RAINFALL VARIATION WITHIN A 4 KM X 4 KM AREA IN WESTERN PUERTO RICO

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ABSTRACT

Algorithms have been developed to estimate near-real-time rainfall from radar and satellites. These data can be ingested into hydrologic models to estimate flash flooding. A major limitation of the methodology, however, is the relatively poor resolution of the remotely sensed rainfall. Large variations in rainfall can occur within the remotely sensed pixel area, which may be important hydrologically. For example, rain gauge data for a storm on October 22, 2006 measured within a 4 km x 4 km area located in a tropical coastal drainage basin in Western Puerto Rico, revealed large spatial variation. The rain gauge network consisted of sixteen gauges distributed throughout the area. The rainfall average and standard deviation for the storm were 40.6 mm and 25.5 mm, respectively. Maximum and minimum recorded gauge rainfalls were 68.1 mm and 5.9 mm, respectively, and the maximum rainfall gradient within the study area was 65 mm per km.

The objective of this paper is to present results of rainfall distribution for selected storms within a 4 km x 4 km study area located near Mayagüez, PR, and to discuss the implications of the results on calibration/validation of quantitative precipitation estimation (QPE). In the future, the rain gauge network will be augmented and will be used to evaluate rainfall estimates from NOAA's Hydro-Estimator and SCaMPR QPE algorithms, NEXRAD, and the UPRM CASA distributed collaborative adaptive sensing radar network.

INTRODUCTION

Rain gauge networks are used to calibrate and validate QPE methods, which may be used as data sources for hydrologic models. The typical approach is to adjust (calibrate) or compare (validate) the rainfall in the QPE pixel with the rain gauge located within the pixel (e.g., Cruz, 2006 and Vila and Velasco, 2002). The QPE result represents a mean rainfall over the pixel area, whereas the rainfall from the gauge represents a point, although it is normally assumed to represent some area. In some cases the QPE pixel area may be millions of square meter in size. National Oceanic and Atmospheric Administration's (NOAA) Hydro Estimator (HE) algorithm (Scofield and Kuligowski, 2003), which utilizes data from the GOES geostationary satellite to estimate rainfall, for example, has a pixel size of 4 km x 4 km (16,000,000

m^2). The National Weather Service's (NWS) NEXRAD (Next Generation Radar) estimates rainfall within a radial coordinate system (base resolution 2 to 4 km), in which the pixel size increases with distance from the radar antenna (Beringer and Ball, 2004). NEXRAD accuracy also decreases with distance from the antenna owing to the curvature of the earth and in some cases the presence of obstructions (e.g., mountains). The differences in temporal and spatial scales make the comparison of QPE methods with ground-based rain gauges difficult (Kuligowski, 1997). Other potential sources of error include rain gauge inaccuracy, and assumptions made in the development of the QPE algorithm that may be violated under local (e.g., tropical) rainfall conditions.

Hydrologic models used to estimate storm hydrographs and flood levels and extent may be sensitive to rainfall distribution at the QPE sub-pixel scale. Bevan and Hornberger (1982) have stated that "… an accurate portrayal of spatial variation in rainfall is a prerequisite for accurate simulation of stream flows". Spatial rainfall variability greatly affects runoff processes in watersheds (Moreiraa et al., 2006). Goodrich (1990) has stated that rainfall runoff accuracy will increase with increasing number of rain gauges in the watershed, which will improve the rainfall spatial characterization representation. Rainfall estimates at a point differ from catchment averages because rainfall varies spatially and the catchment determines the amount of rainfall that is integrated in time and space (Vieux and Bedient, 1998). Moreira et al. (2006) evaluated rainfall spatial variability effects on catchment runoff. The study area was a 2.1 km^2 catchment in Northeast Brazil. Catchment response of the relatively small catchment area was quite sensitive to the occurrence of high rainfall spatial variability. Bell and Moore (2000) evaluated the sensitivity of simulated runoff from using rainfall data from gauges and radar. The rain gauge system consisted of 49 gauges over the 135 km^2 Brue catchment in southwest England. They evaluated convective and stratiform rainfall events. Runoff variability was strongest during convective storm events and weakest during stratiform events. Surprisingly, the author's obtained the best performance using lower resolution of rainfall data and model. This result was attributed to the fact that the original model was calibrated with lower resolution data. Hydrologic models need to be recalibrated when rainfall of a different resolution is used.

