FLASH FLOOD FORECASTING USING WEATHER RADAR AND SATELLITE DATA FOR URBAN CATCHMENT IN RIO DE JANEIRO

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ABSTRACT: According to the World Meteorological Organization, flash floods are the most lethal form of natural hazard (based upon the ratio of fatalities to people affected), and cause millions of dollars in property damage every year. This type of hydrometeorological disaster depends on land surface and atmospheric specifics conditions. A combination of a high rainfall rate with rapid and often efficient runoff production process is common to most events. In Brazil, flash floods can be deadly. Recently in January 2011, landslides, debris flow and flash flood processes in the mountainous region of Rio de Janeiro caused more than 900 fatal victims. During 3 days, the rainfall achieved almost 400 mm, a rate 71% higher than the month average. Despite the significance of these events, few countries in the world have already implemented flash flood warning systems. This is due in part to the technical complexity of predicting extreme events with enough confidence and lead time to take precautionary action. Since flash floods processes happen in the same temporal and spatial scale of severe storms, this paper aims to provide analyses of case studies simulating real-time flash flood forecasting, with high resolution weather radar and satellite rainfall estimates in an urban catchment in Nova Friburgo, Rio de Janeiro. Results indicate that at least some of flash floods can be predicted by the physically based distributed hydrologic modeling, even for shot-lived events on small catchments. Based on the limited observations available, validation indicates that there is good agreement of rising limb of hydrograph between simulated peak discharge and peak discharge observed. This technique has been developed by the Brazilian Centre for Monitoring and Warnings of Natural Disaster (Cemaden) and will be tested in operational environment for pilot catchments in following rainy season, improving flash floods early warnings in Brazil.

Key Words: Distributed Hydrological Modeling, Nowcasting, Remote Sensing of Clouds, Meteorology, Hydrometerology, Hydrology, Rainfall Estimation

1. INTRODUCTION

The topography of Rio de Janeiro state makes it especially prone to flash flood events. The mountainous area near the coast usually act as natural barriers to the warm moist Amazonian and Oceanic air, inducing generation of intense rainfall rates that show high variability in space and time (Padilha, 2011). A combination of a high rainfall rate with rapid and often efficient runoff production process can contribute to serious damage, in particular when urbanization rate increases in risk areas (UCAR, 2010). It was notified that 18 thousand people are living in eminent risk to mass movement in Mountainous Region of Rio de Janeiro (MRRJ) (DRM, 2012), which can also be included in many conterminous watersheds with high flooding risk zones. Methods of protection, counteracting and diminishing impacts, such as forecasting and reaction systems, can help local authorities in limiting flood consequences in a high level of efficiency.

To date, the time required for appropriate public response has typically been much longer than the time between the causative precipitation and the subsequent flash flood. In Brazil, new techniques on diagnostic and forecasting risk levels were started by the creation of Brazilian Centre for Monitoring and Early Warning of Natural Disaster (Cemaden) in 2011, which is responsible to provide early warnings considering both hazard and vulnerability components. The flood warning signal is sent to National Center for Risk Management and then repast to local and provincial authorities, disseminating the information to inhabitants of inundation areas as well as preparing them to flood procedure instructions.

Therefore, the major challenge for Cemaden is to improve techno-bureaucracies with considerable scientific support for most forms of weather related hazard monitoring, prediction and warning. In case of flash floods, recent efforts have focused in distributed precipitation estimates and distributed hydrological modeling, for simulation and prediction in complex urban settings (Sharif et al 2005; Romero et al. 2006). However, the greatest challenge in this contest still on predicting the spatial and temporal distribution of rainfall patterns at very fine scales (Gruntfest et al., 1999; Kuligowski, 1997, Salek et al. 2010; UCAR, 2010). Since weather radar information by itself offers little predictive content, its utility is primarily in the nowcasting environment (Matrosov et al., 2005). Some studies show that for regions uncovered by weather radar, high-resolution diagnoses rely on the coarser resolution data from rain gages and satellite (Gruntfest et al., 1999). Otherwise, the available resolution of satellite data is not always suitable for small spatial and temporal scales associated with flash floods.

