



Improving safety in cities by using GNSS stations to monitor precipitable water vapor with the PPP method

Luiz Filipe Campos do Canto

PhD student, Postgraduate Program in Cartographic Sciences-UNESP, Brazil.
luiz.canto@unesp.br

Paulo de Oliveira Camargo

Professor Doctor, Postgraduate Program in Cartographic Sciences-UNESP, Brazil.
paulo.camargo@unesp.br

João Francisco Galera Monico

Professor Doctor, Postgraduate Program in Cartographic Sciences-UNESP, Brazil.
galera.monico@unesp.br

SUMMARY

Sustainable cities are urban environments designed and developed to promote economic, social and environmental well-being. Climate monitoring plays a vital role in achieving sustainable cities, providing essential data and insights for effective planning, decision-making and strategy implementation. Flooding is a recurring factor in urban areas, necessitating measures to monitor it. Precipitable water vapor (PWV) is a highly variable component and is a parameter for understanding moisture availability and its relationship with precipitation. Different techniques have been developed to estimate and monitor water vapor. Currently, the Global Navigation Satellite System (GNSS) has stood out in the estimation of PWV, due to its high precision and resolution, its cost and the possibility of monitoring. In this work, the Precise Point Positioning (PPP) method was used in near-real time, through the tropospheric delays of five stations in the Brazilian GNSS network, located in different regions, in cities that are frequently affected by heavy rainfall, to calculate PWVs, in order to prove the efficiency of using GNSS. The IBGE's post-processed PPP data was used as a reference for evaluating the results and then analyzing the accuracy. The results proved to be satisfactory for the purpose and consolidate it as a fundamental tool for urban environments to monitor weather events in almost real time.

KEYWORDS: Sustainable cities. GNSS PPP method. Precipitable water vapor.

1 INTRODUCTION

Sustainable cities and communities are urban areas designed and developed with a focus on economic, social and environmental sustainability. They prioritize the well-being and quality of life of residents, as well as minimizing resource consumption and environmental impacts. These cities adopt innovative solutions and practices in areas such as energy, transportation, waste management, urban planning and community engagement to achieve their goals, with the priority of the well-being of present and future generations, addressing social, economic and environmental challenges (LACONTE and GOSSOP, 2016). These cities strive to achieve a harmonious balance between urban development and the preservation of natural resources, while promoting social equity and economic growth. Collaboration and partnerships between various stakeholders, including government authorities, businesses, community organizations and citizens, are essential for building sustainable cities and communities. These partnerships facilitate the sharing of knowledge, the mobilization of resources and the implementation of effective policies and initiatives (GIRARDET, 1999; COHEN and GUO, 2021).

Among the key elements of sustainable development, we can highlight urban planning strategies that promote compact and mixed-use development, reducing the need for long commutes and allowing efficient land use. They prioritize the preservation of green spaces, biodiversity and natural habitats, promoting harmonious coexistence between urban areas and the environment. The promotion of inclusion, social cohesion and community participation, with the priority of affordable housing, access to education, health and cultural amenities for all residents, involving citizens in decision-making processes, encouraging active involvement and empowering communities to shape their urban environment, with social equality, ensuring equal access to essential services, education and health for all residents, promoting diversity, inclusion and social cohesion, fostering a sense of belonging and collective responsibility. The

vision of sustainable cities and communities represents a path towards a more prosperous, equitable and environmentally healthy future. By adopting sustainable practices, cities can become vibrant, resilient and liveable spaces (LACONTE and GOSSOP, 2016; COHEN and GUO, 2021).

A flood refers to an overflow or accumulation of water on land that is typically dry. It occurs when the volume of water exceeds the capacity of the soil or drainage systems to absorb or contain it. Floods can be caused by a number of factors, including heavy rainfall, melting ice, dam failure, storms or a combination of these. They can occur in both natural and urban environments and can range in scale from localized flash floods to large-scale riverine or coastal flooding. Floods wreak havoc on urban infrastructure, leading to severe damage and disruption, having significant impacts on the affected areas, as roads, bridges and public transportation systems become impassable or even destroyed, impeding mobility and emergency response efforts (GIRARDET, 1999; TUCCI, 2003).

