Vol. 3 (2014), pp. 88-93, ISSN 2362 7409

National Scale Rainfall Map Based on Linearly Interpolated Data from Automated Weather Stations and Rain Gauges☆

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Abstract

In response to the slew of disasters that devastate the Philippines on a regular basis, the national government put in place a program to address this problem. The Nationwide Operational Assessment of Hazards, or Project NOAH, consolidates the diverse scientific research being done and pushes the knowledge gained to the forefront of disaster risk reduction and management. Current activities of the project include installing rain gauges and water level sensors, conducting LIDAR surveys of critical river basins, geo-hazard mapping, and information education campaigns. Approximately 700 automated weather stations and rain gauges installed in strategic locations in the Philippines hold the groundwork for the rainfall visualization system in the Project NOAH web portal at http://noah.dost.gov.ph. The system uses near real-time data from these stations installed in critical river basins. The sensors record the amount of rainfall in a particular area as point data updated every 15 minutes. The sensor sends the data to a central server either via GSM network or satellite data transfer, for redundancy. The web portal displays the sensors as a placemarks layer on a map. When a placemark is clicked, it displays a graph of the rainfall data for the past 24 hours. The rainfall data is harvested by batch determined by a one-hour time frame. The program uses linear interpolation as the methodology implemented to visually represent a near real-time rainfall map. The algorithm allows very fast processing which is essential in near real-time systems. As more sensors are installed, precision is improved. This visualized dataset enables users to quickly discern where heavy rainfall is concentrated. It has proven invaluable on numerous occasions, such as the August 2012 and 2013 events when intense to torrential rains brought about by the enhanced Southwest Monsoon (local name Habagat) caused massive flooding in Metro Manila. Coupled with observations from Doppler imagery and water level sensors along the Marikina River, the local officials used this information and determined that the river would overflow in a few hours. It gave them a critical lead time to evacuate residents along the floodplain and no casualties were reported after the event.

1. Introduction

Until recently, researchers and the general public have had limited access to updated rainfall data. In addition, published weather advisories are usually limited to generalized descriptions of atmospheric conditions that are of little use, if at all any, to the public. Efforts to show near-real time rainfall data through automated rain gauges have proven invaluable despite the limitations of the spatial representation of point data. To address this, we take advantage of the automated sensors distributed across the country and use these data to generate an approximation of the spatial extent of a particular rainfall event.

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2. Methodology

This section presents the methodologies used to arrive at a rainfall map of the country. The whole system is subdivided into two processes: (a) data collection from the sensors, and (b) interpolation proper and post-processing. Figure 1 shows a flow diagram of sensor data collection.

Automated rain gauges and weather stations installed in strategic locations all over the country (Figure 2) record the amount of rainfall measured by the number of tips of the device. A tip may be equivalent to one millimeter of rain or one inch of rain over a 15-minute period depending on the size of the tip installed within the sensor. Sensors send data through a GSM gateway by default to a flat MySQL database as a temporary repository of the message in raw format. As redundancy against network failure during extreme weather events, the message is sent from the sensor via satellite through an SMTP gateway to the MySQL database. The MySQL database serves as a temporary receiver of all data sent from the sensors. An SMS parser processes the data and pushes it to a relational PostgreSQL database. Rain gauge readings are converted from

