Remote Sensing QPE Uncertainties Associated with Sub-Pixel Rainfall Variation

ERIC W. HARMSEN
Department of Agricultural and Biosystems Engineering
University of Puerto Rico
P.O. Box 9030, Mayagüez, PR 00681
U.S.A.
eharmsen@uprm.edu

SANTA ELIZABETH GOMEZ MESA
Department of Mathematics
University of Puerto Rico
P.O. Box 9030, Mayagüez, PR 00681
U.S.A.
santagm3@gmail.com

NAZARIO D. RAMÍREZ-BELTRAN
Department of Industrial Engineering
University of Puerto Rico
P.O. Box 9030, Mayagüez, PR 00681
U.S.A
nazario@ece.uprm.edu

SANDRA CRUZ POL
Department of Computer and Electrical Engineering
University of Puerto Rico
P.O. Box 9040, Mayagüez, PR 00681
U.S.A
SandraCruzPol@ieee.org

ROBERT J. KULIGOWSKI
Meteorologist at NOAA/NESDIS Center for Satellite
Applications and Research (STAR)
5200 Auth Rd., Camp Springs, MD 20746-4304
U.S.A.
Bob.Kuligowski@noaa.gov

RAMÓN VASQUEZ
Department of Computer and Electrical Engineering
University of Puerto Rico
P.O. Box 9040, Mayagüez, PR 00681
U.S.A
reve@ece.uprm.edu

Abstract: - Rain gauge networks are used to calibrate and validate quantitative precipitation estimation (QPE) methods based on remote sensing, 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. 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. We hypothesize that many rain gauge networks in environments similar to this study (i.e., tropical coastal), which provide only one rain gauge per remote sensing pixel, may lead to error when used to calibrate/validate QPE methods, and that consequently these errors may be propagated throughout the hydrologic models. The objective of this paper is to describe a ground-truth rain gauge network located in western Puerto Rico which will be available to test our hypothesis. In this paper we discuss results from the rain gauge network, but do not present any QPE validation results. In addition to being valuable for validating satellite and radar QPE data, the rain gauge network is being used to test and calibrate atmospheric simulation models and to gain a better understanding of the sea breeze effect and its influence on rainfall.

In this study, 62 storms were evaluated between August 2006 and August 2007. The area covered by the rain gauge network was limited to a single GOES-12 pixel (4 km x 4 km). Five-minute and total storm rainfall amounts were spatially variable at the sub-pixel scale. Average storm rainfall from more than a quarter (27%) of the 3,627 rain gauge-pairs evaluated were significantly different at the 5% of significance level, indicating significant rainfall variation at the sub-pixel scale. The majority of storms during the study period were locally formed by sea breezes and heating, although the 27% of gauges whose average rainfall amounts were significantly different could not be correlated with any single type of storm.

Key-Words: - satellite pixel, rainfall variability, QPE, rain gauge, radar, validation, hydrologic modeling

1 Introduction

Is it is commonly assumed that a single rain gauge located within a QPE pixel represents the average rainfall for the pixel area (e.g., [1] and [2]). The National Oceanic and Atmospheric Administration's (NOAA) Hydro Estimator (HE) algorithm [3], which utilizes data from the GOES geostationary satellite to estimate rainfall, for example, has an approximate pixel size of 4 km x 4 km (16,000,000 m^2), compared to a cross-sectional area of roughly 0.032 m^2 for the standard National Weather Service tipping bucket gauge. The National Weather Service's (NWS) Next Generation Radar (NEXRAD) 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 [4]. 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); additional details can be found in [5]. The differences in temporal and spatial scales make the comparison of QPE methods with ground-based rain gauges difficult [6]. Other potential sources of error include rain gauge inaccuracy, assumptions made in the development of the QPE algorithm that may be violated under local (e.g., tropical) rainfall conditions, and navigation errors in the satellite pixel coordinates. For example, the navigation errors of the GOES-12 pixels at nadir are on the order of 4-6 km [7].

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 [8] 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 [8]. Goodrich [10] has stated that rainfall runoff accuracy will increase with an increasing number of rain gauges in the watershed, which will improve the representation of the spatial characteristics of rainfall. Rainfall estimates at a point differ from catchment averages because rainfall varies spatially and its spatial distribution over the catchment determines the amount of rainfall that is integrated in time and space [11]. Moreiraa et al. [9] evaluated rainfall spatial variability effects on catchment runoff. The study area was a 2.1 km^2 catchment in northeastern Brazil. The catchment response of the relatively small catchment area was quite sensitive to the occurrence of rainfall with high spatial variability. Bell and Moore [12] evaluated the sensitivity of simulated runoff using rainfall data from gauges and radar. The rain gauge system consisted of 49 gauges over the 135 km^2 Brue catchment in southwestern England. They evaluated convective and stratiform rainfall events. Runoff variability was strongest during convective storm events and weakest during stratiform events. Surprisingly, the authors obtained the best performance using lower-resolution rainfall data and a lower-resolution hydrologic 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., [13], [14], [9],). For instance, Bidin and Chappell [13] 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. [14] studied small scale rainfall variability within a 4.4 ha area in the semiarid USDA Walnut Gulch Experimental (WGE) Watershed in Arizona, USA. 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. [15]) compared rain gauges in Guam at three time scales (5, 15, and 60 min) and three spatial scales (1, 600, and 1100 m). The largest variations occurred for the smallest time scale and the largest spatial scale. The smallest variations occurred for the largest time scale and the smallest spatial scale.