Different results can also be found when comparing distinguish remote sensing tools that use different types of measurement. The overall objective of this study is to test the potential benefits of high resolution weather radar and satellite in a physically based hydrologic model, providing a quantitative flash flood forecasting for an urban environment in Mountainous Region of Rio de Janeiro. Radar reflectivity data from Pico do Couto was used to estimate the rainfall, in addition to Hydroestimate data from GOES 13 satellite. Hydrological model simulating real time forecasting using remote sensing precipitation estimate were compared to outputs produced using rain gauges field, which were assumed to be the best available rainfall information.

2. THE STUDY AREA AND 2011 FLASH FLOOD EVENT

During the south hemisphere summer a climatological feature is highly responsible for southeastern Brazil rainy season, the South Atlantic Convergence Zone (SACZ). Described by Quadro (1994) as an axis of clouds oriented in a northwest-southeast direction, all the way from Amazon to southeast Brazil and Atlantic Ocean, the SACZ can contribute for several extremes events as already studied by Carvalho et al (2002), once the configuration usually last for four to six days. Particularly in January 2011 flash flood, the SACZ got established by the end of the day 10. In this day, landslides events caused the death of five people in São Paulo. In case of SACZ, the air flow coming from warm and moisture areas induce a contribution for moisture convergence and displacement on southeastern Brazil, rising by mechanic force, when the topography passes from 100 to 2000 meters height in less than 40 kilometers length. Once the mountainous region of Rio de Janeiro presents a very irregular geomorphology, the formation of clouds with high vertical growth seems to be also very irregular. Thereby, it is possible to notice a great difference in precipitations values in few meters way, what becomes a problem when the catchment does not have too many rain gauges.

As shown by Pinheiro et al (2011) the synoptic situation of January 2011 was quite unusual for weather forecasting. The two atmospheric models used by INPE for weather prediction, ETA (regional) and GFS (global), predicted well the circulation in large scale over the South America. On the other hand, both models badly represented the precipitation amount over the RJ mountainous region. The most intense rainfall was forecasted for Minas Gerais state, and not for Rio de Janeiro. It was clear that a regional model with 20km by 20km resolution was not able to predict the huge amount of precipitation even 24 hours later.

Some researchers questioned the capability of regional models to predict extreme events, mostly because of the parameterizations used in atmospheric models. Padilla (2011) forecasted extreme events that reached Rio de Janeiro with WRF model, comparing different convective and microphysics parameterizations. The results showed that even a model with 1km by 1km resolution was not able to forecast this particular 2011 event in the mountainous region, the forecasted rainfall did not even reached the right region.

Hydrological stations in Nova Friburgo offered an important data to analyze 12 January 2011 flash flood event. The hydrological gauge Olaria has 24.7 Km² of upstream area and it flood threshold level is equal to 2.18 meters. One hour before the first flood peak, the rain gauge showed a 78.6 mm of hourly rainfall, and 182.8 mm in 24 hours. It only took one hour and half to the river level changes from 0.9 meters to 3.5 meters. An aggravating to the event was the monthly rainfall. Two months before (November and December 2010) the monthly rainfall was more than 100mm above the average over Rio de Janeiro State. This is related to the capacity of the water storage in soil, where the higher rainfall positive anomaly the lesser precipitation will be needed to saturate the soil and cause flooding or landslides (Norbiato, 2008).

3. THE HYDROLOGIC MODEL

The Distributed Hydrological Model (MHD – INPE) is a physically based distributed-parameter hydrologic model. MHD is a reformulation and enhancement of Great Scale Model of Institute of Hydraulic Research (MGB - IPH), which was developed by Collishonn (2001) and firstly applied to southern Brazil basins, and further used to hydrological studies in Amazonian basin (Rodriguez, 2011). According to Collishonn (2001) the structure of the model is based in LARSIM (Bremicker, 1998) and VIC-2L (Wood et al. 1992, Liang et al. 1994; Abdulla e Letternmaier, 1997; Lohmann et al. 1998) models. The evapotanspiration module was applied according Shuttleworth (1993) and Wigmosta et al. (1994). To simulate the one dimensional flow the methodology of Muskingun-Cunge was applied as described by Tucci (1998).

