Serviço Público Federal
Ministério da Educação
Fundação Universidade Federal de Mato Grosso do Sul
Faculdade de Engenharias, Arquitetura e Urbanismo e Geografia - FAENG

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PPGTA
TECNOLOGIAS AMBIENTAIS

DEVELOPMENT OF THE URBAN HYDROLOGICAL DISASTERS SUSCEPTIBILITY INDEX

Campo Grande, MS

2023

FEDERAL UNIVERSITY OF MATO GROSSO DO SUL
FACULTY OF ENGINEERING, ARCHITECTURE AND URBANISM AND GEOGRAPHY
GRADUATE PROGRAM IN ENVIRONMENTAL TECHNOLOGIES

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DEVELOPMENT OF THE URBAN HYDROLOGICAL DISASTERS SUSCEPTIBILITY INDEX

Thesis submitted to the Graduate Program in Environmental Technologies at the Federal University of Mato Grosso do Sul as a partial requirement to obtain the title of Doctor in Environmental Technologies. Concentration area: Environmental Sanitation and Water Resources.

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Campo Grande, MS
2023

DEDICATION

Firstly, I dedicate this work to God. Next, I dedicate to my parents Aparecido Ferreira de Moraes and Marli Bastos Brandão de Moraes for their support, patience and understanding during my Doctorate, as well as my sister Thaisa Brandão Ferreira de Moraes.

ACKNOWLEDGEMENTS

First of all, I would like to thank God for giving me the strength to overcome all the difficulties encountered along this journey.

I would like to thank deeply my parents (Aparecido and Marli), for their love and unconditional support and without them I would not have made it this far.

Profound appreciation and sincere gratitude goes to my thesis advisor Dr. Fábio Veríssimo Gonçalves. Thank you for offering me the thesis that is rich in diversity and creativity. Thank you for being a fantastic mentor and for the valuable experiences and skills that you have given me throughout the way. I am really fortunate to have you as a supervisor.

My warm thanks to Dr. Cláudia Gonçalves Vianna Bacchi, Dr. Jamil Alexandre Ayache Anache, Dr. Keila Roberta Ferreira de Oliveira and Dr. Cristovão Vicente Scapulatempo Fernandes for accepting to be a part of my thesis jury. Special Thanks to Dr. Cláudia Gonçalves Vianna Bacchi for all the support and dedication during these four years of doctoral work.

To the friends who always supported and helped me at all times, especially Daniel Manzi, Fernando Rocha, Giovanni Zanandreis, Henrique Aquino, Laura Braga, Letícia Franco, Lidiane Costa, Raquel Nishimoto and Vinícius Taveira. To my friend Gabriel Mulinari and my sister Thaisa Brandão who even though they were away during these four years, always encouraged and helped me in the most difficult moments.

To Isabella Gatti for all the affection, trust, love and support in the most difficult moments I encountered during my doctorate. As well as José Roberto Gatti, Ana Paula Gatti and João Vitor Gatti for their support, encouragement and suggestions for improvements.

To Foundation to support the development of education, science and technology in the state of Mato Grosso do Sul (FUNDECT) for having believed in my project and for the scholarships during my doctorate. To Coordination of Superior Level Staff Improvement (CAPES) for access to the Periodic Portal. To the Graduate Program in Environmental Technologies (PPGTA), of the Faculty of Engineering, Architecture and Urbanism and Geography (FAENG) of the Federal University Foundation of Mato Grosso do Sul (UFMS) for the opportunity of the Doctorate and support in scientific events.

Finally, I thank the UFMS in Brazil for providing the infrastructure, environments and connections necessary to carry out the research.

CONTENTS

GENERAL ABSTRACT

MORAES, R. B. F. de (2023). Identification of urban hydrographic micro-basins susceptible to hydrological disasters and validation of precipitation estimates via remote sensing. 2023. 124p. Thesis of Doctoral – Graduate Program in Envrironmental Technologies (PPGTA). Federal University of Mato Grosso do Sul (UFMS), Brazil.

The increase in the rate of urbanization linked to inadequate planning of cities and changes in land use and occupation are modifying the surface runoff and infiltration processes of rainwater in the urban areas of several municipalities, contributing to the occurrence of hydrological disasters (floods). At the same time, it is important to highlight the scarcity of consistent and reliable hydrological data on a satisfactory spatio-temporal scale for carrying out hydrological studies, especially in area that is difficult to access, extensive and with low financial resources. In this context, precipitation estimates via remote sensing emerge as promising alternatives to complement surface measurements. The general objective of this work was to develop, apply and validate the Urban Hydrological Disaster Susceptibility Index (UHDSI) from indicators pertinent to different spheres (morphometry, land use and occupation, rainwater infrastructure and environmental), taking into account both infiltration and surface runoff of rainwater in Campo Grande - Mato Grosso do Sul (MS) - Brazil, presented in the first chapter. The results of the UHDSI and historical records of floods applied in each Urban Hydrographic Micro-basins (UHM) obtained a strong correlation ($r > 0.80$), evidencing the reliability and validation of the developed index. In this way, the UHDSI is capable of assisting in the formulation of appropriate political measures and legal norms for ordering land use and occupation, as well as indicating the UHMs that need more attention and mitigating actions from the public power for sustainable socioeconomic development. From the scarcity of reliable and consistent precipitation data verified during the development of the UHDSI in the city of Campo Grande - MS, two new studies were carried out in order to statistically validate the Tropical Rainfall Measurement Mission (TRMM) precipitation estimates in the five geographic regions of the Brazil and to compare the performances of the Global Precipitation Measurement (GPM), TRMM and Global Precipitation Climatology Project (GPCP) precipitation estimates in the daily, monthly and seasonal time scales in the municipality of Campo Grande - MS presented in the second and third chapter, respectively. In general, the results showed that caution is needed before using precipitation estimates on the daily scale, since excellent statistical results were not found on this time scale. However, increasing the time scale considerably improves the correlation and agreement between the precipitation data estimated via remote sensing and the precipitation data observed on the surface, making it possible to better represent the rainfall pattern in the area of interest. Finally, it is expected that the results of this research will help in the planning of various socioeconomic activities that involve precipitation data, such as agriculture, livestock, power generation and identification of areas susceptible to hydrological disasters in regions with climates characterized by dry winters and humid summers.

Keywords: Precipitation. Surface runoff. Infiltration. AHP. QGIS.

RESUMO GERAL

O aumento da taxa de urbanização atrelado ao planejamento inadequado das cidades e às alterações do uso e ocupação do solo estão modificando os processos de escoamento superficial e infiltração de águas pluviais nas áreas urbanas de diversos municípios, contribuindo para a ocorrência de desastres hidrológicos (alagamentos). Concomitantemente, é importante destacar a escassez de dados hidrológicos consistentes e confiáveis em escala espaço-temporal satisfatória para realização de estudos hidrológicos, principalmente em área de difícil acesso, extensa e com baixo recurso financeiro. Nesse contexto, as estimativas de precipitação via sensoriamento remoto emergem como alternativas promissoras para complementarem as medições realizadas em superfície. O objetivo geral desse trabalho foi desenvolver, aplicar e validar o Índice de Susceptibilidade a Desastres Hidrológicos Urbanos (ISDHU) a partir de indicadores pertinentes a diferentes esferas (morfométrica, uso e ocupação do solo, infraestrutura pluvial e ambiental), levando em consideração a infiltração e o escoamento superficial de água pluvial em Campo Grande - Mato Grosso do Sul (MS) - Brasil, apresentado no primeiro capítulo. Os resultados do ISDHU e registros históricos de alagamentos aplicados em cada Microbacia Hidrográfica Urbana (MHU) obtiveram correlação forte ($r > 0.80$), evidenciando a confiabilidade e validação do índice desenvolvido. Dessa forma, o ISDHU é capaz de auxiliar na formulação de medidas políticas adequadas e normas legais para o ordenamento do uso e ocupação do solo, bem como indicar as MHUs que necessitam de mais atenção e ações mitigatórias do poder público para o desenvolvimento socioeconômico sustentável. A partir da escassez de dados de precipitação confiáveis e consistentes verificada durante o desenvolvimento do ISDHU no munícipio de Campo Grande – MS, dois novos estudos foram realizados a fim de validar estatisticamente as estimativas de precipitação *Tropical Rainfall Measurement Mission* (TRMM) nas cinco regiões geográficas do Brasil e comparar os desempenhos das estimativas de precipitação *Global Precipitation Measurement* (GPM), TRMM e *Global Precipitation Climatology Project* (GPCP) nas escalas temporais diária, mensal e sazonal no munícipio de Campo Grande - MS apresentados no segundo e terceiro capítulo, respectivamente. De modo geral, os resultados mostraram que é necessário cautela antes da utilização de estimativas de precipitação na escala diária, visto que não foram encontrados resultados estatísticos excelentes nesta escala de tempo. No entanto, o aumento da escala temporal melhora consideravelmente a correlação e concordância entre os dados de precipitação estimados via sensoriamento remoto e os dados de precipitação observados em superfície, sendo possível representar bem o padrão de chuva na área de interesse. Por fim, é esperado que os resultados dessa pesquisa auxiliem no planejamento de diversas atividades socioeconômicas que envolvam dados de precipitação, como agricultura, pecuária, geração de energia e identificação de áreas susceptíveis a desastres hidrológicos em regiões com climas caracterizados por inverno seco e verão úmido.

Palavras-chave: Precipitação. Escoamento superficial. Infiltração. AHP. QGIS.

GENERAL INTRODUCTION

The growing urbanization linked to changes in land use and occupation and inadequate planning of cities has modified the surface runoff and infiltration processes of rainwater in the Urban Hydrographic Micro-basins (UHMs), contributing to the occurrence of hydrological disasters, such as floods, in the urban areas of different municipalities. These phenomena are severely felt in developing countries (DASH and SAR, 2020), threatening human lives and causing economic losses.

Hence, it is important to identify urban areas susceptible to hydrological disasters arising from precipitation and aggravated by anthropic actions, in order to assist in the formulation of appropriate political measures, guidelines and legal norms for land use planning. In addition to contributing to the process of environmental awareness and education of the population and indicating fragile areas that require attention and mitigation actions from the public administration. This mapping is in line with the Sustainable Development Goals, since is capable of making cities and human settlements inclusive, safe, resilient and sustainable (APPLIED ECONOMIC RESEARCH INSTITUTE - IPEA, 2021).

In recent years, there has been a noticeable increase in the number of studies related to water resources and floods in urban areas (GETAHUN & GEBRE, 2015; SAMANTA et al., 2016; AVAND et al., 2021; PALÁCIO et al., 2021), mainly from indicators and indices (CHEN et al., 2011; GONZALES & AJAMI, 2015; KOOP & VAN LEEUWUEN, 2015; KAZAKIS et al., 2015; MITITELU-IONUS, 2017; CORTÉS et al., 2018; DASH & SAR, 2020). However, Araújo and Dias (2021) point out that there is still a need for environmental research that takes into account qualitative and quantitative aspects in Brazil, in order to direct preventive and minimizing actions to natural disasters.

In this context, the Analytical Hierarchical Process (AHP), developed by Saaty (1977), stands out for carrying out complex environmental studies (SAMANTA et al., 2016), because seeks to discover and correct logical inconsistencies (GOEPEL, 2018), minimizing failures and assisting in the decision-making process. It includes quantitative and qualitative resources (PEREIRA et al., 2020; SINGH & BHAKAR, 2021), combining information from several indicators to form a single evaluation index, being easy to use and highly flexible (ALBULESCU et al., 2022).

Concomitantly, the AHP method is widely used with geotechnologies to improve decision-making processes (SAMANTA et al., 2016). Numerous works have been carried out using the combination of AHP and Geographic Information System (GIS) for flood studies (KAZAKIS et al., 2015; SWAIN et al., 2020; RAMKAR and YADAV, 2021; IKIRRI et al., 2022; MUDASHIRU et al., 2022), being considered an effective aggregation by Dash and Sar (2020), Pereira et al. (2020) and Ramkar and Yadav (2021).

Although, according to Brito and Evers (2016), most works involving the generation of hydrological indicators and indexes ignore the validation stage, being subject to uncertainties. In this sense, Yagoub et al. (2020) recommend the use of hydrological disaster location information available in local newspapers (ESCOBAR et al., 2016), to validate maps of flood susceptible areas generated through spatialized indexes, as performed by Azizat and Omar (2018) and Periyasamy et al. (2018). Moreover, most available hydrological indexes do not include indicators pertinent to different spheres simultaneously, for instance morphometry, land use and occupation, rainwater infrastructure and environmental, limiting the analysis of susceptibility to hydrological disasters.

At the same time, it is worth mentioning that the availability of consistent precipitation data with high spatial and temporal resolution is essential for planning various socioeconomic activities, such as agriculture, livestock, energy generation and identification of areas at risk for hydrological disasters (PRAKASH et al., 2018; ROZANTE et al., 2018). However, traditional precipitation measurements by in-situ gauges are relatively sparse and poorly distributed over the Earth's surface, especially in areas of difficult access and in developing countries (ROZANTE et al., 2018; RODRIGUES et al., 2020a). Besides, their databases generally have a high percentage of sampling failures, limiting the accuracy of hydrological studies (RODRIGUES et al. 2021).

In this scenario, satellite precipitation estimate products emerge as promising alternatives for more accurate hydrological monitoring, because they allow continuous measurements of precipitation with virtually global coverage and high spatio-temporal resolution, regardless of the less accessible regions (TAN and SANTO 2018; WANG et al. 2017; RODRIGUES et al. 2020a; RODRIGUES et al. 2020b), such as the Integrated Multisatellite Retrievals Final Run (IMERG-F) from the Global Precipitation Measurement (GPM) mission, the Multi-satellite Precipitation Analysis (TMPA) from the Tropical Rainfall Measurement Mission (TRMM) and the Global Precipitation Climatology Project Daily (GPCPDAY) and Global Precipitation Climatology Project Satellite-Gauge Combined Precipitation (GPCPMON) from the Global Precipitation Climatology Project (GPCP).

With this in mind, it is necessary to propose complete and validated tools capable of measuring the susceptibility of urban areas to hydrological disasters, as well as seeking solutions for expanding the space-time coverage of precipitation data, especially in developing countries and regions with a high rate of urbanization.

Nevertheless, unfortunately, South America is one of the continents that least presents works with these objectives (DIACONU et al. 2021). The Midwest Region of Brazil, located in the largest floodplain in the world - Pantanal - characterized by a semi-humid tropical climate with a hot and rainy summer (AGRICULTURAL RESEARCH BRAZILIAN CORPORATION – EMBRAPA 2021) lacks these studies, since that were not found complete and validated indexes capable to assess the susceptibility to flood in this region, mainly in the state of Mato Grosso do Sul (MS).

LITERATURE REVIEW

Floods can cause damage to the economy and the environment (DANO et al., 2019; COSTACHE et al., 2020), in the same way that negative impacts on public health, since drives the proliferation of disease vectors (SWEYA & WILKINSON, 2020). The aggravation of these disasters is associated with the modification of the surface runoff and infiltration processes of rainwater, influenced by topographic characteristics, climate change and alteration of land use and occupation (ALI et al., 2020). Therefore, it is necessary to evaluate several indicators in order to classify susceptible areas to floods (AVAND et al., 2021), which may change according to the geographic location of the study area (WANG et al., 2019).

According to Nasiri et al. (2016), vulnerability to flood is usually assessed by the methods: (i) vulnerability curve, (ii) disaster loss data, (iii) computer modelling and (iv) index-based. The latter is recommended by several authors, because aims to ensure a better representation of reality (BALICA et al., 2013; BIRKMANN et al., 2013; NASIRI et al., 2016; AZIZAT & OMAR, 2018). The use of indexes allows simplifying the conditions and behaviour of the system, summarizing complex and multidimensional issues, facilitating interpretations by users and reducing the number of indicators, generating a single value representative of reality, allowing comparisons in time and space (CETESB, 2019; PEREIRA et al., 2020).

However, Malczewski (2006) highlight that to analyse the susceptibility to urban hydrological disasters, it is important to recognize that different indicators have distinct importance for the composition of an index. For this reason, the use of multicriteria methodology plays an essential role in the formulation of indexes (BRITO & EVERS, 2016; PEREIRA et al., 2020), such as the AHP (SAATY, 1977), widely used in environmental studies for weighting of indicators (GALLEGO-AYALA & JUÍZO, 2012; NGUYEN et al., 2016; SAHOO et al., 2016; MACEDO et al., 2018; SWAIN et al., 2020; RAMKAR and YADAV, 2021; SINGH AND BHAKAR, 2021; ALBULESCU et al., 2022; IKIRRI et al., 2022; MUDASHIRU et al., 2022).

In recent years, the AHP method has been associated with the Geographic Information System (GIS) in order to improve decision-making processes (SAMANTA et al., 2016). Including, Dash and Sar (2020) concluded that the GIS-based multicriteria method can be applied anywhere in the world. GIS has become a powerful tool in environmental management, as it facilitates the faster and more efficient analysis of spatial and temporal patterns of environmental impacts (NEMEC & RAUDESSEP-HEARNE, 2012), especially in studies with multiple variables (MALCZEWSKI, 2006).

Table 1 summarizes the main indexes, as well as their respective indicators and bibliographic reference, in relation to susceptibility studies to hydrological disasters (floods) found in the international and national literature. It is possible to infer that there is no consensus on the number of indicators needed to generate an index and a flood risk map, since this depends on factors such as local availability of data, geographic location and climate of the study area and importance of the indicator (YAGOUB et al., 2020). Whereas, Yagoub et al. (2020) highlight that the inclusion of more indicators strengthens the study.

Table 1. Indexes related to susceptibility studies to hydrological disasters, as well as their respective indicators and references.

Index	Indicators	Reference
Flood hazard assessment	Precipitation, detention ponds, river system, depression area, elevation and ratio of impermeable area	Chen et al. (2015)
Flood hazard assessment	Slope, elevation, precipitation, drainage density, land use and soil type	Getahun and Gebre (2015)
Flood risk index	Slope, elevation, distance to river, and land use/cover	Samanta et al. (2016)
Flood vulnerable zones	Precipitation, drainage density, elevation, slope, hydrogeology, geology, soil type, geomorphology and land use/cover	Periyasamy et al. (2018)
Flood hazard index	Precipitation, elevation, distance from the drainage network, soil texture, geology and erosion	Azizat and Omar (2018)
Environmental fragility index	Rainfall, elevation, slope, geology, natural cover, road density, distance from roads and urban centers	Macedo et al. (2018)
Flood susceptibility	Slope, elevation, soil type and land use/occupation	Moura et al. (2019)
Flood-prone areas	Slope, elevation, land use, soil, geology, topographic wetness index, topographic position index and curve number	Yagoub et al. (2020)
Inundation risk index	Slope, altimetry, pedology, vegetation, education, age, income, subnormal clusters and demographic density	Pereira et al. (2020)
Flood hazard index	Flow accumulation, draining capability, elevation, groundwater depth, land use, runoff coefficient, slope and geology	Dash and Sar (2020)
Susceptibility to flooding	Slope, distance to rivers, soils and flood records	Silva et al. (2020)

Continuation of Table 1.

Index	Indicators	Reference
Flood hazard index	Slope, distance from the main river channel, land use/cover, soil, drainage density and rainfall	Ramkar & Yadav (2021)
Degree of danger	Slope, form factor, compactness coefficient, roundness index, drainage density, hydrographic density, sinuosity index	Bortolini et al. (2021)
Susceptibility to flooding	Slope, elevation, accumulated water flow, curve number, soil type, land use/occupation	Palácio et al. (2021)
Flood hazard index	Rainfall, slope, flow accumulation, drainage network density, distance from rivers, permeability and land use/cover	Ikirri et al. (2022)
Flood risk index	Slope, rainfall, population density, average road density per municipality, non-florested areas and social development index	Quesada-Roman (2022)

Morphometric indicators

The morphometric analyse process is the systematic description of the geometry and water courses of a watershed (STRAHLER, 1964), being important to understand the hydrological behaviour (AHER et al., 2014; MALIK et al., 2019), production of sediments (GAJBHIYE et al., 2014; MALIK et al., 2019), erosion (SAHU et al., 2018), surface runoff of rainwater (GAJBHIYE et al., 2015; SAHU et al., 2018), development and management of natural resources (MALIK et al., 2019; SANGMA & GURU, 2020) and studies of natural disasters (SANGMA & GURU, 2020). The knowledge about the physical characteristics (area, perimeter, shape, drainage network and relief) is a basic condition for managing a watershed (MORAES et al., 2018) and a prerequisite for hydrological studies (SANGMA & GURU, 2020).

Moreira and Silva (2010) point out that morphometric indicators make it feasible to propose appropriate measures for land use and occupation and reduction of impacts on the environment. Furthermore, Gajbhiye et al. (2015) state that in places with unavailable or severely limited hydrological data, the use of morphometric indicators can be useful in characterizing the hydrological response of a watershed.

According to Villela and Mattos (1975), the shape of a watershed plays an essential role in its hydrological behaviour. They identified that basins with a more circular shape tend to generate higher flood peaks in relation to elongated basins. If the circular basins have several drains with similar lengths, the flow path is shorter, generating faster and more concentrated responses to rainfall events. While the more elongated basins usually have a main river with several smaller tributaries, where the waters have to travel a longer path to the outlet. Consequently, they tend to present more distributed floods with lower peak flow (VILLELA & MATTOS, 1975).

Several studies have been carried out in order to identify the prioritization of watersheds based on morphometric analyses (AHER et al., 2014; SAHU et al., 2018; MALIK et al., 2019; SANGMA & GURU, 2020). This reinforces the importance of morphometric indicators (shape factor, circularity index, compactness coefficient, drainage density and slope) in hydrological studies of UHMs and watersheds (MORAES et al., 2018), which aim to contribute to the investigation and identification of sources of environmental degradation and vulnerability, to facilitate decision-making by public authorities in the face of possible environmental damage intensified by human action.

Nevertheless, analysing only morphometric indicators is not always enough to portray the hydrological reality of UHMs and watersheds (BRUM et al., 2020). Other indicators need to be considered to assess the hydrological quality of a UHM, especially with regard to infiltration and surface runoff processes of rainwater, such as those related to land use and occupation, rainwater infrastructure and environmental.

Land use and occupation indicators

The inappropriate use and management of urban space causes significant losses of soil, biodiversity and water, as well as floods responsible for damage to the water systems of watersheds (MORAES et al., 2018). Therefore, disciplining land use and occupation is essential to guarantee the quality and quantity of water resources in an UHM.

In this scenario, Araújo and Cândido (2015) developed the Urban Life Quality Index and considered the paving rate and demographic density for its composition. Flotemersch et al. (2016) created the Watershed Integrity Index and found that the construction of impermeable surfaces, loss of wetlands, canalization of streams, cutting of forests, population density, among other indicators classified as stressors, can modify the effectiveness of hydrological regulation (infiltration, percolation, evapotranspiration, recharge of groundwater and surface water) of watersheds, and consequently reduce their integrity. São Pedro et al. (2018) carried out an environmental diagnosis in a Brazilian UHM and concluded that the scarcity of green areas, high population occupation rate and inefficiency or lack of rainwater collection systems are directly related to the occurrence of floods.

The presence of vegetation cover or green space in urban areas provides multiple beneficial effects, such as air purification, noise reduction, shade, thermal comfort (SAMORA-ARVELA, 2017; OLIVEIRA et al., 2018), mitigation of heat waves, decrease in water pollution, increase in the recreational value of the UHM (DEMUZERE et al., 2014; YANG & ZHANG et al., 2021), erosion and flood control (MIGUEZ et al., 2016), in the same way that favouring the infiltration of water and groundwater recharge. On the other hand, high rates of impermeable areas drastically reduce these benefits, reducing the environmental quality of the site (OLIVEIRA et al., 2018). In view of this, Koop and Van Leeuwen (2015) concluded that the green space indicator is essential to improve the assessment of the sustainability of the integrated management of water resources in cities.

Indicators related to land use and occupation contribute to the understanding of anthropic effects on rivers and UHMs (CALLISTO et al., 2019). Garuana et al. (2020) used soil sealing and vegetation cover indicators to assess the environmental quality of ten UHMs. It is also worth highlighting Pellenz and Puchale (2018) in the construction of the Environmental Quality Index for the municipalities of Rio Grande do Sul and Macedo et al. (2018) in the development and validation of the Environmental Fragility Index for the neotropical savannah biome. All these authors considered indicators related to the land use and occupation, in particular the rate of vegetation cover of the evaluated micro-basins, as primordial for the composition of their indices.