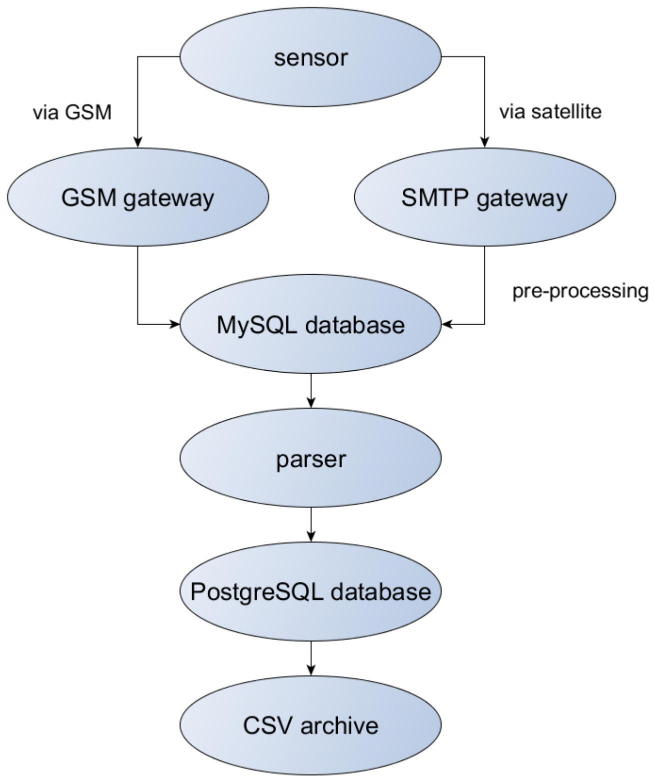

Figure 1: Sensor data collection diagram. Automated weather stations and rain gauges collect rainfall data every 15 minutes.

tips to millimeters of rain if applicable. The parser also converts particular data such as station pressure to atmospheric pressure values when station elevation is present. An external repository site archives the data as comma-separated values for each sensor per day. The archived data is then harvested to be used for interpolation.

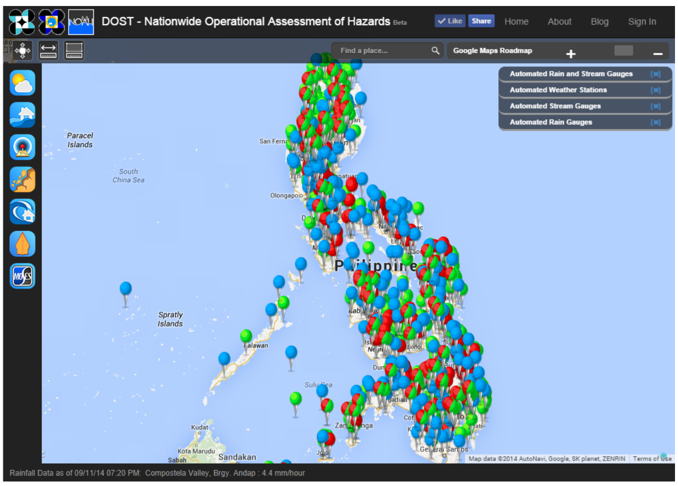

Figure 2: Automated weather stations (blue pins) and rain gauges (green pins) form clusters for easy viewing when the map is zoomed out.

Sensors are distributed to all local government units upon approval of prospective sites for installation from the national weather bureau, PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration). These point data, however, are valid only for the sites where the sensors are installed. Interpolation of these point data to approximate values on a continuous area is therefore applied. Interpolation is a mathematical function that estimates the values at locations where no measured values are available [1]. The computation considers spatial attributes substantially. This spatial dependency indicates that at a point, the area close to it is likely to have similar values. As we move farther from the point, the values drift apart.

A fast interpolation algorithm is essential to create the output rainfall map under a ten-minute interval for near real-time streaming. It should also consider the large and still growing input dataset of more than 1,000 sensors to the system. We use linear interpolation to satisfy both conditions. To implement the algorithm, we use the SciPy library written in Python programming language. It is an open-source software package for scientific computing. Figure 3 shows the flow diagram of the system. The program takes as input the location coordinates and array of rainfall values of each sensor. Values are then interpolated to produce a contour map of the area. The distance between sensors are also considered in the interpolation. An acceptable distance between two sensors is also an input to the program. One sensor is disregarded if it is less than the acceptable distance to another.

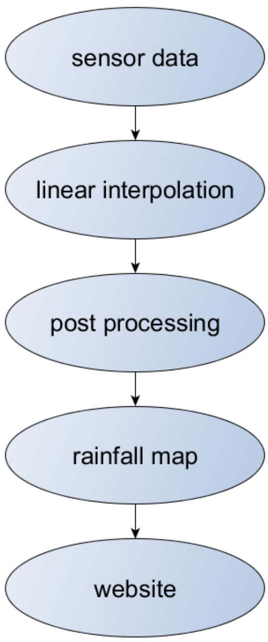

Figure 3: Interpolation flow diagram. Sensor data is used as input parameters to the interpolation.

The color values are based on PAGASA's rainfall intensity color code (Table 1).

The contour map is then intersected by the country's coastline shape. Edge blurring is performed next to address minimal boundary discrepancies between the base map and the coastline data. Finally, the annotation is added to the image. Details such as the number of stations included in the interpolation and the date and time of last update are indicated.