MDH operates based on a digital elevation model of the watershed using square grids, then upscaled to 1km to define the cells for runoff transport. Water components of the hydrologic balance are calculated in each cell for three soil layers, in order to propagate using linear reservoir method. The transport on channel routing is realized considering Muskingun-Cunge (Tucci, 1998), where the Newton-Raphson method was implemented to time steps and river length definition.

The skill of the runoff simulations is expressed in terms of the Nash-Sutcliffe efficiency criterion (NSE; Nash and Sutcliffe, 1970) and Coefficient of Determination (R2).The NSE coefficient diagnoses the model ability to forecast the observed runoff (Gupta et al., 2009; Rodriguez, 2011), and can range from -∞ to 1, where higher values indicate a better agreement (Equation 1). The coefficient of determination (Equation 2) provides information on the degree of correlation between the simulations and the observed values, as much as the ability to diagnose model to reproduce the shape and distribution of the hydrograph (Gupta et al., 2009).

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Qo_i - Qs_i)^2}{\sum_{i=1}^{n}(Qo_i - \overline{Qo})^2} \qquad [1]$$

$$R2 = \left[\frac{n\sum(Qs_iQo_i) - (\sum Qs_i)(\sum Qo_i)}{\sqrt{[n\sum(Qs_i)^2 - (\sum Qs_i)^2][n\sum(Qo_i)^2 - (\sum Qo_i)^2]}}\right]^2 \qquad [2]$$

Where Qo and Qs are the observed and model-simulated discharged values of flow gauge site ate time i, respectively, and $\overline{Qo}$ is the mean observed value.

4. RAINFALL DATA

Rainfall hourly observations from 7 rain gauges operated by the INEA (Environmental Institution of Rio de Janeiro) were obtained and later bucked with 1km resolution.

The Pico do Couto RMT0100D radar is an S band located about 40km from the watershed. The data available for rainfall estimation unable the prediction of whole 11 January case, but some other events will be presented in this paper. The three-dimensional volume scan reflectivity field was used to generate the CAPPI product of 3km, which it means a reflectivity field in a constant height of 3km above the radar. All reflectivity values above 65 dBZ were considered equally constant to avoid overestimation of the rainfall and hail contamination. The relationship typically applied to estimate the rainfall rate *R* (mm h^{-1}) by the radar reflectivity Z (mm^6 m^{-3}) corresponds to Equation (3):

$$R = a Z^{b} \qquad [3]$$

For rain rates associated to convective storms (reflectivity above 35 dBZ) the values of a and b in Eq. (3) are assumed to be *a* = 300 and b = 0.714, according Woodley et al. (1975). In cases of stratriform preciptation (reflectivity below 35 dBZ) the parameters of Marshall et. al (1948) a = 200 and b = 0.625 were applied. Previous studies already investigated the limitation of Pico do Couto radar data in rainfall estimation. Bacelar et al. 2013 suggest a corrective threshold of 2.11 over the rainfall field derived by CAPPI. This value was a result of average estimations for some flash flood events, what showed a significant application in this work. The radar-rainfall field had been accumulated in 1 hour temporal resolution in a scale of 1km x 1km, equally to the rain gages field. Then, the radar-rainfall data were used without further adjustments.

To test the appropriateness of the satellite rainfall estimation, some runoff simulations was driven by hydroestimate data, obtained in Satellite Division and Environmental Systems (DSA) of National Institute for Space Research (INPE). The hydro-estimator is an algorithm that assumes an exponential and empirical relationship for rainfall rates as a function of IR window brightness temperature of GOES 12 (Scofield, 2001), whose the origins go all the way back to the semi-automated Interactive Flash Flood Analyser (Scofield, 1987).