We hypothesize that many rain gauge networks in environments similar to this study (i.e., tropical coastal), which provide only one rain gauge per remote sensing pixel, may be 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 (e.g., GOES Hydro-Estimator [3], SCaMPR [16], NEXRAD and the University of Puerto Rico Collaborative Adaptive Sensing of the Atmosphere radar network). Implications of the results on calibration/validation of QPE methods are discussed.

2 Methodology

During July 2006, sixteen tipping bucket rain gauges (Spectrum Technology, Inc.[1]) were installed within the area covered by one Hydro-Estimator (HE) pixel. The HE has been the operational satellite precipitation algorithm of the National Environmental Satellite, Data, and Information Service (NESDIS) since the fall of 2002 [17]. 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 (Fig. 1). The pixel area was 4 km x 4 km (16 km^2) corresponding to a single GOES pixel. 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.
5. The actual coordinates of the installed rain gauges were recorded and entered into ArcGIS (Fig. 2).

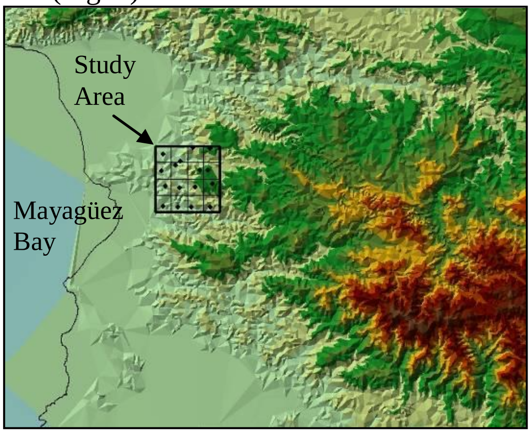


Figure 1. Study area in western Puerto Rico corresponding to a Hydro-Estimator pixel (4 km x 4 km). Colors represent variations in topography.

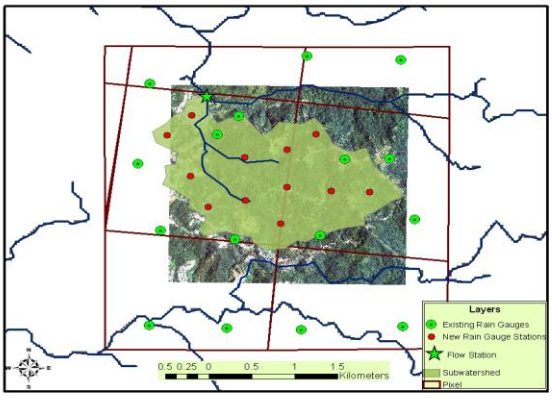


Figure 2. Twenty-eight tipping bucket rain gauges used in the study. The 12 rain gauges installed in June of 2007 were distributed within a subwatershed of the Añasco River.

Some of the rain gauges could not be located close to the center points of the squares because of a 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

[1] Reference to a commercial product in no way constitutes an endorsement of the product by the authors.

producing a random (possibly beneficial) aspect to the locations of rain gauges within each sub-area.

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.

In June of 2007, another 12 tipping bucket rain gauges were added to the network. These rain gauges were distributed within a subwatershed of the Añasco River for future hydrologic evaluation. Figure 2 shows the location of the 12 rain gauges within the subwatershed and the location of a stream gauge (Solinst Levelogger) installed at the outlet of the subwatershed.

Storm data were collected for 62 storms between August 2006 and August 2007. The storm data collected included: start and end times, storm duration, number of operational rain gauges (n), average total storm rainfall, standard deviation, and maximum and minimum rain gauge amounts. Student's t-tests were performed on all pairs of rain gauges for each of the 62 storms (total 3,627 pairs) to determine if significant spatial differences exist in the mean rainfall amounts.

The reason for conducting the significant difference tests was based on the following rationale. QPE methods based on remote sensing usually compare (or adjust) the remotely sensed rainfall estimate based on a single rain gauge located within the remotely sensed pixel. The rain gauge, in virtually all cases, will be randomly located within the pixel (as opposed to, for example, being located at the pixel center). This is because the entity that manages the satellite or radar is typically different than the entity that installed the rain gauges. If there is a large amount of sub-pixel rainfall variation then the QPE will be compared with a rain gauge that does not represent other locations within the pixel. On the other hand, if there is no significant difference between randomly located pairs of rain gauges, then this would suggest that the sub-pixel variability is low and the QPE can be compared (or adjusted) to rain gauges located at any location within the pixel. All statistical analyses were performed using software developed by the authors using MatLab Version 7.3 (MathWorks, Inc.). The t-test function used in this study (ttest2) did not assume equal variances (Behrens-Fisher problem).