In this context, the development of sustainable cities aims to reduce the environmental, social and economic negative impacts arising from urban expansion, being essential the integration between green spaces and urban areas. The disorderly growth of urban centers combined with the absence of green spaces causes both an environmental problem and the dissatisfaction of the residents themselves, since urban vegetation is an important condition for human health and well-being (KABISH et al., 2016) and maintenance of ecosystem systems (HANSEN & PAULEIT, 2014), such as runoff mitigation and erosion prevention (ARTMAN et al. (2017).

Yang and Zhang (2021) concluded that the integration between gray and green infrastructure is ideal for the development of a Sustainable Urban Drainage System, seen as a promising solution for flooding and urban water pollution (HUA et al., 2020). This conclusion emphasizes the importance of green spaces to the social system of cities, as they are capable of contributing to a reduction of up to 27% in runoff volume in a longterm hydrological scenario (YANG et al., 2020). It is important to note that gray infrastructure refers to storage tanks, for example, made of concrete and steel with collection, transport and drainage functions (TAVAKOL-DAVANI et al., 2015). While green refers to vegetated and porous structures to promote infiltration and detention of rainwater runoff in urban areas of watersheds (ECKART et al., 2017).

Rainwater infrastructure indicators

Urban drainage is a complex of measures that seeks to drain rainwater through hydraulic devices (culverts, pipes, channels and ditches, for example) to natural or artificial places, in order to reduce the harm caused by flood, protect the population and provide urban development in a harmonious, agile and sustainable way (TUCCI, 2012). Generally, the absence of this resource is due to the inefficiency of urban planning, causing structural, social and environmental problems in cities (MIGUEZ et al., 2016).

Urban drainage problems are related to improper occupation of the soil, generating high impermeability, combined with the lack of general planning and adequate maintenance of drainage systems (BRITO & SANTANA, 2020). They must be dealt with in an integrated way with other urban problems associated to water. It is essential to connect city planning with urban water use planning, dealt with under the UHM (CANHOLI, 2005).

Studies were carried out in order to identify deficiencies in urban drainage of rainwater in UHMs based on System Fragility Indicators (BRITO & SANTANA, 2020). Among these indicators used, it is possible to highlight the presence and/or absence of: rainwater storage device (COSTA & ROCHA, 2019; BRITO & SANTANA, 2020) and regular maintenance of the urban drainage system (SÃO PEDRO et. al, 2018; BRITO & SANTANA, 2020), as well as the inefficiency of: drainage on roads (BRITO & SANTANA, 2020) and collection devices.

Lakes and reservoirs are important for recreation, flood control, water supply, navigation, nutrient cycling and food production (VON SPERLING, 2012). However, according to Costa and Rocha (2019), the implementation of reservoirs for rainwater storage in isolation is not able to avoid flood problems in urban areas. This action must be combined with other structural and non-structural measures, such as vacating slopes, removing silting from rivers, preserving riparian forests, increasing permeable areas, environmental education of the population, inspection of works, among others. The city of Tokyo even adopted the G-CANS Project, considered one of the largest drainage systems in the world, which is composed of five underground reservoirs, which, coupled with various measures, managed to significantly reduce the damage caused by hydrological events.

With regard to the situation of urban streams, Flotemersch et al. (2016) state that as flow channeling is added to the watershed, its integrity decreases, since modifies the processes of infiltration, percolation, evapotranspiration and groundwater recharge in these areas. Therefore, evaluating the degree of canalization of watercourses, the rainwater storage capacity and the operational efficiency of the runoff of the roads are viable alternatives for hydrological studies in UHMs, which seek to minimize flood problems.

Environmental indicators

Finally, there are environmental indicators capable of significantly altering the natural characteristics of an UHM, either naturally or intensified by human actions. In this scenario, the characteristics of the soil and the precipitation regime are relevant for studies aimed at mitigating problems associated to hydrology in urban areas.

According to Freitas (2018), precipitation data are elements that drive the occurrence of floods and can be classified qualitatively as: much below normal, below normal, normal, above normal and much above normal. However, the range values of these classifications depend on the precipitation regime of the study area. The precipitation indicator is widely used in research related to the occurrence of floods (MORAES et al., 2012; OLIVEIRA et al., 2014; FRANCO & DAL SANTO, 2015) and control of sediment production (MACEDO et al., 2018) in UHMs.

Effective hydrological monitoring is essential for the planning and operation of various sectors of society, for example agriculture, water supply and flood control (SOARES et al., 2016). However, large areas require the presence of several precipitation in-situ gauges and often this is not possible, since diverse regions are difficult to access and do not have sufficient resources for such installations, monitoring and periodic maintenance. Furthermore, these instruments measure rain in a punctual way, not capturing its entire spatial distribution, especially in terrains with complex topography, being susceptible to failures in the detection of precipitation (PEREIRA et al., 2013), which are not always filled in accurately and immediate way. For this reason, the estimation of precipitation by satellite appears as a viable and promising alternative to help these problems.

Nevertheless, Tan and Santo (2018) affirm that a preliminary validation of precipitation estimates by remote sensing is essential to promote improvements in algorithms and in the development of satellite sensors. Since then, several validation studies of satellite precipitation estimates have been carried out in various parts of the world, such as Asia (HOSSEINI-MOGHARI & TANG, 2020), Europe (LOCKHOOF et al., 2014), North America (TIAN et al., 2010) and South America (REIS et al., 2017; MORAES & GONÇALVES, 2021; PEDREIRA JUNIOR et al., 2021; MORAES & GONÇALVES, 2023). In recent years, many of these validation studies have focused on TMPA (MELO et al. 2015, REIS et al., 2017; ABREU et al., 2020; MORAES & GONÇALVES, 2021), IMERG (GAONA et al., 2016; SAHLU et al., 2016; GADELHA et al., 2019; RODRIGUES et al., 2021) and GPCP (SALDANHA et al., 2015; SILVA et al., 2019) products in large regions or watersheds.

Tucci (2004) says that when precipitation is intense and the soil does not have the capacity to infiltrate, a large part of the volume flows into the drainage system, surpassing its natural flow capacity, in which the excess volume causes floods. Hence, the soil type in the urban place is also evaluated as an important indicator for the creation of hydrological disturbances that can cause floods, since it interferes with the water infiltration rate, as well as the speed and amount of surface runoff (FREITAS, 2018) and susceptibility to sediment production.

Zanella et al. (2009) state that rainfall impacts are not only related to climatic conditions, but also to infiltration and runoff processes, which are closely linked to the soil type, vegetation and relief. This way, along with other environmental indicators, a classification of soil types is necessary to identify the region most susceptible to hydrological problems in urban areas, since clayey, silty and sandy soils have different permeability capabilities and particle disaggregation, for example. Furthermore, sediment deposition is a major threat to water bodies. The rate of sediment production in drainages is influenced by complex interactions between rainfall, soil and substrate properties, lithology, slope and terrain characteristics, vegetation cover and land use and management (BUFFINGTON et al., 2004; FRAPPIER & ECKERT, 2007; GUERRA et al., 2017).

Anthropogenic actions in watersheds can reduce (construction of dams) or increase (construction of roads and canalization) the transport of sediments (FLOTEMERSCH et al., 2016). Therefore, assessing the susceptibility to production of sediments in UHMs is effective in urban hydrological studies, because high sediment rates are capable of causing problems, such as silting up of watercourses and obstruction of drainage systems, resulting in flood.

Problem statement

After reviewing the literature, it is possible to verify that there are several indicators that interfere in the infiltration and surface runoff processes of rainwater. Consequently, in order to assess the susceptibility to hydrological disasters in urban areas, it is necessary to develop an index considering the two processes mentioned and simultaneously contemplate indicators referring to morphometric, land use and occupation, rainwater infrastructure and environmental characteristics in the study area, as well as validating the it.

At the same time, it is essential to seek alternative methods for conducting spatially and temporally more representative hydrological studies, since there is a shortage of consistent and reliable precipitation data in much of Brazil, especially in the Midwest Region (GADELHA et al., 2019). In this context, precipitation estimates via remote sensing emerge as promising alternatives to complement surface measurements.

Nevertheless, according to Franchito et al. (2009), Thiemig et al. (2013) and Melo et al. (2015), random errors and uncertainties can occur in satellite precipitation estimates. Salles et al. (2019), Rodrigues et al. (2020a) and Araujo Palharini et al. (2021) evaluated the precipitation estimates from the TRMM and GPM satellites in different regions of Brazil and concluded, in general, that the accuracy of these estimates may be related to factors such as topography, type of precipitation and local climate of the study area. Thus, a performance evaluation is necessary to identify the potential and possible limitations of using satellites to estimate precipitation at the site of interest before application (FRANCHITO et al., 2009; TAN & SANTO, 2018; SILVA et al., 2019).

However, studies evaluating the accuracy of precipitation data obtained by remote sensing versus data measured in-situ are scarce in Brazil, especially in the Midwest Region and in the state of Mato Grosso do Sul (MS) (OLIVEIRA JÚNIOR et al., 2021). In fact, no studies were identified regarding the comparison of different databases of precipitation estimates by satellites exclusively in the state of MS, whose capital has approximately one million people (Brazilian Institute of Geography and Statistics - IBGE 2021) and has been suffering from extreme hydrological disasters, such as floods in your urban area. Therefore, it is necessary to evaluate the performance of precipitation estimates in this region, in order to identify the best precipitation products via remote sensing at different time scales for future hydrological work.

GENERAL OBJECTIVE

- Develop the Urban Hydrological Disasters Susceptibility Index (UHDSI) from indicators pertinent to different spheres (morphometry, land use and occupation, rainwater infrastructure and environmental), taking into account both infiltration and surface runoff of rainwater. As well as carrying out the application of the index developed in UHMs of a municipality located in the Midwest Region of Brazil and its validation from historical records of floods available in local information media.

ESPECIFIC OBJECTIVES

- Statistically validate the TRMM precipitation estimates in relation to the data observed in the Conventional Meteorological Stations in the geographic regions of Brazil;
- Compare the performance of precipitation estimates by GPM, TRMM and GPCP satellites in relation to data observed by in-situ gauges, on daily, monthly and seasonal time scales in the capital of MS.

THESIS ORGANIZATION

This Thesis is organized into three chapters. First, a general introduction, literature review and general and specific objectives of this research are described. Chapter 1 provides a study in which the urban hydrological disaster susceptibility index was developed, applied and validated. Chapter 2 shows a study that aimed to evaluate and validate TRMM precipitation estimates in relation to precipitation data observed on the surface in the geographic regions of Brazil. Chapter 3 presents a study concerning the comparison of the performance of precipitation data estimated via remote sensing (TRMM, GPM and GPCP) in relation to precipitation data observed on the surface in a municipality in the Midwest Region of Brazil. Finally, the final considerations and references of this research are described and Annex I is made available regarding publications in Scientific Journals and Conferences developed throughout the Doctorate period.

CHAPTER 1: DEVELOPMENT, APPLICATION AND VALIDATION OF THE URBAN HYDROLOGICAL DISASTERS SUSCEPTIBILITY INDEX

Abstract

Inadequate planning of cities has modified the infiltration and surface runoff processes of rainwater in Urban Hydrographic Micro-basins (UHMs). The objective of the present work was to develop the Urban Hydrological Disasters Susceptibility Index (UHDSI) from indicators pertinent to different spheres and apply it in UHMs of a municipality in the Midwest Region of Brazil. Historical records of floods available on information media were used to validate the UHDSI. The indicators selected for the composition of the UHDSI were average slope (Sa), coefficient of compactness (Kc), drainage density (Dd), demographic density (Ddem), degree of surface permeability (DSP), susceptibility to production of sediment (SPS), daily precipitation (Pd), degree of canalization of watercourses (DCW), condition of storm drains (CSD) and rainwater retention devices (RRD). The methodology adopted was Analytical Hierarchical Process (AHP) linked to the Geographic Information System (GIS). The Pd and DSP indicators were the most significant for the composition of the index. The results of the UHDSI and historical records applied in each UHM obtained a strong correlation (r > 0.80), evidencing the reliability and validation of the index. AHP and GIS integration offers a simple alternative to dealing with complex problems involving contrasting indicators over a large area. The UHDSI is capable of assisting in the formulation of appropriate political measures, guidelines and legal norms for land use and occupation, as it indicates the UHMs that require attention and mitigating actions from the public power for a sustainable socioeconomic development.

Keywords: Flood. GIS. Multicriteria method. AHP. Urban Hydrographic Micro-basin. Indicator.

1.1. Introduction

Growing urbanization has modified surface runoff and infiltration processes of rainwater in Urban Hydrographic Micro-basins (UHMs). The changes made to the landscape for the implantation and expansion of cities directly affect the natural hydrological dynamics, modifying the path through which the water circulates. Alteration in land use and city inadequate planning contribute significantly to increasing susceptibility to hydrological disasters, such as floods. Its effects are severely felt in developing countries (Dash and Sar 2020), threatening human lives and economic conditions (Duan et al. 2016; Luino et al. 2016).

Bui et al. (2019) concluded that approximately 200 million people are affected annually by floods, while global economic losses are estimated at around 60 billion USD each year because to hydrological disasters (Janizadeh et al. 2019). Specifically in Brazil, according to the National Agency for Water and Basic Sanitation (ANA 2021), 49.4% of Brazilian municipalities declared a situation of emergency or public calamity due to flood and flash flood at least once between 2003 and 2020.

Hence, it is essential to identify urban areas susceptible to disasters arising from precipitation and aggravated by human actions, in order to assist in the formulation of appropriate policy measures, guidelines and legal norms for spatial planning (Swain et al. 2020; Albulescu et al. 2022). In addition to contributing to the process of environmental awareness and education of the population and indicating fragile areas that require attention and mitigation actions from the public authorities. This mapping is also in line with the Sustainable Development Goals, as it is capable of making cities and human settlements inclusive, safe, resilient and sustainable (Institute of Applied Economic Research - IPEA 2021).

In recent years, there has been a noticeable increase in the number of studies related to floods (Samanta et al. 2016; Swain et al. 2020; Avand et al. 2021; Palácio et al. 2021; Ramkar and Yadav 2021; Costache et al. 2022; Mudashiru et al. 2022), mainly from indicators and indexes (Chen et al. 2011; Koop and Van Leeuwuen 2015; Kazakis et al. 2015; Mititelu-Ionus 2017; Dash and Sar 2020; Ikirri et al. 2022). However, Araujo and Dias (2021) highlight that there is still a need for environmental research that takes into account qualitative and quantitative aspects in Brazil, in order to direct preventive and minimizing actions to natural disasters.

Indicators are powerful tools to support effective decision-making, raise awareness, provide meaningful information and track progress towards defined goals (Sangwan et al. 2018). They can function at different levels of assessment - global, national or local (Silva et al. 2016). While index it is the final added value of a calculation procedure in which indicators are even used in its composition (Singh and Bhakar 2021). According to the Environmental Company of the State of São Paulo (CETESB 2019), its main advantages are the ease of communication with the lay public, the higher status than isolated indicators and the fact that it represents an average of several indicators in a single number, combining different measurement units into a single unit.

Pereira et al. (2020) and Albulescu et al. (2022) state that the multicriteria methodology makes an important role in the formulation of indexes and aggregation of contrasting indicators. In this context, the Analysis Hierarchical of Process (AHP), developed by Saaty (1977), stands out for carrying out complex environmental studies (Samanta et al. 2016; Swain et al. 2020; Msaddek et al. 2022), since which seeks to discover and correct logical inconsistencies (Goepel 2018), minimizing failures and assisting in the decision-making process. In addition, it includes quantitative and qualitative resources (Pereira et al. 2020; Singh and Bhakar 2021), combining information from several indicators to form a single evaluation index, being easy to use and highly flexible (Albulescu et al. 2022).

Concomitantly, the AHP method is widely used with geotechnologies to improve decision-making processes (Samanta et al. 2016). The use of geotechnologies, such as Remote Sensing (RS) and Geographic Information System (GIS), facilitate obtaining detailed information with low financial cost and timely in large areas (Msaddek et al. 2022). SR enables the acquisition of information without the need for direct contact with the study area. GIS allows the creation of a georeferenced database, spatial and temporal analyses, and the production of maps that help in the elaboration of management and conservation strategies, as well as the prioritization of the use of financial resources in an efficient and rational way (Bortolini et al. al. 2021). Including, numerous works have been carried out using the combination of AHP and GIS for flood studies (Stefanidis and Stathis 2013; Ouma and Tateishi 2014; Kazakis et al. 2015; Memon et al. 2020; Swain et al. 2020; Ramkar e Yadav 2021; Ikirri et al. 2022; Mudashiru et al. 2022), being considered an effective aggregation by Luu and Von Meding (2018); Dash and Sar (2020), Pereira et al. (2020), Silva et al. (2020) and Ramkar and Yadav (2021).

Although, according to Brito and Evers (2016), most works involving the generation of hydrological index ignore the validation stage, being subject to uncertainties. This way, Yagoub et al. (2020) recommend using the locations of hydrological disasters available in historical records of local information media (Escobar et al. 2016), to validate maps of susceptible areas to flood generated through spatialized index, as performed by Azizat and Omar (2018), Periyasamy et al. (2018) and Ikirri et al. (2022). Luino et al. (2016) emphasize that correct territorial planning for the prevention and mitigation of hydrological risk cannot ignore the wealth of information that can be obtained from historical research in newspapers. In addition, most available hydrological indexes do not include indicators pertinent to different spheres simultaneously, such as morphometry, environmental, urban infrastructure, precipitation, among others, limiting the analysis of susceptibility to hydrological disasters.

With this in mind, it is necessary to propose complete and validated tools capable of measuring the susceptibility of urban areas to hydrological disasters, especially in developing countries and regions with a high rate of urbanization. Even so, unfortunately, South America is one of the continents that least presents works with this objective (Diaconu et al. 2021). The Midwest Region of Brazil, located in the largest floodplain in the world - Pantanal - characterized by a semi-humid tropical climate with a hot and rainy summer (Agricultural Research Brazilian Corporation – EMBRAPA 2021) lacks these studies, since that were not found complete and validated indexes capable to assess the susceptibility to flood in this region, mainly in the state of Mato Grosso do Sul (MS).

Therefore, the objective of this work was to develop the Urban Hydrological Disasters Susceptibility Index (UHDSI) from indicators pertinent to different spheres (environmental, morphometry, urban infrastructure and precipitation), taking into account both infiltration and surface runoff of rainwater. As well as carrying out the application of the index developed in UHMs of a municipality located in the Midwest Region of Brazil and its validation from historical records of floods available in local information media.

1.2. Methodology

The study area was the municipality of Campo Grande, capital of the state of MS, Midwest Region of Brazil. It is located in the surroundings of the Paraná and Paraguay Watersheds, with an altitude ranging between 500 and 675 meters according to the Municipal Agency for the Environment and Urban Planning (PLANURB 2020). Its relief is gently undulating, providing the formation of an extensive urban core, characterized by a widespread occupation interspersed with fragments of pasture fields and *Cerrados*[1] (Weingartner 2008).

Campo Grande has a total area of 8,082.97 km², of which 360 km² are urban areas, an estimated population of 916,001 persons, a demographic density of 113 persons/km² and an urbanization rate of 98.66% (Brazilian Institute of Geography and Statistics - IBGE 2021; PLANURB 2020). According to the Koppen classification, the climate is in the transition range between the humid mesothermal subtype (Cfa) without drought or a little drought and the humid tropical subtype (Aw), with a rainy season in summer and a dry season in winter (PLANURB 2020). In addition, the municipality is characterized by the presence of *Cerrado* vegetation, predominantly dark red latosol soil, thirty-three watercourses with urban springs and twelve UHMs (PLANURB 2020), which were evaluated in the present study. Figure 1 shows the location, hydrography and UHMs of Campo Grande – MS.

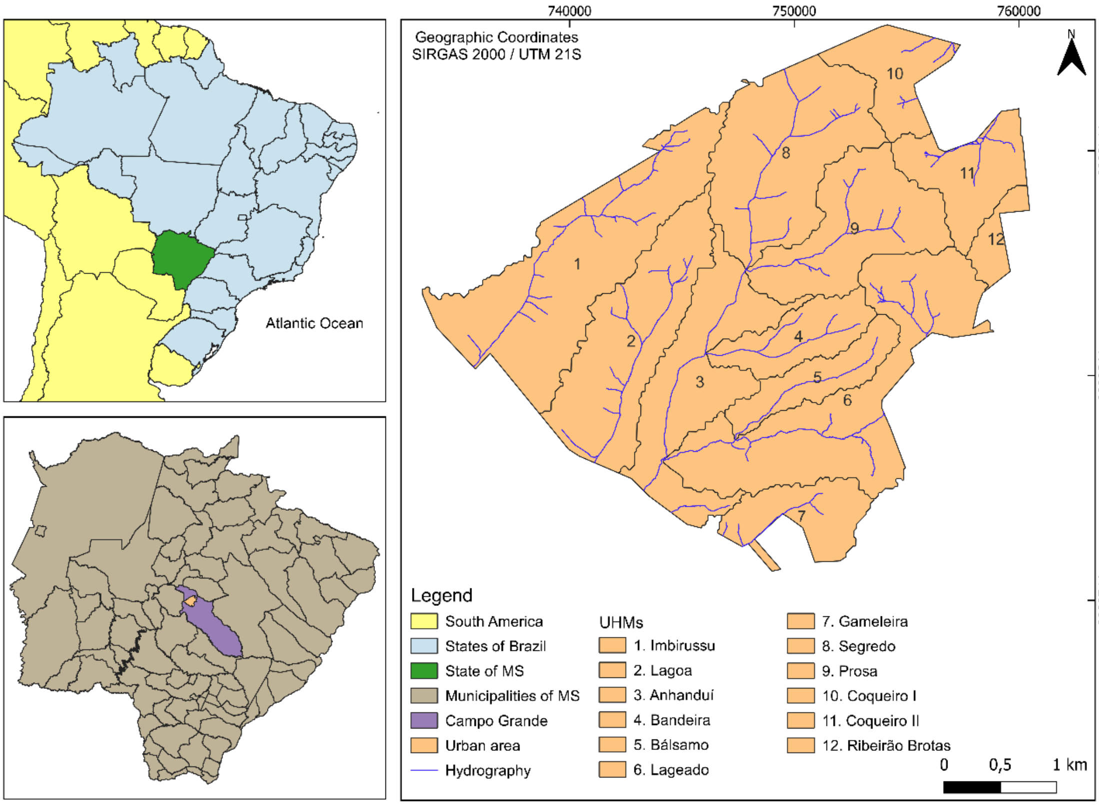

Fig. 1 Location of the municipality, hydrography and UHMs of Campo Grande – MS, Brazil. Source: Authors

[1] Cerrado is a Brazilian biome, characterized especially by the biome (in the international sense) savannah, but also by seasonal forest and countryside.

The subdivision of a higher-order hydrographic basin into hydrographic micro-basins facilitates the identification and control of environmental problems and the establishment of priorities for the attenuation or mitigation of these problems. Moreover, it allows expanding the detailing of the data in the region of interest (Pinto et al. 2016). Hence, the urban area of Campo Grande was divided into twelve UHMs based on the elevation digital model image (SRTM3-S21-W55-v2) of the study area available on the United States Geological Survey website (USGS 2022) and with support of Quantum Geographic Information System software (QGIS 2022).

The development of UHDSI consisted of seven stages: i. selection, ii. standardization, iii. weighting, iv. consistency (of the indicators), v. calculation, v. application and vii. validation (of the index) in the UHMs of Campo Grande. Methodology and steps similar to those used by Gallego Ayala and Juízo (2012), Macedo et al. (2018), Swain et al. (2020), Singh and Bhakar (2021), Mudashiru et al. (2022) and Ikirri et al. (2022) in the development of its hydrological indexes and maps. Figure 2 displays the flowchart referring to the methodology adopted in this work.