One of the most serious consequences of flooding is the threat to human health and safety, as essential facilities such as hospitals can be damaged, impacting on essential services. Rapidly rising floodwaters pose a risk of drowning, especially for those caught off guard or unable to escape. The force of the water can also cause structural collapses, leading to injuries and deaths. In addition, flood waters become contaminated with pollutants, sewage and chemicals, posing health risks such as waterborne diseases, respiratory illnesses and skin infections. The displacement of affected populations to temporary shelters or overcrowded evacuation centers further increases vulnerability and disease. In addition, electrical and communication networks are often compromised, hampering rescue and recovery operations. Managing and mitigating the risks associated with flooding is essential to protecting lives and property, and proactive measures to mitigate flood risks must be prioritized. This includes robust urban planning, improved drainage systems, preservation of natural floodplains and public awareness campaigns, as well as ensuring the resilience of communities and infrastructure in flood-prone areas (CASTRO, 2003; SANTOS, 2007).

Although natural factors, such as heavy rainfall and overflowing rivers, have historically caused flooding in cities, the role of human activities in exacerbating this problem cannot be overlooked. Anthropogenic causes, such as urbanization, inadequate infrastructure, deforestation and climate change, have contributed significantly to the increased frequency and severity of flooding events in urban areas. The rapid growth of cities and urban sprawl have led to the replacement of natural landscapes with impermeable surfaces such as concrete and asphalt. These surfaces prevent water from infiltrating into the ground, leading to increased runoff during rainfall events. The excessive volume of surface runoff overloads drainage systems, causing urban flooding. In addition, the expansion of impermeable areas reduces the availability of natural water storage and retention spaces, exacerbating flood risks (TINGSANCHALI, 2017; LI and CHENG, 2018).

According to Johansen (2017) and Tingsanchali (2017), anthropogenic climate change is altering global weather patterns, resulting in more frequent and intense rainfall in certain regions. Warmer temperatures increase the amount of moisture in the atmosphere, leading to

heavy rainfall and increasing the risk of flooding. The urban heat island effect, caused by the concentration of concrete and asphalt in cities, exacerbates these effects. Rising sea levels due to climate change also increase the risk of coastal flooding, especially in low-lying cities and due to unplanned urban development in vulnerable areas. Construction in these areas disrupts natural flood absorption zones, displacing water into surrounding areas and increasing the risk of flooding. The encroachment of floodplains reduces their capacity to absorb excess water during flood events, leaving cities more susceptible to flooding.

According to Guerra and Vitte (2004), Brazil, a country known for its diverse landscapes and abundant water resources, faces significant challenges when it comes to flooding in its cities. With a combination of natural factors and human activities, flooding has become a recurring problem, causing substantial damage to urban areas and posing risks to the population. Brazil's territory covers several climatic zones, from tropical rainforests to semi-arid regions. Some areas experience heavy rainfall, particularly during the rainy seasons, leading to an increased risk of flooding. Regions such as the Amazon rainforest, the Pantanal and coastal cities are particularly prone to flooding due to their unique geographical characteristics and proximity to bodies of water. Rapid urbanization in Brazil has led to the expansion of cities and the construction of infrastructure, often without sufficient consideration for flood risks. Inadequate drainage systems, especially in older urban areas, are ill-equipped to deal with heavy rainfall, resulting in water accumulating in streets, houses and public spaces. Overloaded drainage networks lead to urban flooding, disrupting daily life, damaging property and posing health risks.

According to Mendonça and Danni-Oliveira (2007), Brazil, like other countries, is experiencing the impacts of climate change, which are aggravating the risks of flooding. Changes in rainfall patterns, increased intensity of rainfall events and rising sea levels pose challenges for cities, especially along the coastal area. The increased frequency and intensity of extreme weather events further increases the vulnerability of urban areas to flooding, requiring adaptation measures and climate change mitigation strategies. In addition, the country faces significant socio-economic disparities and many low-income communities are affected by flooding. Informal settlements, often located in vulnerable areas such as floodplains and hillsides, lack adequate infrastructure and are more susceptible to flooding. Residents of these areas face increased risks to their safety, health and economic stability during flood events, highlighting the need for inclusive and resilient urban planning.

Monitoring rainfall in urban areas is extremely important for mitigating the risks associated with intense precipitation, improving flood management strategies and promoting sustainable urban development. One of the main reasons for monitoring rainfall in urban areas is to improve flood management strategies. Urbanization often leads to the replacement of permeable surfaces with impermeable ones, reducing the natural absorption of rainwater. Consequently, heavy rainfall events can result in rapid runoff and flash floods. By monitoring rainfall in real time, authorities can promptly alert residents and implement emergency response plans to mitigate the impact of flooding, saving lives and minimizing property damage. By analyzing historical data, researchers and urban planners can identify patterns and establish long-term trends, allowing them to make informed decisions about infrastructure development,

stormwater management and flood preparedness (WONG and CHEN, 2019).