Storms were classified according to whether they were locally formed by sea breezes and heating, or generated by large weather systems of either easterly or westerly origin. For this it was necessary to gather supplementary information on the synoptic weather conditions, and the local pattern and timing of convection near Mayagüez, Puerto Rico. Supplementary information included large scale maps of upper winds and precipitable water, visible or IR satellite and radar images, and radiosonde profiles at San Juan. The types of weather systems observed were:

- Localized = isolated over western Puerto Rico with trade wind convergence
- Tropical westerly trough = southwesterly moist flow and SW-NE cloud bands
- Tropical easterly wave = deep easterly flow with widespread cloudiness
- Upper westerly trough = westerly flow in mid-levels coming down from north
- Cold front = frontal cloud band penetrating from Florida

3 Results

As an example of the measured rainfall data, Fig. 3 shows the depth of rainfall measured every 5 minutes by sixteen rain gauges on 6 August 2006. Figure 4a shows the spatial distribution of total rainfall for the same storm. It is clear that the rainfall can vary significantly within the satellite pixel area. The average and standard deviation for the rainfall were 30.8 mm and 13.6 mm, respectively, while the maximum and minimum recorded rainfall were 55.6 mm and 9.2 mm, respectively. In addition to 6 August 2006 (4a), Fig. 4 shows the rainfall variation for storms occurring on 16 August (4b), 18 August (4c) and 22 October (4d), 2006. For these storms, the maximum rainfall gradients were 20.4, 56.9, 55, and 65 mm/km, respectively. Spatial variation in rainfall distribution as shown in Fig. 4 is commonly observed during the "wet" season (August through November) in western Puerto Rico.

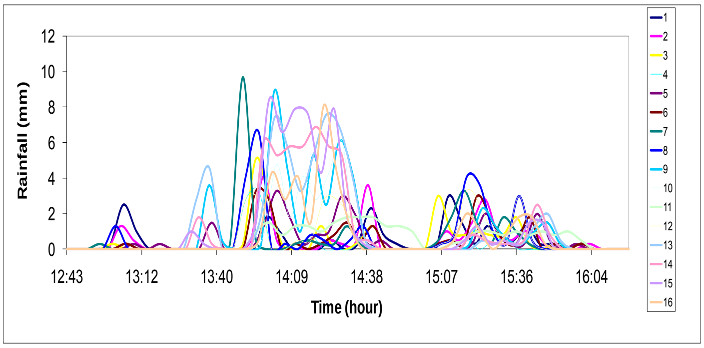
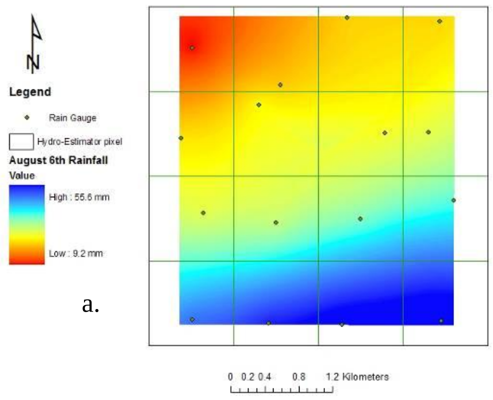
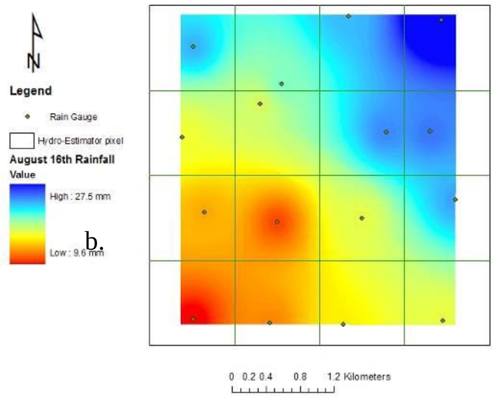
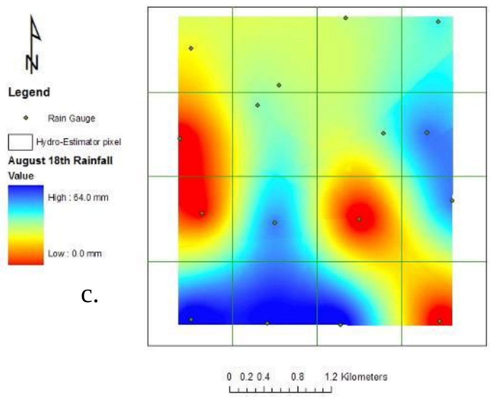


Figure 3. Rainfall measured from rain gauges on August 6th, 2006.

