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Rainfall monitoring in urban areas in the Amazon using weather radar on the SipamHidro platform

Monitoramento de chuva em área urbana na Amazônia através do radar meteorológico na plataforma SipamHidro

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Abstract

Meteorological radar allows the monitoring and prediction in short and very short-term time intervals of storm movement. The objective of this research is to evaluate the weather radar effectiveness for extreme precipitation events forecasting using the SipamHidro rainfall in urban area application. This assessment was carried out considering the storm that occurred in Manaus on March 25, 2023. Observations from pluviometers installed in the urban area of Manaus by CEMADEN and estimated precipitation determined using the TITAN software were used. The evaluation was based on Pearson correlation coefficient, cartographic representations and comparison between observed and predicted. The results show that: a) The event generated more than 135 occurrences of disasters due to extreme rain in the city of Manaus; b) forecasts obtained by radar tend to underestimate observed precipitation by between 31% and 72%, but their spatial distribution is similar; c) the correlations between precipitation obtained by radar and observed precipitation in neighborhoods with rain gauges were from r= 0.59 a r= 0.95, except at the nearby area of the radar; d) the analysis between the predicted and observed times indicates a tendency to adequately anticipate the start of the storm. There were significant correlations between radar data and rain gauges, except in the vicinity of the radar. Despite the lack of precision in extreme rainfall measurements, radar has shown potential as an early forecasting tool, highlighting the importance of its continued development to improve the response to extreme events in urban areas.

Keywords:
Disaster risk reduction, extreme precipitation, Radar forecast.

Resumo

O radar meteorológico permite o monitoramento e previsão do deslocamento tempestades em intervalos de tempo de curto e curtíssimo prazo (nowcasting). O objetivo desta pesquisa é avaliar a eficácia do radar meteorológico para a previsão evento extremos de precipitação a partir da aplicação Chuva em Área Urbana do SipamHidro. Esta avaliação considerou a tempestade que

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ocorreu em Manaus no dia 25 de março de 2023. Foram utilizadas as observações de pluviômetros instalados na área urbana de Manaus pelo CEMADEN e as estimativa de precipitação determinadas com o uso do software TITAN. A avaliação baseou-se em cálculos de correlação, representações cartográficas e comparação entre os horários observados e previstos. Os resultados mostram que: a) O evento gerou mais de 135 ocorrências de desastres por extremo de chuva na cidade de Manaus; b) as previsões obtidas pelo radar tendem a subestimar entre 31% e 72% a precipitação observada, mas sua distribuição espacial é similar; c) as correlações entre as precipitações obtidas pelo radar e as observados nos bairros com pluviômetro foram de r= 0.59 a r= 0.95, exceto nas proximidades do radar; d) a análise entre os horários previstos e observados indicam uma tendência de antecipação adequada do início da tempestade. Houve correlações significativas entre os dados do radar e os pluviômetros, exceto nas proximidades do radar. Apesar da pouca precisão em medições de chuvas extremas, o radar mostrou potencial como ferramenta de previsão antecipada, destacando a importância do seu desenvolvimento contínuo para melhorar a resposta a eventos extremos em áreas urbanas.

Palavras-chaves:
Redução de riscos e desastres, Precipitações extremas, previsão por Radar.

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I. INTRODUCTION

Weather radar is a tool that collects atmospheric information within its range through the return of electromagnetic pulses emitted into the atmosphere. This device not only identifies cloud formations but also estimates the intensity of associated precipitation, the vertical structure of storms, and their movement. Thus, it has become an important and widely used tool for storm monitoring and for short-term and very short-term weather forecasting (nowcasting) of up to 2 hours (Han et al., 2009).

The reflectivity originating from clouds began to be correlated with the distribution of their droplet sizes based on the study by Marshall et al. (1947). This led to a direct association with the precipitation rate in millimeters per hour. Based on these estimates of precipitation intensity (rain rate) and the distance of the rainy area to a specific location, authorities can take preventive measures against severe storms (Carvalho et al., 2019; Ochoa-Rodriguez et al., 2019).

In Brazil, there has been an increase in the occurrences of hydrological disasters, such as flooding, intense rains, flash floods, inundations, and mass movements. The years 2021 and 2022 alone saw a number of occurrences higher than that recorded in the entire 1990s, with 3.960 and 2.389 occurrences respectively (BRASIL, 2022). The number of people affected has also increased, reaching 4.848.917 in 2020, 3.916.837 in 2021, and 11.894.018 in 2022 (BRASIL, 2022). The IPCC's Hydrological Cycle Assessment Report (AR6) indicates that the global hydrological cycle is intensifying due to rising global temperatures, resulting in greater variability in precipitation and more intense rain and drought events (IPCC, 2021). This scenario may

increase the risk of landslides and flash floods in the context of climate change for Brazil (Marengo et al., 2021).

Aiming to monitor hydrometeorological risks in the Legal Amazon, the Integrated System for Hydrometeorological Monitoring and Alert (SipamHidro) project was initiated by the Center for Management and Operation of the Amazon Protection System (Censipam) in 2014. This initiative seeks to develop and implement methodologies for the surveillance of severe hydrometeorological events within the Amazon region. SipamHidro is a digital platform that utilizes an open architecture to amalgamate various geotechnologies, methodologies, and automated processes into one database. This computational framework delivers resources for the observation, analysis, and prediction of hydrometeorological events (Carvalho et al., 2019).

The urban area rainfall forecasting module of SipamHidro plays a crucial role by generating storm forecasts on a reduced time scale, providing information up to 1 hour in advance. Such a tool is of great importance for speeding up the understanding of meteorological events, making the actions of civil defense and other agencies, often carried out at the neighborhood level, more efficient and effective. This module was developed as a client-server system through a web service, with the browser acting as the main client component, utilizing maps for visualizations and interacting with scripts responsible for data acquisition on PostgreSQL file servers (Carvalho et al., 2019).

Rain monitoring in urban areas within the SipamHidro framework is carried out using data generated by weather radars installed in the Amazon. These radars play a key role in the identification, tracking, and short-term forecasting (nowcasting) of storms that may pose risks to the local population within the radar's coverage area. The tool is functional and integrates additional information such as images from the GOES-16 satellite in infrared, water vapor, and visible bands, and the atmospheric discharge model from the GLM (Geostationary Lightning Mapper) of the same satellite.