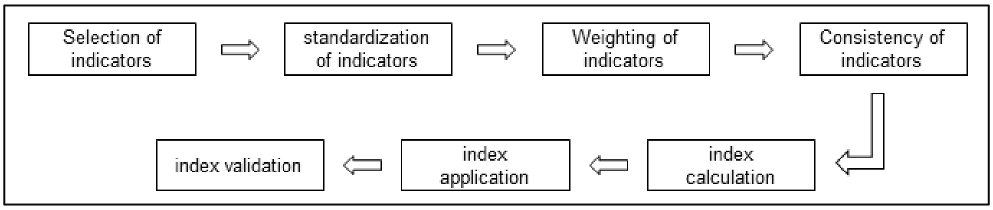

Fig. 2 Flowchart of the steps used to develop the UHDSI

1.2.1. Selection of indicators

The selection of indicators for the composition of the UHDSI was carried out through a literature review, as performed by Hooper (2010), Gallego-Ayala and Juízo (2012), Swain et al. (2020), Ramkar and Yadav (2021), Singh and Bhakar (2021) and Mudashiru et al. (2022) in the elaboration of their hydrological indexes. Indicators with potential interference in the infiltration and surface runoff processes of rainwater in UHMs, accessible, measurable and with reference values were prioritized (Singh and Bhakar 2021). In other words, indicators that are easy to measure, available in municipal, state or national databases and preferably quantitative.

After reviewing the literature, it was possible to verify that there is no consensus on the number of indicators necessary to generate an index and map of susceptibility to hydrological disasters, since this depends on factors such as local availability of data, geographic location and climate of the study area and importance of the indicator (Yagoub et al. 2020). However, Yagoub et al. (2020) highlight that the inclusion of more indicators strengthens the study.

Thus, in order to assess susceptibility to hydrological disasters in urban areas, it is necessary to consider simultaneously indicators related to morphometric, environmental, precipitation and urban infrastructure characteristics in the study area. Therefore, the indicators selected for the composition of the UHDSI were average slope (Sa), coefficient of compactness (Kc), drainage density (Dd), demographic density (Ddem), degree of surface permeability (DSP), susceptibility to production of sediments (SPS), daily precipitation (Pd), degree of canalization of watercourses (DCW), condition of storm drains (CSD) and rainwater retention devices (RRD).

1.2.1.1. Average Slope

According to Diaconu et al. (2021) and Palacio et al. (2021), slope influences flood phenomena significantly. Micro-basins with higher slopes tend to have faster surface runoff (Ramkar and Yadav 2021), while areas with lower slopes, in other words, flatter, there is a substantial decrease in water movement, increasing the probability of accumulation of rainwater (Asare- Kyei et al. 2015). Thus, regions located close to valleys are more prone to flood (Cabrera and Lee 2020). On the other hand, it is important to highlight that in relation to the infiltration dimension, these classifications reverse, since low slopes can further the infiltration and percolation of water in the soil, contributing to the minimization of hydrological disasters, even if remotely when compared to the surface runoff. The Sa of each UHM was generated in the QGIS (2022) software from the SRTM3-S21-W55-v2 image with 3-arc spatial resolution referring to the elevation digital model available in the USGS (2022).

1.2.1.2. Compactness coefficient

The compactness coefficient (Kc) is the ratio between the perimeter and the area of the watershed (Moraes et al. 2018), according to Equation 1. It is a dimensionless number that varies with the shape of the watershed, regardless of its size. This way, the more irregular it is, the greater the Kc will be, that is, the closer to unit one, the more circular and subject to flood will be the basin (Villela and Mattos 1975). Kc is always greater than or equal to 1, and is also known as the Gravelius index (Malik et al. 2019).

$$\mathrm{Kc} = \frac{0{,}28\ .\ \mathrm{P}}{\sqrt{\mathrm{A}}} \qquad (1)$$

Where Kc = compactness coefficient, P = perimeter of watershed (km) e A = area of watershed (km²).

1.2.1.3. Drainage density

The drainage density (Dd) is the ratio between the sum of the length of watercourses of all orders and the total area of the watershed (Horton 1932), according to Equation 2. Dd indicates the degree of efficiency of the basin's drainage (Moraes et al. 2018) and mainly influences surface runoff, since the more channels present in the basin, the faster the water from precipitation will reach the outlet (Souissi et al. 2020). The Dd is a significant indicator in the prioritization analysis of watersheds. It can vary from 0.5 km/km² in poorly drained basins to 3.5 km/km² or more in well drained basins (Villela and Mattos 1975). The Dd of each UHM was generate in the QGIS (2022) software from the same image used for delimitation of the UHMs and Sa.

$$\mathrm{Dd} = \frac{\sum \mathrm{Lt}}{\mathrm{A}} \qquad (2)$$

Where Dd = drainage density (km/km²), Lt = sum of the length of watercourses of all orders pertinent watershed (km) e A = area of watershed (km²).

1.2.1.4. Demographic density

The Brazilian urbanization process has occurred intensely and rapidly in recent years (Moraes et al. 2018). Quantitative transformations resulted in profound qualitative changes, affecting the quality of urban space due to the lack of infrastructure. According to Acioly and Davidson (1998) and Mudashiru et al. (2022), high demographic density (Ddem) may offer greater risks of environmental degradation, pollution and overloading of infrastructure. Thus, challenges arise related to public policies, management and organization of the territory. In this context, Ramkar and Yadav (2021) and Mudashiru et al. (2022) say that it is essential to analyze the Ddem in studies of susceptibility to hydrological disasters in urban areas. Most of the time, this indicator is directly related to the impermeability of the surface and according to Ramkar and Yadav (2021), it is able to assess the losses and social damage suffered by the community due to floods. The Ddem is the ratio between the number of persons and the area of the respective UHM, according to Equation 3.

$$\text{Ddem} = \frac{\text{Nper}}{\text{A}} \tag{3}$$

Where Ddem = demographic density (persons/hectares), Nper = number of persons in UHM e A = area of UHM (hectares).

1.2.1.5. Degree of surface permeability

The degree of soil sealing is a successful indicator and widely applied for urban planning, since quantitatively describes the proportion of fenced urban surface built or not in UHMs (Lakes and Kim 2012). According to Rueda (2008), the urban planning of a city directly affects the susceptibility to hydrological disasters, because the soil sealing reduces infiltration and increases surface runoff of rainwater. Hence, it is necessary to evaluate the degree of surface permeability (DSP) of the study area, in order to minimize possible environmental problems.

In this scenario, Rueda (2008) developed the Soil Biotic Index (SBI), which calculates the degree of naturalness of the soil, based on the relationship between the functionally significant areas in the natural cycle and the total area of the analysed site, that is, permeable, semipermeable and impermeable areas. This index was even use in urban studies in Germany (Rueda 2008), Spain (Rueda 2010) and Brazil (Moreira 2020).

Therefore, the DSP indicator for UHMs was propose in this work, according to Equation 4 and methodology by Rueda (2010). The permeable soil class refers to green areas and natural water bodies, with an impact factor of 1.0. The semipermeable class is one that, without being in its natural state, still allows water to infiltrate, such as vacant lots, and has an impact factor of 0.5. Finally, the impermeable class is divided into constructed impermeable soil (impact factor 0.0) and non-constructed impermeable soil (impact factor 0.3), since the latter allows impermeable pavement to be replaced by permeable pavement.

$$\text{DSP} = \frac{\sum(\text{Fi.Ai})}{\text{At}} \tag{4}$$

Where DSP = degree of surface permeability, Fi = impact factor of class i; Ai = class i area (km²) e At = total area (km²).

Regarding surface permeability, Rueda (2010) proposes 30 and 35% as a minimum and desirable objective, respectively, of vegetation cover in a city, aiming to minimize environmental problems, such as flood. Like Oke (1973), who highlighted the need for at least 30% of vegetation cover in a given space to maintain a thermal balance in urban areas. While cities with green areas of less than 5% of the total have characteristics similar to those of a desert. To identify the area of each surface class (permeable, semipermeable and impermeable built or not) in the UHMs, were used CBERS - 4A satellite images with spatial resolution of 2 meters (National Institute for Space Research - INPE 2022) and semi-supervised classification was applied in the QGIS (2022) software through the *dzetsaka* plugin. The classification and standardization of the intervals of the DSP results was performed using the equal count (quartile) mode in QGIS (2022) itself.

1.2.1.6. Susceptibility to production of sediments

Sediment deposition is a threat to water bodies and is influenced by complex interactions between rainfall regime, soil properties, lithology, slope, vegetation cover and land use and management (Frappier and Eckert 2007; Guerra et al. 2017). Evaluating the susceptibility to production of sediments (SPS) in UHMs of a simple, objective and inexpensive way is fundamental in urban hydrological studies, since high sedimentation rates are capable of causing problems, such as silting up of watercourses and obstruction of drainage systems, resulting in environmental, social and economic problems for society and public administration.

In this study, the SPS indicator was proposed, constructed from relevant variables regarding the susceptibility to erosion and, consequently, siltation of water bodies in UHMs, according to studies by Luz et al. (2015), Carvalho (2017), Queiroz (2017), Caldas et al. (2019), Agra and Andrade (2020) and Aires et al. (2022). The variables selected for the composition of the SPS were soil type, average slope, vegetation cover and unpaved streets in the UHMs.

Based on a bibliographic survey and analysis of the characteristics of each variable in relation to susceptibility to erosion processes (detachment and transport of sediments) and siltation, values from 1 to 5 were suggested for the ranges of results for each variable, as shown in Tables 1 and 2, with value 1 (less susceptibility to production of sediments) and value 5 (greater susceptibility to production of sediments). Subsequently, the AHP method was applied to establish the weights of the variables in the composition of the SPS indicator, according to Equation 5. Table 3 defines the SPS classes suggested in this work.

Table 1 Proposition of classes of susceptibility to detachment and transport of sediments based on soil type

Soil type	Value	Reference
Haplic Gleisol and Organosol	1	Carolino de Sá (2004), Luz et al. (2015) and Agra and Andrade (2021)
Dystrophic Red Latosol, Dystrophic Yellow Latosol, Dystrophic Yellow-Red Latosol and Dystrophic Red Nitosol	2	Queiroz (2017) and Agra and Andrade (2021)
Plintosol, Luvisol and Spodosol	3	Luz et al. (2015) and Aires et al. (2022)
Quartzite Neosol and Cambisol	4	Queiroz (2017) and Agra and Andrade (2021)
Litholic Neosol and Regolitic Neosol	5	Carolino de Sá (2004), Queiroz (2017), Luz et al. (2015) and Aires et al. (2022)

Table 2 Proposition of classes of susceptibility to the detachment and transport of sediments according to the average slope and percentages of vegetation cover and unpaved streets in UHMs

Indicator / Value	1	2	3	4	5
Average slope (%)	< 1,5	1,5 a 3,0	3,1 a 4,5	4,6 a 6,0	> 6,0
Vegetation cover (%)	> 35	25 a 30	15 a 24	05 a 14	< 05
Unpaved streets (%)	< 10	10 a 20	21 a 30	31 a 40	> 40

Fonte: Adapted slope of Luz et al. (2015); Saraiva et al. (2016) and Pires and Carmo Júnior (2018). Adapted vegetation cover of Oke (1973) and Rueda (2010).

$$\mathrm{SPS} = 0{,}45.(\mathrm{VST}) + 0{,}24.(\mathrm{VSa}) + 0{,}16.(\mathrm{VVC}) + 0{,}15.(\mathrm{VUS}) \qquad (5)$$

SPS = susceptibility to production of sediments

VST = value referring to the soil type in the UHM

VSa = value referring to the average slope in the UHM

VVC = value referring to the vegetation cover in the UHM

VUS = value referring to unpaved streets in the UHM

Table 3 classes of susceptibility to production of sediments

SPS	Results
Very low	1,00 a 1,74
Low	1,75 a 2,49
Moderate	2,50 a 3,24
High	3,25 a 4,24
Very high	4,25 a 5,00

1.2.1.7. Daily precipitation

Daily precipitation (Pd) is one of the most relevant indicators for environmental and climate studies, by virtue of numerous impacts it can have on society when it occurs in excess or scarce. Extreme precipitation events significantly alter the usual characteristics of a given region, causing inconvenience to the population, whether in large urban centres, with floods, as well as prolonged droughts in the countryside (Nóbrega et al. 2015). Burgess et al. (2015) emphasize that the analysis of extreme precipitation is relevant for infrastructure and flood control projects, especially currently with climate change.

In this context, understanding the behaviour of precipitation is essential for urban planning. In this study, the Pd indicator was proposed in order to establish classes of normal and extreme rainfall quantities for the UHMs through the statistical technique of quantiles (Xavier and Xavier 1987). This technique was developed by Pinkayan (1966) and widely used in studies that aim to classify and monitor precipitation in different parts of the Brazilian territory, such as in the states of Paraíba (Almeida et al. 2013), Pernambuco (Nóbrega et al. 2015), Bahia (Santos et al. 2016; Lopes et al. 2019) and Tocantins (Lopes et al. 2019).

Table 4 shows the intervals of the quantile orders used: 0.35, 0.65, 0.85 and 0.95 (Pinkayan 1966; Almeida et al. 2013; Santos et al. 2016; Lopes et al. 2019), as well as the respective classifications of daily precipitation levels, since according to Freitas (2018), precipitation data can be qualitatively classified as: far below normal, below normal, normal, above normal and far above normal. These classes allow the simple and objective assessment of anomalous levels of precipitation, such as dry or rainy extremely episodes, as well as the normal pattern (Santos et al. 2016).

Table 4 Classification level intervals according to the quantile thresholds used

Pd	Quantile threshold	Value
Far below normal	$Pd \leq P_{0,35}$	5
Below normal	$P_{0,35} < Pd \leq P_{0,65}$	4
Normal	$P_{0,60} < Pd \leq P_{0,85}$	3
Above normal	$P_{0,85} < Pd \leq P_{0,95}$	2
Far above normal	$Pd > P_{0,95}$	1

Precipitation data for the study area were obtained from eleven meteorological stations used by the city hall and one belonging to INMET (2023) from October 1, 2020 to November 30, 2022. Data were organized daily and from according to the location of the stations and hydrological disasters found in the historical record of information media used to validate the UHDSI, the lowest precipitation that resulted in flood was identified in each UHM of Campo Grande - MS. After, values 1, 2, 3, 4 and 5 were assigned to the quantile thresholds, with 5 being the lowest precipitation that caused these disasters and 1 being the highest. That is, the UHM rated 5 (worst case scenario) means that it is susceptible to hydrological disasters even with much less than normal rainfall, while the UHM rated 1 (best case scenario) only happens to hydrological disasters with far above normal rainfall, or this is a relatively predictable scenario.

1.2.1.8. Degree of canalization of watercourses

Flotemersch et al. (2016) affirm that as flow channelling is added to the watershed, its integrity decreases, due to modifies the infiltration, percolation, evapotranspiration and groundwater recharge processes in these areas. The same authors claim that this action negatively interferes with the hydrological and chemical regulation of water and sediments in the watershed. Channelling watercourses has the direct consequence of reducing the catchment area of watersheds (Palmer et al. 2005) and the infiltration of water into the soil, favouring floods.

Freitas (2018) highlights out that canalization provides an increase in flow velocity and transfers hydrological problems downstream of the drainage, which require actions aimed at favouring water infiltration in order to be minimized. Therefore, the indicator degree of canalization of watercourses (DCW) was proposed, in which as the percentage of channelled watercourses in the UHMs increases, the value referring to this indicator increases, that is, it worsens its respective performance for quality hydrology of the respective study area in relation to the infiltration of rainwater into the soil. On the other hand, it increases the capacity of the micro-basin to drain rainwater to other areas. The DCW was calculated from the ratio between the length of channelled watercourses and the total length watercourses of the UHMs, according to Equation 6.

$$\mathrm{DCW} = \frac{\mathrm{LCW}}{\mathrm{TLW}} \,.100 \qquad (6)$$

Where DCW = degree of canalization of watercourses (%), LCW = length of channelled watercourses in the UHM (km) e TLW = total length watercourses (channelled and non-channelled) in the UHM (km).

1.2.1.9. Condition of storm drains

The drainage system should be understood as the set of existing infrastructure in a city to capture, transport and finally release surface water (Pereira et al. 2021). When this system is well designed and properly maintained, the risk of flood is considerably reduced, avoiding economic, social and environmental damage. In short, the drainage network prevents the accumulation of water in the lower areas through the rapid drainage of rainwater, aiming at the safety and health of the population.

In this scenario, it is important to assess if the maintenance of storm drains is adequate in all UHMs, since they are devices responsible for the initial and direct capture of rainwater from streets and sidewalks, as well as transport to underground galleries. Therefore, meeting the minimum condition for cleaning and maintenance of storm drains per region of study is paramount for preventing water accumulation in the UHMs, based on the assumption that the appropriate dimensioning, location and quantity of both these devices, as well as the others belonging to the subgroups of the drainage system.

In this way, the indicator of condition of storm drains (CSD) was proposed, in which based in-situ visit to all UHMs, it was possible to classify the CSD into good, regular and poor. The good condition means that most of the storm drains in the evaluated area are clean and without accumulation of sediments, branches and general solid residues, that is, with adequate maintenance. The regular condition symbolizes that approximately half of the analysed storm drains are not adequate maintained. On the other hand, the poor condition characterizes that most of the storm drains are obstructed by sediments, branches or general solid residues, that is, without adequate maintenance.

1.2.1.10. Rainwater retention devices

The presence and adequate maintenance of natural and/or artificial rainwater retention devices (lakes, reservoirs, dams, pools, etc.) in urban environments is essential for recreation, water supply, navigation, nutrient cycling, food production and flood control, mainly (Von Sperling 2012). This way, the indicator of rainwater retention devices (RRD) for UHM was proposed, based on the relationship between presence/absence and adequate/inadequate maintenance of these devices.

RRD was classified as well maintained, poorly maintained and absent. The well maintained class means that there is RRD in the UHM and with adequate maintenance, that is, without silting up, without accumulation of solid waste and does not cause danger to the population. The poorly maintained class symbolizes that there is RRD in the UHM, but without adequate maintenance. Finally, the absent class characterizes that there is no RRD in the UHM.

1.2.2. Standardization of indicators

The ranges of results for each indicator were standardized in order to remove the influence of different measurement units (Macedo et al. 2018). The results of the indicators were divided into 5 ordinal classes, called values 1, 2, 3, 4 and 5, with 1 being less susceptible and 5 being more susceptible to the occurrence of hydrological disasters (floods), in view of the processes of infiltration and surface runoff of rainwater in the UHMs. Tables 5 and 6 show the standardized indicators for the composition of the UHDSI in relation to infiltration and surface runoff of rainwater, respectively.

Table 5 Standardized indicators for the composition of the UHDSI in relation to rainwater infiltration

Indicator	Unit	Result	Value
Average slope (Sa)	%	0,00 - 1,00	1
		1,01 - 2,00	2
		2,01 - 3,00	3
		3,01 - 4,00	4
		> 4,00	5
Compactness coefficient (Kc)	-	> 1,80	1
		1,61 - 1,80	2
		1,41 - 1,60	3
		1,21 - 1,40	4
		1,00 - 1,20	5
Drainage density (Dd)	km/km²	0,00 - 0,49	1
		0,50 - 1,49	2
		1,50 - 2,49	3
		2,50 - 3,49	4
		> 3,49	5
Demographic density (Ddem)	per/ha	07 - 14	1
		15 - 19	2
		20 - 23	3
		24 - 25	4
		> 25	5
Degree of surface permeability (DSP)	%	49,9 – 57,2	1
		41,8 – 49,8	2
		38,9 – 41,7	3
		36,9 – 38,8	4
		31,7 – 36,8	5
Susceptibility to production of sediments (SPS)	-	1,00 - 1,74	1
		1,75 - 2,49	2
		2,50 - 3,24	3
		3,25 - 4,24	4
		4,25 - 5,00	5
Daily precipitation (Pd)	mm/day	> 45,56	1
		25,64 - 45,56	2
		13,13 - 25,63	3
		5,15 - 13,12	4
		0,00 - 5,14	5
Degree of canalization of watercourses (DCW)	%	00 - 10	1
		11 - 25	2
		26 - 40	3
		41 - 50	4
		> 50	5
Condition of storm drains (CSD)	-	Good	1
		Regular	3
		Poor	5
Rainwater retention devices (RRD)	-	Well maintained	1
		Poorly maintained	3
		Absent	5

Table 6 Standardized indicators for the composition of the UHDSI in relation to rainwater surface runoff

Indicator	Unit	Result	Value
Average slope (Sa)	%	> 4,00	1
		3,01 - 4,00	2
		2,01 - 3,00	3
		1,01 - 2,00	4
		0,00 - 1,00	5
Compactness coefficient (Kc)	-	> 1,80	1
		1,61 - 1,80	2
		1,41 - 1,60	3
		1,21 - 1,40	4
		1,00 - 1,20	5
Drainage density (Dd)	km/km²	> 3,49	1
		2,50 - 3,49	2
		1,50 - 2,49	3
		0,50 - 1,49	4
		0,00 - 0,49	5
Demographic density (Ddem)	per/ha	07 - 14	1
		15 - 19	2
		20 - 23	3
		24 - 25	4
		> 25	5
Degree of surface permeability (DSP)	%	31,7 – 36,8	1
		36,9 – 38,8	2
		38,9 – 41,7	3
		41,8 – 49,8	4
		49,9 – 57,2	5
Susceptibility to production of sediments (SPS)	-	1,00 - 1,74	1
		1,75 - 2,49	2
		2,50 - 3,24	3
		3,25 - 4,24	4
		4,25 - 5,00	5
Daily precipitation (Pd)	mm/day	> 45,56	1
		25,64 - 45,56	2
		13,13 - 25,63	3
		5,15 - 13,12	4
		0,00 - 5,14	5
Degree of canalization of watercourses (DCW)	%	> 50	1
		41 - 50	2
		26 - 40	3
		11 - 25	4
		00 - 10	5
Condition of storm drains (CSD)	-	Good	1
		Regular	3
		Poor	5
Rainwater retention devices (RRD)	-	Well maintained	1
		Poorly maintained	3
		Absent	5

1.2.3. Weighting of indicators

To analyse the susceptibility to urban hydrological disasters, it is important to recognize that different indicators have distinct importance for the composition of an index (Malczewski 2006). For this reason, was carried out the AHP, developed by Saaty (1977) and widely used in environmental studies for indicator weights weighting (Gallego-Ayala and Juízo 2012; Nguyen et al. 2016; Sahoo et al. 2016; Macedo et al. 2018; Swain et al. 2020; Ramkar and Yadav 2021; Singh and Bhakar 2021; Albulescu et al. 2022; Costache et al. 2022; Ikirri et al. 2022; Mudashiru et al. 2022; Zhang et al. 2022).

The AHP method is a multicriteria decision-making technique based on the arrangement of factors in a hierarchical structure that allows the identification of the relative importance of each element under analysis through a peer comparison system (Gallego Ayala 2012). AHP has the capacity to include quantitative and qualitative resources in the decision-making process (Singh and Bhakar 2021), as well as to occur from an individual or collective perspective (Ossadnik et al. 2016), being suitable for local and regional susceptibility studies (Liu et al. 2018).

Each specialist compared the indicators in pairs in a matrix, so that each interaction was assigned a degree of importance, as shown in Table 7, which helped in ranking the indicators. When indicator A was more important than indicator B, it received a score x, and likewise, indicator B received a reciprocal importance of 1/x in relation to indicator A (Macedo et al. 2018). Two levels of comparison between pairs were used: (a) comparison between the proposed dimensions (infiltration and surface runoff), relatively simple, since there are only two (b) comparison between the proposed indicators within each dimension (more complex). It is also worth mentioning that the judgments were carried out by specialists in water resources with diplomas in environmental, civil and agronomic engineering and environmental technologies.

Table 7 Degree of importance of the relationships between the analysed elements (Saaty 1977)

Importance	**Definition**
1	Equal importance between the two elements
2	Intermediate value between equal and light importance
3	Light importance of one element compared to another
4	Intermediate value between light and strong importance
5	Strong importance of one element compared to the other
6	Intermediate value between strong and very strong importance
7	Very strong importance of one element compared to the other
8	Intermediate value between very strong and absolute importance
9	Absolute importance of one element compared to another
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocal values of previous values

In this scenario, there are two alternatives that stand out to obtain the aggregate results of group decisions: Aggregation of Individual Judgments (AIJ) and Aggregation of Individual Priorities (AIP) (Forman and Peniwati 1998). For this study, the AIP was used, since according to Ossadinik et al. (2016), this method offers a wide range of applications, being suitable for both small and large groups, as well as decision settings with common or conflicting goals.