Numerous small-scale rainfall variation studies have been conducted (e.g., Bidin and Chappell, 2003; Goodrich et al., 1995; Moreiraa and Krajewski et al., 2003). Bidin and Chappell (2003) evaluated rainfall variation for differing wind fields with 46 rain gauges within a 4 km^2 rainforest in Northeastern Borneo. They observed a very high degree of spatial variability. Seasonal totals were correlated with gauge separation distance, aspect and topographic relief. Changes in rainfall patterns over the 4 km^2 catchment were related to complex local topographic effects in the regional wind field. Goodrich et al. (1995) studied small scale rainfall variability within a 4.4 ha area in the semiarid USDA Walnut Gulch Experimental (WGE) Watershed, Arizona. The average observed rainfall gradient was 1.2 mm/100 m. They concluded that the assumption of rainfall uniformity in convective environments similar to the WGE Watershed is invalid. Krajewski et al., 2003 compared rain gauges in Guam at three time scales (5, 15, and 60 min) and thee spatial scales (1, 600, and 1100 m). The largest variations occurred for the smallest time scale and the large spatial scale. The smallest variations occurred for the smallest time scale and the large spatial scale.

We hypothesize that most rain gauge networks used in environments similar to this study (i.e., coastal tropical, sea breeze induced, convective-orographic rainfall) are inadequate to calibrate/validate QPE methods, and that consequently QPE data may be inadequate to use with hydrologic models. The objective of this paper is to present results from a rain gauge network that will be used to validate several QPE methods: Hydro-Estimator, SCaMPR, NEXRAD and the University of Puerto Rico (UPRM) Collaborative Adaptive Sensing of the Atmosphere (CASA) radar network. Implications of the results on calibration/validation of QPE methods are discussed.

METHODOLOGY

During July 2006, sixteen WatchDog™ tipping bucket rain gauges (Spectrum Technology, Inc.*) were installed within the area of one HE pixel. Each rain gauge was equipped with a data logger capable of storing rainfall depth every 5-minutes over a 24 day period. The study area was located near to the University of Puerto Rico's Mayagüez Campus (UPRM) in western Puerto Rico (Figure 1). The pixel area was 4 km x 4 km (16 km^2). This area was divided into sixteen evenly spaced squares of 1 km^2 each. To locate the rain gauges the following steps were used: 1. The center points of the Hydro-Estimator (HE) pixels were obtained from NOAA's National Environmental Satellite, Data and Information Service (NESDIS). 2. An appropriate HE pixel was selected, which included a relatively large range of topographic relief east of the Mayagüez Bay in western Puerto Rico. 3. Using ArcGIS, sixteen points were located (evenly spaced) within the HE pixel. 4. With the assistance of a ground positioning system (GPS), properties (mainly residential) were located which were as close as possible to the center point locations identified in step no. 3. In each case it was necessary to obtain permission from the property owner before installing the rain gauges; and 5. The actual coordinates of the installed rain gauges were recorded and entered into ArcGIS (Figure 2).

The data logger clocks were synchronized and programmed to record cumulative rainfall depth every 5 minutes. All rain gauges were placed in areas free from obstructions. It was necessary to locate a few of the gauges on roof tops (approximately 5 meters above the ground) owing to inappropriate conditions on the ground. An effort was made to level each of the rain gauges to assure proper functioning.

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* Reference to a commercial product in nowise constitutes an endorsement of the product by the authors.