The city of Manaus is frequently exposed to threats and damages resulting from storms, including floods, waterlogging, and mass movements, especially in the northern and eastern areas. These events are recorded due to several aspects: An intense rainy season from January to May (averaging 280.8 mm/month); rugged terrain with steep slopes to the north and east of the city while flat and swampy in the southern, central, and central-western portions; lands susceptible to these processes are generally occupied in the form of precarious settlements, areas with limited or non-existent urban infrastructure, inhabited by a socioeconomically vulnerable population, as evidenced in recent studies (CPRM, 2019; Moreira, Mota, 2020; Ramos et al., 2019).

The Manaus weather radar has a fundamental role in the operational monitoring of short and very short-term weather forecasts conducted by Censipam. Data generated by the radar are of great importance for research related to the analysis of extreme weather events (Farias et al., 2017), understanding the seasonal behavior of storms (Giangrande et al., 2023), and the development of numerical models for weather forecasts that incorporate information from the radar (de Sousa et al., 2022). This enables a notable improvement in the spatial and temporal resolution of short-term forecasts related to storms.

The purpose of the study was to assess the effectiveness of the tool included in the urban area rain monitoring module of SipamHidro in forecasting a precipitation event that was recorded in Manaus on March 25, 2023, and resulted in damage to the local community. Among the documented incidents, there were landslides, floods, waterlogging, and inundations.

II. METHODOLOGY

The Manaus weather radar, operated by the Força Aérea Brasileira (FAB) in partnership with the Centro Gestor e Operacional do Sistema de Proteção da Amazônia (Censipam), is an S-band Doppler type (10 cm wavelength) with scans every 12 minutes. It is located at the Ponta Pelada airport (sbmn), Manaus-AM. The operational scan of the radar reaches a radius of 240 km, however, the rate is estimated only within a radius of 120km (Figure 1).
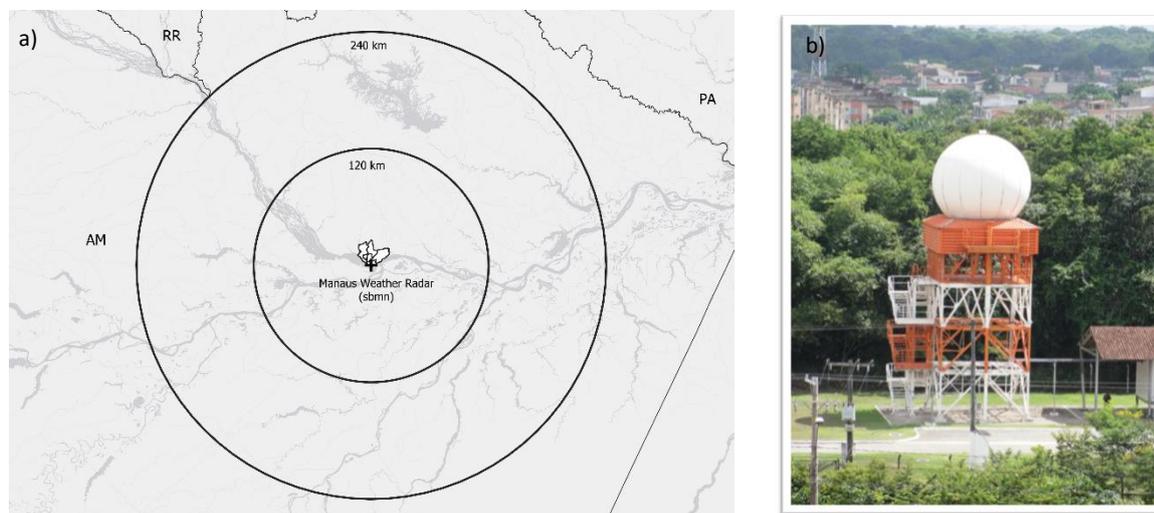

Figure 1: Operation of the Manaus weather radar. a) Location and operational radius of the Radar. b) Image of the Radar installed in Manaus. Source: Authors and Censipam, 2023.

The TITAN software (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) allows the extraction of measured and estimated data by the weather radar. The application identifies a storm as being a contiguous three-dimensional region considering parameters such as reflectivity, volume, height, and others, along with trajectory data such as speed, forecast of intensification, and others. In the spatial

representation area, the storm clusters or cells will be represented by ellipses or polygons at the Universal Time Coordinated (UTC). Besides identifying storms, it is also possible to obtain forecasts of the movements of convective cells. TITAN produces a forecast based on the extrapolation of the recent behavior of the observed tracks. The short-term forecast of the position and size of the cells is based on a linear fit to the recent behavior of the storm trajectory (Dixon and Wiener, 1993) (Figure 2).
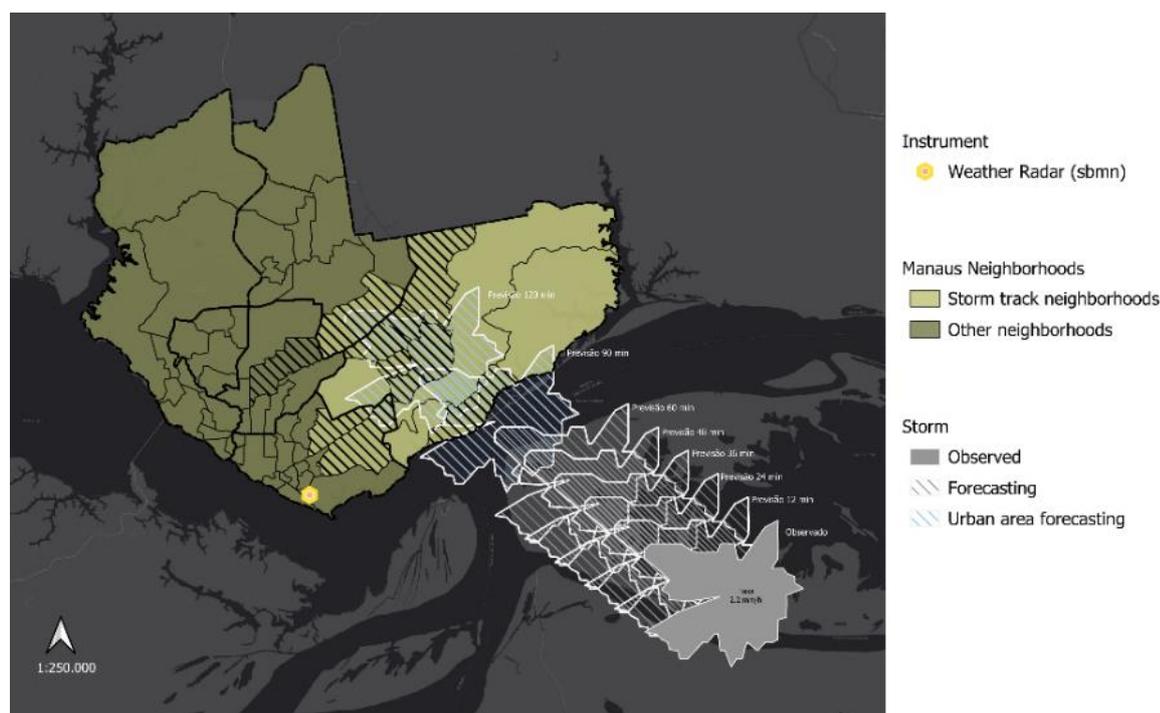

Figure 2: Illustration of storm movement forecasting by TITAN. Source: Authors.