Table 1 lists the statistics associated with 62 storms which occurred between August 2006 and August 2007. The table includes storm start and end times, storm durations, number of operational rain gauges (n), average total storm rainfall, standard deviation, maximum and minimum rain gauge amounts, and storm classification. The overall average for each of the parameters is presented at the bottom of Table 1. On average, the rain storms started at 15:02 and ended at 17:22, with an average duration of 2.33 hours. The average, maximum, and minimum rainfall depths were 15.94 mm, 30.14 mm and 4.53 mm, respectively.







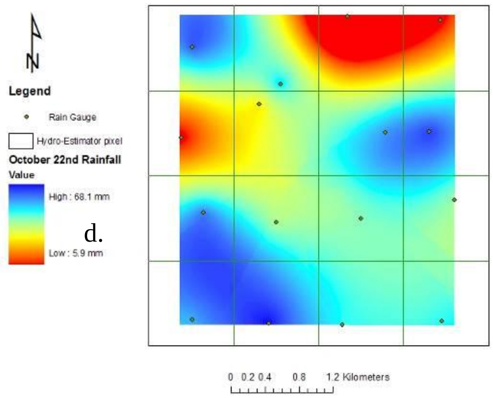


Figure 4. Spatial distribution of rainfall for storms on 6 August (a), 16 August (b), 18 August (c) and 22 October (d), 2006.

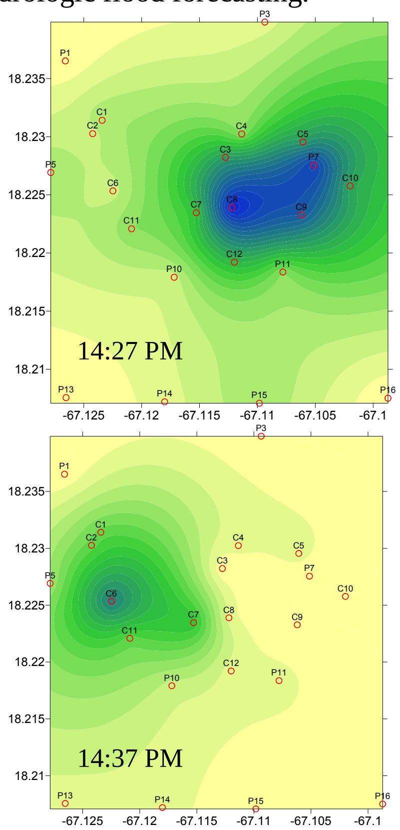
The distribution of the storm classifications were as follows: localized = 23 cases, upper westerly trough = 16 cases, tropical westerly trough = 6 cases, tropical easterly wave = 11 cases, and cold front = 6 cases. These results indicate the importance of the localized sea-breeze induced storm to the local hydrology. The average rainfalls produced from each type of storm were 15.5 mm, 14.4 mm, 27.03 mm, 17.2 mm, and 9 mm for localized, upper westerly trough, tropical westerly trough, tropical easterly wave, and cold front storms, respectively.

In mid-June 2007, 12 additional rain gauges were added within a small subwatershed located within the 4 km x 4 km pixel as shown in Fig. 2. Fig. 5 shows the variation in 5 minute rainfall at four different times (14:27, 14:37, 15:32 and 16:22) on 27 June 2007. Large variations can be observed between the individual 5 minute intervals.

Results of a Student's t-test analysis of 3,627 rain gauge-pairs from the 62 storms are presented in Table 2. The results have been sorted from highest to lowest Percent of t-test Showing Significant Differences. The average rainfall for 932 rain gauge-pairs (27%) were significantly different at or below the 5% of significance level. This result indicates that in more than one out of every four cases considered, significant sub-pixel variation existed. Furthermore, in these cases, use of one of the rain gauges to either calibrate or validate a remotely sensed QPE method, would have introduced a source of error. No observable correlation existed between Percent of t-test Showing Significant Differences and Type of Storm, Date, season, or Total Average Storm Rainfall. Figure 6 shows the variation in percent of t-tests showing significant differences in average rainfall between rain gauge pairs with number of storms.

4 Discussion

Typically QPE methods are compared with existing rain gauge networks. For example, Cruz Gonzalez (2006) compared the HE algorithm with an existing U.S. Geological Survey rain gauge network in Puerto Rico (125 rain gauges). 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 Figs. 4 and 5 illustrate, a large difference could be obtained depending upon where the rain gauges were located within the pixels. Statistically speaking, one out of every four rain gauges would not be representative of the rainfall occurring at other locations within the pixel. This problem is reduced when averaging estimates over time, but is most acute for short-term estimates within a single storm (Fig. 5); the type of data needed for real-time hydrologic flood forecasting.