1.2.4. Consistency ratio of indicators

Before aggregating the results, the consistency ratio (CR) was calculated for the weights attributed to the indicators by each specialist, in order to verify whether CR < 0.10, showing consistency between the results obtained (Saaty 1977), from the Equation 7. That is, if A was more important than B, and B more important than C, then C could not be more important than A. This calculation procedure aims to minimize possible failures in assigning degrees of importance (Swain et al. 2020).

$$CR = \frac{CI}{RI} \tag{7}$$

Where RI is a fixed value, referring to the size of the matrix and defined by Saaty (1977).

The CI is the Consistency Index determined from Equation 8:

$$CI = \frac{(\lambda\text{máx} - n)}{(1 - n)} \tag{8}$$

Where $\lambda_{\text{máx}}$ is the largest or main eigenvalue of the matrix of variables and n is the order of the matrix.

1.2.5. UHDSI calculation

From the general weights obtained by the AIP aggregation of the AHP for the dimensions and indicators, the UHDSI was formulated according to Equation 9.

$$UHDSI = Wa \,.\, \sum_{i=1}^{n} Iai.\,Vai + Wb \,.\, \sum_{i=1}^{n} Ibi.\,Vbi \tag{9}$$

Where: Wa = weight of the infiltration dimension (a); Wb = weight of surface runoff dimension (b); Iai = weight of indicator i in dimension a; Vai = value of indicator i in dimension a; Ibi = weight of indicator i in dimension b; Vbi = value of indicator i in dimension b.

1.2.6. UHDSI application

The UHDSI was applied to each UHM in the study area, in order to classify them as very high, high, moderate, low or very low susceptibility to hydrological disasters (floods). The ranges of UHDSI results that reference each susceptibility class were obtained from the equal count (quartile) mode in the QGIS (2022) software. It is important to emphasize that the delimitation of the UHMs and the construction of the maps of the indicators and of susceptibility to hydrological disasters were also developed in the QGIS (2022) software. Information pertaining to the population and urban infrastructure of the study area (roads, soil type and rainwater retention devices) was extracted from the IBGE (2022) and PLANURB (2022) databases, respectively.

1.2.7. UHDSI validation

For the validation of the UHDSI, research was carried out in the main digital information media in the municipality of Campo Grande - MS, identifying the neighbourhoods, streets and intersections, and consequently the UHMs, which most flood occurred in the period from 2018 to 2022. Then, with the support of the QGIS (2022) software, was made a map referring to the rate of historical record of hydrological disasters in each UHM and compared to the susceptibility map generated by the UHDSI, with the purpose of verifying if really occurred more hydrological disasters (bigger rates) in the UHMs considered most susceptible by the index generated in this work. Validation methodology used and praised by Escobar et al. (2016), Azizat and Omar (2018), Periyasamy et al. (2018), Yagoub et al. (2020) and Mudashiru et al. (2022).

Finally, the Pearson Correlation Coefficient (r) was calculated between the UHDSI and the rate of historical record of hydrological disasters in each UHM, in order to identify perfect positive correlation (1), very strong (0.90 to 0.99), strong (0.70 to 0.89), moderate (0.50 to 0.69), weak (0.01 to 0.49), no correlation (0) or negative correlation (-0.01 to -1) between the data, as used by Moraes and Gonçalves (2021) in a study carried out in Brazil. According to Larson and Farber (2010), the closer to 1 or -1 means that the data are directly or inversely proportional, respectively. It is important to point out that in this work, the historical record rate is the number of floods recorded within the UHM of interest divided by their respective area.

1.3. Results and discussion

Figure 3 presents the classifications of UHMs in the municipality of Campo Grande - MS in relation to the Sa, Dd, DSP and DCW indicators with regard to the infiltration dimension of rainwater, while Figure 4 shows the classifications of these same indicators in relation the surface runoff dimension of rainwater in the UHMs. Figure 5 shows the classifications of the UHMs concerning the Kc, Ddem, SPS, Pd, CSD and RRD indicators regarding to both dimensions. Equation 10 displays the UHDSI according to the weights of the indicators acquired during the AHP by the experts.

In general, the Pd and DSP indicators were the most significant for susceptibility to urban hydrological disasters in both analysed dimensions (infiltration and surface runoff of rainwater). It is also worth mentioning the Sa and DCW indicators in relation to surface runoff, in the same way that the RRD and SPS indicators in relation to infiltration. All these indicators obtained the highest weights in the composition of the UHDSI. On the other hand, the Dd and Kc indicators received lower weights. This probably it happened because these indicators tend to remain constant, since the processes that lead to their modifications generally require long periods, and only in particular cases do they act forcefully and definitively (Albulescu et al. 2022).

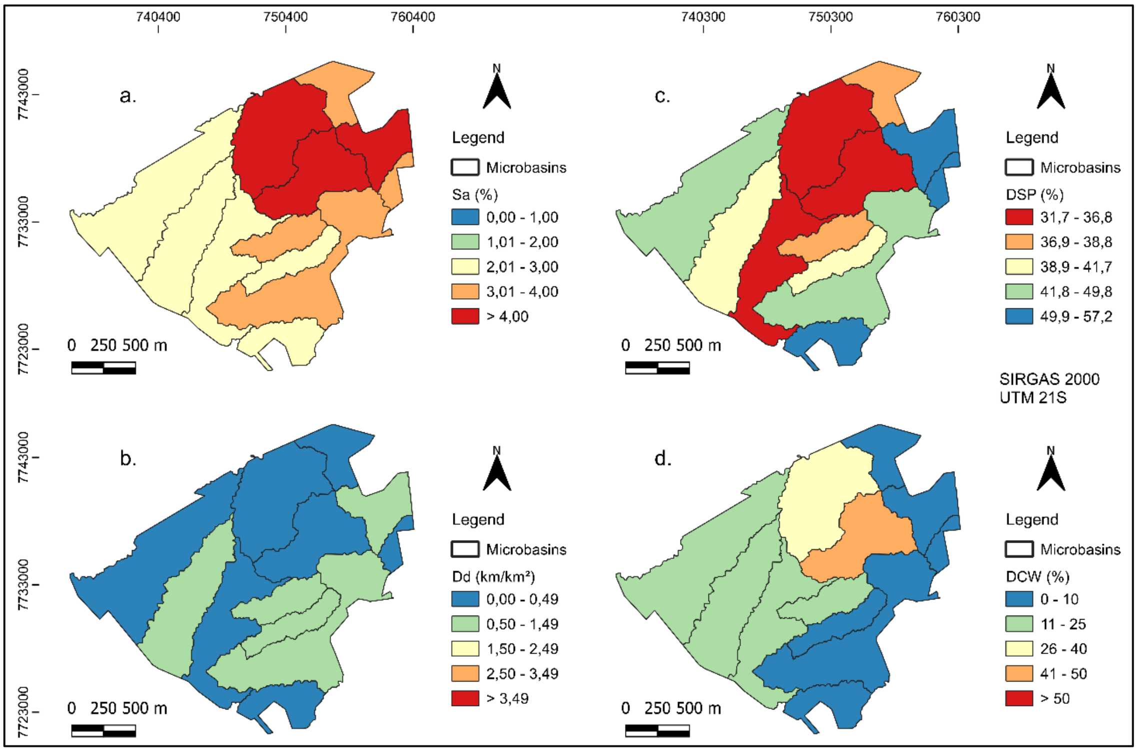

Fig. 3 Classification of UHMs in relation to the Sa (a), Dd (b), DSP (c) and DCW (d) indicators with regard to infiltration of rainwater. Source: authors

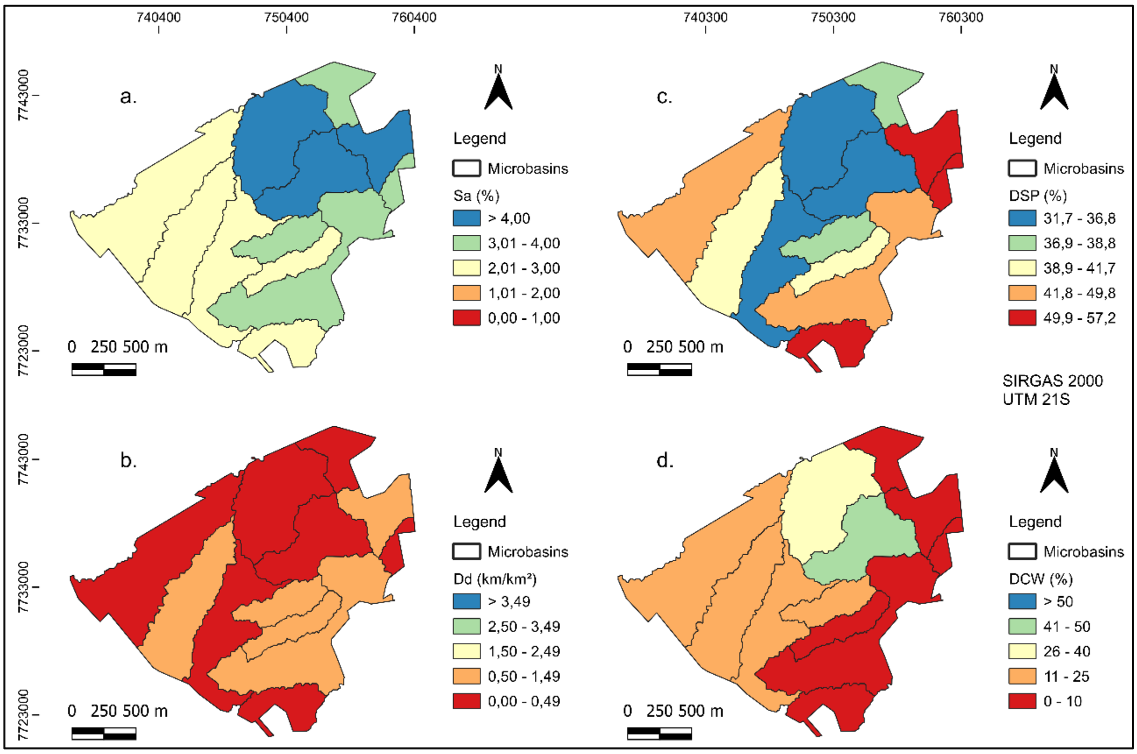

Fig. 4 Classification of UHMs in relation to the Sa (a), Dd (b), DSP (c) and DCW (d) indicators with regard to surface runoff of rainwater. Source: authors

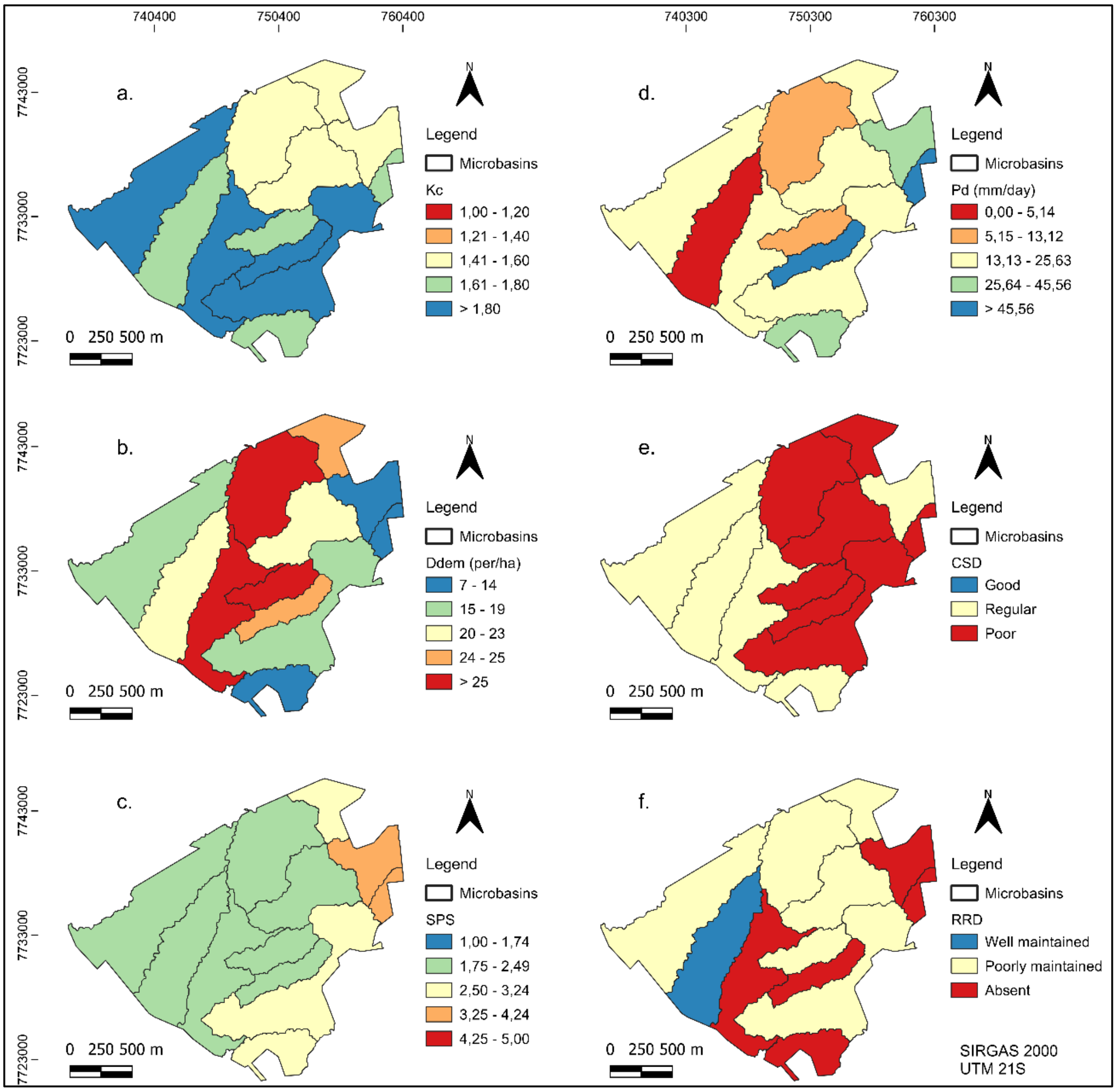

Fig. 5 Classification of UHMs in relation to Kc (a), Ddem (b), SPS (c), Pd (d), CSD (e) and RRD (f) indicators with regard to infiltration and surface runoff of rainwater. Source: authors

$$\text{UHDSI} = 0{,}50.(0{,}08.\text{VSa} + 0{,}06.\text{VKc} + 0{,}07.\text{VDd} + 0{,}26.\text{VDSP} + 0{,}04.\text{VDdem} + 0{,}09.\text{VSPS} + 0{,}16.\text{VPd} + 0{,}05.\text{VDCW} + 0{,}06.\text{VCSD} + 0{,}13.\text{VRRD})_{\text{infiltration}} + 0{,}50.(0{,}15.\text{VSa} + 0{,}06.\text{VKc} + 0{,}07.\text{VDd} + 0{,}15.\text{VDSP} + 0{,}03.\text{VDdem} + 0{,}04.\text{VSPS} + 0{,}16.\text{VPd} + 0{,}14.\text{VDCW} + 0{,}11.\text{VCSD} + 0{,}09.\text{VRRD})_{\text{surface runoff}} \quad (10)$$

Where UHDSI = Urban Hydrological Disasters Susceptibility Index, VSa = value of the average slope of the UHM, VKc = value of the compactness coefficient of the UHM, VDd = value of the drainage density of the UHM, VDSP = value of the degree of surface permeability of the UHM, VDdem = value of the demographic density of the UHM, VSPS = value of the susceptibility to production of sediments of the UHM, VPd = value of the daily precipitation of the UHM, VDCW = value of the degree of canalization of watercourses of the UHM, VCSD = value of the condition of storm drains of the UHM e VRRD = value of the rainwater retention devices of the UHM. First values in relation to infiltration and then surface runoff.

In this context, Santangelo et al. (2011) and Swain et al. (2020) concluded that precipitation, topography and soil type significantly influence the occurrence of hydrological disasters, such as floods, corroborating the results of this work. According to Niranjan Kumar et al. (2013) and Ramkar and Yadav

(2021), the main reason for flood is continuous high-intensity rain in a specific region for an extended period. In the same way that the inadequate capacity and condition of RRDs (reservoirs, diversion channels, dams, ponds and dikes) linked to the accumulation of solid waste in the urban area (Kleidorfer et al. 2014; Pavan Kumar et al. 2015). Albulescu et al. (2022) claim that these devices have multiple purposes, such as flow regulation, flood mitigation and reducing the impact of extreme hydrological disasters on human communities.

The influence of permeable areas on flood risks has been widely studied, reiterating its crucial role in hydrological and climatic processes (Swain et al. 2020). Albulescu et al. (2022) and Ikirri et al. (2022) state that forest areas delay and mitigate the impact of hydrological disasters, since the treetops and root systems absorb part of the rainwater. Concomitantly, Swain et al. (2020) point out that densely inhabited and urbanized areas are relevant to the hydrological dynamics of watersheds. Generally, these areas are impermeable and have sewage systems, considerably altering the patterns of infiltration and runoff of rainwater (Albulescu et al. 2022).

According to Swain et al. (2020), surface permeability significantly interferes with soil moisture, water infiltration, runoff and frequency of hydrological disasters. The same authors even state that the construction of paved roads results in an increase in the percentage of impermeable surfaces, providing a reduction in groundwater recharge and changes in topography that, in turn, affect the surface runoff of rainwater. Lakes and Kim (2012) and Msaddek et al. (2022) say that land cover (permeable and impermeable) is a key indicator for examining water and soil vulnerability at the scale of watersheds.

For Ngo et al. (2021), Chao et al. (2021), Costache et al. (2022) and Wang et al. (2022), slope is the most relevant indicator for surface runoff of rainwater. It has a significant impact on the occurrence of hydrological disasters because it is able to control runoff velocity (Costache and Bui 2020; Sahana et al. 2020). Steep areas are responsible for the high velocity of surface runoff of rainwater (Ramkar and Yadav 2021), while low slopes support the slow flow of these waters and allow the accumulation of water in small depressions of the topographic surface, being highly correlated with the occurrence of flood (Elmahdy et al. 2020; Albulescu et al. 2022).

With regard to the SPS indicator, the soil erosion process stands out, which is an environmental problem that happens mainly in areas with little or no vegetation cover (Swain et al. 2020), accelerating the production and accumulation of sediments and contributing to the incidence of flood. Incidentally, Mudashiru et al. (2022) say that soil type plays a crucial role in determining susceptibility to flood in any region. The water holding capacity and infiltration characteristics of a given soil can control the severity of flood (Hirst and Ibrahim 1996), with the runoff rate being higher in clayey soils compared to silty-sandy soils (Ramkar and Yadav 2021), since sandy soils are more permeable and have a greater infiltration capacity (Lappas and Kallioras 2019). On the other hand, sandy soils are more susceptible to the detachment and transport of sediments than clayey and organic soils.

Figure 6a presents the map of susceptibility to hydrological disasters of the UHMs of Campo Grande - MS, built from the application of the UHDSI developed in this work. Figure 6b shows the map referring to the rates of historical records of hydrological disasters that occurred in the UHMs of Campo Grande - MS in the period from 2018 to 2022. The colours blue, green, yellow, orange and red represent very low, low, moderate, high and very high susceptibility to hydrological disasters, respectively. It is possible to observe that Bandeira, Prosa, Segredo, Anhanduí and Coqueiro I UHMs have high to very high susceptibility to hydrological disasters (Figure 6a). On the other hand, Imbirussu, Lagoa, Bálsamo, Lageado, Gameleira, Coqueiro II and Ribeirão Brotas UHMs have low to very low susceptibility (Figure 6a).

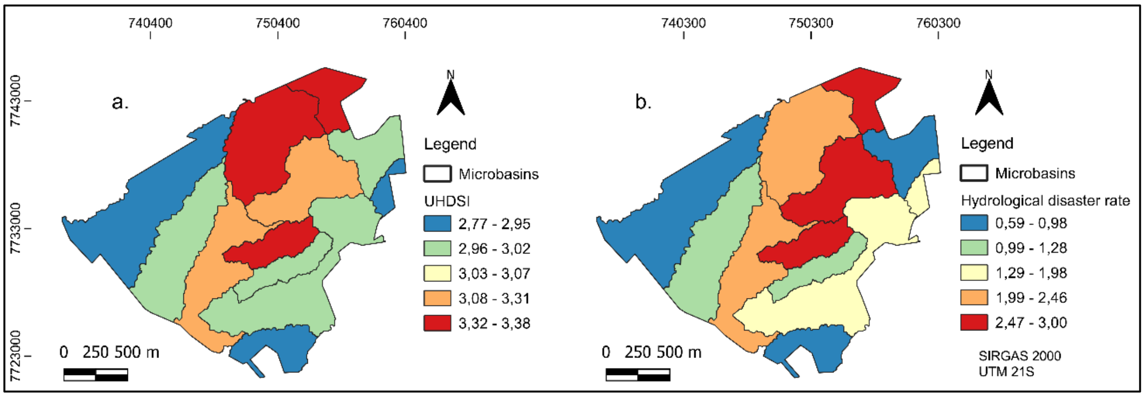

Fig. 6 Map of susceptibility to hydrological disasters by UHDSI (a) and map of historical records rate of hydrological disasters by digital information media (b). Source: authors

The Anhanduí, Bandeira, Segredo and Prosa UHMs are mostly located in the central region of Campo Grande - MS and are characterized by high rates of Ddem (Figure 5b) and smaller DSPs (Figure 3c), and consequently, high soil impermeability, according to Figure 7. This explains the role of urbanization in contributing to the generation of flood, since it is capable of influencing hydrological processes, such as infiltration rate, surface runoff velocity, evapotranspiration, evaporation (Souissi et al. 2020) and concentration time (Mudashiru et al. 2022). These UHMs also have a higher DCW than the other UHMs.

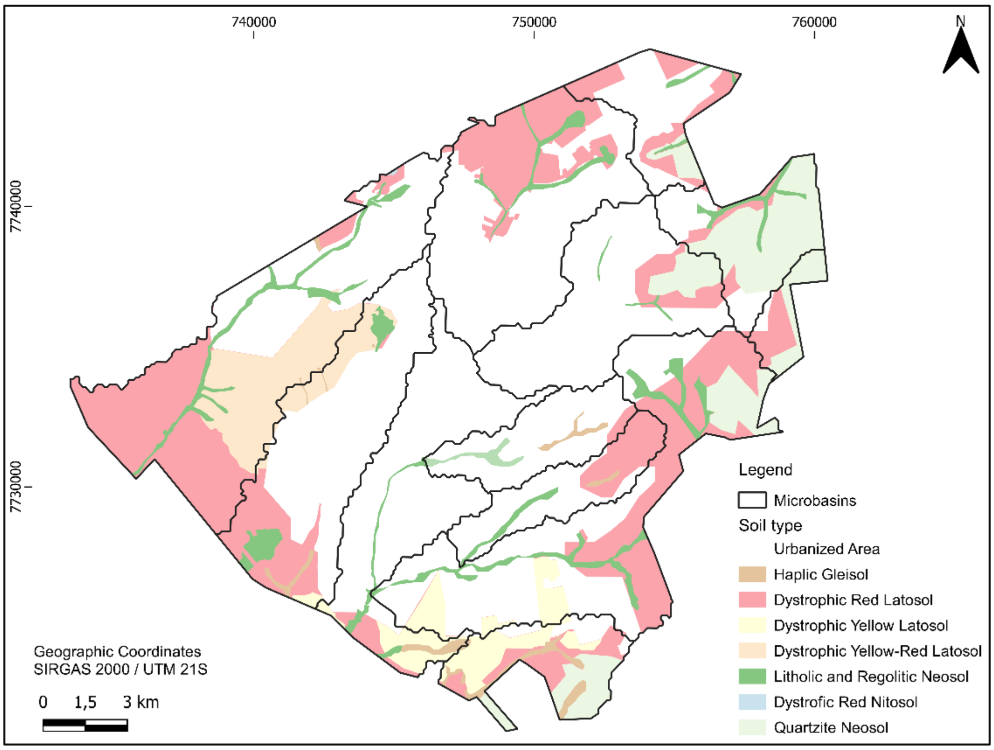

Fig. 7 Map of soil type in the UHMs of Campo Grande – MS

In addition, the Segredo, Prosa and Bandeira UHMs contain RRDs such as lakes, dams and reservoirs, in the same way that numerous storm drains distributed along the mostly paved roads in the region. However, these devices do not receive periodic and adequate maintenance, since were identified problems of siltation of the Lake of Park Nações Indígenas (UHM Prosa) and Lake of Amor (UHM Bandeira), and the accumulation of solid waste in the storm drains, as shown in Figures 8 and 9, respectively. Consequently, this contributes to the obstruction of the drainage system and reduction in the volume of RRDs, favouring floods in the region.