Each rain formation identified is assigned an ID. If this trend in the trajectory's behavior changes, such as the breaking up or merging of new cores, it may receive a new unique ID. The parameters for storm identification in this study are: a minimum reflectivity of 35 DBZ, a minimum volume of 16 km³, and a minimum height of 2 km and a maximum of 30 km. The process of storm tracking data also starts from the TITAN's MDV (Meteorological Data Volume) file, converted from the raw radar data, transformed into XML, and subsequently forwarded to the Database. This information is then made available to SipamHidro via an API, allowing access as a visualization layer in the system (Carvalho et al., 2019; IPMET, 2005).

The radar data processing utilizes four tools from the Lidar Radar Open Software Environment (LROSE[1]) project. From the Radar data in Plan Position Indicator (PPI), the Radx2Grid tool transforms the spherical grid coordinates collected by the ground radar into a regular grid, Cartesian coordinates, generating reflectivity data in Constant Altitude Plan Position Indicator (CAPPI). After this process, the

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[1] Available at https://nsf-lrose.github.io/index.html.

PrecipAccum tool calculates the precipitation rate, and the Mdv2Vil tool estimates the liquid water content in each vertical column. Finally, the PrintMdv tool transforms the data from a regular grid to text format (Carvalho et al., 2019; Lrose-blaze, 2019), as illustrated by the flowchart in figure 3.

In the SipamHidro database (Figure 3), when the trajectory forecast file intersects with the urban area polygon, it generates a new file with the following attributes: forecasted neighborhood or city name (neighborhood_name), corresponding municipality (municipality), the radar responsible for the forecast (radar), the ID of the identified storm (storm_id), the forecast event time (time_event), the observed radar time (time_radar), and the precipitation rate (average_rate) (Carvalho et al., 2019)The radar can estimate the amount of precipitation on the ground by performing a time integration of the precipitation rate R (mm/h). The precipitation rate from the PrecipAccum application in mm/h is calculated for each 12-minute scan, based on the number of targets (cloudiness) present in the scan (Nogueira et al., 2015). The precipitation rate, together with the identification of the storm trajectory, are the main functionalities of TITAN used in the application.
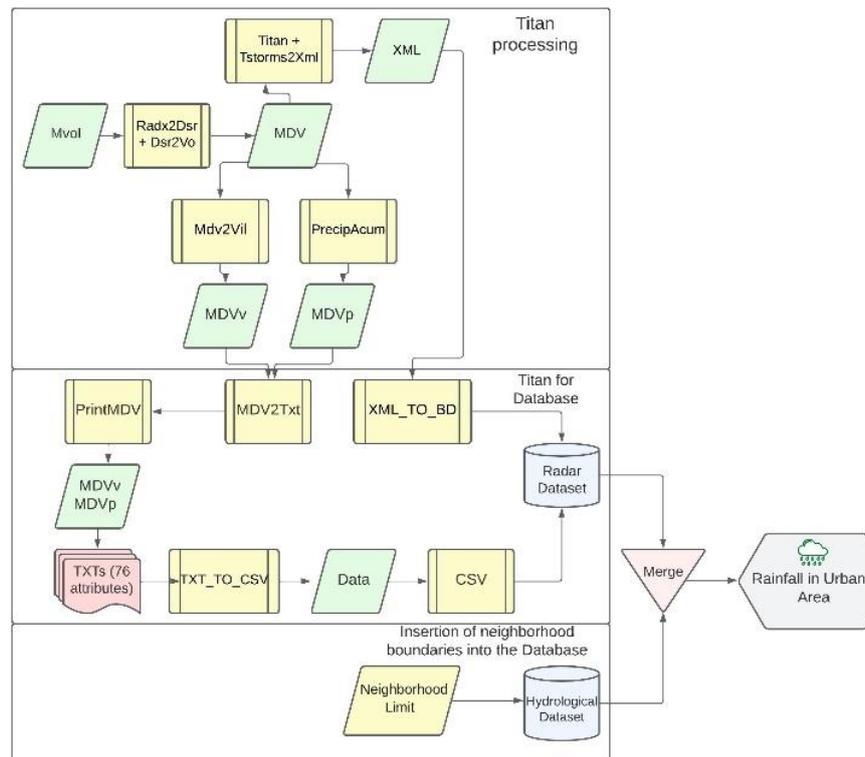

Figure 3: Flowchart of the data acquisition processes by TITAN and the availability of the product on the platform. It was divided into three stages. TITAN Processes: Acquisition of raw data, grid transformation, and precipitation estimate; Conversion and storage: conversion of the data to text and storage in the database; Integration with geographic boundaries and intersection with radar data: when there is an intersection between the forecast polygon and the neighborhoods, the system will indicate precipitation forecast for the neighborhood. Organization: Authors.

To assess the relationship between radar-predicted precipitation and ground-observed precipitation, eight rain gauges from the Centro Nacional de Monitoramento e Alertas de Desastres Naturais (Cemaden) that were in operation on the day of the event, until 16 UTC, were used. At this time, the Centro de Cooperação da Cidade (CCC) and the Secretaria Municipal de Segurança Pública e Defesa Social (Semseg) of the Manaus City Hall released notes on the occurred disasters, reporting the rainfall accumulations for each region, provided by Cemaden. This was also when the storm ended and the Civil Defense structures began to operate.