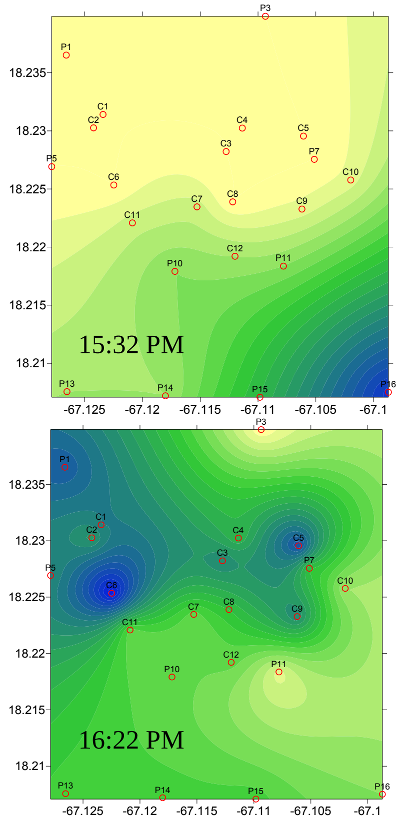


Figure 5. Spatial distribution of 5-minute rainfall values at 14:27, 14:37, 15:32 and 16:22 hours, for a storm occurring on 27 June, 2007.

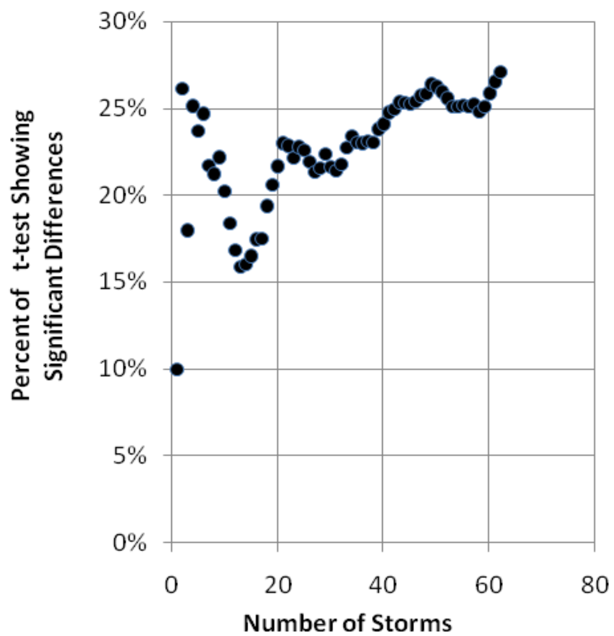


Figure 6. Percent of t-tests showing significant differences in average rainfall between rain gauge pairs vs. number of storms.

ISBN: 978-960-6766-83-1 ISSN: 1790-2769

5 Summary and Conclusion

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 (average total storm rainfall), several 5-minute intervals within a single storm on 27 June 2007, and tabular data were presented for 62 storms. Rainfall was observed to be variable within the 4 km x 4 km study area. Average storm rainfall from more than one quarter (27%) of the 3,627 rain gauge-pairs evaluated for the 62 storms were significantly different at the 5% of significance level, indicating significant rainfall variation at the sub-pixel scale. A conclusion of this study is that for existing rain gauge networks (e.g., USGS) used in environments similar to this study (i.e., coastal tropical), significant sub-pixel variation can be expected in one out of every four pixels on average. In these cases, use of one of the rain gauges to either calibrate or validate a remotely sensed QPE method will introduce a source of error into the QPE and will be propagated through any hydrologic model used. The practical consequences of this error propagation are that the hydrologic parameters derived as part of the hydrologic model calibration will be incorrect.

6 Acknowledgement

Financial support was received from NOAA-CREST, NSF-CASA, NASA-IDEAS, USDA HATCH (H-402) and USDA-TSTAR (100). We would especially like to thank Dr. Robert Kuligowski of NOAA NESDIS for providing information related to the GOES-12 satellite and the Hydro-Estimator QPE algorithm. Thanks also to Dr. Mark Jury of the University of Puerto Rico-Mayagüez Physics Department for his assistance in determing storm classifications. Finally, we would like to thank the numerous students that helped install rain gauges and collect rainfall data throughout the project: Edvier Cabassa, Jerak Cintrón, Ian García, Mariana León Pérez, Melvin Cardona, Ramón Rodríguez, Marcel Giovanni Prieto, Víctor Hugo Ramírez, Yaritza Pérez, Romara Santiago, Alejandra Roja, Jorge Canals, Julian Harmsen and Lua Harmsen.

References:

[1] Cruz Gonzalez, B., 2006: Validacion del Algoritmo Hidro-Estimador en la Region de Puerto Rico (Validation of the Hydro-Estimator Algorithm in the Puerto Rico Region). Tesis Departamento de ININ, Universidad de Puerto Rico, Recinto Universitario de Mayagüez, Julio (in Spanish).

[2] Vila D. and I. Velasco, 2002. Some experiences on satellite rainfall estimation over South America. Proceedings, 1st International Precipitation Working Group (IPWG) Workshop Madrid, Spain.

[3] Scofield, R.A. and R.J. Kuligowski, 2003: Status and outlook of operational satellite precipitation algorithms for extreme-precipitation events. Wea, Forecasting, 18, 1037-1051.