In Brazil, rainfall monitoring is mainly carried out by the National Institute for Space Research (INPE), the National Water and Sanitation Agency (ANA) and the National Institute of Meteorology (INMET). INPE is responsible for monitoring rainfall and weather conditions throughout Brazil using satellite remote sensing technologies. INPE's Center for Weather Forecasting and Climate Studies (CPTEC) operates weather monitoring stations and satellite systems that provide valuable data on rainfall patterns and other meteorological variables. The ANA is responsible for managing water resources in Brazil, including monitoring rainfall and river levels, operating a network of rainfall monitoring stations across the country, collecting data on precipitation. INMET is the institution responsible for providing information and monitoring climatic conditions in Brazil. It has a network of rain gauge stations, which are pieces of equipment responsible for measuring and recording the amount of rainfall in different regions of the country, as well as using weather radar and satellites. In addition, various regional and state bodies and academic institutions also play a role in monitoring rainfall in Brazil.

Precipitation is a complex meteorological phenomenon influenced by various atmospheric factors. Precipitable Water Vapor (PWV), which represents the total amount of water vapor in a vertical column of the atmosphere, has shown promise as a key parameter for understanding moisture availability and its relationship to precipitation, providing valuable information on moisture availability and facilitating rainfall estimation and forecasting. PWV plays a vital role in the water cycle, with a direct influence on the formation and intensity of rainfall. Higher PWV values indicate a higher moisture content in the atmosphere, suggesting a greater potential for precipitation. Correlations between PWV and precipitation have been observed, with studies showing that changes in PWV can precede rainfall events. By monitoring and analyzing PWV, it is possible to obtain information about atmospheric moisture conditions and improve rainfall forecasts (ZIV and REUVENI, 2022; KELSEY, RILEY and MINSCHWANER, 2022; REN et al., 2023).

According to Leick, Rapoport and Tatarnikov (2015), different techniques are capable of monitoring PWV, including radiosondes, water vapor radiometers and solar photometers. However, these techniques do not meet the current need for real-time monitoring. A promising and expanding technology, with low-cost instruments and installation, capable of obtaining PWV with high precision and spatial and temporal resolutions in near real time, is through the satellite navigation system (Global Navigation Satellite System - GNSS). GNSS refers to a constellation of satellites in space, working together with receivers and terrestrial systems, to provide precise positioning and navigation data, via signals in space, so that GNSS receivers are able to calculate position, speed and time. The main GNSS systems in operation today include the Global Positioning System (GPS) maintained by the United States, the Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) developed by Russia, Galileo via the European Union and BeiDou by China. The main methods of positioning via GNSS receivers are absolute positioning and relative positioning (SEEBER, 2003; MONICO, 2008).

Precise Point Positioning (PPP) is carried out absolutely, and involves only the use of a receiver. The method models errors by combining observations with satellite orbits/clocks,

generated from a network of global reference stations and sent via satellite or internet. Its level of positional accuracy is high and processing can be carried out in near real time or in post-processed mode (MONICO, 2008; MARQUES, 2012). For details on the system, see Monico (2008), Marques (2012) and Langley, Teunissen and Montenbruck (2017). In recent years, research has demonstrated the potential of PPP to estimate PWV, exploiting the delays in GNSS signals caused by atmospheric humidity, in terms of accuracy, temporal resolution and cost-effectiveness, making it a promising approach for estimating PWV in various meteorological and atmospheric studies.

The Brazilian Network for Continuous Monitoring of GNSS Systems (RBMC) comprises GNSS stations positioned throughout Brazil, offering wide coverage and allowing users to access precise positioning information, which provides observations once a day or in real time to determine coordinates. These stations are equipped with state-of-the-art GNSS receivers and antennas, guaranteeing high-quality data collection and providing support for surveying, mapping, engineering, environmental monitoring and natural risk assessment. However, improving the accuracy and efficiency of the information collected for sustainable cities can only be achieved by expanding the network of GNSS stations.