The Sectorization of Geological Risk Areas for Manaus, produced by the Serviço Geológico Brasileiro (SGB) and the Manaus Civil Defense (CPRM, 2019), was used for the identification of areas susceptible to hydrometeorological disasters. This geospatial information consists of the identification and characterization of the portions of the territory subject to suffering losses or damages caused by adverse geological events (SGB, 2021). The sectors were analyzed by neighborhood to verify their extension (area) and categorized by risk degree. Due files are in shapefile format, they will be visualized and processed using the Qgis software 3.32.3 Lima version.

Through thematic maps and graphical comparison, and correlation analysis were evaluated the anticipation time of the storm (forecasted), the relationship between the accumulated precipitation predicted and the accumulated precipitation observed in the impacted neighborhoods and zones, the spatial relationship between what was observed and forecasted in neighborhoods and zones. The graphical comparison and statistical analysis were performed with the RStudio software 2023.09.0 version, and the analysis and cartographic production with the QGIS software 3.32.3 Lima version.

The Pearson correlation coefficient (Equation 1) was the descriptive statistical metric used to analyze the relationship between the precipitation radar-predicted data and the precipitation surface-observed data, as used in Ochoa-Rodriguez et al. (2019), Pappa et al. (2021), and Sebastianelli et al. (2010). The value of r is an indicator of the correlation, in this case, between the observed and simulated values, with a variation range between -1 and 1, where the value 1 indicates a perfect fit. In this case, the higher the value of r, the greater the degree of linear association between the variables; if positive, it indicates a positive linear association between the variables, if negative, it indicates a negative linear association between these variables. For this purpose, we used data from Cemaden automatic rain gauges such as observed precipitation, which were downloaded directly from the Cemaden platform, as well as radar data downloaded directly from the SipamHidro database.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad (1)$$

Rain gauge data are originally arranged in hourly accumulations when there is no rain $= 0$ or in ten-minute increments when they record rain > 0. The radar performs a scan every twelve minutes and records in the database when the rate is > 0. To make both compatible, the forecast and rain gauge data were accumulated every 30 minutes to normalize and obtain the pairs needed for analysis. The data were analyzed only when there were corresponding pairs in the format $(x > 0, y > 0)$, (Sebastianelli et al., 2010).

III. RESULTS

According to information available to the press from the CCC and the Semseg, on March 25, 2023, until 6 p.m., Manaus recorded more than 135 occurrences of disasters due to heavy rains. Of these occurrences, 62 were related to flooding, 25 to collapses, and 22 to landslides. Satellite images (Figure 04) reveal the presence of convective cells with significant vertical development in the Manaus region, with cloud top temperatures ranging between -80°C and -70°C. These conditions were observed in the period between 10:00 and 17:00 UTC.
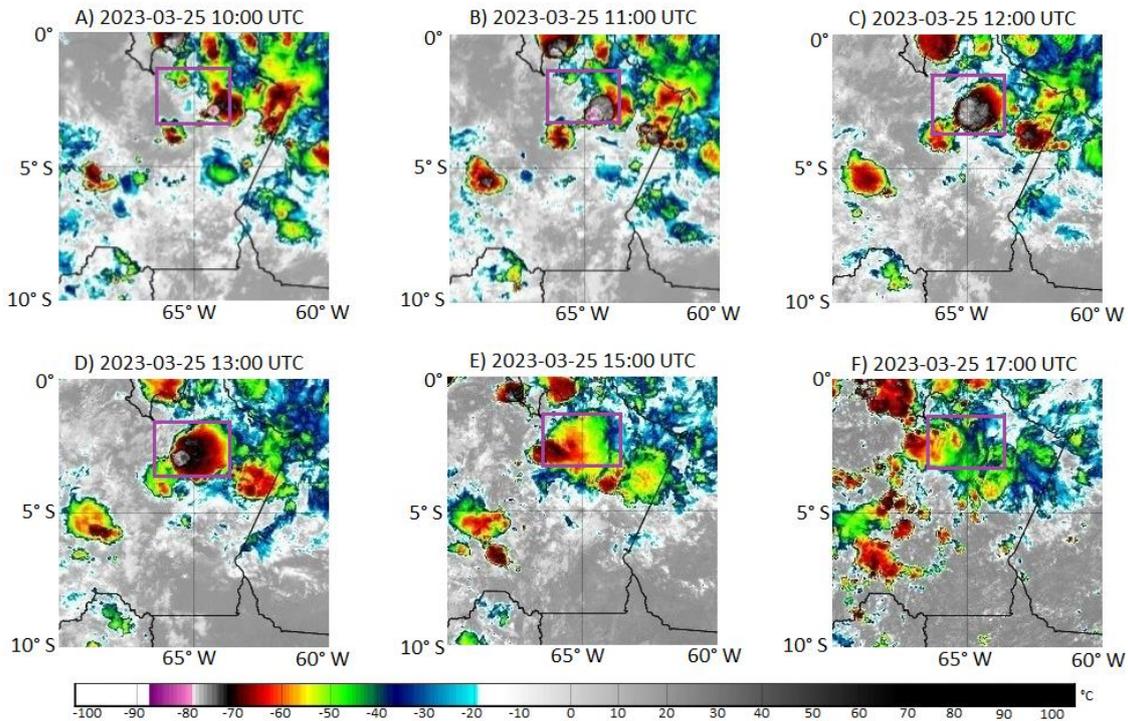

Figure 4: GOES-16 Satellite Images in Channel 13 (Infrared) on March 25, 2023: A) 10:00 UTC; B) 11:00 UTC; C) 12:00 UTC; D) 13:00 UTC; E) 15:00 UTC; and F) 17:00 UTC. The colors in the legend represent temperatures in °C at the cloud tops. The rectangle indicates the region of the city of Manaus (3.11° S; 60.025° W). Source: INPE, CPTEC, and NOAA.