Fig. 8 Silting up of Lakes at Segredo and Bandeira UHMs, respectively (Campo Grande News, 2022)

Fig. 9 Obstruction of storm drain at Segredo UHM

The south part of Anhanduí UHM and the Coqueiro I UHM classified with high and very high susceptibility to urban hydrological disasters from the ISDHU, respectively, are further away from the central region of Campo Grande - MS. The main problems of these UHMs in relation to flood relate to the absence, insufficiency or poor conditions of RRDs, as well as crucial elements for the proper functioning of the drainage system, such as storm drains. At the same time, it is important to emphasize that the peripheral UHMs have the highest percentages of unpaved roads, that is, dirt roads. This contributes enormously to the production of sediments in these micro-basins, which are carried away during precipitation and cause the obstruction and malfunction of existing drainage devices both in the region itself and downstream. Figure 10 shows the distribution of paved and unpaved roads in the study area.

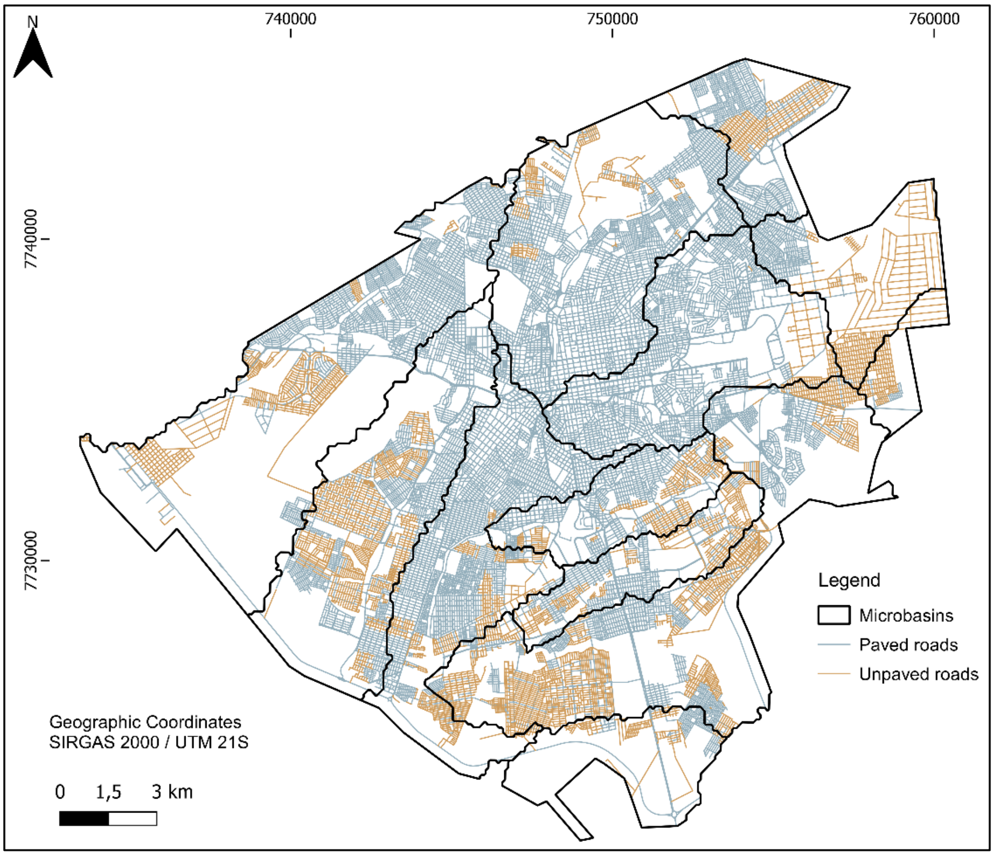

Fig. 10 Map of paved and unpaved roads in Campo Grande – MS

The results obtained in this work corroborate with Ramkar and Yadav (2021) and Mudashiru et al. (2022), since the authors concluded that densely urbanized areas have moderate to very high levels of flood risk. Similar findings were reported by Lakes and Kim (2012), Kazakis et al. (2015) and Tossi et al. (2019). Furthermore, in studies carried out in Northeast Brazil, Santos (2015) and Alves (2017) described those problems of cleaning and maintenance of drainage elements, linked to high rates of urbanization and surface impermeability, make the municipality of Campina Grande - Paraíba susceptible to floods.

In this context, Zhang et al. (2022) state that the regulation of sediments contributes to the control of hydrological disasters. At the same time, Albulescu et al. (2022) say that human interventions in the form of engineering infrastructure act as instruments for improvement, reducing hydrological vulnerability and increasing the sense of security. Therefore, it is recommended to encourage the construction and periodic maintenance of RRDs and drainage elements in the study area, in order to mitigate the occurrence of floods, especially in extreme precipitation events during the summer.

Concomitantly, it is proposed to prohibit new construction without prior studies in UHMs with very high susceptibility to urban hydrological disasters as suggested by Ikirri et al. (2022), in order to minimize possible environmental, social and economic damage. Moreover, the strengthening and expansion of programs aimed at the periodic monitoring of hydrological data in the study area is advised, since the scarcity of these data represents a barrier to the sustainable management of UHMs that suffer from floods (Yadav and Mangukiya 2021), mainly in developing countries (Costache et al. 2022). Including, periodic assessments of the UHDSI should be carried out in the area where it is applied, due to changes in the natural and socioeconomic conditions specific to each UHM (Albulescu et al. 2022), as well as updates of the hydrological and urban infrastructure databases (roads, plumbing, storm drains, impermeable areas, etc.).

In this sense, a quantitative analysis of the storm drains distributed in the UHMs is suggested, in order to assess whether they comply with the minimum necessary according to the municipality's Master Plan and specific laws. It is worth mentioning that this analysis was not performed in this study, because the municipal public administration does not have these data and there was no time to count this drainage equipment. The quantification of storm drains is essential both for future studies and for controlling the cleaning and maintenance schedule of these structures, reinforcing the need to build and update municipal databases.

Finally, it is necessary to encourage a program that aims to increase the permeable area in the central region of the municipality, to mitigate infiltration and surface runoff problems (Ikirri et al. 2022). Dixon et al. (2016) concluded that the restoration of watercourse margins significantly contributes to reducing peak stormwater discharge in watersheds, while Lakes and Kim (2012) concluded that the risk of flood is directly proportional to the degree of soil sealing in Seoul, capital of South Korea, resulting in the inclusion and expansion of green spaces throughout the urban development process by local authorities.

When comparing the maps in Figure 6, it is possible to verify that the UHMs classified with high and very high susceptibility to hydrological disasters according to the UHDSI are exactly the same ones that had the highest rates of hydrological disasters reported in information media. In fact, Pearson's Correlation Coefficient indicated a strong correlation ($r > 0.80$) between the results of the UHDSI and the rates of historical records of hydrological disasters of the UHMs, as shown in Table 8. This indicates satisfactory performance and validation of the methodology and index developed in this work to identify UHMs susceptible to hydrological disasters.

Table 8 Correlation between UHDSI results and the rate of hydrological disasters identified in the historical record at each UHM

UHM	Area (km²)	Number of hydrological disasters	UHDSI	Rate of hydrological disasters
1	59,36	51	2,77	0,86
2	40,47	51	3,02	1,26
3	36,19	80	3,26	2,21
4	15,01	45	3,34	3,00
5	13,52	17	3,02	1,26
6	53,68	101	3,02	1,88
7	15,34	09	2,92	0,59
8	45,04	92	3,38	2,04
9	32,59	82	3,10	2,52
10	14,87	38	3,32	2,56
11	18,61	17	2,97	0,91
12	05,32	07	2,95	1,32
Pearson's Correlation Coefficient (r)			**0,84**	

The susceptibility map to hydrological disasters developed in this work is capable of providing useful information for land use and occupation planning, allowing the identification of UHMs conducive to safe urban development (Bathrellos et al. 2016). Then, the susceptibility map can be used by planners, engineers and public policy makers to find ideal regions for sustainable urban growth (Mudashiru et al. 2022).

The UHDSI can be applied in any region of the world, but due to the spatial and temporal variability of the relevant indicators for the occurrence of floods, the mapping of susceptibility to these disasters is quite regional (Mudashiru et al. 2022). Therefore, the selection and standardization of the indicators used in the composition of the UHDSI can be modified based on the specific characteristics of the area of interest, to allow the efficient application of the methodology of this work. Consequently, when replicated in another area of study, the weights of the UHDSI indicators will depend on the analyses carried out by local decision-makers. According to Mudashiru et al. (2022), this can be a disadvantage, since it depends on the degree of uncertainty and knowledge of the decision-makers, so monitoring the consistency ratio limit is essential for all specialists.

For this reason, the limitation of the multicriteria method used in this work is highly related to the decision-making process, which requires a certain number of paired comparisons by experts based on the number of indicators used (Mudashiru et al. 2022). Including, Madruga and Evers (2016) and Ikirri et al. (2022) concluded that, although the multicriteria decision methodology is easy to implement, it is characterized by uncertainty based on the subjectivity of decision makers. However, it is worth noting that the experts/decision-makers in this study have a doctorate and experience in the areas of environmental, civil and agronomic engineering and environmental technologies. In addition, all analysis reached the satisfactory limit for the consistency ratio in obtaining indicator weights during the AHP, as performed by Mudashiru et al. (2022).

1.4. Conclusions

The objective of this work was to develop the UHDSI from indicators pertinent to different spheres and apply it in UHMs in the municipality of Campo Grande - MS in the Midwest Region of Brazil. Historical records of floods available on information media were used to validate the UHDSI. The indicators used in the composition of the UHDSI were Sa, Kc, Dd, Ddem, DSP, SPS, Pd, DCW, CSD and RRD. The Pd and DSP indicators were the most significant for susceptibility to urban hydrological disasters in both analysed dimensions (surface runoff and infiltration of rainwater). While Sa and DCW were relevant in relation to surface runoff and RRD and SPS in relation to infiltration. This reinforces the concept that indicators pertinent to different spheres are crucial for analysing the hydrological susceptibility of UHMs and should be analysed together.

Bandeira, Segredo, Prosa, Coqueiro I and Anhanduí UHMs were classified with high to very high susceptibility to hydrological disasters according to UHDSI. The main characteristics of these UHMs consist of higher soil sealing rates and population density than the other UHMs analysed, as well as insufficient and poor condition of the RRDs and crucial elements for the proper functioning of the drainage system, such as storm drains. The results of the UHDSI and historical records applied in each UHM obtained a strong correlation ($r > 0.80$), evidencing the reliability and validation of the developed index.

In this way, AHP and GIS integration offers a simple alternative to deal with complex problems involving contrasting indicators over a large area. Therefore, the methodology adopted in this work can be replicated in other areas, in order to identify UHMs susceptible to hydrological disasters, provided that new attributions of degrees of importance to the indicators are made by local specialists, according to the specific characteristics of the area of interest and respecting the consistency ratio limit (CR < 0.10). Finally, the UHDSI is capable of assisting in the formulation of adequate political measures, guidelines and legal norms for the ordering of land use and occupation, as it indicates the UHMs that require more attention and mitigating actions from the public power for an adequate and sustainable socioeconomic development.

The next chapter will address a validation study of precipitation estimates via remote sensing in Brazil, since during the development of the UHDSI it was identified very difficult to obtain consistent precipitation data from surface meteorological stations for the implementation of the Pd indicator in the urban area of the municipality of Campo Grande - MS. In addition, numerous authors have also reported this difficulty in different regions of Brazil and the world. Therefore, it is important to look for alternatives to complement the precipitation data observed on the surface and consequently increase the efficiency of future hydrological studies, including the results of the referred index obtained in this chapter, since the more complete the databases of the indicators, the better the results of the UHDSI.

Acknowledgements

To the Support Foundation for the Development of Education, Science and Technology of the State of Mato Grosso do Sul (FUNDECT) for the granting of the scholarship during the Doctorate. To Federal University of Mato Grosso do Sul (UFMS) and to the Postgraduate Program in Environmental Technologies (PPGTA) for the opportunity for the Doctorate. To the National Institute of Meteorology (INMET) and the City Hall of Campo Grande - MS for providing the necessary data to carry out this study.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish All authors agree to publish.

Author Contributions Rafael Brandão Ferreira de Moraes: Writing, theoretical development, statistical analysis and making figures and tables. Fábio Veríssimo Gonçalves: Writing, analysis of results and reviews.

Funding This work is supported by Doctoral scholarship from the FUNDECT for the first author (Public Notice n.19/2019).

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Availability of Data and Materials Some of the data are publicly available and their references are provided in the manuscript. Other restricted data are available from the corresponding author upon reasonable request and with permission of the source department.

Code availability Not applicable.

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CHAPTER 2: VALIDATION OF TRMM DATA IN THE GEOGRAPHICAL REGIONS OF BRAZIL

Abstract
The low density of precipitation gauges, the areas of difficult access and the high number of missing values hinder a rapid and effective hydrological monitoring. Thus, the present study aims to statistically validate the precipitation estimates by the data Tropical Rainfall Measuring Mission (TRMM) in relation to the data observed in the Conventional Meteorological Stations (CMSs) in the geographic regions of Brazil. The statistical indicators used were: Correlation Coefficient (r), Mean Absolute Error (MAE), Percentage of Bias (Pbias), T-Test and Mann-Witiney Test. It is concluded that the precipitation data estimated via TRMM are effective and reliable alternatives for hydrological studies in areas that do not have in-situ gauges and/or need to fill missing values in the five regions of the country, especially in the driest months and in larger time scales.

Keywords: Estimate; Precipitation; TRMM; Conventional meteorological station; Geographic region.

Resumo
A baixa densidade de estações meteorológicas superficiais, áreas de difíceis acessos e elevada quantidade de valores ausentes prejudicam um monitoramento hidrológico rápido e eficaz. Assim, o presente estudo tem como objetivo validar estatisticamente as estimativas de precipitação pelo produto de satélite Tropical Rainfall Measuring Mission (TRMM) em relação aos dados observados nas Estações Meteorológicas Convencionais (EMCs) nas regiões geográficas do Brasil. Os indicadores estatísticos utilizados foram: Coeficiente de Correlação (r), Erro Médio Absoluto (EMA), Percentual de Bias (Pbias), Teste-T e Teste de Mann-Witiney. Conclui-se que os dados de precipitação estimados via TRMM são alternativas eficazes e confiáveis para estudos hidrológicos em áreas que não possuem medidores in-situ e/ou necessitem de preenchimento de valores ausentes nas cinco regiões do país, sobretudo nos meses mais secos e em escalas maiores de tempo.

Palavras-chave: Estimativa; Precipitação; TRMM; Estação meteorológica convencional; Região geográfica.

2.1. Introduction

Effective hydrological monitoring is essential for the planning and operation of various sectors of society, such as agriculture, livestock, navigation, water supply, flood control, among other analyzes involving hydrological basin balance and river flow regime (Soares et al., 2016). According to World Meteorological Organization (2008), a minimum density of precipitation gauges is important to avoid problems in the development and management of water resources in physiographic units. World Meteorological Organization (2008) recommends at least one Conventional Meteorological Station for each: 900 km2 of coastal, 250 km2 of mountains, 575 km2 of interior plains, 25 km2 of small islands and 10 000 km2 of polar or arid region.

However, these recommendations are not always possibles, since several regions are difficult to access and do not have sufficient resources for such installations, monitoring and periodic maintenance. In addition, these instruments measure the local rain, not capturing its spatial distribution, especially in land with complex topography, being susceptible to precipitation detection failures (Pereira et al., 2013), which are not always filled in a way effective and immediate. In this scenario, the precipitation estimate using satellite appears as a viable option to complement the spatial and temporal constraints from traditional stations. Hence, studies were carried out in order to identify the best satellite to estimate the rainfall regime in some areas of Brazil, from the comparison of data estimated via satellite with data observed in-situ.

Reis et al. (2017) evaluated the performance of precipitation estimates of the Tropical Rainfall Measuring Mission (TRMM) and Hydroestimator (HYDROE) satellites in the Sapucaí River Basin. Nogueira et al. (2018) analyzed the performance of the products of the TRMM and Climate Hazards Group InfraRed Precipitation (CHRIPS) satellites in the state of Minas Gerais. Ringard et al. (2015) examined the estimates of TRMM, Climate Prediction Center Morphing Technique (CMORPH) and Precipitation Estimation from Remotely-Sensed Information using Artificial Neural Network (PERSIANN) satellites in the North Region of Brazil. In general, all these authors concluded that the TRMM satellite provides the best precipitation estimate in their respective study areas, showing good performance even in more extreme events such as El Niño (Erazo et al., 2018), encouraging validation of this dataset in other regions of the country, in order to use it in future hydrological studies.

Some authors are already using only the precipitation dataset from the TRMM satellite for hydrological studies around the world, such as Santos et al. (2019) to analyze the spatio-temporal variability of rain in the State of Paraíba in Brazil, Darzi (2018) to analyze precipitation in the Pantanal Biome in Brazil, Corporal-Lodangco & Leslie (2017) to identify climatic zones in the Philippines and Islam & Uyeda (2007) in Bangladesh. Nevertheless, it is recommended that before using satellite precipitation estimates to fill missing values or even substitute in-situ gauges in studies, it is necessary to perform the statistical validation of these data for the respective region to be evaluated identifying possible inconsistencies and not compromising the result of the research (Silva et al., 2019).

Considering the challenges encountered to characterize the rainfall regime of a region from in-situ gauges and the need to validate the estimated data via satellite, this study aims to statistically validate the TRMM precipitation estimates in relation to the data observed in the Conventional Meteorological Stations in the geographic regions of Brazil, in order to use them in hydrological monitoring in an effective and reliable way in all areas of the country, even the most remote ones.

2.2. Material and methods

The study areas of this work comprise the South, Southeast, Midwest, North and Northeast Regions of Brazil, characterized by economic, cultural, and climatic differences. Table 1 shows the states, area, population, topographic surface, climate, vegetation and main rivers, agricultural production and economy of each region, according to the Brazilian Institute of Geography and Statistics (IBGE) (Instituto Brasileiro de Geografia e Estatística, 2010) and Brazilian Agricultural Research Corporation (EMBRAPA) (Empresa Brasileira de Pesquisa Agropecuária, 2021). The dataset used are the satellite precipitation estimates, product of Tropical Rainfall Measuring Mission (TRMM) 3B42 V7 - denominated virtual stations - and the precipitation data observed in the Conventional Meteorological Stations (CMSs) – in-situ gauges - from January 2010 to December 2019. The study was carried out on the monthly and annual scales based on the accumulated precipitation.

Table 1. Main characteristics of the Brazilian geographic regions.

Features	South	Southeast	Midwest	North	Northeast
States	RS, SC and PR	SP, MG, RJ and ES	MS, MT and GO	AM, PA, AC, RR, RO, AP and TO	MA, PI, CE, RN, PB, PE, AL, SE and BA
Area (km²)	576 743	924 565	1 606 239	3 851 281	1 551 991
Population	29 975 984	88 371 433	16 297 074	18 430 980	57 071 654
Relief	Plateaus and plains	Mountain ranges and plains	Plateaus and plains	Plains and depressions	Plains, depressions and plateaus
Climate	Subtropical	Tropical and tropical altitude	Semi-humid tropical	Equatorial	Equatorial humid, semi-arid tropical and humid coast
Vegetation	Araucaria forest and grasses	Atlantic forest	Wetland and savannah	Amazon rainforest	Caatinga
Main rivers	Paraná, Jacuí and Itajaí	Tietê, Paraíba do Sul and Paraná	Paraguai and Xingu	Amazonas and Tocantins	São Francisco and Parnaíba
Main agricultural production	Rice	Sugar cane	Soy	Extractivism	Sugar cane and fruitful
Main economy	Agriculture, industry and tourism	Industry and agriculture	Agriculture and livestock	Fishing, extractivism and livestock	Tourism

Figure 1 represents the study areas with the locations of the analyzed stations. The South Region comprises the states of Rio Grande do Sul (RS), Santa Catarina (SC) and Paraná (PR). Southeast by São Paulo (SP), Minas Gerais (MG), Rio de Janeiro (RJ) and Espírito Santo (ES). Midwest by Mato Grosso do Sul (MS), Mato Grosso (MT) and Goiás (GO). North by Amazonas (AM), Pará (PA), Acre (AC), Roraima (RR), Rondônia (RO), Amapá (AM) and Tocantins (TO). Finally, Northeast Region by Maranhão (MA), Piauí (PI), Ceará (CE), Rio Grande do Norte (RN), Paraíba (PB), Pernambuco (PE), Alagoas (AL), Sergipe (SE) e Bahia (BA).

TRMM is a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA) and aims to measure the intensity and area of rain cover around the tropical and semitropical area, where two thirds of the world’s rains occur (Tan et al., 2015). TRMM data were collected from the Agrometeorological Monitoring System, administered by the IT sector of the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária, 2020) directly in the form of accumulated precipitation in millimeters (mm) at the virtual stations. Whereas the observed data from CMSs were acquired from the Meteorological Database for Teaching and Research of the National Institute of Meteorology (INMET) (Instituto Nacional de Meteorologia, 2020).

First, CMSs were screened, selecting only those that provided complete monthly and annual data from 2010 to 2019, in other words, without missing values. Therefore, 17 CMSs were identified in the South Region, 28 in the Southeast, 17 in the Midwest, 23 in the North and 26 in the Northeast. The Table S1, available in supplementary section, shows the municipalities in which INMET CMSs are located with their respective state and geographic region. From their location, the virtual stations (TRMM) were chosen by using the nearest-neighbor interpolation technique. Next, all data were separated and organized on monthly and annual spreadsheets. Subsequently, variability analysis and statistical tests were carried out in order to validate the estimated TRMM data in relation to the data observed in the CMSs.

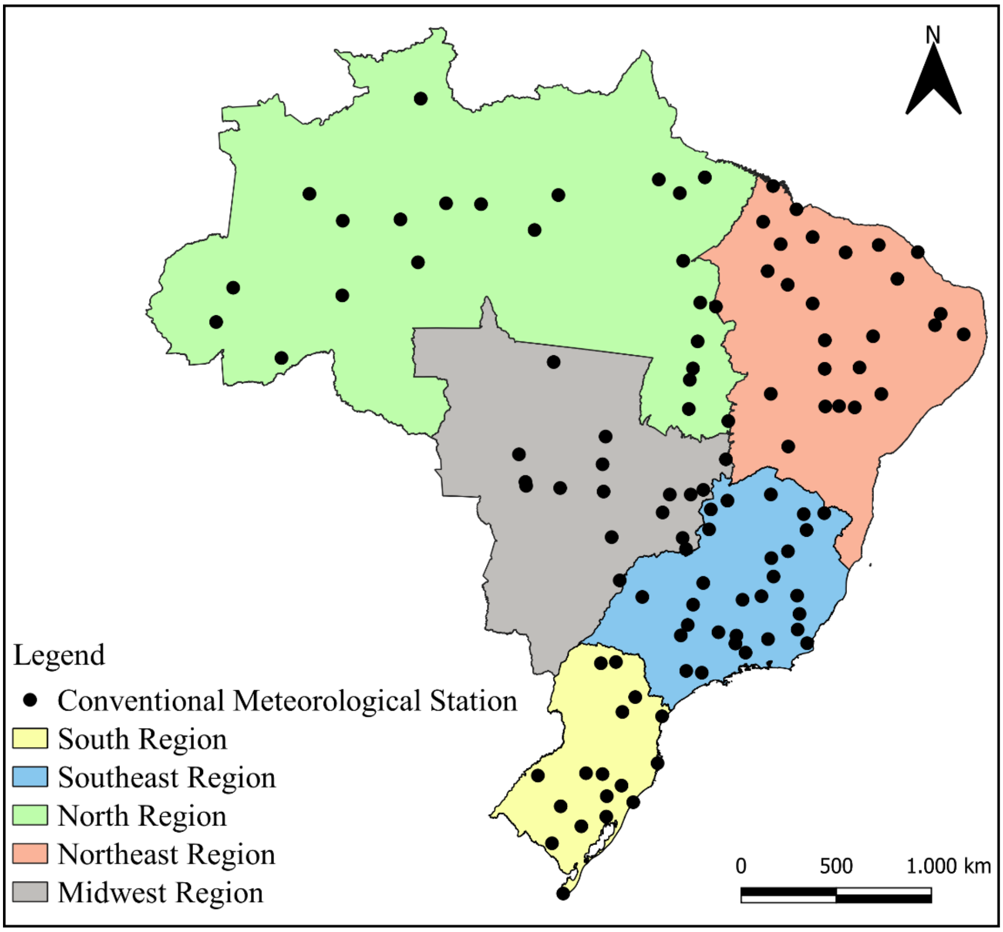

Figure 1. Geographic regions of Brazil and location of in-situ gauges.