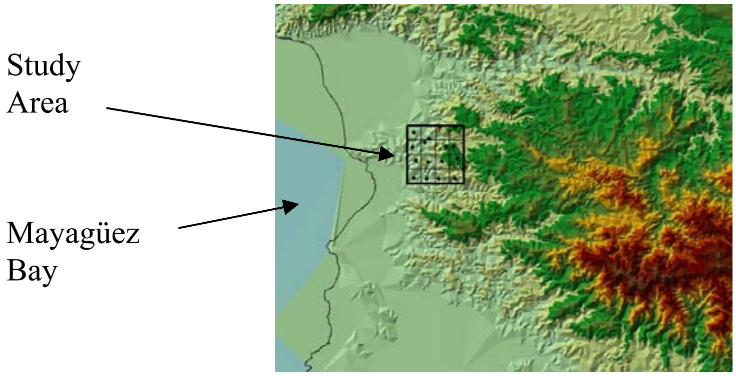

Figure 1. Study area corresponding to a Hydro-Estimator pixel (4 km x 4 km). Colors represent variations in topography.

RESULTS AND DISCUSSION

Figure 2 shows the final location of the rain gauges within the HE pixel area. Note that some of the rain gauges could not be located close to the center points of the squares because of lack of access. The problem-areas were generally located within undeveloped valleys which could not be accessed. Consequently the final locations of rain gauges were not evenly spaced; however, this resulted in producing a random (possibly beneficial) aspect to the locations of rain gauges within each sub-area.

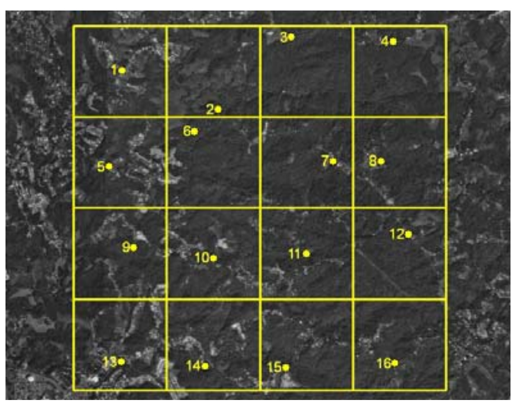

Figure 2. Air photo showing final locations of the 16 rain gauges.

As an example of the measured rainfall data, Figure 3 shows the depth of rainfall measured every 5 minutes by the sixteen gauges on August 6th, 2006. Figure 4a shows the spatial distribution of total rainfall for the same storm. It is clear that the rainfall in the satellite pixel area can vary significantly. The average and standard deviation for the rainfall were 30.8 mm and 13.6 mm, respectively. Maximum and minimum recorded rainfall were 55.6 mm and 9.2 mm, respectively.

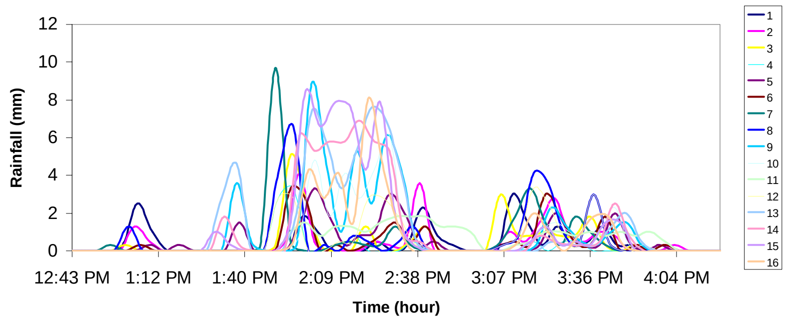

Figure 3. Rainfall measured from rain gauges on August 6th, 2006.