The occurrences of intense rainfall of greater severity were recorded in the East Zone, in the neighborhoods of Armando Mendes (Sharp Community) and Gilberto Mestrinho. Other occurrences were also addressed in the neighborhoods of Zumbi, Japiim (Comunidade Manaus 2000), São José Operário, and Jorge Teixeira (Nova Floresta Community). According to the press, there were also records in the neighborhoods of Jorge Teixeira (Nova Floresta Community), Tancredo Neves, Distrito Industrial I, Parque 10 de Novembro, and Colônia Antônio Aleixo (Figure 5).
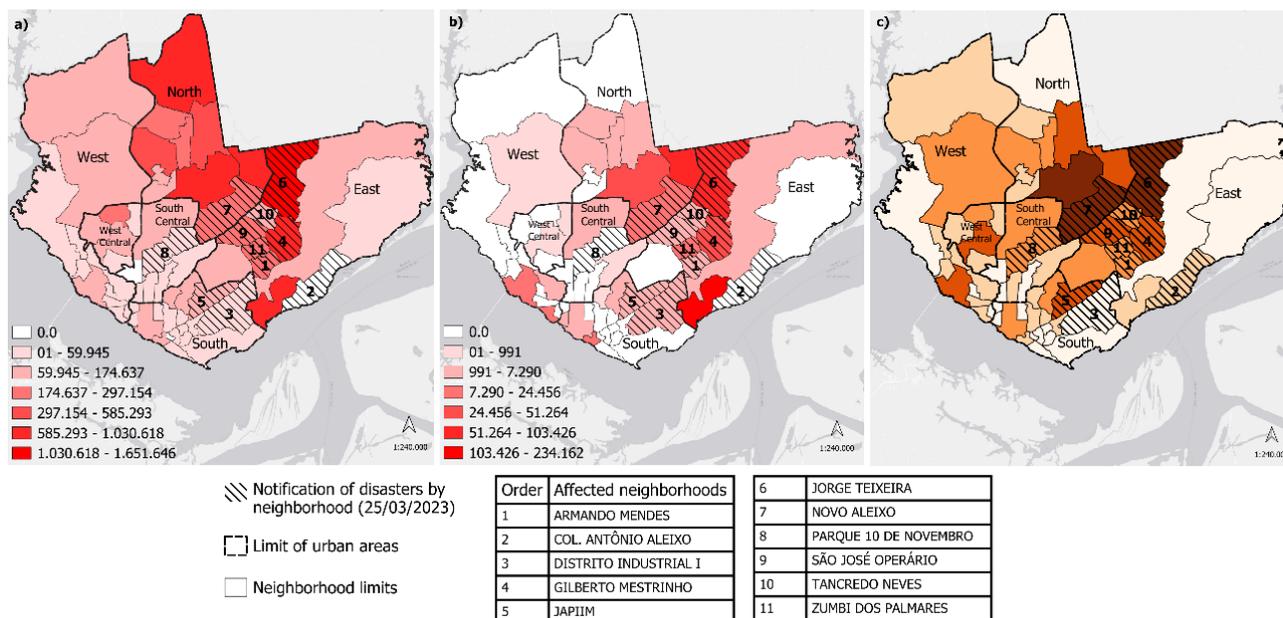
Figure 5: Map of the total risk areas (CPRM), demographic density by neighborhood with records of disaster occurrences on March 25, 2023. a) Sum of risk areas by Neighborhood (m²); b) Sum of R4 risk areas by Neighborhood (m²); c) demographic density by neighborhood. Source: SGB, Manaus Civil Defense, and Censipam.

Observing Figure 5, it is possible to identify that some occurrences were located in neighborhoods that present the highest concentrations of areas classified as risk sectors, including those with a very high risk degree classification (R4), as designated by the SGB and Manaus Civil Defense (CPRM, 2019). Notably, the East Zone, which was the region most affected by disasters according to the CCC, contains three of the six neighborhoods in Manaus with the highest concentration of areas classified as risk sectors, with the Jorge Teixeira neighborhood being the most prominent, which recorded disaster occurrences on March 25, 2023. Furthermore, this region includes two of the three neighborhoods in the entire city with the highest concentration of areas classified as very high-risk sectors, with the Mauazinho neighborhood being the most notable, although it did not record occurrences on March 25, 2023.

On the day of the event, all neighborhoods in Manaus recorded rains as predicted. From the 15 neighborhoods (Figure 6) that accumulated the highest daily forecast rates, 10 are located in the eastern

region, which was the most affected by the storms, as reported by authorities and the press. Of the 11 neighborhoods where the municipality and the press reported impacts due to rain, 9 are among the 17 neighborhoods with the highest predicted rain rates. Considering that all forecasts were a "*success event*", i.e., there was a match between the predicted and the observed, we identify that the forecast timing by neighborhood coincides with the observed data at the Cemaden surface weather stations in the East Zone of Manaus.

The neighborhoods of Puraquequara (150.9 mm) and Distrito Industrial II (137.7 mm), which accumulated the highest consecutive rain forecasts, are neighborhoods of low population density and large territorial extension, resulting in a wide coverage area for storm forecasts and very few risk sectors. The neighborhoods of Parque 10 de Novembro and Japiim are included in the list due to the disaster occurrences recorded, although they are not among those that presented the most voluminous forecasts by radar, these records had a significant impact on the population. It is relevant to highlight that these neighborhoods are located near the radar, placing them within the coverage area known as the "blind cone" or cone of silence.
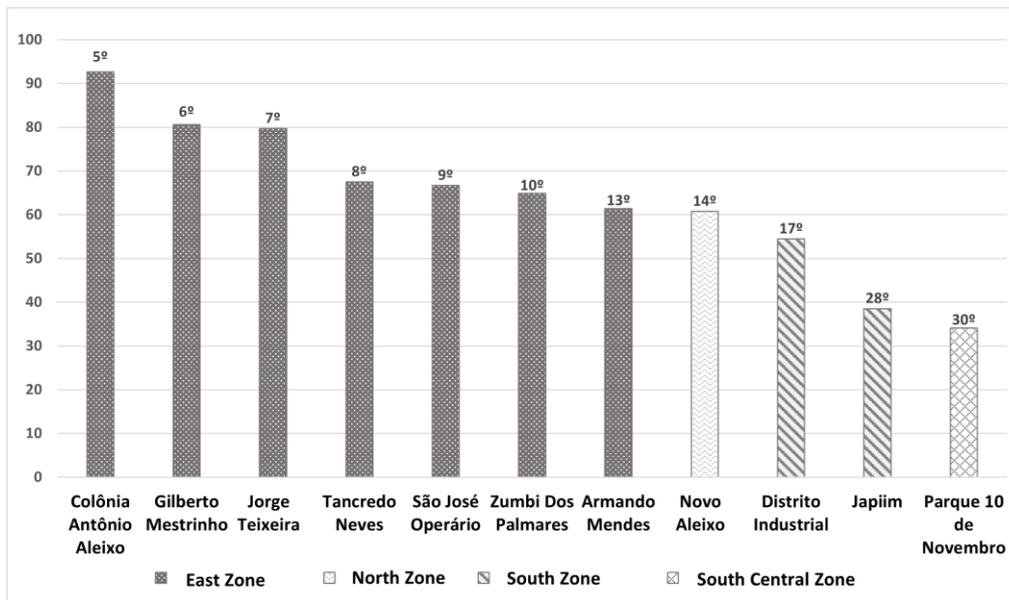

Figure 6 - Order of precipitation accumulations in millimeters (Y-axis), by forecast for neighborhoods with disaster occurrence records. Source: CENSIPAM; CCC.