5. WATERSHED CHARACTERISTICS

The Bengala watershed was forecasted in an area of approximately 160 km^2 (Figure 1). A 30 m grid size was found sufficient to describe the topography and land surface features of the watershed. The topography and land use/cover data were obtained from the INPE database. Soils are classified as the Soil Conservation Service Group A, clay of highly plastic, while in the mountainous region, exposed rocks can also be found over the upstream flow, consequently considered impervious areas. The Nova Friburgo city is heavily channelized and is drained by a combination of trapezoidal, rectangular and natural ground channels.

Information from the automated level gauge operated by the INEA was used to estimate the flow (m^3/s) for further calibration and validation. The flow was estimated using a relationship of raing curve from National Water Agency hydrological station in the same section of the automated level gauge (Figure 2).

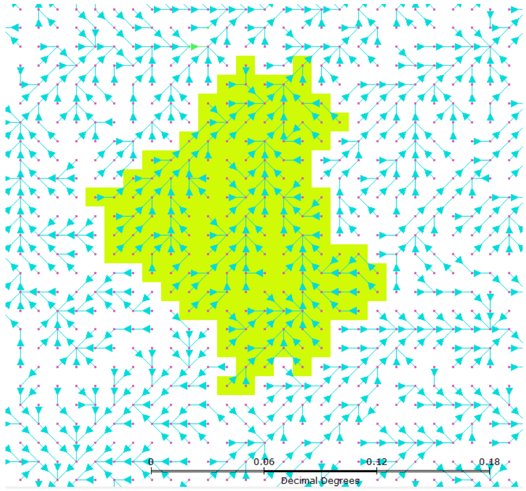

Figure 1: Representation grid cells (1km x 1km) in Bengala watershed (Nova Friburgo – Rio de Janeiro)

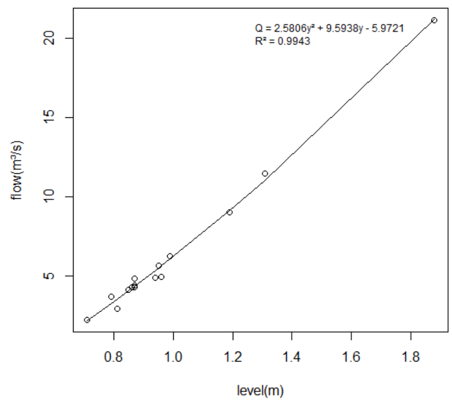

Figure 2: Raing curve for Conselheiro Paulino hydrological station (58832000)

6. RESULTS AND DISCUSSION

INEA rain gauges derived rainfall was used to drive the calibrated MHD model in a single evaluation runoff simulation, from 2009 to 2012. As a general overview, the Figure 3 and Table 1 show a good MDH skill for the characterization of Bengala basin response through the years. Therefore, the results indicate a reasonably goodness of fit for the main peak discharges in some cases of flash flood during this 4 years, showing a NSE value of 0.5. In some cases, the rainfall data from rain gauges was not able to represent the real amount of precipitation over the watershed.

The MHD was then set up for forecast module, to test the January 12 2011 flash flood event as real time evaluation. Unfortunately, the weather radar Pico do Couto was out of operation in this event, what turned impossible to drive runoff simulation with radar rainfall estimation. Since the DSA-INPE also had problems with satellite data storage, it was not able to simulate either with satellite rainfall estimation. Thus, the Figure 4 shows the hydrograph of forecasted runoff using only rain gauges. According to the Table 1, the event peak flow was possible to be forecasted by the rain gauges available in the site of catchment, showing a NSE value of 0.85 and R2 of 0.93. On the other hand the model could not fit well the rising limb of the hydrograph.

Table 1: NSE efficiency criterion and R2 for the forecasted episodes at stream gauge of INEA.

	Rain Gauge		Weather Radar		Satellite	
Flood Events	NSE	R2	NSE	R2	NSE	R2
Calibration 2009-2012	0.55	0.75	-	-	-	-
Jan 12 2011	0.85	0.93	-	-	-	-
Oct 15 2011	0.80	0.94	0.21	0.60	0,07	0,52

To compare the rainfall estimation by weather radar and satellite data, the 15 October of 2011 was choose to be forecasted (Figure 5). The radar and satellite errors in peak discharge and runoff volume from the flood hydrographs are about 4 times as larger compared to rain gauges (Table 1). In this particular event, even the radar and satellite was able to represent the rainfall over the watershed, the values of NSE and R2 were under the reasonable.