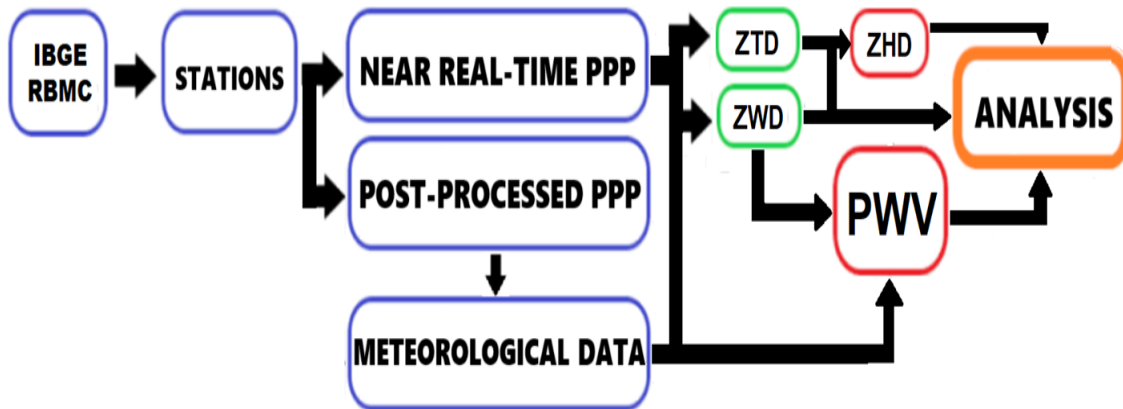
2 OBJECTIVE

In view of the above, the work aims to investigate and analyze the improvement of safety in cities, through the use of GNSS stations for monitoring Precipitated Water Vapor (PWV), using the Precise Point Positioning (PPP) method in near real time, to understand the availability of moisture and its relationship with precipitation in urban areas, the benefits for weather forecasting resources and aid in climate change research, with a view to mitigating the risks associated with intense precipitation, providing subsidies for urban planning, improving flood management strategies and promoting sustainable urban development.

3 METHODOLOGY

In order to demonstrate the potential of using the GNSS system to help estimate and forecast rainfall, the PPP technique was used in near-real-time and post-processed to calculate the PWVs, using data collected from GNSS observations from five RBMC stations, for each region of Brazil, located in cities that suffer consequences when they are hit by heavy rainfall and due to the availability of meteorological data (INMET), over the course of 03/31/2023 (DOY 90). Figure 1 illustrates the methodological process for estimating the PWV and Table 01 shows the stations and cities used.

Figure 1 - Methodological process



Source: Prepared by the authors, 2023.

Table 1 - Information on the stations used

Region	City	Station names	Latitude	Longitude
North	Manaus	AMUA	-3,09184	-60,03157
North East	João Pessoa	PBJP	-7,13628	-34,87342
South East	Belo Horizonte	MGJP	-19,86986	-43,96509
South	Florianópolis	IFSC	-27,59443	-48,54208
Midwest	Cuiabá	CUIB	-15,55526	-56,06986

Source: Prepared by the authors, 2023.

The neutral atmosphere is an electrically neutral layer and its sub-layer closest to the surface is known as the troposphere, where it has around 80% of the total mass of the neutral atmosphere and almost all of the water vapor. The total tropospheric delay (ZTD) of the signal transmission path is defined in Equation 1.

$$ZTD = m_{f_h} ZHD + m_{f_w} ZWD \quad (1)$$

Where ZHD and ZWD are the hydrostatic and wet delays at zenith, respectively; m_{f_h} and m_{f_w} are the hydrostatic and wet mapping functions, respectively. See Sapucci (2001), Sapucci (2005) and Gouveia (2019) for more details on zenith delay estimates and mapping functions. The PWV is not a raw observation, but needs to be derived by certain methods and models, which can be through ZWD according to the following Equations 2 and 3.

$$PVW = \Pi \cdot ZWD \quad (2) \quad \Pi = \frac{10^6}{\rho_w R_v [(K_3/T_m) + K'_2]} \quad (3)$$

Where ρ_w is the density of liquid water ($999,97 \text{ kg/m}^3$), R_v is the gas constant of water vapor ($461,525 \text{ JK}^{-1}/\text{kg}^{-1}$), T_m denotes the weighted average temperature of the atmosphere, K'_2 ($22,1 \text{ K}/\text{mb}$) and K_3 ($3739 \text{ k}^2/\text{mb}$) are experimentally determined constants. The T_m used was the one developed by Sapucci (2005), who modeled functions for the 5 regions of Brazil based on radiosonde data. The function used to calculate T_m was Equation 4.

$$T_m = T_S \cdot a + P_S \cdot b + U_R \cdot c + d \quad (4)$$

The terms T_S , P_S e U_R , are respectively, atmospheric pressure, temperature and relative humidity respectively. The values of the coefficients a, b, c and d for the respective Brazilian regions are shown in Table 2.

Table 2 - Coefficient values for Brazilian regions

Region	a	b	c	d
North	0,61390	0	0,020243	102,815
North East	0,55843	0,012718	0	108,149
South East	0,44330	0	-0,032011	155,717
South	0,36278	0	-0,050706	183,950
Midwest	0,52286	0,004765	0	126,612

Source: Sapucci, 2005.