In a note directed to the Rain Control Center (CCC) of the Manaus City Hall in 2023, the National Center for Monitoring and Early Warning of Natural Disasters (Cemaden) released information about the accumulated rainfall in the urban areas of Manaus based on readings from its rain gauges until 4 p.m. UTC (12 p.m.). The corresponding values were as follows: East Zone with 122 millimeters, North Zone with 89 millimeters, West Zone with 54 millimeters, South-Central Zone with 85 millimeters (average of the surrounding regions), South Zone with 47 millimeters, and West-Central Zone with 82 millimeters. These

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data were then compared with the accumulated rainfall estimates made by the Titan System for the same period and areas (Figure 7) using the daily rainfall characterization method of Gouvea et al. (2018).
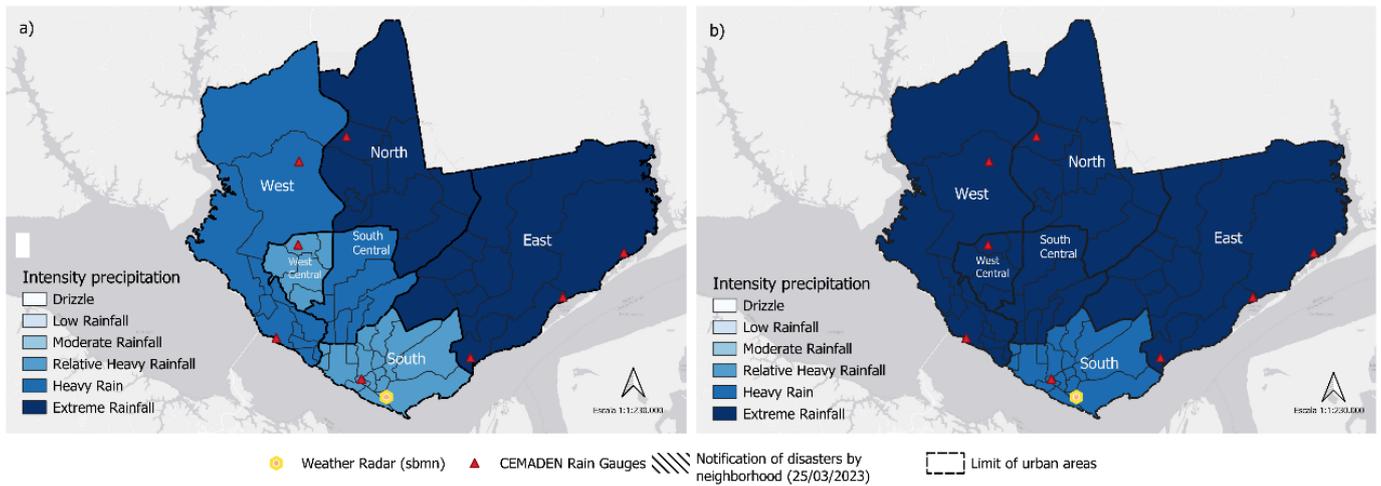

Figure 7: Spatial distribution of accumulations by collection equipment: (a) Weather Radar and (b) Rain Gauge. Source: CEMADEN and CENSIPAM.

The application in forecast underestimated the observed precipitation by 31% for the East Zone (83.7mm), 39% for the North Zone (54.30mm), 52% for the West Zone (25.9mm), 67% for the South-Central and South Zones (27.9mm and 15.5mm, respectively), and 72% for the West-Central Zone (23.1mm). Although the estimated precipitation tended to underestimate the values observed by the rain gauges, its spatial distribution by zones was similar, except for the West and West-Central zones, where there was a notable difference. The East Zone, once again, showed notable data variability when compared to the others. This difference is explained in more detail later.

About forecasting the onset of the storm, initial predictions made by the weather radar (Table 1) identified the start of rainfall between 1:06 a.m. and 1:30 a.m. for the neighborhoods of Puraquequara, Colônia Antônio Aleixo, and Mauazinho. For the Tarumã, Santa Etelvina, and Redenção neighborhoods, rainfall was expected to begin within the timeframe of 1 a.m. to 1:30 a.m.

A comparison between the radar forecasted hours and the hours recorded by rain gauges revealed a discrepancy of 10~20 minutes longer in Puraquequara, Colônia Antônio Aleixo, and Mauazinho. This discrepancy increased to 24~47 minutes for Tarumã, Santa Etelvina, and Redenção. It's important to note that these results refer to the first forecasts and subsequent forecasts tend to be closely with observed hours as they include new features of the storm behavior.

Table 1 – Comparison between the times forecasted by the application and observed by the rain gauge for the first two storms.

Neighbourhood	Storm	Observed Radar (UTC)	Forecast hour (UTC)	Observed Rain gauge (UTC)
Puraquequara	1	09h24	10h:54	10h:30
	2	09h:36	10h:36	
Colônia Antônio Aleixo	1	09h:24	10h:54	10h:40
	2	09h:36	10h:36	
Mauazinho	1	09h:24	10h:54	10h:40
	2	10h:36	11h:00	
Tarumã	1	10h:12	12h:12	11h:40
	2	10h:36	12h:06	
Santa Etelvina	1	10h:12	12h:12	11h:30
	2	10h:36	11h:36	
Redenção	1	10h:12	12h:12	11h:20
	2	10h:36	12h:06	

Source: CENSIPAM

The comparison between the observed data and the radar forecasts generally shows that the forecasts tend to underestimate the observed values (Figure 8). About neighbourhoods, Colônia Antônio Aleixo (Figure 8b) and Puraquequera (Figure 8a), in the East Zone, showed the best correspondence in rainfall records (mm/h) and hourly forecasts (hh:mm). The Tarumã (Figure 8e) and Santa Etelvina (Figure 08f) neighbourhoods in the North Zone showed good agreement between forecast times, but less agreement for higher precipitation accumulations.