[4] Beringer D.B. and J.D. Ball, 2004: The Effects of NexRad Graphical Data Resolution and Direct Weather Viewing on Pilots' Judgments of Weather Severity and Their Willingness to Continue a Flight. DOT/FAA/AM-04/5. [Available from the Office of Aerospace Medicine, Federal Aviation Administration 800 Independence Ave. SW Washington, DC 20591.]

[5] Young, C. B., B. R. Nelson, A. A. Bradley, J. A. Smith, C. D. Peters-Lidard, A. Kruger, and M. L. Baeck, 1999: An evaluation of NEXRAD precipitation estimates in complex terrain. J. Geophys. Res., 104(D16), 19691-19703.

[6] Kuligowski, R. J. 1997: An overview of the National Weather Service quantitative precipitation estimates. TDL Office Note 97-4, NOAA/NWS/MDL, 28 pp. [Available at http://www.nws.noaa.gov/im/pub/tdl97-4.pdf.]

[7] Hilger, D. W., and T. J. Schmit, 2007: An overview of the GOES-13 Science Test. Preprints, 3rd Symp. on Future National Operational Environmental Satellites, San Antonio, Amer. Meteor. Soc., CD-ROM, P1.31

[8] Bevan, K.J. and G.M. Hornberger, 1982: Assessing the effect of spatial pattern of precipitation in modeling stream flow hydrographs. Water Resour. Bull., 18, 823-829.

[9] Moreiraa L.F.F., A. M. Righetto, and V. M. Medeiros, 2006: Uncertainty analysis associated with rainfall spatial distribution in an experimental semiarid watershed, Northeastern Brazil. Preprints, 3rd Biennial Meeting of the International Environmental Modelling and Software Society, Burlington, VT.

[10] Goodrich, D.C., 1990: Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. Ph. D. Dissertation. University of Arizona. Tucson, AZ.

[11] Vieux, B.E. and P.B. Bedient. 1998: Estimation of rainfall for flood prediction from WSR-88D reflectivity: A case study, 17–18 October 1994. Wea. Forecasting, 13, 507-513.

[12] Bell, V.A. and R. J. Moore, 2000: The sensitivity of catchment runoff to rainfall data at different spatial scales. Hydrol. Earth System Sci., 4, 653-667.

[13] Bidin, K. and N. A. Chappell, 2003. First evidence of a structured and dynamic spatial pattern of rainfall within a small humid tropical catchment. Hydrology and Earth System Sciences, 7(2), 245-253.

[14] Goodrich, D. C, J.M. Faures, D.A. Woolhiser, L.J. Lane, and S. Sorooshian. 1995: Measurement and analysis of small-scale convective storm rainfall variability. J. Hydrol. 173 (1-4), 283-308.

[15] Krajewski, W. F., G.J. Ciach and E. Habib, An analysis of small-scale rainfall variability in different climatic regimes, Hydrol. Sci. J. 48 (2003), pp. 151–162.

[16] Kuligowski, R. J., 2002: A self-calibrating GOES rainfall algorithm for short-term rainfall estimates. J. Hydrometeor., **3**, 112-130.

[17] Kuligowski, R. J., 2004. Re-calibrating the operational Hydro-Estimator satellite precipitation algorithm. 13th Conference on Satellite Meteorology and Oceanography. 20-23 September, 2004. Norfolk, VA.

12th WSEAS International Conference on SYSTEMS

Table 1. Rainfall statistics from 62 storms between August 2006 and August 2007.