Rainfall Intensity	Color Code
light	light blue
moderate	blue
heavy	dark blue
intense	orange
torrential	red

Table 1: PAGASA's rainfall intensity color coding system

An output rainfall map (Figure 4) shows torrential rains in Panay and Negros islands over a three-hour period. Local government units are advised to monitor water levels using automated stream gauges installed along bridges in major rivers in the area.

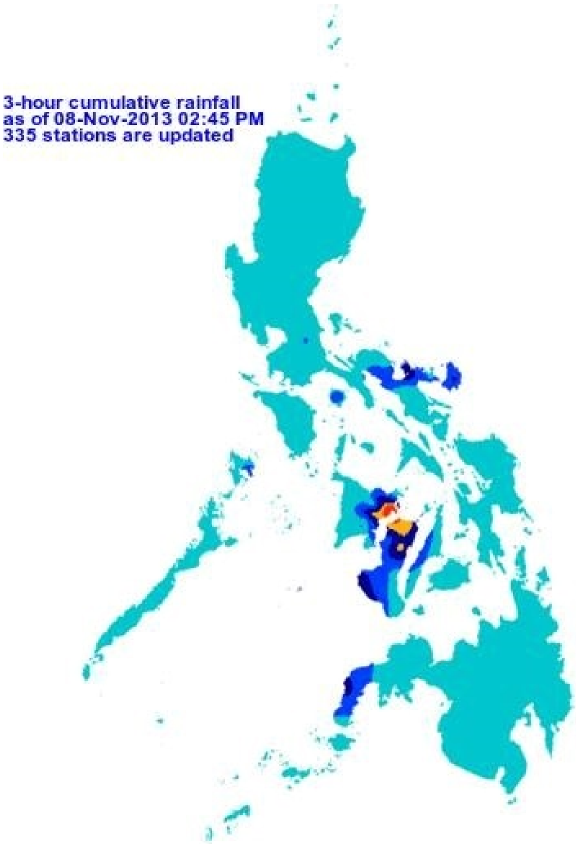

Figure 4: A three-hour accumulated rainfall map of the country during Typhoon Haiyan on November 8, 2013.

In Figure 5, the Rainfall Contour item under the OVERVIEW tab and the Stream Gauges item under the WEATHER STATIONS tab are checked. Image transparency is set automatically to 50 percent in the Project NOAH web portal to reveal terrain and critical area information. The upper watershed of the Cagayan de Oro River Basin experienced torrential rainfall as shown in the map. The user can then click on the stream gauges installed to monitor increase in water level, which may result to floods.

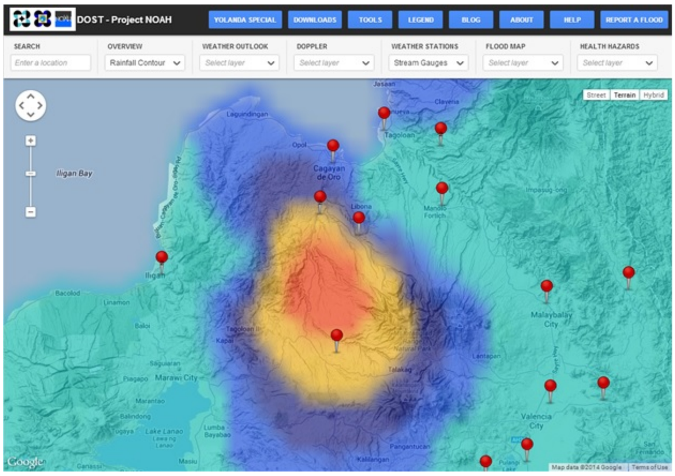

Figure 5: The Project NOAH web portal showing the rainfall contour and automated stream gauges.

3. Successful Utilization of the NOAH Website

On December 4, 2012, Typhoon Bopha (local name Pablo), a Category 5 typhoon, made landfall in Mindanao, south of the Philippines. PAGASA warned that the typhoon was one of the strongest to make landfall in the Philippines that year, and the brunt of the rainfall would be in the northern part of Mindanao, including Cagayan de Oro City. [2]

Cagayan de Oro City is one of the highly-urbanized cities in Mindanao, with a population of more than 600,0000 residents [3]. The city had barely recovered from the devastating Typhoon Washi (local name Sendong) the year before, which resulted to 674 fatalities in the city alone. [4]

Bracing for yet another impending disaster, the Local Disaster Risk Reduction and Management Office (LDRRMO) of Cagayan de Oro City monitored the volume of rainfall through the rainfall contour and noticed the intense-torrential rain in the Cagayan de Oro upper watershed. The automated rain gauges and automated stream gauges which were installed in strategic locations within the watershed areas in the region showed an exponential rise in the rainfall volume.