Figure 4 also shows the rainfall variation for storms occurring on August 16th (4b), August 18th (4c) and October 22nd (4d), 2006. For these storms (including August 6th, 4a), the maximum rainfall gradients were 20.4, 56.9, 55, and 65 mm/km. Figure 5 shows a box plot of the rainfall data for the four storms. Table 1 lists the statistics associated with twenty storms which occurred between August and November, 2006. The table includes storm start and end times, storm durations, number of operational rain gauges (n), total rainfall, standard deviation, and maximum rain gauge minus minimum rain gauge amounts. Figure 6 presents the total rainfall amounts verses storm standard deviations for all twenty storms listed in Table 1.

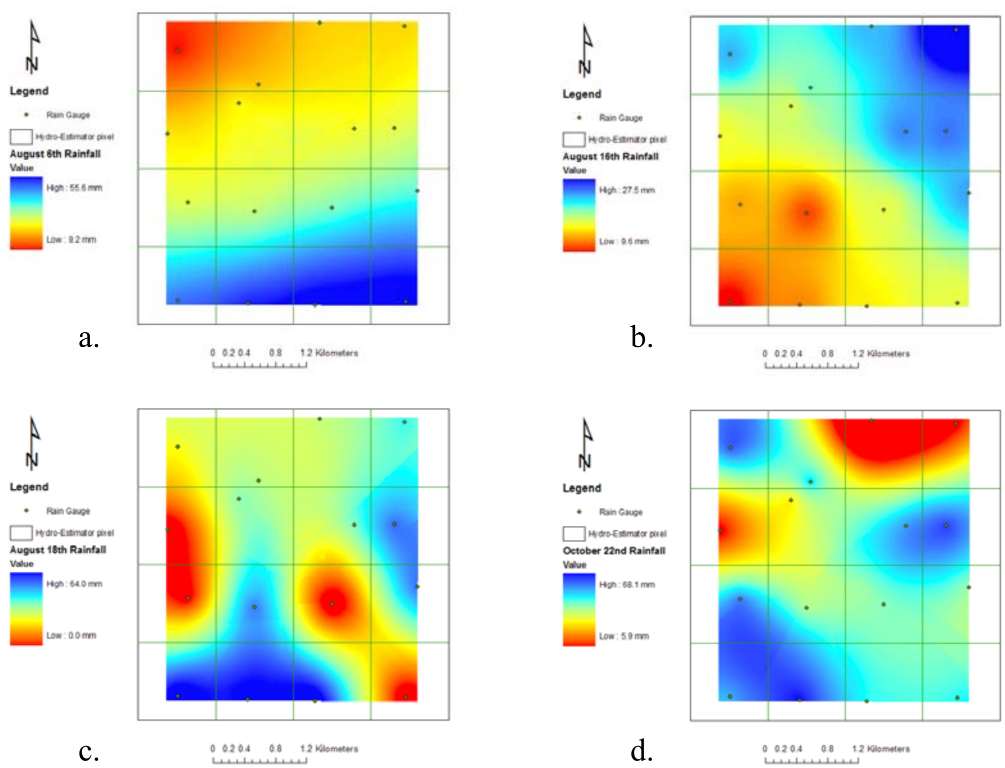

Figure 4. Spatial distribution of rainfall for storms on August 6th (a), August 16th (b), August 18th (c) and October 22(d), 2006.

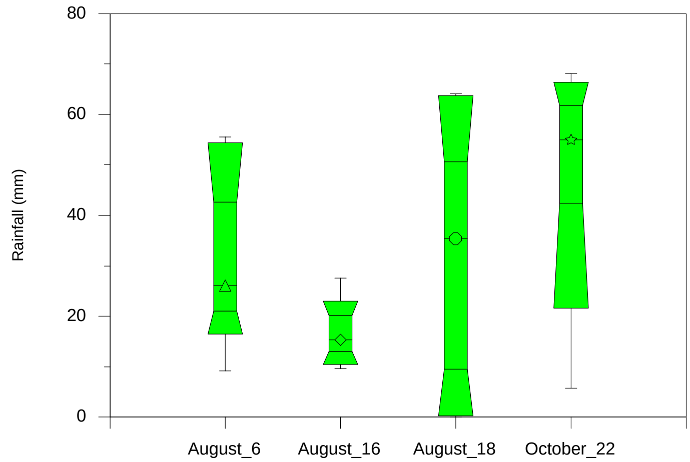

Figure 5. Rainfall variation for August 6, 16 and 18, and October 22, 2006. Horizontal lines in each box represent (from bottom to top) are the minimum, 10th percentile, 25th percentile, 50th percentile, 75th percentile, 90th percentile, and the maximum values of rainfall (mm). The symbol is the median rainfall.