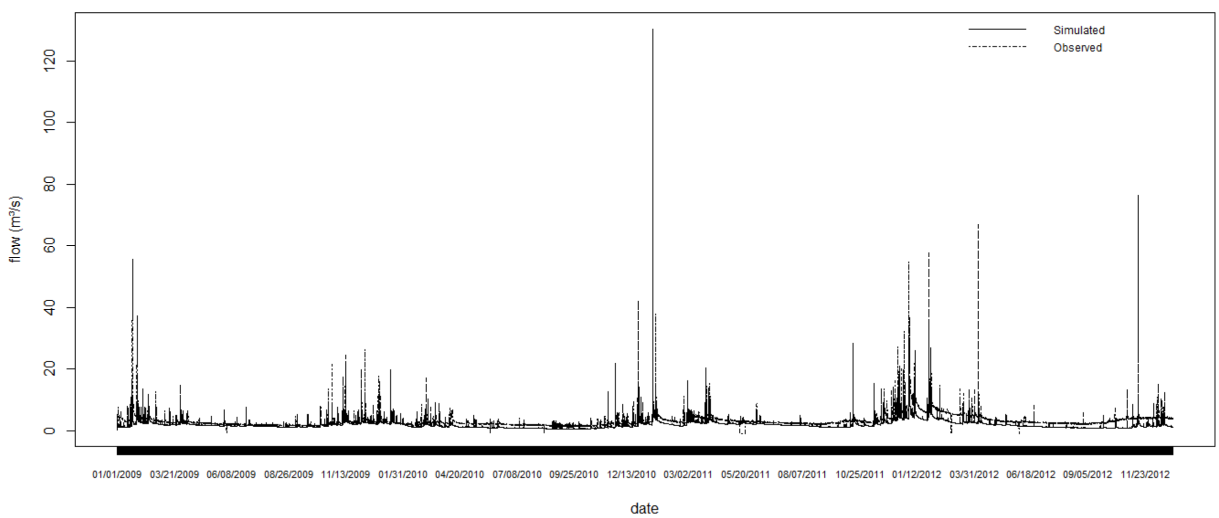

Figure 3: Simulated and Observed runoff hydrographs driven by rain gauges from 2009 to 2012.