When Typhoon Bopha made landfall in the upper watershed area of the Cagayan de Oro River in Bukidnon, the volume of rainfall and water level were monitored by the disaster management officers and the local government units through the NOAH website.

On December 4, 2014, at 12:50 PM, a sudden rise of water level in Bubunawan Bridge, Bukidnon was reported by the automated stream gauge in the area. The 7.65-meter increase reflected on the website in near real-time (Figure 6). The researchers of Project NOAH immediately called the local authorities to warn them of imminent flooding in the Cagayan de Oro River.

Just in time, the LDRRM officers also monitored the NOAH website, and had already ordered the evacuation of residents living in low-lying areas along the Cagayan de Oro River. With the data provided by the sensors, the local government unit and the disaster officers were empowered by the information, which helped them save their communities. The early warning system was effectively utilized in the community, resulting to zero casualties in Cagayan de Oro City during Typhoon Bopha.

Cagayan de Oro City was spared from the trauma of yet another disaster and since then, they have continued rebuilding their communities and their lives.

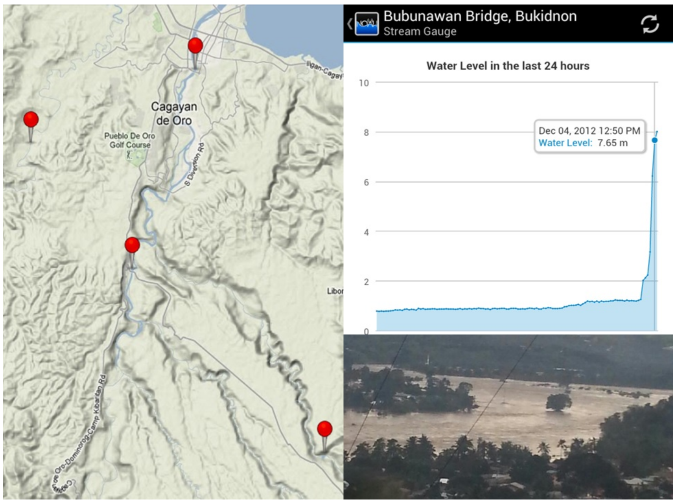

Figure 6: Clockwise from left: (1) The Bubunawan Bridge stream gauge is located upstream of the Cagayan de Oro river (red pin on lower right). (2) A spike on the hydrograph of the stream gauge was visualized in the NOAH website in near real-time. (3) After four hours, the downstream condition of the Cagayan de Oro river shows an increase in water level and sediment.

The city of Marikina, located in the eastern part of Metro Manila, is among the most flooded cities in the metro where casualties are often anticipated. With more than 400,000 residents [5], their exposure and vulnerability to flood hazards is heightened by the meandering Marikina River which flows through the heart of the city. The Marikina River system easily overflows especially after incessant and heavy rains.

Marikina City had its fair share of disasters, from Typhoon Ketsana (local name Ondoy) which affected 15,600 residents and the Habagat in 2012 and 2013 which resulted to more than 100 casualties.

With the citys constant experience on flooding, they devised an early flood warning system including the deployment of local sirens in the community level, with alert levels categorized from 1 to 4.