Storm No.	Date	Storm start	Storm end	Storm Duration (hr)	n	Total Average Storm Rainfall (mm)	Maximum (mm)	Minimum (mm)	Type of Storm
1	6-Aug-06	13:32	14:42	1.17	16	30.8	55.50	9.20	Tropical westerly trough
2	14-Aug-06	17:12	18:37	1.42	12	11.48	27.20	0.30	Localized
3	16-Aug-06	12:54	16:49	3.92	16	16.62	27.50	9.60	Tropical easterly wave
4	18-Aug-06	12:53	18:38	5.75	13	41.59	63.70	4.50	Tropical westerly trough
5	20-Aug-06	16:28	19:48	3.33	12	19.08	27.50	8.90	Localized
6	22-Aug-06	15:00	23:23	8.38	13	23.88	44.00	9.40	Localized
7	25-Aug-06	14:03	14:53	0.83	12	6.84	10.40	6.40	Tropical Easterly Wave
8	26-Aug-06	12:18	13:13	0.92	12	5.82	8.60	4.10	Tropical easterly Wave
9	1-Oct-06	21:19	0:32	3.22	12	24.17	37.70	12.00	Tropical Easterly Wave
10	2-Oct-06	21:06	22:26	1.33	13	3.30	13.00	0.90	Localized
11	8-Oct-06	17:39	18:45	1.10	15	9.72	17.80	4.50	Upper Westerly trough
12	10-Oct-06	21:35	23:54	2.32	15	2.46	3.00	1.60	Upper Westerly trough
13	14-Oct-06	15:20	17:45	2.42	14	25.80	32.90	12.30	Tropical westerly trough
14	21-Oct-06	11:28	13:32	2.07	13	7.33	18.60	0.50	Upper Westerly trough
15	23-Oct-06	14:05	23:57	9.87	13	49.93	68.10	5.70	Localized
16	27-Oct-06	13:05	16:58	3.88	13	11.21	24.40	0.50	Upper Westerly trough
17	3-Nov-06	14:05	16:06	2.02	13	20.21	40.60	11.30	Localized
18	12-Nov-06	15:51	17:40	1.82	13	13.64	32.60	1.80	Localized with cold front
19	13-Nov-06	16:46	18:15	1.48	12	11.43	32.30	1.30	Cold Front
20	16-Nov-06	14:26	17:18	2.87	10	19.34	41.40	0.60	Cold Front
21	18-Nov-06	14:17	15:52	1.58	10	10.29	25.50	0.90	Cold front
22	24-Nov-06	13:41	16:57	3.27	13	9.50	16.90	5.00	Localized
23	7-Dec-06	14:27	19:28	5.02	12	4.74	12.20	1.00	Localized
24	9-Dec-06	13:56	16:52	2.93	11	31.82	58.70	8.60	Upper Westerly trough
25	20-Dec-06	15:09	17:04	1.92	13	35.38	58.50	16.60	Localized
26	23-Dec-06	14:54	16:29	1.58	13	1.56	3.70	0.60	Localized
27	28-Dec-06	13:37	15:17	1.67	13	6.27	13.10	0.80	Cold front
28	31-Dec-06	14:37	15:52	1.25	12	5.13	21.70	0.30	Upper Westerly trough
29	9-Jan-07	18:50	20:03	1.22	10	7.94	17.30	1.90	Localized
30	4-Feb-07	16:33	17:43	1.17	10	0.34	0.80	0.30	Tropical Easterly Wave
31	15-Feb-07	16:57	19:37	2.67	12	21.73	36.20	10.20	Localized
32	19-Feb-07	12:27	14:02	1.58	12	2.40	4.70	0.30	Cold Front
33	24-Feb-07	18:24	20:19	1.92	13	4.53	12.40	0.30	Cold Front
34	28-Feb-07	18:00	20:40	2.67	13	23.83	57.70	8.60	Localized
35	18-Mar-07	13:27	14:57	1.50	11	5.58	11.30	2.00	Upper Westerly trough
36	19-Mar-07	17:41	21:01	3.33	11	17.28	22.10	10.00	Upper Westerly trough
37	21-Mar-07	13:07	14:27	1.33	11	5.95	11.30	2.10	Upper Westerly trough
38	25-Mar-07	17:27	19:22	1.92	11	21.85	37.00	4.10	Upper Westerly trough
39	21-May-07	15:33	17:39	2.10	12	6.13	26.60	0.60	Localized
40	23-May-07	15:46	18:48	3.03	12	15.83	20.70	1.80	Upper Westerly trough
41	24-May-07	11:49	17:49	6.00	9	55.40	129.40	28.20	Upper Westerly trough
42	25-May-07	17:33	21:35	4.03	10	6.33	26.60	1.40	Upper Westerly trough
43	27-May-07	15:29	17:48	2.32	10	15.60	34.90	1.50	Upper Westerly trough
44	28-May-07	15:15	17:49	2.57	10	8.58	13.60	6.40	Upper Westerly trough
45	31-May-07	15:59	18:30	2.52	10	10.50	15.70	0.60	Upper Westerly trough
46	23-Jun-07	14:22	16:19	1.95	22	7.38	13.20	4.00	Localized
47	24-Jun-07	12:32	17:10	4.63	20	31.50	54.80	1.80	Localized
48	25-Jun-07	13:37	15:47	2.17	20	5.32	8.90	0.80	Localized
49	27-Jun-07	13:36	18:26	4.83	22	37.85	63.10	12.80	Tropical Easterly Wave
50	2-Jul-07	13:21	15:33	2.20	18	16.39	30.30	3.80	Localized
51	3-Jul-07	14:28	16:43	2.25	19	7.83	11.10	2.60	Localized
52	5-Jul-07	13:53	16:12	2.32	19	13.53	21.08	5.60	Localized
53	7-Jul-07	16:43	17:38	0.92	19	28.48	54.90	12.10	Tropical Easterly Wave
54	11-Jul-07	12:53	20:58	8.08	19	21.50	32.26	12.60	Tropical Westerly Trough
55	17-Jul-07	12:58	16:06	3.13	19	29.63	41.65	0.30	Tropical Westerly trough
56	18-Jul-07	14:45	17:50	3.08	22	12.86	25.40	0.30	Tropical Westerly trough
57	22-Jul-07	13:38	15:23	1.75	20	14.83	34.20	1.10	Tropical Easterly Wave
58	23-Jul-07	13:13	14:18	1.08	20	13.95	25.15	1.90	Tropical Easterly Wave
59	25-Jul-07	14:25	15:45	1.33	11	4.31	14.60	0.60	Localized
60	31-Jul-07	14:40	16:25	1.75	11	13.15	36.90	0.30	Localized
61	5-Aug-07	13:25	17:17	3.87	20	21.23	53.30	0.30	Tropical Easterly Wave
62	6-Aug-07	13:58	16:02	2.07	22	19.38	32.20	0.30	Tropical Easterly Wave
Average		15:02	17:22	2.33	14	15.94	30.14	4.53	