For the analysis of data variability, the following statistical indicators were calculated: Correlation Coefficient (r), Mean Absolute Error (MAE) and Bias Percentage (Pbias). The r is the measure of the strength and direction of a linear relationship between two variables (Equation 1) (Larson & Farber, 2010). The MAE quantifies the error associated with rainfall estimates, corresponding to the average of the absolute differences between the observed and estimated values (Equation 2). While Pbias measures the average tendency of TRMM data to over or underestimate the observed data (Equation 3).

$$r = \frac{(E - Em).(O - Om)}{\sqrt{\sum_{i=0}^{n}(Ei - Em)^2 . \sum_{i=0}^{n}(Oi - Om)^2}} \tag{1}$$

$$EMA = \frac{\sum_{i=0}^{n}|Ei - Oi|}{n} \tag{2}$$

$$Pbias = \sum_{i=0}^{n}\frac{(Ei - Oi)}{\sum_{i=0}^{n}Oi}.100 \tag{3}$$

Where: Ei = value estimated by the satellite in time interval i; Oi = value observed on the surface in time interval i; n = number of data analyzed; Em = average value estimated by the satellite and Om = average value observed on the surface.

The correlation coefficients were classified as positive correlation: perfect (1), very strong (0.90 to 0.99), strong (0.7 to 0.89), moderate (0.50 to 0.69), weak (0.01 to 0.49), no correlation (0) and negative (-0.01 to -1), a convention like the one proposed by Callegari-Jacques (2003). The closer to 1, 0 and -1 it means that the data are directly proportional, without correlation and inversely proportional, respectively (Larson & Farber, 2010).

Statistical tests were started from the verification of the normality of each group of data using the Shapiro-Wilk Test. If one group or both (TRMM and/or INMET) were non-normal, then the Mann-Witney Test was performed ($\alpha = 5\%$). However, if the two groups were normal, their respective variances were calculated using the Levene Test. In the condition that the two variances are statistically equal, if the T-Test were calculated assuming equal variances, otherwise it would be T-Test assuming different variances.

Finally, if P from the T-Test or Mann-Witney Test was greater than 0.05, the two groups were considered (January TRMM and January INMET, February TRMM and February INMET, etc. on the monthly scale or 2010 TRMM and 2010 INMET, 2011 TRMM and 2011 INMET, etc. on the annual scale) with statistically equal means, at the 95% significance test ($\alpha = 0.05$). Otherwise, $P < 0.05$, groups with statistically different means (Larson & Farber, 2010). Figure 2 shows the flowchart of the methodology of statistical tests in a summarized way.

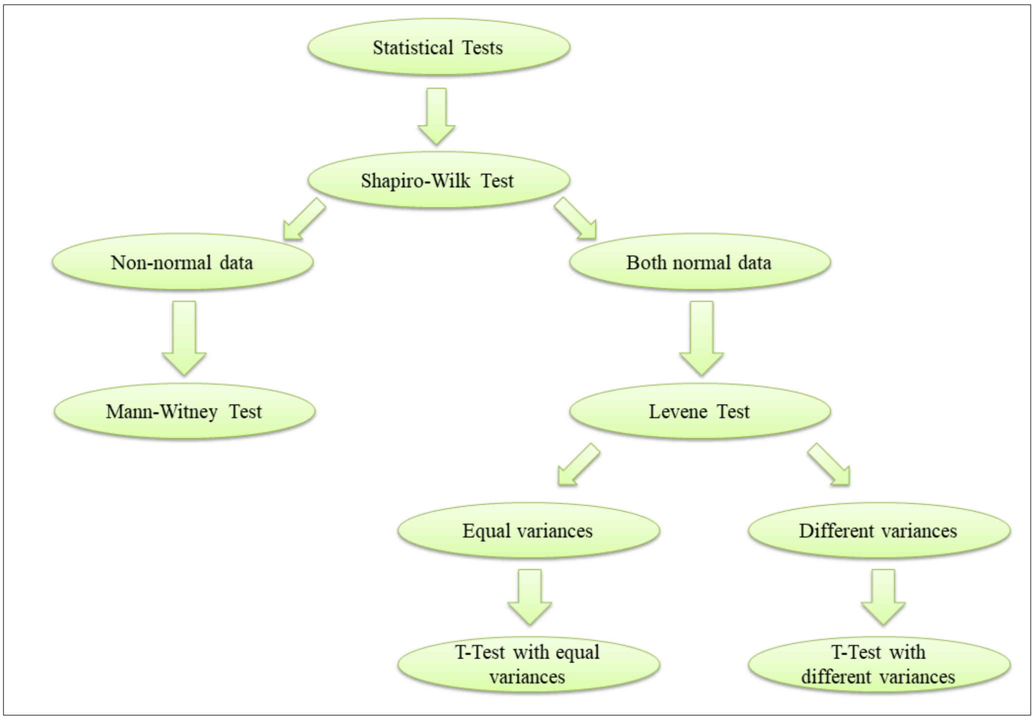

Figure 2. Flowchart of statistical tests.

It is important to emphasize that more than one statistical indicator was evaluated along with statistical tests, due to the period responsible for low rainfall, especially winter in most of Brazil. Because if an CMS measures a local rain of 2 mm and the TRMM does not estimate it over its respective catchment area, or vice versa, consequently there will be a difference of 200% between the data or even a negative correlation coefficient, for example. Nonetheless, this does not mean a poor performance of the TRMM satellite, since the difference in mm is small and the other statistical analysis can find satisfactory results (r, MAE, Mann-Witney Test and T-Test).

After validating the estimated precipitation data via satellite, the Thiessen Polygon methodology was used in the Quantum Geographic Information System (QGIS) version 3.16 software to calculate the average annual precipitation of a Brazilian State from data observed in conventional meteorological stations and data estimated on the TRMM satellites, in order that show the best distribution of the last group of data, based on the generation of a greater number of polygons and probably results closer to reality.

2.3. Results and discussion

Figure 3 shows the graphs referring to the occurrence rates of the coefficients of perfect positive correlation, very strong, strong, moderate, weak, and negative between the estimated TRMM data and observed INMET data on the monthly scale by geographic region of Brazil. It can be seen that the months between May and September, the driest period in most of Brazil, are responsible for the occurrence of the highest rates of strongest positive correlations ($r \geq 0.70$) among the data from the TRMM and INMET in the South and Southeast Regions. While in the Midwest these correlations are concentrated only in the months of June, July and August. The North Region centralizes the most significant positive correlations only in the months of June and August, whereas in the Northeast this occurs from December to March.

In general, between the months of October to April, the wettest period in most of the brazilian territory, the amount of moderate and weak positive correlation coefficients increases considerably in the South and Midwest Regions. While in the Southeast, the correlations are more distributed between strong, moderate and weak in the same period, except for April, the month with the highest weak correlation rate (53%) between the TRMM and INMET data.

In the North, the data correlation resulted in correlation coefficients classified as moderate and weak ($r < 0.70$) in the approximately 60% of the statistical analysis for the first four months of the year. On the other hand, the Northeast Region presents this inferior correlation performance mainly in the months of April and June. Still, in relation to the monthly variability of data from satellites and in-situ gauges, Figure 4 and 5 shows the results of Pbias and MAEs, respectively, of part of the analysis carried out in the South, Southeast and Midwest Regions.

From Figure 4 it is possible to conclude that in the months of strongest correlations in the South, Southeast and Midwest Regions, from May to September mainly, TRMM data are overestimated when compared to those observed in CMS. In the South they are overestimated between +1 and + 25% predominantly, from May to July. In the Southeast they are overestimated between +1 and + 25% mainly in the month of May and reach very significant percentages in August and September (Arinos - MG with + 298% and Januária - MG with + 280%, respectively, for example), as well as in some analysis located in other brazilian regions, such as the Midwest (Aragarças - GO with + 161%, Matupá - MT with + 343%, Poxoréo - MT with + 130%, etc.). By contrast June and July there is no definite trend in the Southeast. The results of Pbias by municipality can be seen in Figure S1, as well as MAE results in Table S2.

However, many of these subs and/or overestimated results, as well as some correlation coefficients (Figure 3) are classified as contestable, since the Southeast, Midwest, North (part of the state of Tocantins) and Northeast are characterized by having part of their territories located in areas with hot and dry climate. According to Empresa Brasileira de Pesquisa Agropecuária (2021), among the predominant climates of the Southeast, Midwest and Northeast Regions are tropical (dry winter), semi-humid tropical (dry winter) and semi-arid (hot and dry), respectively. Thus, low or nonexistent rainfall from May to September is common in these regions, it can cause large differences between the data and even a negative correlation coefficient, because small local precipitation can be captured by in-situ gauges and not by the TRMM satellite or vice versa.

In this context, although significant overestimations were found in some analysis of the Midwest, such as + 355% in Matupá - MT in July and + 63% in Goiânia - GO in September, their MAEs were 2.8 and 3.1 mm, respectively, according to Table S2. Furthermore, even though relatively low overestimations were identified in the month of August in the South Region, high MAEs were found, such as 75 and 60 mm in Porto Alegre and Londrina in the same period, respectively. These facts reinforce the importance of analyzing several statistical indicators simultaneously, since an isolated result classified as terrible may not represent reality, such as the overestimates of Matupá, Goiânia and Aragarças, among others.

Moreover, it is important to highlight that the analysis of statistical variability in this study were carried out based on initial data of monthly accumulated precipitation at the level of each season, while other studies such as Pereira et al. (2013), used average precipitation values for geographic regions. This can be a justification for results that refer to a lower performance of the TRMM, because when comparing the spatial averages of estimated and observed precipitation, super and underestimation errors tend to compensate, increasing the chance of greater agreement between the two variables (Soares et al., 2016).

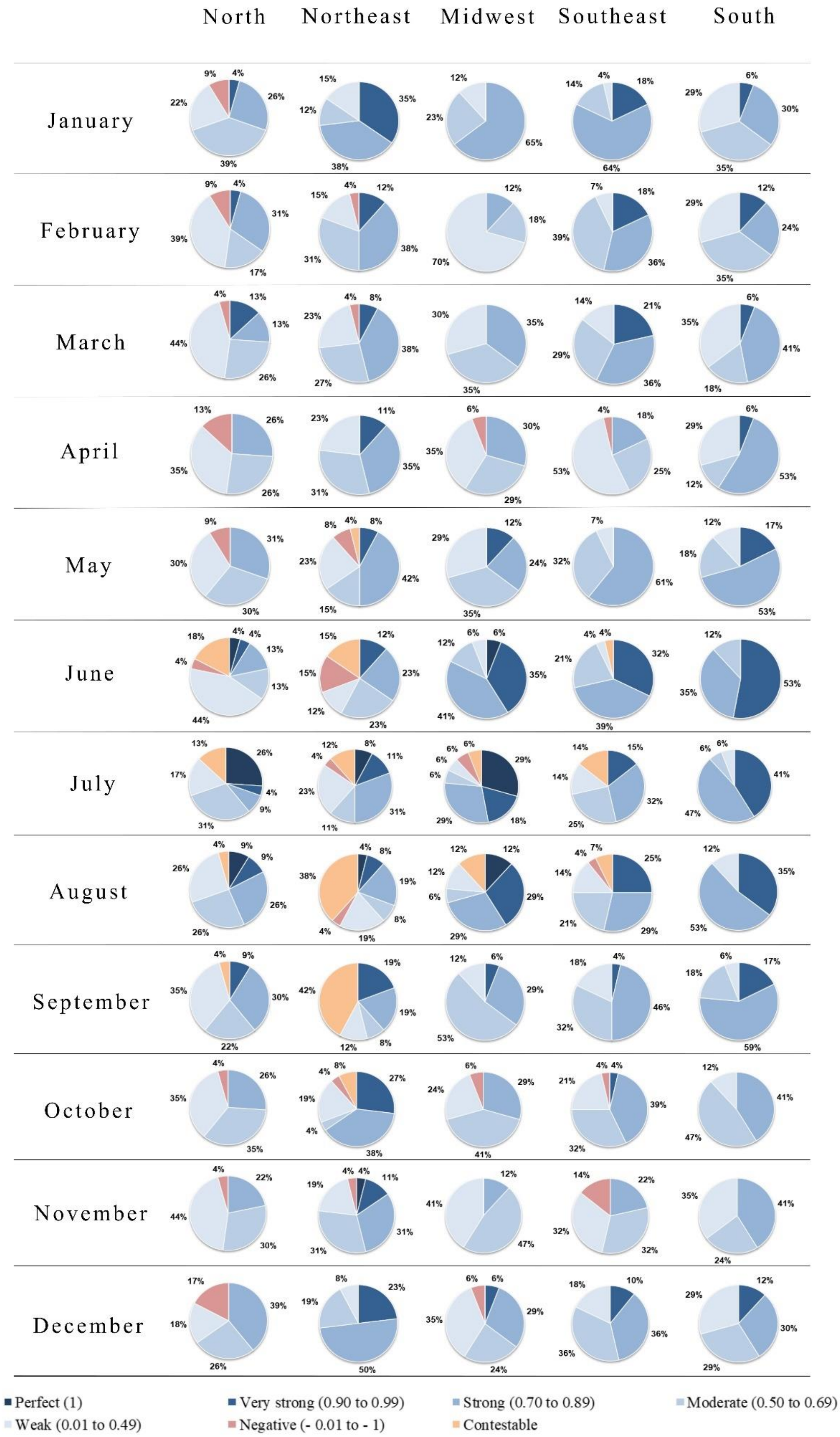

Figure 3. Graphs related to the performance of the monthly correlation coefficient analysis by geographic region.

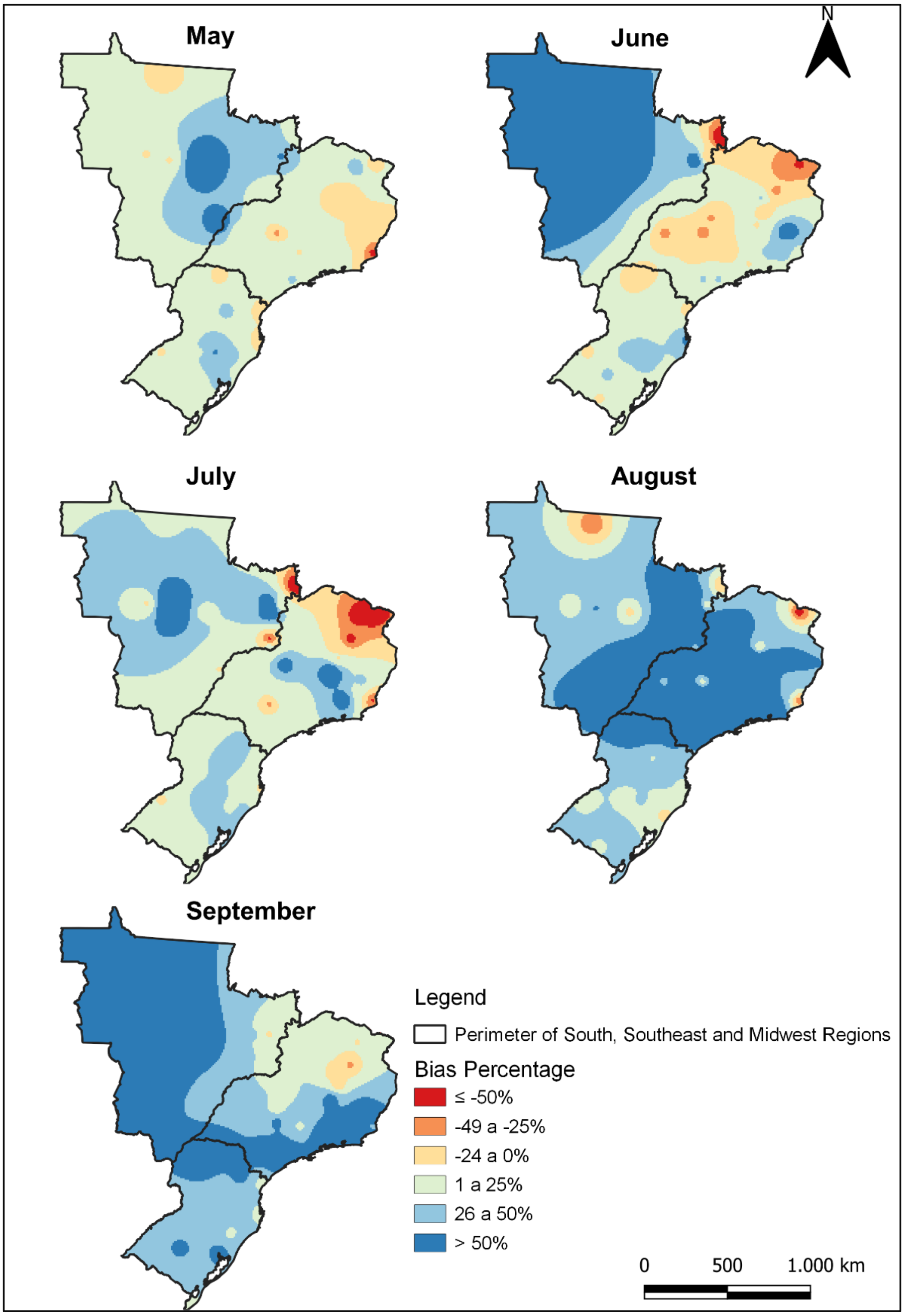

Figure 4. Result of the Percentage of Bias (Pbias) of the analysis carried out in the months of May to September in the Southeast, Midwest, and South Regions.

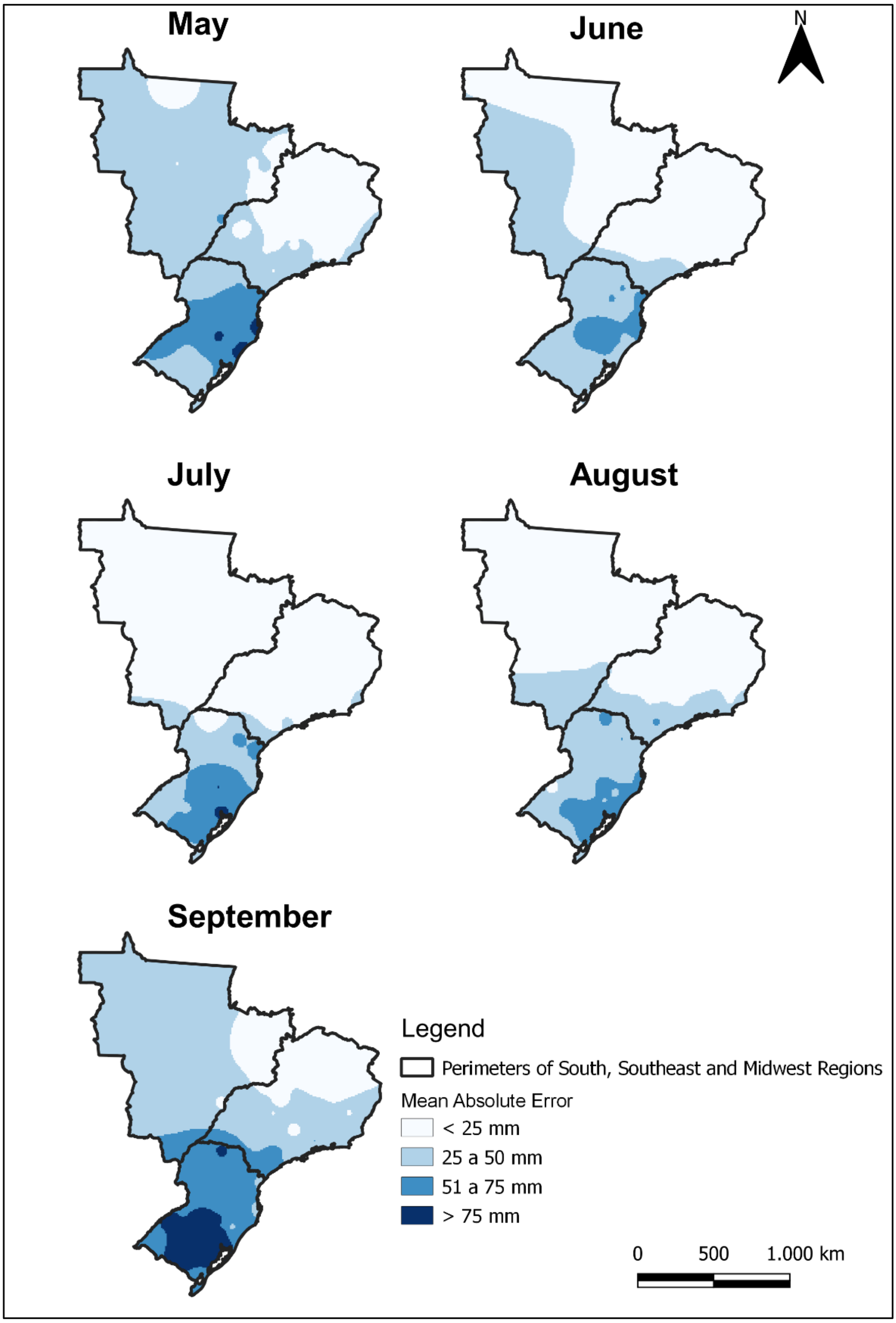

Figure 5. Mean Absolute Errors (MAEs) from May to September for partial analysis of the South, Southeast and Midwest Regions.

Figure 6 represents the graph with the percentages of the statistical tests for each region that resulted in a significant difference between the averages from the estimated accumulated rainfall and observed on the monthly scale, from the Shapiro-Wilk, Levene, T-Student and Mann-Witney Tests. It is possible to conclude a good performance of the precipitation estimates in the months of January, February, May to August, November and December for the South Region, since no statistically significant differences were identified between the means of the two groups of data ($P > 0.05$, $\alpha = 5\%$) in none of the parametric and non-parametric tests performed. The exceptions were March, April, September and October, which obtained a significant difference between the data averages in 5.9% of the analysis of the first three months mentioned and 11.8% in October.

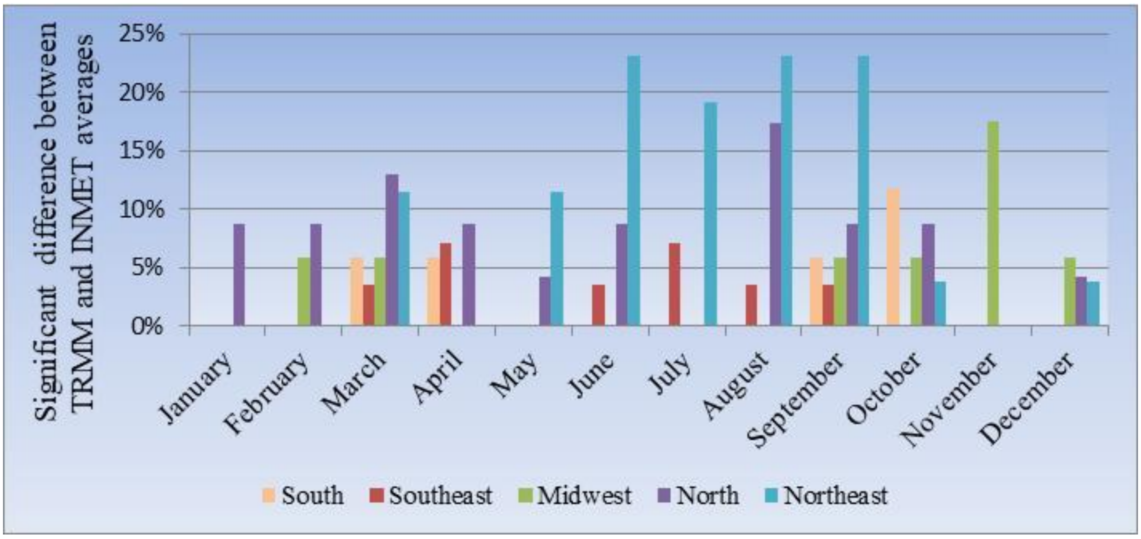

Figure 6. Percentage of monthly analyzes performed that showed a significant difference between the averages of INMET and TRMM data by Brazilian geographic region.