When the Marikina River reaches 15 meters above sea level in Sto. Nino station, a short intermittent blast which lasts for 30 seconds means that Alert Level 1, or warning has been hoisted over the area. Intermittent blasts that last for one minute mean that Alert Level 2 (16 meters above sea level) has been raised and residents are advised to prepare. A continuous blast that lasts for five minutes signifies that Alert Level 3 (17 meters above sea level) is in effect, and that residents must immediately move to a safer area. A continuous uninterrupted blast that lasts for 10 minutes indicates that the river is at a critical level (Alert Level 4) with the waters now 18 meters above sea level. At this point, a forced evacuation of residents in the area will be carried out. [6]

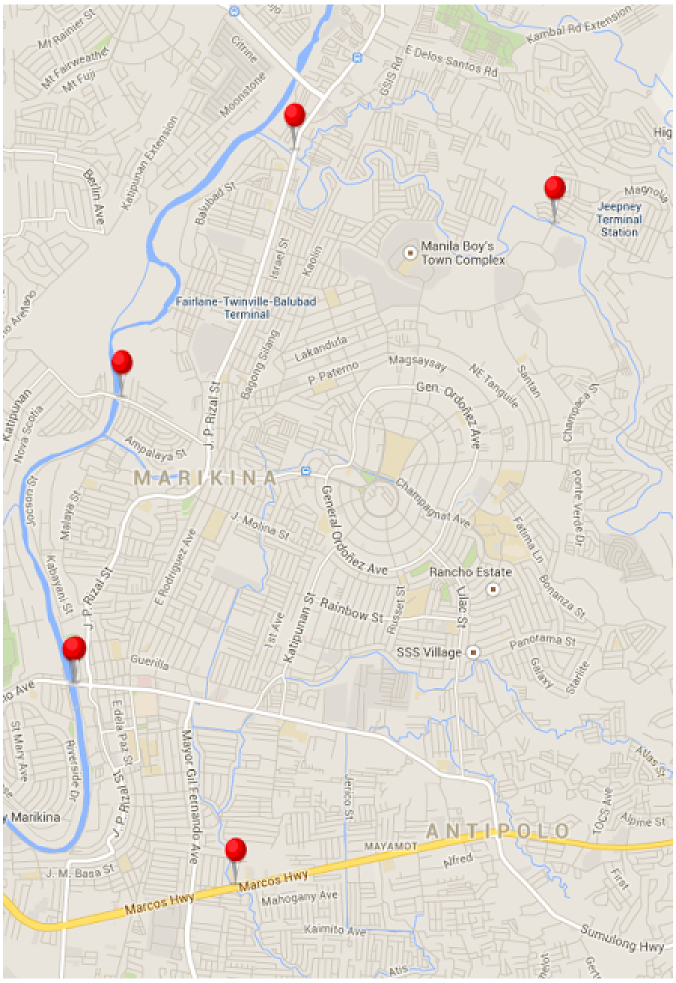

Figure 7: Five stream gauges are installed along the Marikina River; in barangays Nangka, Sto. Nino, Fortune, Tumana, and along Balinti Creek. Markers are also placed in strategic areas along the river system so residents can monitor the water level themselves.

On August 17, 2013, Typhoon Trami (local name Maring) made landfall in Metro Manila. PAGASA warned the city to expect heavy to intense rains and prepare for possible flash floods. As Trami made landfall, the rainfall contour in the NOAH website indicated heavy to intense rains in the Upper Marikina Watershed.

The City Disaster Risk Reduction and Management Office (CDRRMO) then prepared for the evacuation of residents in low-lying areas and those living along the Marikina River, especially in the villages of Nangka and Tumana. By monitoring the stream guages in the NOAH website, they complemented their community's warning system. They used both systems before issuing their warnings.

The CDRRMO monitored the water level in Marikina River through the NOAH website and shared the information to the public through social media. As the stream gauges showed a continuous rise in water level, the CDRRMO ordered for the emergency evacuation of residents and relayed the necessary response to the communities vulnerable to the flood. The local government aptly coordinated the preparation and response to the impending disaster before the flood reached them.

With the active monitoring of the rainfall amount and water level from the data streamed by the sensors to the NOAH website, Marikina City had no casualties when the typhoon hit them.

Project NOAH's role in achieving a zero-casualty count in Marikina City was reported in the media after the typhoon waned. Paul Sison, the public information officer in Marikina City said in media interviews that without Project NOAH, they would not have comprehensively coordinated preparedness and response mechanisms in their community.

"Without NOAH, you don't know what to expect," Sison said in an interview with the Philippine Daily Inquirer after the typhoon. [7]

4. Conclusions and Recommendations

A runtime assessment of the algorithm implemented for the interpolation process is performed on a server with specifications as seen on Table 2. The actual server has the same specifications.