To demonstrate how cities can monitor and anticipate probable rainfall, the PPP of the chosen stations was carried out in near-real time by obtaining GNSS observation data via the NTRIP protocol, using the BKG Ntrip Client (BNC) software version 2.12.18, available at <<https://igs.bkg.bund.de/ntrip/bnc>>. To gain access to the Caster servers, which are responsible for distributing the RCTM correction, navigation and observable data from the network's stations, it was necessary to register at <<https://register.rctm-ntrip.org/cgi-bin/registration.cgi>>. Registration requires confirmation, with an average response time of one day. After validation, the user has access to the servers.

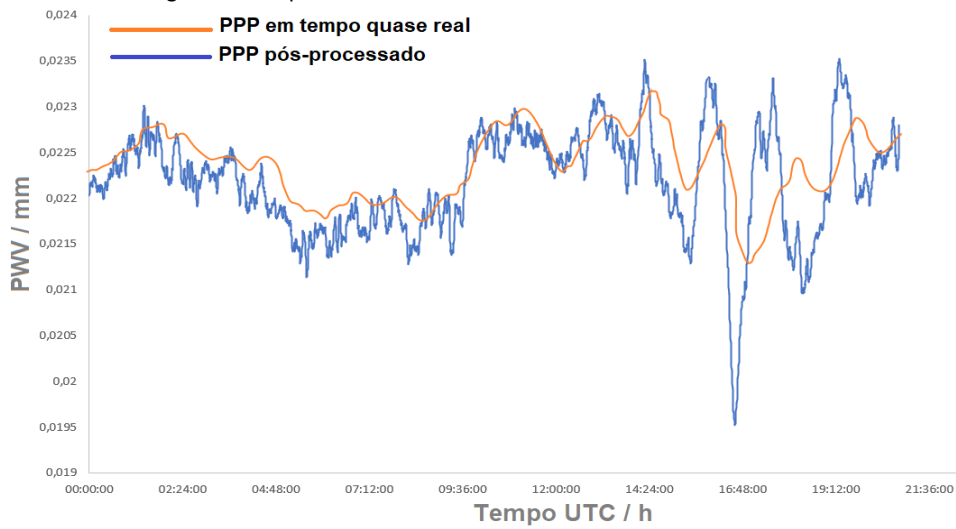
Brazil, through the IBGE, also provides data flow and GNSS corrections from the stations belonging to the RBMC, in real time (RBMC-IP), through the TCP/IP protocol and also uses NTRIP via the Internet. Registration for access to the RBMC-IP service can be done via the link <<https://www.ibge.gov.br/cadastro-dgc>>. The BNC program calculates tropospheric delays using Saastamoinen's empirical models.

The data in mode post-processed through the IBGE's online service, was used as a reference for evaluating the results, as it provides tropospheric products from the PPP, and the ZTD and ZWD values were used in this work. The ZHD was calculated according to Equation 1. For more information on the files generated, corrections, the empirical tropospheric model and the data available for processing, see IBGE (2020). The data used were ZTD and ZWD and the ZHD and PWV were calculated, according to INMET meteorological data and T_m from Equation 4 and parameters in Table 2, according to the region. The analysis to assess accuracy was based on statistical measures of the errors between observed values and predictions.

4 RESULTS

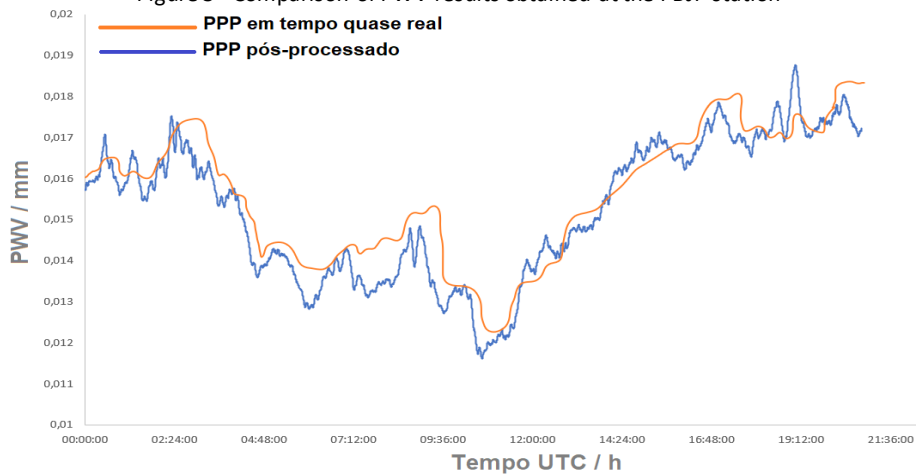
Figures 2 to 6 illustrate the comparison of the PWV calculated in near-real time and through post-processing of the data via the IBGE online service for each station defined.