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

ISBN: 978-960-6766-83-1 ISSN: 1790-2769
ISBN: 978-960-6766-83-1 797 ISSN: 1790-2769

12th WSEAS International Conference on SYSTEMS

Table 2. Results of Student's t-test for all combination of rain gauge-pairs for 62 sorms.

Date	Total Average Storm Rainfall (mm)	Type of Storm	Number of t-tests Performed	Percent of t-test Showing Significant Differences
31-Jul-07	13.15	Localized	45	71%
5-Aug-07	21.23	Tropical Easterly Wave	28	68%
6-Aug-07	19.38	Tropical Easterly Wave	91	59%
27-Jun-07	37.85	Tropical Easterly Wave	45	53%
24-Feb-07	4.53	Cold Front	36	53%
21-May-07	6.13	Localized	55	53%
12-Nov-06	13.64	Localized with cold front	66	52%
24-May-07	55.40	Upper Westerly trough	45	51%
18-Nov-06	10.29	Cold front	36	50%
18-Aug-06	41.59	Tropical westerly trough	105	47%
9-Jan-07	7.94	Localized	55	45%
28-Feb-07	23.83	Localized	55	45%
13-Nov-06	11.43	Cold Front	66	42%
14-Aug-06	11.48	Localized	78	42%
27-May-07	15.60	Upper Westerly trough	45	42%
25-Jul-07	4.31	Localized	45	42%
16-Nov-06	19.34	Cold Front	55	42%
24-Jun-07	31.50	Localized	36	42%
9-Dec-06	31.82	Upper Westerly trough	66	38%
23-May-07	15.83	Upper Westerly trough	36	36%
19-Feb-07	2.40	Cold Front	45	33%
25-May-07	6.33	Upper Westerly trough	55	33%
22-Jul-07	14.83	Tropical Easterly Wave	28	32%
27-Oct-06	11.21	Upper Westerly trough	78	32%
23-Jun-07	7.38	Localized	45	31%
25-Jun-07	5.32	Localized	55	31%
22-Aug-06	23.88	Localized	91	30%
1-Oct-06	24.17	Tropical Easterly Wave	91	30%
17-Jul-07	29.63	Tropical Westerly trough	21	29%
31-Dec-06	5.13	Upper Westerly trough	66	27%
21-Mar-07	5.95	Upper Westerly trough	55	27%
11-Jul-07	21.50	Tropical Westerly Trough	28	25%
28-May-07	8.58	Upper Westerly trough	55	24%
23-Oct-06	49.93	Localized	78	23%
31-May-07	10.50	Upper Westerly trough	39	23%
19-Mar-07	17.28	Upper Westerly trough	66	23%
18-Jul-07	12.86	Tropical Westerly trough	36	22%
25-Mar-07	21.85	Upper Westerly trough	55	20%
24-Nov-06	9.50	Localized	66	20%
2-Jul-07	16.39	Localized	21	19%
3-Nov-06	20.21	Localized	66	18%
20-Dec-06	35.38	Localized	55	18%
20-Aug-06	19.08	Localized	78	18%
26-Aug-06	5.82	Tropical easterly Wave	78	18%
21-Oct-06	7.33	Upper Westerly trough	78	18%
15-Feb-07	21.73	Localized	45	16%
3-Jul-07	7.83	Localized	28	11%
6-Aug-06	30.8	Tropical westerly trough	120	10%
18-Mar-07	5.58	Upper Westerly trough	91	10%
5-Jul-07	13.53	Localized	28	7%
7-Dec-06	4.74	Localized	66	6%
23-Dec-06	1.56	Localized	36	6%
28-Dec-06	6.27	Cold front	55	5%
14-Oct-06	25.80	Tropical westerly trough	91	4%
25-Aug-06	6.84	Tropical Easterly Wave	78	4%
2-Oct-06	3.30	Localized	78	3%
16-Aug-06	16.62	Tropical easterly wave	120	2%
8-Oct-06	9.72	Upper Westerly trough	105	0%
10-Oct-06	2.46	Upper Westerly trough	105	0%
4-Feb-07	0.34	Tropical Easterly Wave	21	0%
7-Jul-07	28.48	Tropical Easterly Wave	21	0%
23-Jul-07	13.95	Tropical Easterly Wave	21	0%
	Average		Total	Average
	15.94		3627	27%

ISBN: 978-960-6766-83-1 798 ISSN: 1790-2769
ISBN: 978-960-6766-83-1 798 ISSN: 1790-2769