Table 1. Rainfall statistics from 20 storms between August and November, 2006.

Storm No.	Date	Storm Start Time	Storm End Time	Storm Duration (hours)	n	Total Rainfall (mm)	St. Dev (mm)	Max (mm)	Min (mm)
1	08/06/06	13:32	14:42	1.17	16	30.8	13.6	55.5	9.2
2	08/14/06	17:12	18:37	1.42	15	9.3	9.6	27.2	0.0
3	08/16/06	12:54	16:49	3.92	15	16.6	4.7	27.5	9.6
4	08/18/06	12:53	18:38	5.75	15	33.8	22.7	64.1	0.0
5	08/20/06	16:28	19:48	3.33	15	14.3	10.3	27.5	0.0
6	08/22/06	15:00	23:23	8.38	16	19.4	13.3	44.0	0.0
7	08/25/06	14:03	14:53	0.83	15	5.2	3.3	10.4	0.0
8	08/26/06	12:18	13:13	0.92	16	4.4	2.8	8.6	0.0
9	10/01/06	21:19	0:32	3.22	15	18.2	12.2	37.7	0.0
10	10/02/06	21:06	22:26	3.22	15	2.7	2.2	7.5	0.0
11	10/08/06	17:39	18:45	1.10	15	9.1	4.6	17.8	0.0
12	10/10/06	21:35	23:54	2.32	15	2.3	0.7	3.0	0.0
13	10/14/06	15:20	17:45	2.42	15	22.6	10.1	32.9	0.0
14	10/21/06	11:28	13:32	2.07	15	6.0	6.0	16.6	0.0
15	10/23/06	14:05	23:57	9.87	15	40.6	25.5	68.1	5.7
16	10/27/06	13:05	16:58	3.88	13	9.1	7.1	17.4	0.0
17	11/03/06	14:05	16:06	2.02	13	15.2	13.0	40.6	0.0
18	11/12/06	15:51	17:40	1.82	13	10.2	11.8	32.6	0.0
19	11/13/06	16:46	18:15	1.48	13	7.9	9.5	32.3	0.0
20	11/16/06	14:26	17:18	2.87	13	12.1	16.0	41.4	0.0
21	11/18/06	14:17	15:52	1.58	11	7.5	8.1	21.5	0.0
22	11/24/06	13:41	16:57	3.27	12	8.8	4.5	16.9	0.5
23	12/07/06	14:27	19:28	5.02	13	4.1	3.2	12.2	0.0
24	12/09/07	13:56	16:52	2.93	13	26.8	18.9	58.7	0.0
Average		15:18	18:29	3.1	14.3	14.0	9.7	30.1	1.0

n stands for sample size or the number of operational rain gauges.