Figure 2 - Comparison of PWV results obtained at the AMUA station



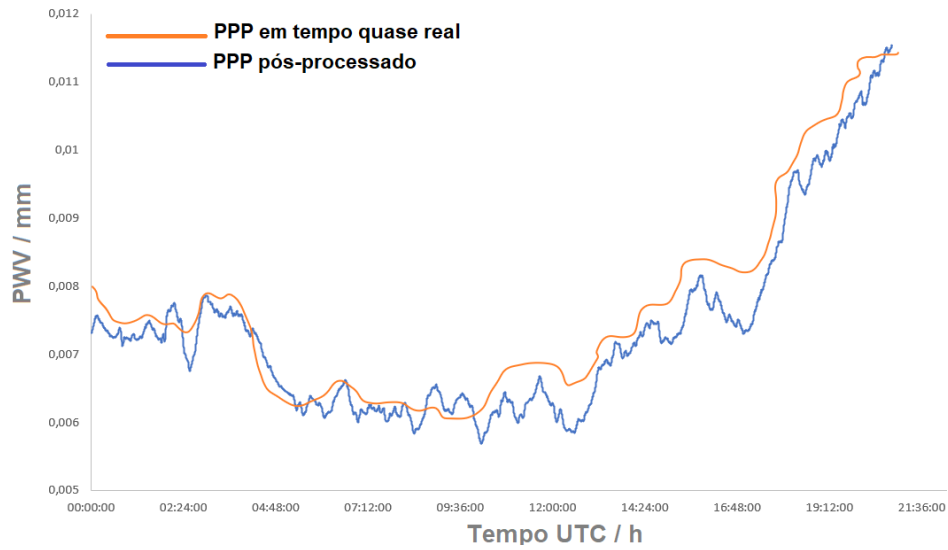
Source: Prepared by the authors, 2023.

Figure 3 - Comparison of PWV results obtained at the PBJP station



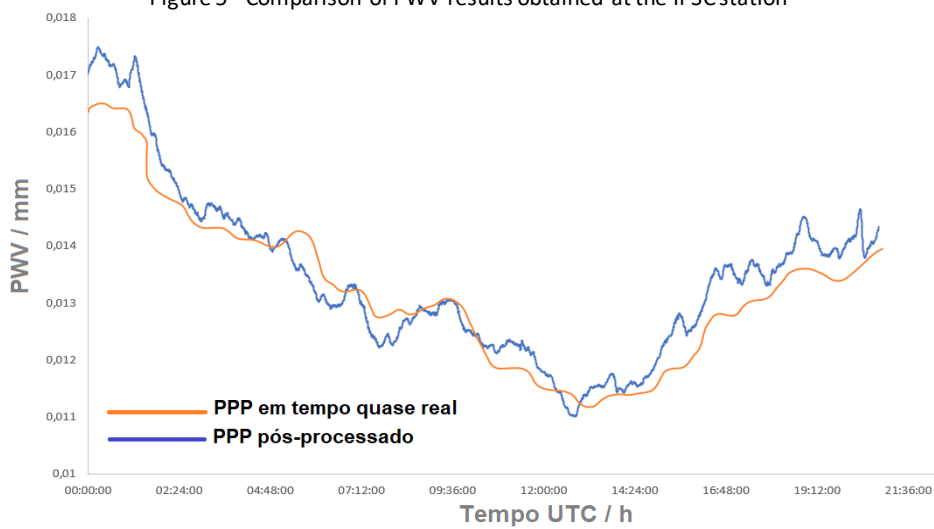
Source: Prepared by the authors, 2023.