In Mauazinho neighborhood (Figure 8c) in the East Zone and Redenção neighborhood in the West-Central Zone, although the forecast for the start time of the storm was correct, there was an underestimation of the forecast rainfall for higher accumulation totals and the total duration of the event was not predicted. In contrast, Compensa neighborhood (Figure 8g) in the West Zone and Santa Luzia neighborhood (Figure 8d) in the South Zone, showed a significant discrepancy between the observed data and the radar forecasts.

There was no correlation between the observed data and the forecasts in the surrounding area of the radar, in Santa Luzia (Figure 8d), at 2.1km away, and in Compensa (Figure 8g) at 8.6km away, near and in the direction of the urban center of Manaus. As observed by Sebastianelli et al. (2010), there was little or no correlation in areas near the radar or in areas with vertical obstacles, such as buildings, which can cause interference from ground targets. Harrison, Driscoll, and Kitchen, (2000) explain that radar beams can reflect off terrestrial objects, resulting in noise and, consequently, returning inaccurate measurements of precipitation. The South (Santa Luzia neighbourhood), Central-South and Central-West (Redenção neighbourhood) and part of the West (Compensa neighbourhood), are regions which had an impact on the forecasts due these features.
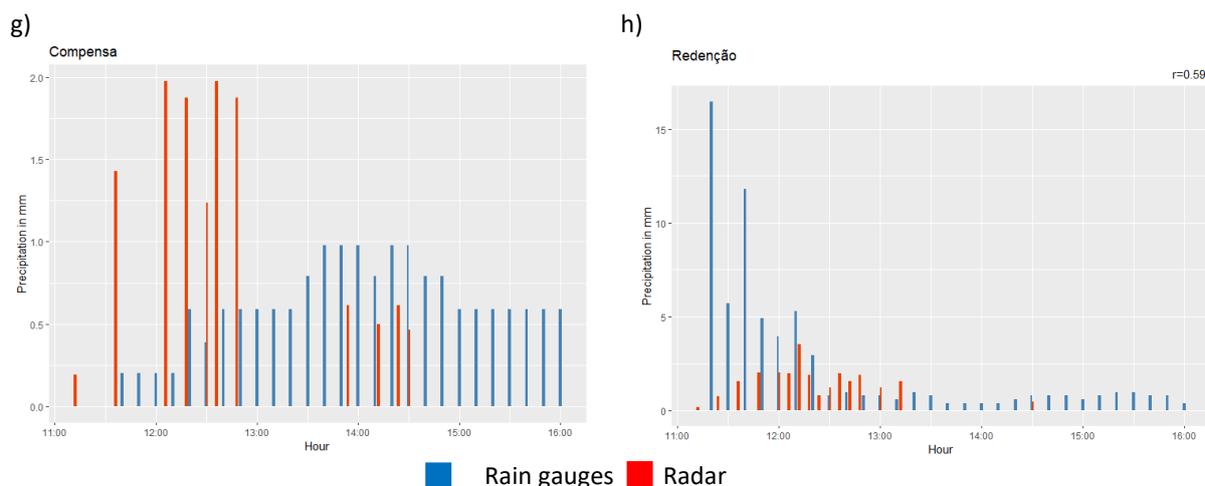
g)

h)
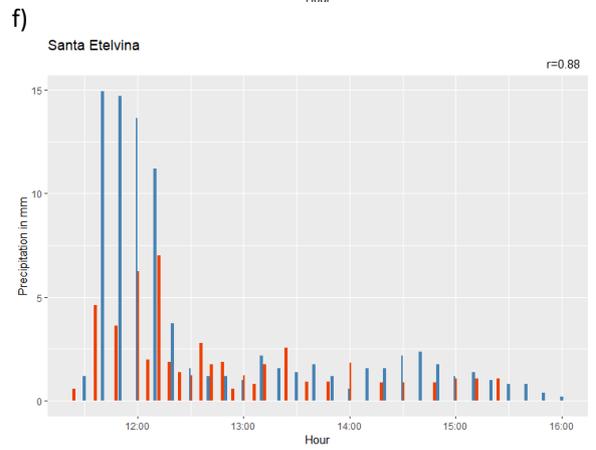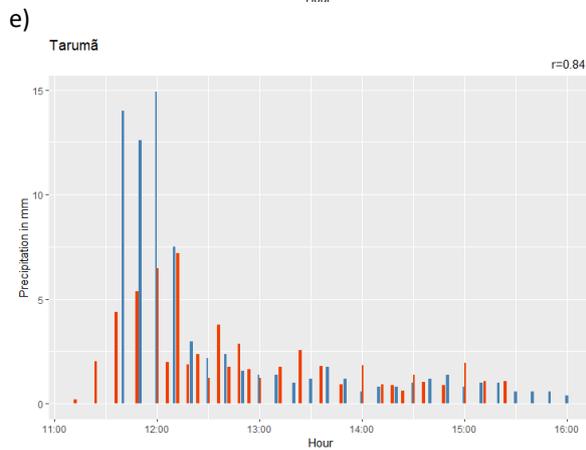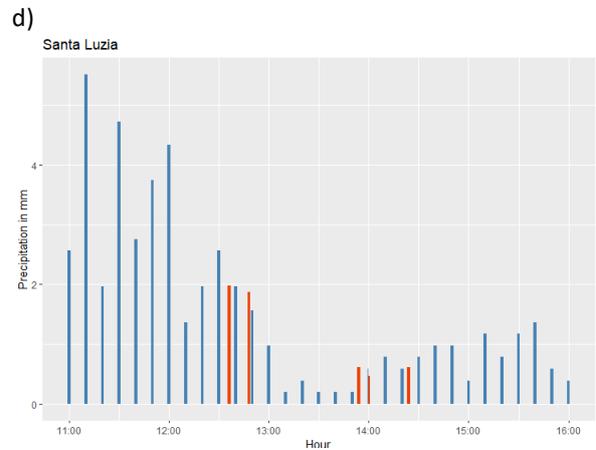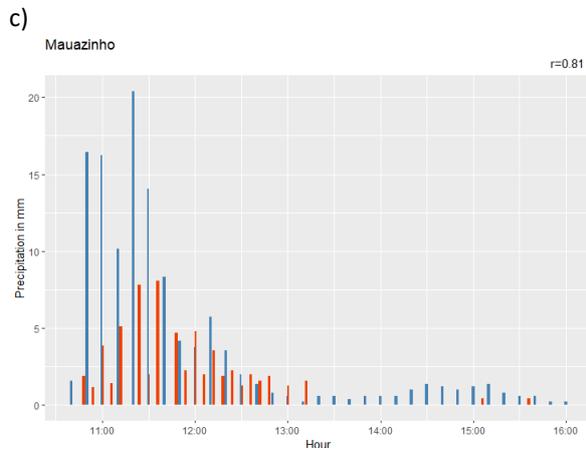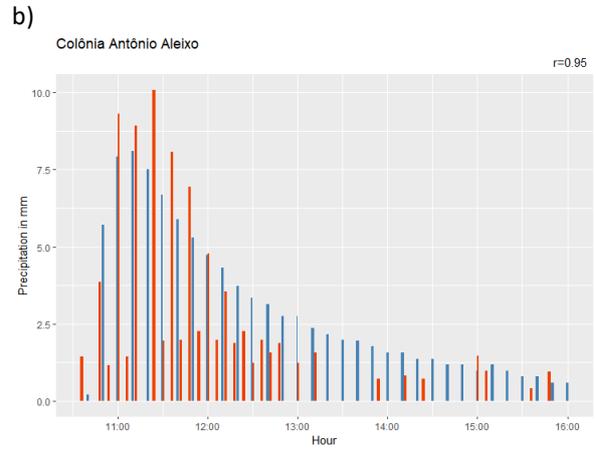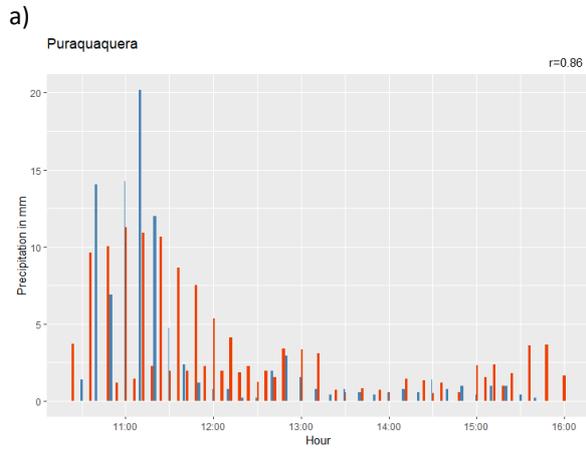
Figura 8: Comparison between the forecasted rainfall records and observed rain gauges and the respective correlations when have paired records in both types of equipment. Source: Censipam and Cemaden.