In the Southeast Region, it is noteworthy that although most months between October and February have the highest rates of weak and moderate correlations between the data, no statistically significant difference was noticed between their respective averages from the T and Mann-Witney Tests ($P > 0.05$, $\alpha = 5\%$), as shown in Figure 6. The exception is April, which has a weak positive correlation between the data in more than 50% of the 28 statistical analysis carried out this month. Indeed, April was identified a significant difference between the group averages of approximately 7% of the parametric and non-parametric tests performed in the Southeast Region, that is, the greatest proportion of difference found, next to July, when compared to the other months.

Despite the poor performance in April, it is possible to use precipitation estimates derived from the TRMM data in locations that do not have rain monitoring networks in the Southeast of Brazil, as concluded by Camparotto et al. (2013) in the state of São Paulo, Aires et al. (2016) in the Paraopeba River Basin and Silva et al. (2019) in the states of São Paulo and Paraná.

In the Midwest Region, the results show that from April to August, the driest period, no significant differences were identified between the means of the estimated TRMM data in relation to those observed by INMET. While in the rainy season, from September to March, at least one comparison showed a significant difference between the data averages, with emphasis on the month of November. At the same time, it is important to highlight that the months of February, April and December presented the worst correlations between the data in this region. This may be associated with the amount of rainfall for each month and the more accuracy of estimating non-occurrence of rain than exact amount of rain in greater volume (Soares et al., 2016).

In general, the Midwest Region achieved an interesting performance of the estimates generated by the TRMM, especially in drier months. Thus, it is possible to use this satellite in places that do not have CMSs in this region and/or need to fill missing values. In fact, Pessi et al. (2019) reached this same conclusion for the State of Mato Grosso, when they identified a strong correlation between the precipitation estimates through the TRMM 3B43 satellite and the observations coming from the network of conventional pluviometric stations in this state.

In the North Region, only two months did not show significant differences between the averages of the estimated and observed data - July and November. However, this does not detract from the good performance of the TRMM satellite, since in the other months the rate of municipalities with a significant difference between the data averages was low, being 4.3% in May and December and 8.7% in January, February, April, June, September and October. The exceptions were March and August with 13 and 17.4%, respectively.

In comparison to the Midwest Region, for example, which did not present any statistical divergence between the data averages from April to August, a possible justification is that the North Region has a predominantly equatorial climate, that is, characterized by high rates of precipitation and well distributed (Empresa Brasileira de Pesquisa Agropecuária, 2021). Besides, due to the large territorial extension of the North, more local rains may occur and not be accounted for by CMSs, as these stations are fixed and cannot measure precipitation in a distributed manner, such as the TRMM satellite.

Despite this, the statistical results show a good performance among the estimated and observed data for the North Region. Santos et al. (2018) concluded that precipitation estimates from the TRMM V7 satellite can be used to represent precipitation rates in the Iriri River Basin, located in North Brazil, for hydrological modeling purposes. Erazo et al. (2018) concluded that this same satellite provides reliable rainfall estimates even in more extreme events, such as El Niño, validating its use in regions with sparse rainfall stations and high rainfall variability.

Furthermore, in a study carried out in the North Region, Almeida et al. (2015) concluded that the TRMM product rainfall estimates are a good alternative source of data for the Amazon region according to statistical parameters, representing well the seasonal variability of rainfall. Thus, according to the same authors, the TRMM satellite can assist in rainfall studies of regions with low density of surface information, as well as in filling missing values and homogenizing precipitation data in CMS.

Regarding the monthly analysis of precipitation, there is the Northeast Region, which is composed of nine states with different physical, social and economic characteristics. According to Empresa Brasileira de Pesquisa Agropecuária (2021), this region has several characteristic climates, such as: humid equatorial, tropical, semi-arid and humid coastal. In view of the extensive territorial area and climatic diversity found in the region, the results found in Figure 6 show that the Northeast Region presents a lower performance when compared to the others, since in the monthly scale significant differences were observed between the means of the two groups of data in 23.1% of the analysis in the months of June, August, and September, 19.2% in July and 11.5% in the months of March and May.

This inferior performance may be related to the great climatic variety of the region, which presents poorly distributed rain, isolated and sometimes with an irrelevant daily amount, factors that together make it difficult to capture the sensors and consequently in the final monthly sum. In addition, the extensive coastal strip of the Northeast Region presents maritimity and a precipitation regime quite different from the interior, which can compromise the quality of the satellite estimates, as observed by Bernardi (2016), who found worse performance of the TRMM estimates in the coastal strip of your study area.

In this context, the TRMM satellite estimates the precipitation in a distributed area and not local like CMS. Thus, the northeastern interior, which presents little rainfall, which often occurs in more isolated parts, can contribute to reduce the satellite's efficiency. However, despite the low performance when compared to other regions, estimates of rainfall from the TRMM generally reproduce the temporal pattern of the pluviometric regime in the Northeast Region, both in terms of seasonality and in terms of spatial distribution of rainfall, such as concluded by Soares et al. (2016) for the state of Paraíba.

Figures 7 and 8 highlight the behavior of precipitation estimates via TRMM satellite compared to data observed by CMS in the the annual scale, with respect to the correlation coefficient (r) and the significant statistical differences between the means of the groups studied, respectively.

In general, the results in Figure 7 express that the estimated data are more correlated to those observed by CMS in the annual scale than in the monthly scale in the five brazilian geographic regions. However, the Southeast, Midwest, North and Northeast Regions stand out, as they portray $r \geq 0.70$ in more than 80% of the statistical analysis carried out in their respective stations, especially the Midwest with 44 and 45% of very strong and strong positive correlation, respectively. As well as the Northeast Region with a 48% very strong correlation between the estimated and observed data in its perimeter.

On the other hand, the South Region shows a lower performance compared to the others in the annual scale, since it obtained only 11% of very strong correlation between the data and the highest rates of weak and moderate correlations (10 and 29%, respectively). Nonetheless, this result does not invalidate the TRMMs accuracy in this region, since, according to Figure 8, no significant differences were found between the averages of the two groups of data in practically no year of the studied period, except for 2014.

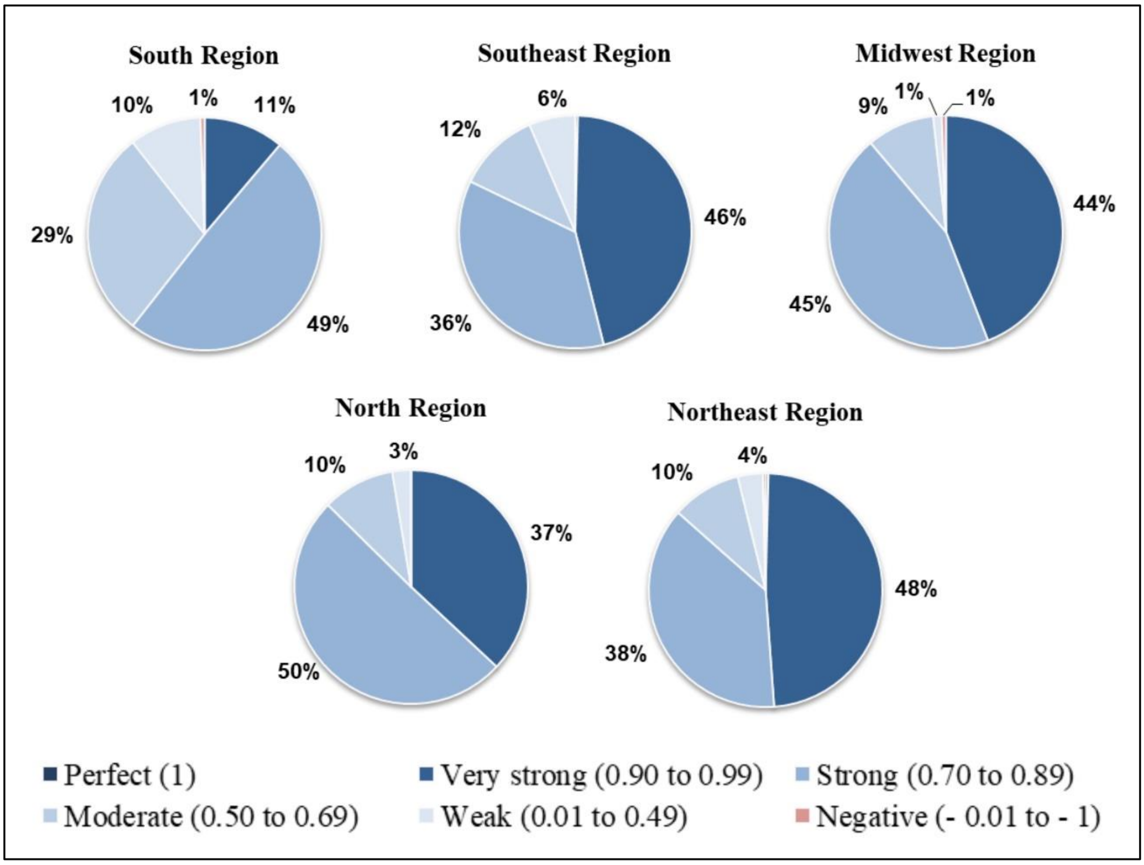

Figure 7. Graphs relating to the performance of the annual correlation coefficient analysis by geographic region.

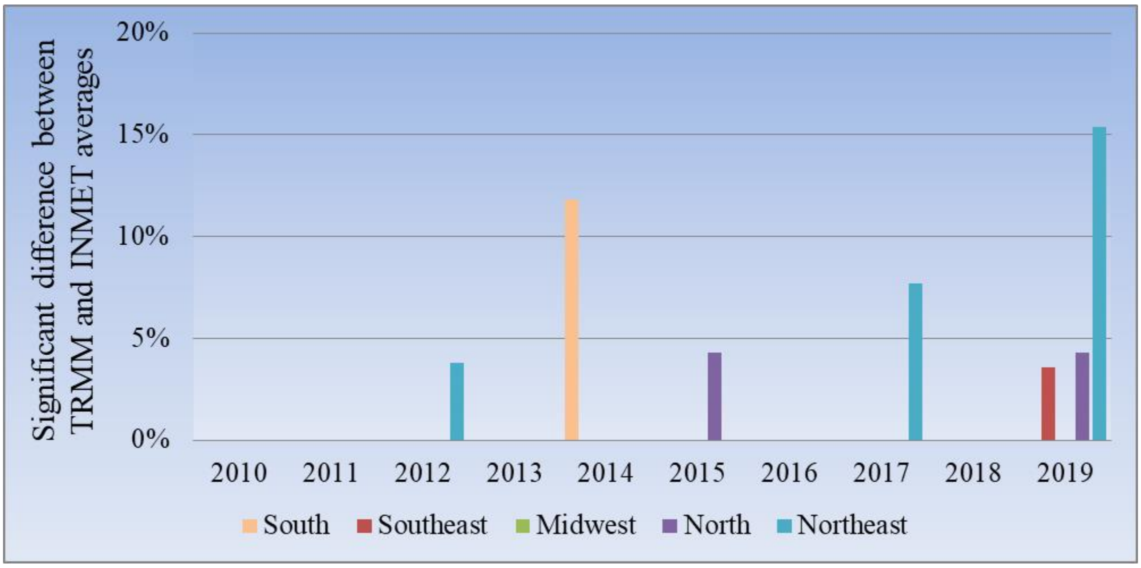

Figure 8. Percentage of annual comparisons made that showed a significant difference between the averages of the INMET and TRMM data by Brazilian geographic region.

In summary, all regions showed excellent performance on the annual scale, both in the correlation of the data and in the absence of a significant difference between the precipitation averages of the TRMM and CMS data, mainly in the Midwest and Southeast. This corroborates with the observations of Iqbal & Athar (2018) and Reis et al. (2017) who concluded that the larger the time scale of analysis, the better the precipitation estimate of the TRMM satellite, since a longer period allows temporal errors in the rain estimates to be compensated so that the total accumulated in the period is closer to that observed (Soares et al., 2016).

Finally, the average annual precipitation calculation for the state of Goiás (GO) and the Distrito Federal (DF) was carried out from 2010 to 2016, using the Thiessen Polygon methodology to compare the results from CMSs and TRMM (Table 2). The Figure 9 shows the Thiessen Polygons traced in the state of GO and DF according to the meteorological stations used, that is, in-situ (INMET) or virtual (TRMM).

The results in Table 2 show that the average annual rainfall calculated, only from the CMSs and TRMM located in the same geographic coordinates or as close as possible (Figures 9A and 9B), show relatively close results and a very strong positive correlation between the observed data and estimated ($r = 0.90$). According to Instituto Brasileiro de Geografia e Estatística (2020), the areas of the State of GO and the DF together are 346 006 km², while the areas of the Thiessen Polygons totaled 345 889 km² (Figures 8A and 8B) and 345 888 km² (Figure 9C), that is, a difference of only 0.03% in relation to the official measure, representing practically perfect agreement between them.

Table 2. Average annual rainfall in the state of Goiás and the Distrito Federal calculated from CMSs and TRMM.

Stations used	Year	Precipitation by Thiessen Polygons (mm)
INMET	2010	1,477.6
TRMM*		1,413.8
TRMM		1,374.9
INMET	2011	1,601.4
TRMM*		1,596.6
TRMM		1,603.2
INMET	2012	1,498.6
TRMM*		1,534.4
TRMM		1,516.1
INMET	2013	1,676.5
TRMM*		1,732.1
TRMM		1,748.6
INMET	2014	1,519.5
TRMM*		1,468.9
TRMM		1,486.6
INMET	2015	1,366.0
TRMM*		1,449.1
TRMM		1,498.7
INMET	2016	1,337.5
TRMM*		1,203.8
TRMM		1,244.2

*Only TRMM data located in the same geographic coordinates as INMET CMSs or as close as possible.

Moreover, the average annual precipitation was calculated based on TRMM data in the same locations as the in-situ gauges of INMET, in addition to other TRMM inserted in areas that were empty (Figure 8C), to homogenize the distribution of TRMM virtual stations in the state. These results obtained a greater difference when compared to the first (only CMSs), due to the fact of recalculating the Thiessen Polygons based on more TRMM data and, therefore, probably closer to reality, since the greater the number of Thiessen Polygons, the more distributed is the rainfall throughout the state. In fact, this is another advantage of the data estimated via satellite, that is, in addition to being reliable and effective, they have a greater spatial distribution in the region to be evaluated.

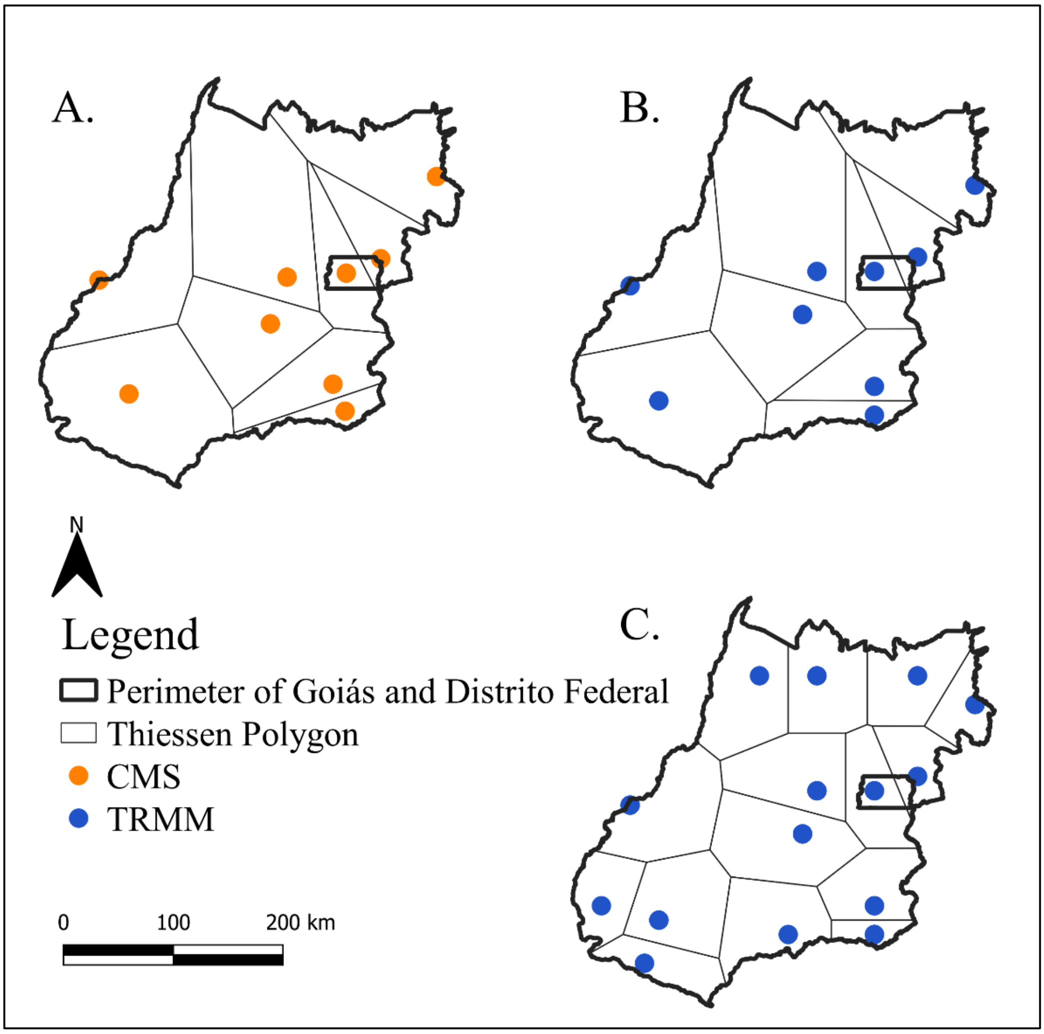

Figure 9. Maps with Thiessen Polygons from data from INMET (A) and TRMM (B and C) in State of Goiás and Distrito Federal. CMS = Conventional Meteorological Station and TRMM = Tropical Rainfall Measuring Mission.

2.4. Conclusions

The present study aimed to statistically validate satellite precipitation estimates in relation to data observed in conventional meteorological stations in the five geographic regions of Brazil. The correlation coefficient, mean absolute error, percentage of bias, mann-witney test and t-test were calculated between the two groups of data in the monthly and annual scales.

Regarding numerous problems and low density of surface weather stations with complete rainfall data in different regions of Brazil, it is concluded that the data estimated via TRMM satellite are effective, reliable and better distributed. Furthermore, if the precipitation data estimated via satellite have already been validated and extracted for a particular region of interest, they can optimize hydrological monitoring studies in areas without conventional meteorological stations or with a high number of missing data.

Regarding the monthly scale, the statistical indicators analyzed between estimated and observed precipitation data obtained the best performances over the months considered driest in the five geographic regions. More specifically, May to September in the South, Southeast and Midwest, June and August in the North and December to March in the Northeast. The monthly statistical tests had excellent performances in every month of the five geographic regions, concentrating a significant difference between the averages of the monthly estimated and observed data in less than 15% of the analyzes carried out in each region.

Moreover, it is concluded that the performance of precipitation estimates is more satisfactory on a larger scale of time, that is, annual when compared to the monthly one, and that much more estimated precipitation data per square kilometer is available than data observed in in-situ gauges, significantly increasing the precision and accuracy of rain analysis in a region. Finally, for future work on the validation of precipitation data via satellite in other regions of the world, it is recommended to use more than one statistical indicator of variability, in addition to parametric and/or non-parametric statistical tests, to increase the accuracy and not compromise the conclusion of the respective study, positively or negatively, based on only one result. Thus, the existence of CMSs is essential for the validation of precipitation data obtained via satellite, requiring the continuity and expansion of the current network of in-situ gauges.

The next chapter will address a performance comparison study of the precipitation estimates from the TRMM, Global Precipitation Measurement (GPM) and Global Precipitation Climatology Project (GPCP) satellites in a region located close to the urban area of the municipality of Campo Grande - MS, in order to identify the most efficient satellite product for that area and possibly apply it to the daily precipitation (Pd) indicator of the UHDSI developed in Chapter 1, improving the space-time resolution of the data. This study was carried out using seven statistical indicators.

Acknowledgements

To the Support Foundation for the Development of Education, Science and Technology of the State of Mato Grosso do Sul (FUNDECT) for the granting of the scholarship during the Doctorate. To the Federal University of Mato Grosso do Sul (UFMS) for the opportunity of the Doctorate. To the National Institute of Meteorology (INMET) and the Brazilian Agricultural Research Corporation (EMBRAPA) for making data available from conventional and TRMM meteorological stations, respectively.

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Authors contributions

Rafael Brandão Ferreira de Moraes: Writing, theoretical development, statistical analysis and making figures and tables.

Fábio Veríssimo Gonçalves: Writing, analysis of results and reviews.

Supplementary material

Supplementary material accompanies this paper.

Table S1. Location of Conventional Weather Stations
Table S2. Mean Absolute Errors (MAEs) from May to September for partial analysis of the South, Southeast and Midwest
Figure S1. Result of the Percentage of Bias (Pbias) of the analysis carried out in the months of May to September in the Southeast, Midwest, and South Regions

This material is available as part of the online article from https://www.scielo.br/j/rbrh

CHAPTER 3: COMPARISON OF THE PERFORMANCE OF ESTIMATED PRECIPITATION DATA VIA REMOTE SENSING IN THE MIDWEST REGION OF BRAZIL

Abstract

Consistent precipitation data are essential for hydrological studies and planning of diverse socioeconomic activities. However, the low density of in-situ gauges, areas of difficult access and high percentage sampling failures hinder an effective hydrological monitoring in most Brazilian municipalities. The objective of the present study is to compare the performance of precipitation estimates from the Global Precipitation Measurement (GPM), Tropical Rainfall Measurement Mission (TRMM) and Global Precipitation Climatology Project (GPCP) satellites in relation to precipitation data observed on the surface on daily, monthly and seasonal time scales, from 2011 to 2019 in the capital of Mato Grosso do Sul (MS), Midwest Region of Brazil. Seven statistical indicators were used. In general, the performance of the GPM and GPCP estimates are similar and better than the TRMM estimates on the daily scale. On the monthly and seasonal scales, the GPM estimates stand out from the others. It was possible to verify that all precipitation estimates are more reliable in larger time scales and drier periods. Finally, it is concluded that the precipitation estimates of the GPM, TRMM and GPCP satellites can be an alternative in areas that do not have in-situ gauges or need to fill sampling failures. Nevertheless, it is recommended to expand the in-situ gauges network in Brazil, mainly in the Midwest Region, in order to allow new spatially and temporally more representative studies.

Keywords GPM · TRMM · GPCP · Estimate · Precipitation

3.1. Introduction

The availability of consistent precipitation data with high spatial and temporal resolution is essential for planning various socioeconomic activities, such as agriculture, livestock, energy generation and identification of areas at risk for hydrological disasters (Prakash et al. 2018; Rozante et al. 2018). However, traditional precipitation measurements by in-situ gauges are relatively sparse and poorly distributed over the Earth's surface, especially in areas of difficult access and in developing countries (Rozante et al. 2018; Rodrigues et al. 2020a). In addition, their databases generally have a high percentage of sampling failures, limiting the accuracy of hydrological studies (Rodrigues et al. 2021).

In this scenario, satellite precipitation estimate products emerge as promising alternatives for more accurate hydrological monitoring, because they allow continuous measurements of precipitation with virtually global coverage and high spatio-temporal resolution, regardless of the less accessible regions (Tan and Santo 2018; Wang et al. 2017a; Rodrigues et al. 2020a; Rodrigues et al. 2020b), such as the Integrated Multisatellite Retrievals Final Run (IMERG-F) from the Global Precipitation Measurement (GPM) mission, the Multi-satellite Precipitation Analysis (TMPA) from the Tropical Rainfall Measurement Mission (TRMM) and the Global Precipitation Climatology Project Daily (GPCPDAY) and Global Precipitation Climatology Project Satellite-Gauge Combined Precipitation (GPCPMON) from the Global Precipitation Climatology Project (GPCP). These products have been widely used in regional and global meteorological and climatological studies (Singh et al. 2018; Rodrigues et al. 2020b; Singh et al. 2020; Wang et al. 2021; Yu et al. 2021).

