the NEXRAD precipitation surface and interpolated rainfall surfaces from different methods

Surface	Minimum	Maximum	Average
NEXRAD vs. IDW	0.532	0.825	0.772
NEXRAD vs. Spline	0.612	0.892	0.787
NEXRAD vs. Kriging	0.587	0.886	0.782

Figures 5 and 6 show examples of spatial distribution of rainfall from NEXRAD and interpolated gauge measurements using the spline interpolation method. Compared with Figure 6, Figure 5 has a more continuous (or realistic) spatial rainfall patterns and would better describe the spatial pattern of rainfall. In most places, the value in Figure 5 is smaller than its corresponding value in Figure 6, indicating that the radar data underestimated the rainfall amount.

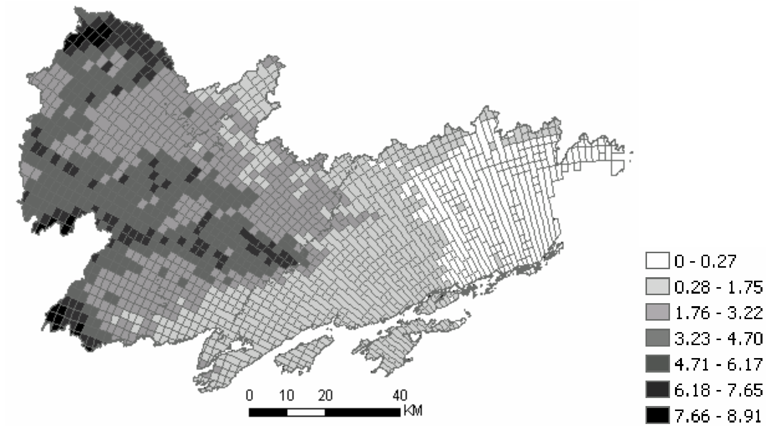

Fig. 5. Daily NEXRAD rainfall surface on July 22, 2002

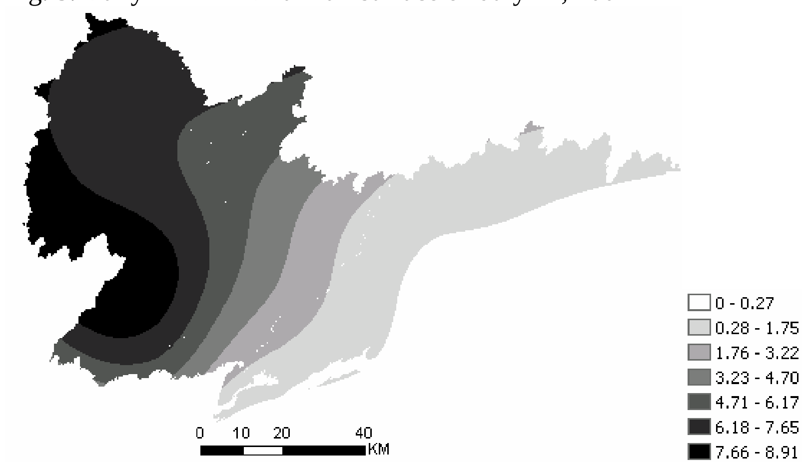

Fig. 6. Rainfall surface interpolated from rain gauge data on July 22, 2002 using the spline interpolation method

4. Summary and conclusions

This study compared the NEXRAD precipitation data and rain gauge measurements for five individual months in 2002 to 2004 for two conservation authority regions in Eastern Ontario. The NEXRAD data was evaluated using gauge data as the reference. The results show that a good correlation (0.78) exists between the NEXRAD precipitation data and rain gauge measurements. The NEXRAD precipitation has a better correlation with the rain gauge measurements for heavier rainfalls.

Statistical analyses suggest that radar precipitation underestimates the daily precipitation for 62% of rainfall days. This underestimation is more common when the rainfall is small, suggesting that there is more uncertainty in NEXRAD precipitation when it is used to estimate small rain events.

The evaluation of spatial patterns of rainfall suggests that radar precipitation shows more continuous patterns than the interpolated surfaces from rain gauges. Among the three interpolated methods, the spline interpolation method generated the surface with the highest average correlation with the radar precipitation.

Several recommendations have been made to the two conservation authorities regarding the implementation of NEXRAD in their flood monitoring, water budget analysis, and definitions of regional drought and flood. Firstly, based on our analysis, the NEXRAD precipitation has a good correlation with rain gauges, especially for large rainfall events. Considering that the small rainfall events contribute a relatively small portion of the total precipitation, and most of this rain usually either absorbs into the soil or evaporates and doesn’t enter into the stream flow, the NEXRAD products can play an important role in real-time flood monitoring and water budget analysis during heavy rainfall events in regions within the working range distance of the NEXRAD system.

However, further research should be done regarding the reliability of NEXRAD by using more detailed rain gauge measurements. In addition, snowfall is not considered in this study and should be examined. Finally, complete hourly precipitation data for all Environment Canada stations must be collected for additional studies, as well as other meteorological data, such as wind speed and temperature, to test the sensitivity of different NEXRAD products under different seasons and climate conditions.

5. Acknowledgement

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