The high correlation in Antônio Aleixo $r = 0.95$, Santa Etelvina $r = 0.88$, Puraquequara $r = 0.86$, Tarumã $r = 0.84$ and Mauazinho $r = 0.81$ is explained by the appropriate distance between the radar and the neighbourhoods (6km and 18km), little noise interference from ground obstacles and the correlation of precipitation data accumulated every 30 minutes.

In Sebastianelli et al. (2010) which characterised radar measurement errors by the distance from the target, it was observed that the correlation begins to increase from 6km to 62km, remaining in the range of $r = 0.6$. Pappa et al. (2021) also used the correlation coefficient to analyse the efficiency of radar forecasts and considered correlations above $r = 0.8$ as good results.

Redenção showed a correlation equal to 0.59, although this is an acceptable correlation (Sebastianelli et al., 2010), is necessary to investigate how it differs from the others. This rain gauge is in the direction of terrestrial obstacles that could affect the signal, but at a distance that possibly does not interfere with the azimuth scan, so it is reasonable to consider that this fact is relevant to this result. Considering that there are some particularities in the measurement and compatibility for comparing the amount of rainfall in two different devices, such as the rain gauge and the radar (Ochoa-Rodriguez et al., 2019; Sebastianelli et al., 2010), other details can be considered in the adjustment between the data for this area.

Despite of the lack of precision in rainfall measurements at extreme magnitudes (mm/h), as observed in previous studies (Ochoa-Rodriguez et al., 2019), the results of application proved to have the potential to act as an early forecasting tool for adverse weather events. The analysis revealed that the application generally showed a very strong and strong correlation between the forecast and the observed on the ground, anticipating the event by at least 1 hour and 6 minutes for the Mauazinho and Puraquequara neighbourhoods, and 1 hour and 16 minutes for the Colônia Antônio Aleixo neighbourhood. In the other

neighbourhoods where there were no rain gauges for comparison purposes, the application was able to anticipate the event for more than 41 neighbourhoods until 10am UTC.

IV. CONCLUSION

This study assessed the efficiency of SipamHidro module for monitoring rainfall in urban areas in predicting a rainfall event recorded in Manaus on 25 March 2023. The results reveal a number of crucial aspects for understanding the tool ability to anticipate adverse weather events and improve risk management in urban areas.

The rain forecast module, integrated into SipamHidro, proved to be a vital tool for anticipating storms on a reduced time scale, providing information approximately 1 hour in advance. The time analysis between the predicted and observed times highlighted this tendency to anticipate the start of the storm adequately. Time variations were considered to be within an acceptable range, such as 32 minutes to 2 hours in anticipation between forecast and observed in Tarumã and 6 minutes to 1 hour in anticipation in Puraquequara. This capacity for anticipation, particularly in neighbourhoods such as Mauazinho, Puraquequara and Colônia Antônio Aleixo, demonstrates the practical utility of the tool in management severe weather events, anticipating emergency actions such as alerts, sound signals, mobilization of civil defense agencies targeted at neighbourhoods with the greatest potential for damage, due to the potential for disaster, among other measures.

The comparison between weather radar forecasts and observed data indicated that, in general, there was an underestimation of the forecast values, especially in neighbourhoods such as Compensa and Santa Luzia, due to the radar's physical and location limitations. However, the most accurate matches were in the neighbourhoods of Colônia Antônio Aleixo, Santa Etelvina, Puraquequera, Tarumã and Mauazinho, indicating notable efficiency in these locations. The spatial distribution of rainfall, although showed similar results in forecasts across most of the city, revealed notable differences in the West and Centre-West zones. These discrepancies can provide valuable insights for improving the accuracy of forecasts in these specific areas.

While a minor inaccuracy was observed in the measurements of rainfall at extreme magnitudes, the application of the module demonstrated significant potential as an early forecasting tool. The high correlation between the forecasts and the observed data, especially in strategic areas, emphasizes the importance of continuing development and refinement of this technology to improve the ability to forecast and respond to adverse weather events in urban areas. This study contributes to understanding the

complexities involved in forecasting weather events in urban contexts and emphasizes the necessity for innovation and improvement of existing tools.

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V. Referências

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