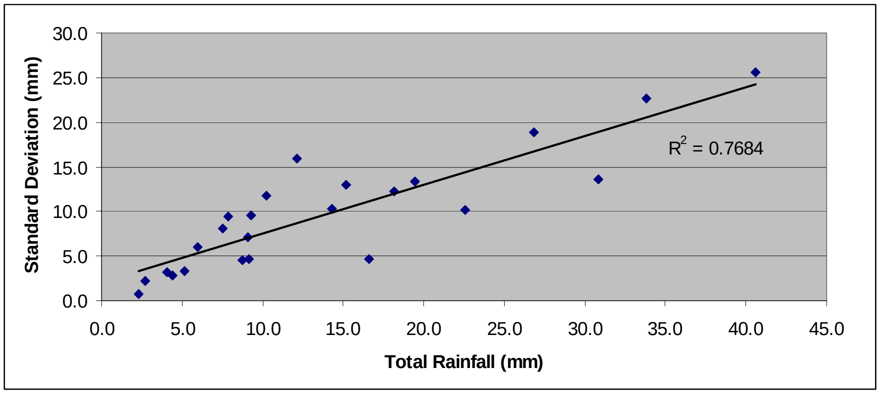

Figure 6. Total rainfall (mm) versus storm standard deviation for the twenty storms corresponding to Table 1.

Virtually all storms that occurred during the study period (August through November, 2006) were the sea-breeze induced, convective, orographic type storm common in western Puerto Rico. The importance of the sea breeze on the western end of the island is that it converges with the prevailing more easterly low level flow (which can move around from day to day), and this dictates the focus of afternoon convection (personal communication, P. Stripling, NWS). Spatial variation in rainfall distribution in the area during the "wet" season is commonly observed, as shown in Figure 4. The data from frequency distributions (not shown), at least for the four storms evaluated, did not appear to be normally distributed. However, the Shapiro-Wilk Normality test values for the total rainfall data for August 6, 16 and 18, and October 22 were 0.91, 0.95, 0.91 and 0.85, respectively, indicating normality at least for the first three dates. A Shapiro-Wilk value ≥ 0.9 indicates normality. The spatial variations are also shown in the Figure 5 using a box plot (Dat@xiom Software, Inc., 2001). Box plots are useful for showing the skewness of a data set; that is if the median line (50th percentile) is not equidistant from the 25th and 75th percentiles, the data is skewed. Box plots are also useful for showing the characteristics of the data side-by-side.

Table 1 indicates that on average the storms began at 15:18, ended at 18:29 with an average duration of 3.1 hours. The average number of operational rain gauges was 14.3. Not all sixteen gauges were functional throughout the study period owning to gauge plugging, insufficient data logger battery power, and in one case the gauge (no. 14) was removed from the site and lost, owing to construction activities. The average, standard deviation, minimum and maximum rainfall for the 20 storms were 14 mm, 9.7 mm, 1 mm, and 30.1 mm, respectively. All but three storms had gauges that registered zero rain. Figure 6 shows the total rainfall amount versus standard deviation for the twenty storms. There is relative good correlation between the total rainfall amount and standard deviation (r^2= 0.77). Figure 6 suggests that larger rainfall events will exhibit larger real rainfall variation within the 4 km x 4 km study area. The implications of this from a QPE standpoint is that with larger storm events it should be easier to obtain QPEs within some defined range (e.g., 1 standard deviation).

Typically QPEs are compared with existing rain gauge networks. For example, Cruz (2006) compared the HE algorithm with an existing U.S. Geological Survey rain gauge network in Puerto Rico (Figure 1). If we were to superimpose the QPE pixels over the area of the island, for example the HE method having a pixel resolution of 4 km x 4 km, the individual rain gauge would fall at some random location within an HE pixel. As Figure 4 illustrates, a large difference could be obtained depending upon where the rain gauges was located within the pixel. It is noted that, at least for the four storms considered in Figure 4, there was no apparent temporal correlation. This implies that if the QPE method were calibrated based on a rain gauge network similar to that shown in Figure 7, a large number of data sets would need to be used, and then the QPE could only be expected to perform well on average and not for any specific storm.

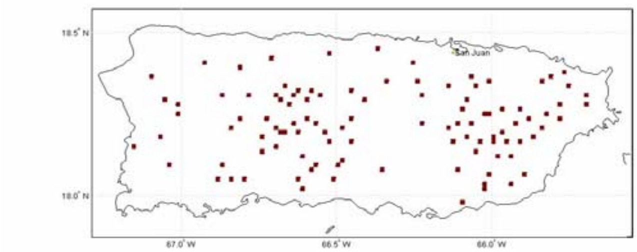

Figure 7. Locations of 125 U.S. Geologic Survey rain gauges in Puerto Rico (Cruz, 2006).