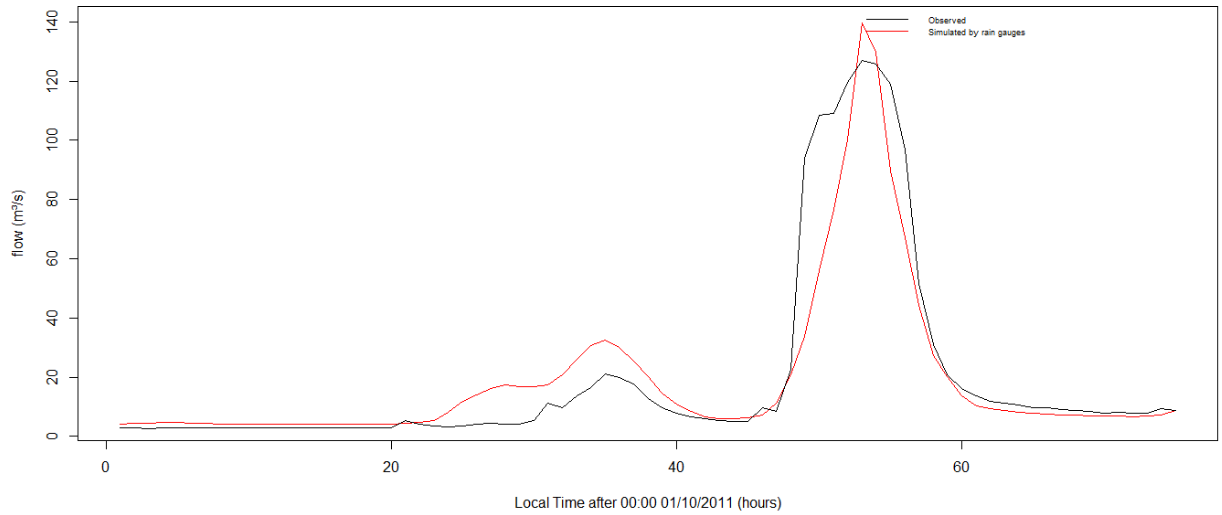

Figure 4: Simulated and Observed runoff hydrographs driven by rain gauges for January 12 2011 flash flood event.

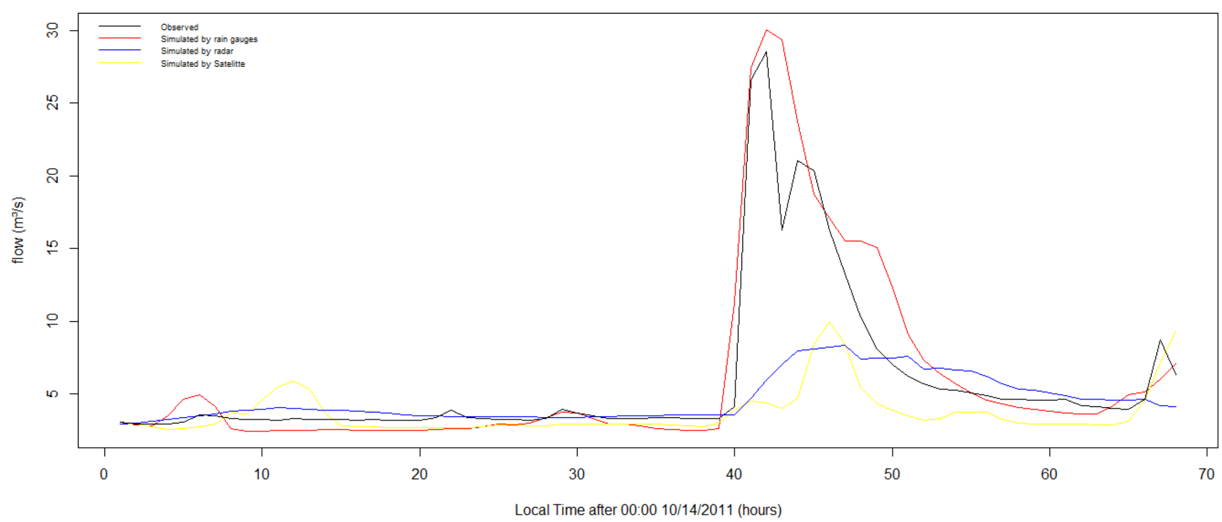

Figure 5: Simulated and Observed runoff hydrographs driven by rain gauges, radar rainfall estimation and satellite rainfall estimation for October 15 2011 flash flood event.

7. SUMMARY AND CONCLUSIONS

A preliminary attempt to simulate runoff nowcasts in highly urbanized small catchment is presented to demonstrate utility of nowcasting techniques in flash flood forecasting. The precise hydrological response of Bengala watershed to rainfall events, in terms of the induced runoff, is strongly determined by the spacial and temporal variability of precipitation. Either radar or satellite could represent well the amount of precipitation in 15 October 2011 event. Although, validation indicates that there is good agreement of rising limb of hydrograph between simulated peak discharge and peak discharge observed when using only rain gauges.

Some advanced techniques in nowcasting environment show that the best rainfall estimation is when radar, satellite, rain gauge are merged, (Kuligowsk, 1997; UCAR, 2010.; Ahnert, P., 2010.; Salek, M. Novak, P. 2010) what could possible avoid some problems showed in Bengala runoff simulations. After further adjustments, this technique will be tested in Cemaden operational platform (SALVAR) for pilot catchments in following rainy season, improving flash floods early warnings in Brazil.

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