Memory	8 GB
Processor	2.00 Ghz
Operating system	CentOS 5.8

Table 2: Server Specifications

Table 3 and Figure 8 show the results of the assessment. The number of sensors included in the interpolation were determined randomly. Column 1 in Table 3 shows the runtime or the execution time of the program starting from sensor data parsing, actual linear interpolation, to post-processing of the rainfall map. Column 2 shows the number of sensors actually used for the test runs. The program removes particular sensor data in the computation that are not updated. The third column shows the intended number of sensors to be included in the run.

Figure 8 shows the linear trend when the number of sensors included was increased for each run. Note, however, that a decrease in runtime was also observed when 378 and 435 sensors were included in the runs. One reason is the program's exclusion of particular sensors that are below the acceptable distance.

The system has been used as a very effective early warning system to flood-prone communities as discussed in the previous section. However, it is equally important to ensure the validity, accuracy, and timeliness of the output. Recommendations and corresponding courses of action are discussed hereafter to improve the systems overall implementation and enhancement of communication channels.

The Law of Large Number dictates that having a large set of observations will make the set closer to its expected value.

runtime (s)	sensors used for the run	total no. of sensors
20.75	62	100
36.25	88	150
47.50	114	200
70.50	174	300
118.00	230	400
188.50	278	500
224.25	326	600
215.75	378	700
294.75	427	800
257.25	435	all

Table 3: Random runtime results of the interpolation algorithm

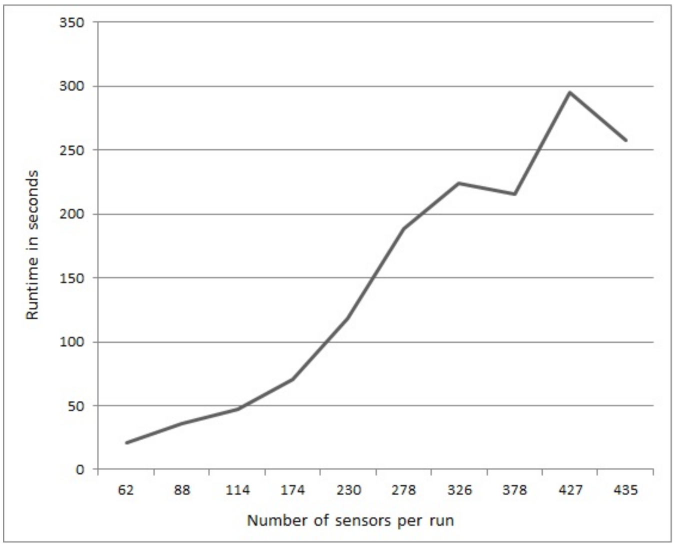

Figure 8: A graph of the number of updated sensors per run and corresponding runtime based on Table 3.

The error in sensor values is proportional to the distance of the sensors or data points from each other, and as the distance between the sensors decreases, theoretically, there is less error in the interpolation. It is therefore recommended that more sensors be deployed in the country. Another phase of the sensor deployment project is ongoing and will be completed by 2016. A dense sensor network is expected to cover critical locations as approved by the national weather bureau.

Tweaking the input parameters is also recommended to improve accuracy. The Philippines, with its highly variable topography and tropical climate, receives rainfall which varies from 965 to 4,064 millimeters annually (http://kidlat.pagasa.dost.gov.ph/cab/climate.htm). Studies suggest adding the elevation as an input parameter to the interpolation, which is also an important factor in rainfall distribution. In a research and development study by Hofierka et al. [8] on precipitation interpolation, the incorporation of terrain improved their spatial model in terms of its predictive error and spatial pattern. The approach was implemented using datasets from Switzerland and Slovakia.

Having a dense sensor dataset and adding additional input parameters also equate to an increase in runtime due to the amount of data to be processed. To address this, the following options may be explored:

a). Higher server specifications especially processing power can significantly decrease runtime.
b). Decreasing sensor data communication time to the servers can improve network latency. This can also be reduced by removing the temporary flat database.
c). Using a different programming language and native libraries may be explored and compared with the existing implementation of the interpolation algorithm. For instance, R is a highly extensible language and environment for statistical computing and graphical representation.

Finally, a comparison of results with other rainfall maps in the Philippines is needed to ensure that the methodology employed is accurate. Data on rainfall intensity detected by several Doppler radars deployed in different parts of the country may also be used to assess the accuracy of the rainfall maps visually.

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