Figure 4 - Comparison of PWV results obtained at the MGJP station

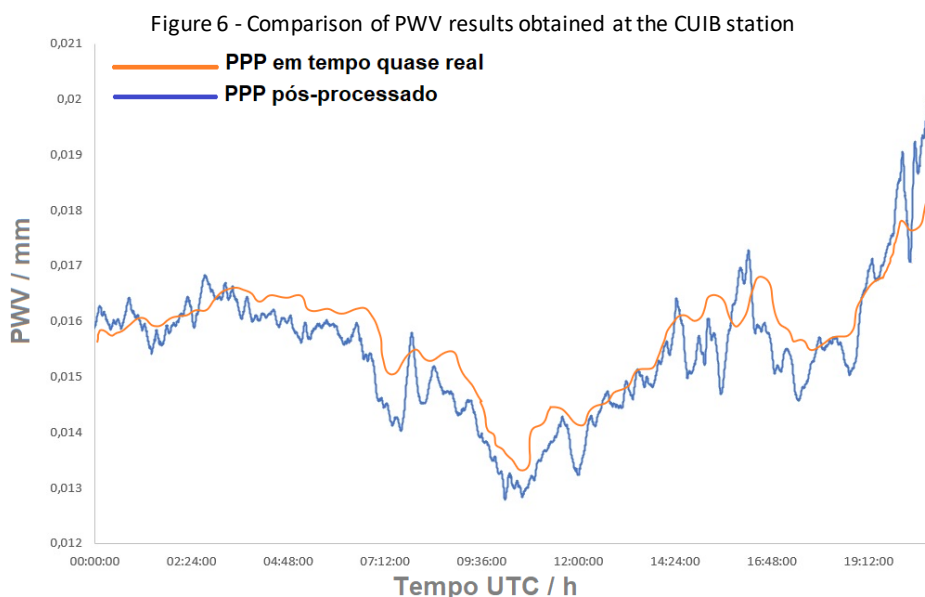


Source: Prepared by the authors, 2023.

Figure 5 - Comparison of PWV results obtained at the IFSC station



Source: Prepared by the authors, 2023.



Source: Prepared by the authors, 2023.

By evaluating Figures 2 to 6, it is possible to see the variability of humidity patterns in Brazilian territory and deduce the relevant influence of factors such as latitude, proximity to the coast, prevailing winds and the presence of large rivers and forests, with the possibility of local variations within each region. In addition, Brazil's climate is subject to natural climate variability phenomena which can influence humidity levels on a larger scale. The results, in a general analysis, illustrate greater detail in the variability of the water vapor content when post-processing is carried out. However, the near-real-time solution remains close to the general behavior of the post-processing.

The average results of the tropospheric delays between the values obtained in near-real time and post-processed and their respective standard deviations are shown in Table 3.

Table 3 - Average result and standard deviation of tropospheric delays

Station	ZHD	ZWD	ZTD
AMUA	2,28643 ± 0,00112	0,35954 ± 0,03945	2,65637 ± 0,05476
PBJP	2,28750 ± 0,00122	0,24614 ± 0,04615	2,53912 ± 0,06725
MGJP	2,09973 ± 0,00117	0,12230 ± 0,04360	2,22306 ± 0,06643
IFSC	2,25747 ± 0,00108	0,22954 ± 0,03662	2,53500 ± 0,07009
CUIB	2,22889 ± 0,00099	0,25233 ± 0,02899	2,49865 ± 0,05723

Source: Prepared by the authors, 2023.

Overall, with the results of the statistical measures shown in Table 3, it helps to assess the acceptability of the data based on the amount of variability at the desired level of confidence around the PPP solution in near-real time, achieving satisfactory results compared to the post-processed ones from the IBGE.

5 CONCLUSION

The vision of sustainable cities and communities represents a path to a more prosperous, equitable and environmentally friendly future. By adopting sustainable practices in urban planning and community engagement, cities can become livable spaces. Flooding poses a multifaceted threat to urban areas, affecting infrastructure, human safety, the economy, the environment and social well-being. Recognizing the increasing frequency and severity of these events, cities must prioritize proactive measures to mitigate flood risks. By taking comprehensive measures, cities can build resilience and better protect their inhabitants from the devastating effects of flooding, ensuring a safer and more sustainable future. In Brazil, flooding in cities is a complex challenge influenced by geographical factors, changes in land use, urbanization, socioeconomic disparities and the impacts of climate change. Monitoring rainfall in urban centers is indispensable for building resilient cities and adapting to the challenges of a changing climate. Accurate, real-time rainfall data allows authorities to improve flood management strategies. Brazil has a vast and diverse geographical area, encompassing different climatic zones and ecosystems. Therefore, a collaborative effort between different agencies and institutions is needed to ensure comprehensive rainfall monitoring coverage throughout the country.

The work ratifies the importance of using GNSS systems to investigate the spatial distribution of water vapor and climate studies, using PWV estimation to prove the efficiency of using GNSS in relation to other techniques, especially in terms of low cost and operation in all weather conditions. Near-real-time PPP mode has great potential for monitoring PWV and other relevant parameters. Expanding the network of GNSS stations in all urban centers, where the stations are equipped with meteorological sensors, for PWV monitoring is a crucial step towards improving weather forecasting, climate studies, hydrological applications and disaster management. The availability of a dense network of stations allows for accurate and comprehensive PWV measurements. Urban areas often have distinct microclimates compared to neighboring rural regions due to the presence of buildings, roads and other infrastructure. These urban microclimates can influence local weather patterns and precipitation. Real-time PWV monitoring helps to understand the spatial variability of water vapor content in an urban environment, providing valuable information for localized weather forecasts and urban climate studies.