As an example, estimated total rainfall from NEXRAD for the storm on August 6th, 2006 is shown in Figure 8 and may be compared (approximately) with Figure 4a. Results in Figure 8 are shown as average values for NEXRAD grid cells (2 km) obtained using the National Climate Data Center's (NCDC) Java NEXRAD Viewer (http://www.ncdc.noaa.gov:80/oa/radar/jnx/). On the southern side of the pixel, NEXRAD produced values in the range of 22 to 37 mm, whereas the values from the rain gauges ranged from 45 to 56 mm (rain gauges nos. 12 through 16, Figure 2). On the northern side, NEXRAD produced from 13 to 18 mm, while rain gauges indicated a range between 9 to 21 mm (rain gauges nos. 1 through 4, Figure 2). The average area-weighted total rainfall amounts were 20.8 mm and 30.8 mm, respectively, for NEXRAD and the rain gauge network. It of interest to note that NOAA's HE algorithm did not detect any rainfall on this day for this pixel. This may be attributable to a relatively high cloud top temperature detected within this pixel by the GOES satellite (Kuligowski, R. personal communication).

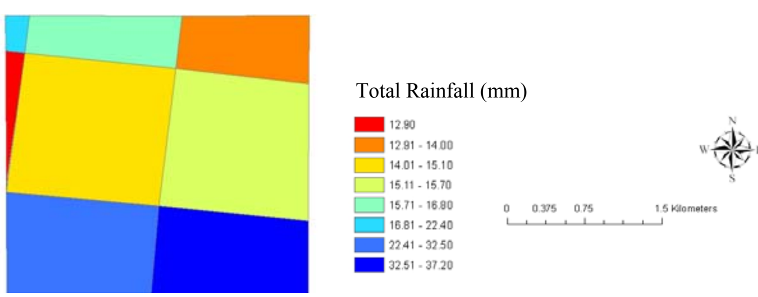

Figure 8. Total rainfall estimated from NEXRAD for study area for August 6th, 2006.

SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate the spatial rainfall variability within a QPE pixel (4 km x 4 km HE pixel) in a tropical watershed located in western PR. Graphical data were presented for four storms and tabular data were presented for an additional sixteen storms. Rainfall was observed to be highly variable within the 4 km x 4 km study area. Comparisons of rainfall were made between the rain gauge network and two QPE methods (NEXRAD and HE) for August 6th, 2006. The average area-weighted total rainfall amounts were 20.8 mm and 30.8 mm, respectively, for NEXRAD and the rain gauge network. The HE method did not detect any rainfall on this day in the study pixel. A conclusion of this study is that that most existing rain gauge networks (e.g., USGS) used in environments similar to this study (i.e., coastal tropical, sea breeze induced, convective-orographic rainfall) are inadequate to calibrate/validate QPE methods.

Future work will include rigorous comparisons of rainfall measured from the rain gauges and rainfall estimated from four QPE methods (HE and SCaMPR algorithms, NEXRAD, and the UPRM CASA distributed collaborative adaptive radar network) for differing types of storms. This will include time scales on the order of 5 to 15 minutes, which is the scale needed for real-time flood forecasting. Future work will also include the establishment of a similar rain gauge network in southwestern PR (Lajas area) where the rainfall characteristics are different. It is hoped that the statistical characteristics of rainfall in the study area may be used to improve QPE in the region.

ACKNOWLEDGEMENT

We would like to thank the following students for their help on this project: Marcel Giovanni Prieto, Victor Hugo Ramirez, Yaritza Perez, Romara Santiago, Alejandra Roja, Jorge Canals, Julian Harmsen and Lua Harmsen. We also want to thank NOAA CREST for their financial support of this project. Additional support was received from NASA EPSCoR, USDA-TSTAR (100) and NSF-CASA projects.

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