REFERENCES

CASTRO, A.L. **Manual de Desastres: desastres**. Ministério da Integração Nacional, 2003.

COHEN, S.; GUO, D. **The Sustainable City**. Columbia University Press, 2021. 352 p.

GIRARDET, H. **Creating Sustainable Cities**. Green Books for the Schumacher Society, 1999. 77 p.

GOUVEIA, T. A. F. Função de mapeamento brasileira da atmosfera neutra e sua aplicação no posicionamento GNSS na América do Sul. 129f. Tese (Doutorado em Ciências Cartográficas). Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente. 2019.

- GUERRA, A. J. T.; VITTE, A. C. **Reflexões sobre a geografia física no Brasil**. Bertrand Brasil, 2004. 282 p.
- IBGE. **IBGE-PPP**: Serviço on-line para Pós-Processamento de dados GNSS. Editora IBGE, 2020. 65 p.
- JOHANSEN, B. **Climate Change**: An Encyclopedia of Science, Society and Solutions. ABC-CLIO, 2017. 1180 p.
- KELSEY, V.; RILEY, S.; MINSCHWANER, K. Atmospheric precipitable water vapor and its correlation with clear-sky infrared temperature observations. **Atmospheric Measurement Techniques**, n. 15, p. 1563–1576, 2022.
- LACONTE, P; GOSSOP, C. **Sustainable Cities**: Assessing the Performance and Practice of Urban Environments. I. B. Tauris & Company, 2016. 256 p.
- LANGLEY, R. B.; TEUNISSEN, P. J.; MONTENBRUCK, O. **Handbook of Global Navigation Satellite Systems**. Springer, 2017. 1292 p.
- LEICK, A.; RAPOPORT, L.; TATARNIKOV, D. **GPS Satellite Surveying**. Wiley, 2015. 840 p.
- LI, R.; CHENG, C. T. Urban flooding: from urban to regional scale. **Journal of Hydrology**, n. 558, 11-21. 2018.
- MARQUES, H. A. PPP em tempo real com estimativa das correções dos relógios dos satélites no contexto de rede GNSS. 244f. Tese (Doutorado em Ciências Cartográficas). Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente. 2012.
- MONICO, J. F. G. **Posicionamento pelo GNSS**: Descrição, fundamentos e aplicações. Editora UNESP, 2008. 476 p.
- MENDONÇA, F.; DANNI-OLIVEIRA, I. M. **Climatologia**: Noções Básicas e Climas do Brasil. Oficina de Textos, 2007. 208 p.
- REN, D.; WANG, Y.; WANG, G.; LIU, L. Rising trends of global precipitable water vapor and its correlation with flood frequency. **Geodesy and Geodynamics**, 2023.
- SANTOS, R. F. (org.) **Vulnerabilidade Ambiental**. MMA, 2007. 192 p.
- SAPUCCI, L. F. Estimativas do IWV utilizando receptores GPS em bases terrestres no Brasil: sinergia entre a geodésia e a meteorologia. 200f. Tese (Doutorado em Ciências Cartográficas). Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente. 2005.
- SAPUCCI, L. F. Estimativa do vapor d’água atmosférico e avaliação da modelagem do atraso zenital troposférico utilizando GPS. 167f. Dissertação (Mestrado em Ciências Cartográficas). Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente. 2001.
- SEEBER, G. **Satellite Geodesy**. Walter de Gruyter, 2003. 589 p.
- TINGSANCHALI, T. Urban flooding: vulnerability, risks, and responses. **Sustainable Water Resources Management**, n. 3, p. 279-289, 2017.
- TUCCI, C. E. M. Águas urbanas. In: TUCCI, C.E.M; BERTONI, J.C. Inundações urbanas na América do Sul. Porto Alegre: ABRH/Rhama, 2003. Cap.2, pp.11-36.
- WONG, T. H.; CHEN, Y. Understanding urban flood resilience: A review of progress and challenges. **Journal of Hydrology**, n. 575, 633-643. 2019.
- ZIV, S. Z.; REUVENI, Y. Flash Floods Prediction Using Precipitable Water Vapor Derived from GPS Tropospheric Path Delays Over the Eastern Mediterranean. **IEEE Transactions on Geoscience and Remote Sensing**, n. 60, p. 1-17, 2022.