Nevertheless, according to Franchito et al. (2009), Thiemig et al. (2013) and Melo et al. (2015), random errors and uncertainties can occur in satellite precipitation estimates. Salles et al. (2019), Rodrigues et al. (2020a) and Araujo Palharini et al. (2021) evaluated the precipitation estimates from the TRMM and GPM satellites in different regions of Brazil and concluded, in general, that the accuracy of these estimates may be related to factors such as topography, type of precipitation and local climate of the study area. Thus, a performance evaluation is necessary to identify the potential and possible limitations of using satellites to estimate precipitation at the site of interest before application (Franchito et al. 2009; Tan and Santo 2018; Silva et al., 2019).

Additionally, Tan and Santo (2018) affirm that a preliminary validation of precipitation estimates by remote sensing is essential to promote improvements in algorithms and in the development of satellite sensors. Since then, several validation studies of satellite precipitation estimates have been carried out in various parts of the world, such as Asia (Hosseini-Moghari and Tang 2020), Europe (Lockhoof et al. 2014), North America (Tian et al. 2010) and South America (Reis et al. 2017; Moraes and Gonçalves 2021; Pedreira Junior et al. 2021). In recent years, many of these validation studies have focused on TMPA (Melo et al. 2015, Reis et al. 2017; Abreu et al. 2020; Moraes and Gonçalves 2021), IMERG (Gaona et al. 2016; Sahlu et al. 2016; Gadelha et al. 2019; Rodrigues et al. 2021) and GPCP (Saldanha et al. 2015; Silva et al. 2019) products in large regions or watersheds.

Nonetheless, the performance of the GPM IMERG product, more recent in relation to the others, was little analysed in Brazilian watersheds (Rodrigues et al. 2021). New studies with longer periods of recording GPM data are needed for better qualitative analysis (Reis et al. 2017). At the same time, it is necessary to increase attention to hydrological studies on small areas with scarce data on in-situ precipitation (Reis et al. 2017), due to the occurrence of floods after heavy rains, especially in urban areas. Although, studies evaluating the accuracy of precipitation data obtained by remote sensing versus data measured in-situ are scarce in Brazil, especially in the Midwest Region and in the state of Mato Grosso do Sul (MS) (Oliveira Júnior et al. 2021).

In fact, no studies were identified regarding the comparison of different databases of precipitation estimates by satellites exclusively in the state of MS, whose capital has approximately one million people (Brazilian Institute of Geography and Statistics - IBGE 2021) and has been suffering from extreme hydrological disasters, such as floods in your urban area. Therefore, the objective of this study was to compare the performance of precipitation estimates by GPM, TRMM and GPCP satellites in relation to data observed by in-situ gauges, on daily, monthly and seasonal time scales in the capital of MS.

3.2. Methodology

3.2.1 Study Area

The study area is inserted in the municipality of Campo Grande, located in the central part of the state of MS, Midwest Region of Brazil, according to Figure 1. The municipality occupies an area of 8,082.978 km² with estimated population of 916,001 people (IBGE 2021), has an average annual precipitation of 1,570 mm and altitude between 500 and 675 m (Municipal Agency for the Environment and Urban Planning - PLANURB 2021). The climate of Campo Grande, according to the Koppen classification, is in the transition range between the humid mesothermal subtype (Cfa) without drought or small drought and the humid tropical subtype (Aw), with a rainy season in the summer and a dry season in the winter (PLANURB 2021).

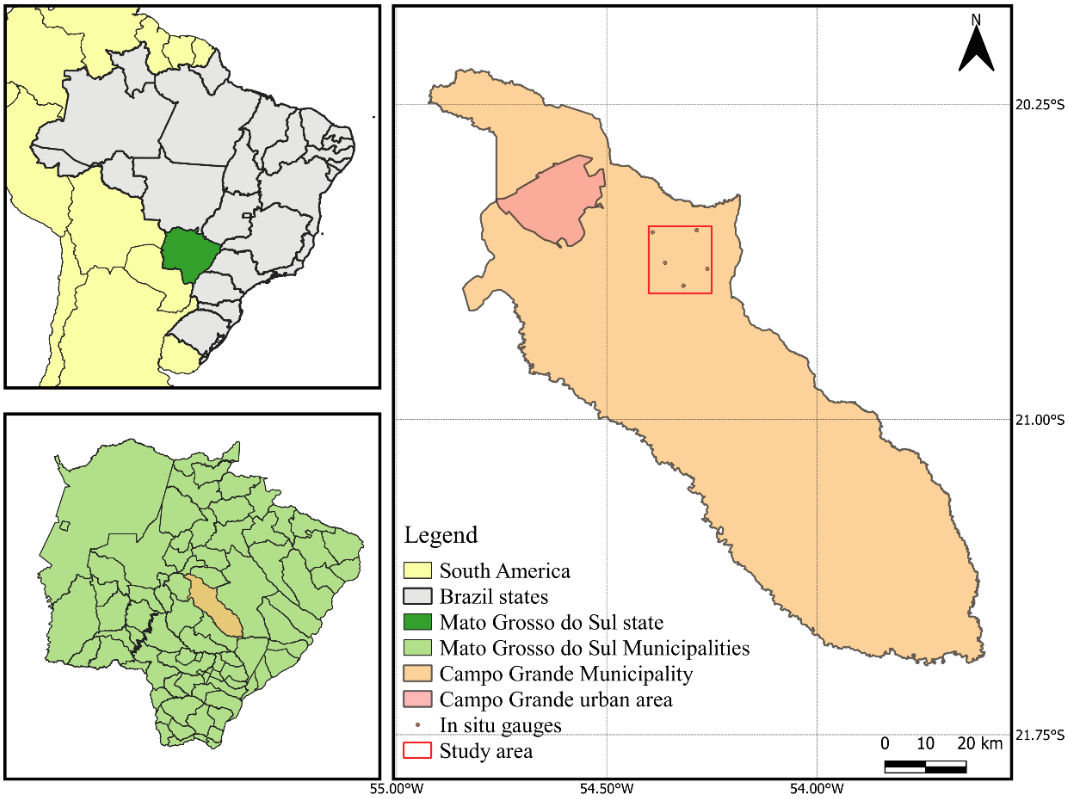

Fig. 1 Study area

3.2.2 Satellite Precipitation Products

Satellite precipitation estimate data were obtained from the Giovanni portal of the National Aeronautics and Space Administration (NASA) (https://giovanni.gsfc.nasa.gov/giovanni/). Products from the TRMM, GPM and GPCP were used. TRMM satellite orbits at an angle of 35° in relation to the Equator and provides precipitation products between latitudes 50° North and 50° South, with three hours, daily or monthly temporal resolution and 0.25° x 0.25° or 0.50° x 0.50° spatial resolution of according to the chosen product (Huffman et al., 2007). In this study, Multi-satellite Precipitation Analysis (TMPA) product of the seventh version (3B42V7) TRMM was used, with 0.25° x 0.25° spatial resolution and daily/monthly temporal resolution.

The GPM mission stands out for the use of a constellation of international satellites, which aim at a more accurate monitoring of rain and snow (Huffman et al. 2015). Unlike TRMM, the GPM satellite orbits at an angle of 65° and provides products with precipitation and snow information across the globe (Hou et al. 2014), with 30 minutes, daily or monthly temporal resolution, and 0.10° x 0.10° spatial resolution. In this study, Integrated Multisatellite Retrievals Final Run (IMERG-F) version 6 product of GPM level 3 was used, with 0.10° x 0.10° spatial resolution and daily/monthly temporal resolution.

GPCP seeks to maintain a homogeneous global record of precipitation. It is formed based on rainfall information from more than 6,700 surface weather stations distributed around the world and precipitation estimates from the geostationary satellites (Silva et al. 2019). Currently, GPCP provides products with daily and monthly temporal resolution and 0.50° x 0.50° spatial resolution. In this study, GPCP version 3.2 Daily Precipitation Data Set (GPCPDAY) and GPCP version 3.2 Satellite-Gauge Combined Precipitation Data Set (GPCPMON) products were used, with daily and monthly temporal resolution, respectively.

It is important to note that there are other alternative methods to estimate precipitation, such as the Global Land Data Assimilation (GLDAS) and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis products. However, they tend to present a high level of uncertainty when convective precipitation regimes occur (Ferguson et al., 2012; Bosilovich et al. 2017). On the other hand, according to Khodadoust Siuki et al. (2017) and Almagro et al. (2021), remote sensing products (TRMM, GPM and GPCP) provide more reliable precipitation estimates and, therefore, were prioritized in the present study. In fact, in a study carried out in the state of Mato Grosso – Brazil, Pedreira Junior et al. (2021) concluded that the TRMM, GPM and GPCP estimates obtained more satisfactory results than the GLDAS and MERRA products, since remote sensing products assimilate a higher frequency of high intensity precipitation events (Sun et al. 2018), being common the occurrence of convective rains in the region studied, similar to Campo Grande - MS. Almagro et al. (2021) concluded that satellite-based precipitation products are more reliable than ERA-5 for five of six biomes of Brazil.

Concomitantly, Andrade et al. (2022) also concluded that satellite-based precipitation products (TMPA, IMERG, and CHIRPS) generally outperform model-based precipitation products (TerraClimate with a spatial resolution of 0.04° and ERA-5 Land with a spatial resolution of 0.1°). The authors say that a possible explanation is that the CHIRPS and IMERG products, for example, undergo surface calibration (Xu et al. 2022). Additionally, CHIRPS uses TMPA 3B42 V7 data to calibrate global precipitation estimates (Huffman et al. 2007; Katsanos et al. 2016). However, regarding the CHIRPS product, Cavalcante et al. (2020) concluded in a study covering nine Brazilian states that, despite having a spatial resolution of 0.05°, this product does not represent the trends in rainfall indices well, and is not recommended for projects of hydraulic structures and studies of flooding and extreme events of precipitation. At the same time, Paredes-

Trejo et al. (2017) concluded that the CHIRPS product has a poor ability to detect rainfall in the Northeast Region of Brazil, as well as López-Bermeo et al. (2022) in Colombia, who reached results that infer that CHIRPS is an acceptable source of precipitation information for an annual scale, but unsatisfactory for a daily scale. Therefore, the CHIRPS product was not used in this study.

3.2.3 In-situ Gauges

To evaluate the precipitation estimates of the products of the TRMM, GPM and GPCP satellites, a set of precipitation data observed at 5 surface weather stations (in-situ gauges) was used as reference. These stations are located approximately 20 km from the urban area of the municipality of Campo Grande and are managed by the Laboratory of Hydrology, Erosion and Sediments (HEROS) of the Faculty of Engineering, Architecture and Urbanism and Geography (FAENG) of the Federal University of Mato Grosso do South (UFMS). Table S1, available in supplementary section, presents information about the localization in-situ gauges and percentage of sampling failure in the rainfall time series.

3.2.4 Statistical Analysis

The performance of the TRMM, GPM and GPCP precipitation estimates in relation to the data observed in the in-situ gauges was evaluated from August 2011 to December 2019 through the following statistical indicators: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Pearson's Correlation Coefficient (r), Willmott Index (d), Probability of Detection (POD), False Alarm Rate (FAR) and Critical Success Index (CSI). Indicators used for comparison and validation of various precipitation databases around the world (Reis et al. 2017; Rozante et al. 2018; Tan and Santo 2018; Gadelha et al. 2019; Paredes-Trejo et al. 2019; Amorim et al. 2020; Pedreira Junior et al. 2021; Rodrigues et al. 2021).

The MAE and the RMSE quantify the errors of the estimated data in relation to the observed ones, according to Equations 1 and 2, respectively. The MAE records, in units of the analysed variable, the level of general agreement between the two sets of data, regardless of the sign. The RMSE measures the square of the deviation between the data, being more sensitive to larger errors, better describing the accuracy of the satellites. The lower the result of these indicators, the better the satellite's performance to represent the precipitation dataset (Tan and Santo 2018; Rodrigues et al. 2021).

The r measures the degree of linear correlation between estimated and observed precipitation, Equation 3. The r values were classified as proposed by Hinkle et al. (2003) and used by Torres et al. (2020)

for validation of different precipitation databases in Brazil. The Table S2 presents the *r* classification used in this work. The *d* shows the agreement between the estimated and observed data, ranging from 0 to 1, that is, the worst and best performance of the estimates, respectively (Willmott 1981). The *d* is calculated from equation 4.

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n} |\mathrm{Ei} - \mathrm{Oi}|}{n} \tag{1}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\mathrm{Ei} - \mathrm{Oi})^2}{n}} \tag{2}$$

$$r = \frac{\sum_{i=1}^{n} (\mathrm{Ei} - \bar{\mathrm{E}}).(\mathrm{Oi} - \bar{\mathrm{O}})}{\sqrt{\sum_{i=1}^{n} (\mathrm{Ei} - \bar{\mathrm{E}})^2}\ \sqrt{\sum_{i=1}^{n} (\mathrm{Oi} - \bar{\mathrm{O}})^2}} \tag{3}$$

$$d = 1 - \frac{\sum_{i=1}^{n} (Ei - Oi)^2}{\sum_{i=1}^{n} (|Ei - \bar{\mathrm{O}}| + |Oi - \bar{\mathrm{O}}|)^2} \tag{4}$$

Where, Ei = estimated precipitation by satellite; Oi = observed precipitation by in-situ gauge; n = number of observations; $\bar{E}$ = average estimated precipitation; $\bar{O}$ = average observed precipitation.

POD, FAR and CSI were calculated to assess the satellite precipitation detection capability (Ebert et al. 2007; Wilks 2011), based on Equations 5, 6 and 7, respectively. According to Tan and Santo (2018), POD is known as the hit rate, calculated by the ratio between the number of precipitation occurrences correctly detected by the satellite and the total number of actual precipitation events. The FAR defines the fraction of events that were predicted but did not occur, being calculated by the ratio between the number of falsely detected precipitation events (false alarm) and the total number of detected precipitation events. While CSI measures the overall fraction of precipitation events correctly detected by the satellite.

The POD, FAR and CSI values range from 0 to 1, with 1 being the perfect score for POD and CSI, and 0 being perfect for FAR (Tan and Santo 2018). Days with precipitation and without precipitation were differentiated by applying a common limit of 1 mm/day (Yong et al. 2010), as adopted in validation studies of precipitation estimates by satellites (Paredes-Trejo et al. 2019; Rodrigues et al. 2021).

$$POD = \frac{a}{a + c} \tag{5}$$

$$FAR = \frac{b}{a + b} \tag{6}$$

$$CSI = \frac{a}{a + b + c} \tag{7}$$

Where, a = days with observed and estimated rain, b = days with estimated rain, but without observed rain, c = days with observed rain, but without estimated rain, d = days without observed and estimated rain.

It is important to highlight that in-situ gauges measure precipitation punctually, and there may be considerable differences from one gauge to another. On the other hand, satellites estimate the average precipitation in a pixel (10 km x 10 km – GPM, 25 km x 25 km – TRMM and 50 km x 50 km – GPCP). According to Duan et al. (2016), there is a clear problem of scale incompatibility between point-based precipitation data (in-situ gauges) and grid products (satellites), and it is common in evaluation and validation studies of precipitation data, to increase the area of influence of the point-based rainfall data for the same grid scale that rainfall products from satellites. In this scenario, there are many interpolation techniques to achieve this scaling up, such as simple algorithmic averaging (Xie and Xiong 2011), Thiessen polygon (Liu et al. 2015), inverse distance weighting (IDW) (Hu et al. 2014) and the Kriging method (Khandu et al. 2016). However, each interpolation method has its advantages and disadvantages, and its performance depends on several factors (Hofstra et al. 2008) and varies from region to region (Duan et al. 2016).

Hence, the specialized literature has used numerous methodologies to compare precipitation data estimated by remote sensing and data observed at the surface, since there is no standardized methodology for verifying and analysing these data (Feitosa and Oliveira 2020). Duan et al. (2016) and Chen et al. (2018) say that it is practically impossible to identify an optimal method applicable in all areas of study. In this work, Thiessen polygon method was used because it is relatively easy to implement and its application is popular in studies of evaluation and validation of precipitation data in Brazil, as Curtarelli et al. (2014), Reis et al. (2017), Moraes and Gonçalves (2021) and Brasil Neto et al. (2022).

In this work, we chose to compare the daily, monthly and seasonal averages of the observed and estimated data from August 24, 2011, to December 31, 2019. To obtain the average precipitation of the in-situ gauges, the Thiessen Polygon method was applied in the Quantum Geographic Information System (QGIS) software version 3.22.5 (QGIS 2022), as well as Moraes and Gonçalves (2021), in which the average precipitation is calculated by weighting the rainfall values of each gauge for its area of influence (WMO 1994). Finally, it is important to emphasize that the density of in-situ gauges distributed in the Midwest Region is low (Gadelha et al. 2019), consequently we had difficulty finding gauges with time series filled in without sampling failures. Concomitantly, Tang et al. (2018) and Gadelha et al. (2019) highlight that errors increase when comparing precipitation data estimated via satellite and observed on the surface in areas with low density of gauges.

Therefore, in this work it was decided to use the same geographic coordinates (-54.4W, -20.7S, -54.25W, -20.54S – Figure 1) both to delimit the Thiessen polygons from the gauges and to download the precipitation estimates via satellite on the website (https://giovanni.gsfc.nasa.gov/giovanni/), in order to standardize the area analysed, increase the density of in-situ gauges in the evaluated area and not compromise the results. Another interesting point to highlight is that Thiessen polygons were generated daily according to the gauges with filled precipitation data, changing the number of in-situ gauges over the study period (Gadelha et al. 2019). That is, if on day X the five gauges had data, then the Thiessen polygons were generated considering the five points. If on day Y, a gauge had sampling failure, it was disregarded that day and the Thiessen polygons were generated based on 4 gauges. This detailed analysis was performed every day of the studied period.

3.3. Results and Discussion

3.3.1 Daily Analysis

Figure 2 shows the results of *r*, *d*, MAE, RMSE, POD, FAR and CSI of the precipitation estimates from the GPM, TRMM and GPCP satellites when compared to the precipitation data observed on the surface on a daily scale, according to the month and in general (every day of the study period regardless of the month). Overall, the daily precipitation estimates showed moderate correlation with the precipitation data observed on the surface, since the *r* of the GPM, TRMM and GPCP satellites were 0.67, 0.62 and 0.67, respectively. These results corroborate with Sahlu et al. (2016), Sharifi et al. (2016), Kim et al. (2017), Wang et al. (2017b), Tan and Santo (2018), Hosseini-Moghari and Tang (2020) and Le et al. (2020) who found a moderate correlation between GPM estimated data and those observed on the surface. However, the TRMM daily *r* found in this work is slightly lower than that found by Reis et al. (2017) in the Southeast Region of Brazil (r = 0.70).

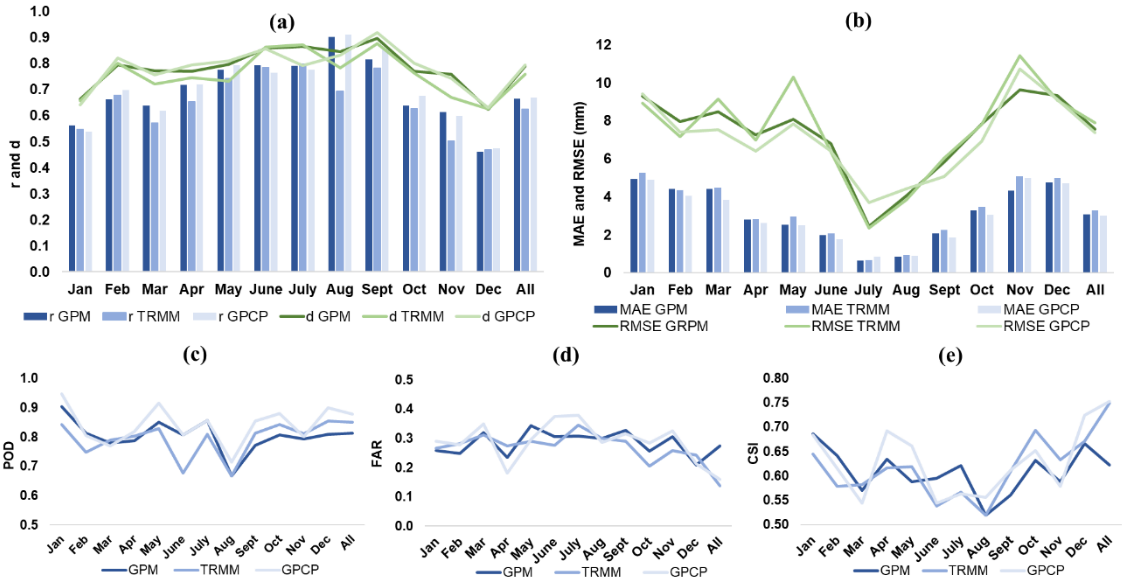

Fig. 2 Results of *r* and *d* **(a)**, MAE and RMSE **(b)**, POD **(c)**, FAR **(d)** and CSI **(e)** of GPM, TRMM and GPCP precipitation estimates in relation precipitation data observed in surface on daily scale

The daily data estimated from April to September obtained the best results of correlation and agreement with the data observed on the surface, mainly from the GPM (0.72 < r < 0.90 and 0.77 < d < 0.90) and GPCP (0.72 < r < 0.91 and 0.79 < d < 0.92). The months from November to January were responsible for the worst daily results of *r* and *d* for the GPM (0.46 < r < 0.61 and 0.62 < d < 0.76), GPCP (0.47 < r < 0.60 and 0.63 < d < 0.74) and TRMM (0.47 < r < 0.55 and 0.63 < d < 0.67) satellites, as verified by Abreu et al. (2020) in their work on validating TRMM data in MS.

It is worth mentioning that many convective rains occur in the period from October to December in the state of MS (Pessi et al. 2019), and this can compromise the results, because the surface weather stations measure rainfall in a punctual way, while satellites average over a given area according to their spatial resolution. In addition, Tan and Santo (2018) highlight that monthly rainfall gauges are used to calibrate the GPM IMERG product, and such calibration obviously does not represent daily rainfall well, especially in regions characterized by high spatial and temporal variability of precipitation.

With regard to the MAE and RMSE, the GPCP daily precipitation estimates performed better in most months and in the overall analysis compared to the GPM and TRMM estimates. The months from April to September had the lowest MAEs for the three satellites (MAE < 3.00 mm), mainly in June, July and August, while from November to March had the highest daily MAEs. The lowest RMSEs occurred in the daily estimates from June to September and the highest from November to March and May. In general, the months with the highest daily errors showed seasonality compatible with the period of intense rainfall (summer in the southern hemisphere), while the dry period (winter in the southern hemisphere) presented smaller errors (Reis et al. 2017).

In the general context, without division by month, the MAEs of the GPM, TRMM and GPCP satellites were 3.08 mm, 3.28 mm and 3.00 mm, respectively, while the RMSEs were 7.55 mm, 7.90 mm and 7.36 mm, respectively. More satisfactory results than the 12.65 mm (GPM) and 12.54 mm (TRMM) RMSEs found by Amorim et al. (2020) in a watershed located in the state of Goiás, Midwest Brazil and RMSEs of 12.00 mm (GPM) and 15.40 mm (TRMM) identified by Le et al. (2020) in Vietnam. On the other hand, they are superior to the 6.60 mm RMSE (TRMM) found by Reis et al. (2017) in the Southeast Region of Brazil and to the 3.85 mm RMSE (GPM) identified by Hosseini-Moghari and Tang (2020) in Iran.

GPCP showed better performance in detecting daily rainfall greater than 1 mm (POD = 0.88), in relation to GPM and TRMM (POD of 0.81 and 0.85, respectively). In addition, GPCP obtained a FAR of 0.16 and a CSI of 0.75, that is, low false alarm rate and high precipitation hits rate, standing out in relation to the other two satellites in the general scenario, whereas Pedreira Junior et al. (2021) concluded better rain detection performance for the TRMM satellite compared to the GPM and GPCP in the state of Mato Grosso. In a study conducted throughout Brazil, Gadelha et al. (2019) found good agreement from the GPM satellite in detecting daily precipitation events in most of the country, with POD and CSI values greater than 0.6. Digging deeper into a daily analysis according to each month, the highest POD was 0.95 (January – GPCP) and the lowest 0.67 (August – GPM and TRMM), highest FAR 0.38 (June and July – GPCP) and lowest 0.18 (April – GPCP) and higher CSI 0.72 (December – GPCP) and lower 0.52 (August – GPM and TRMM).

From the analysis of all statistical indicators on the daily scale, it is possible to infer that the precipitation estimates from the GPM and GPCP satellites are similar and more reliable than the TRMM estimates in the study area of the present work. Incidentally, Rozante et al. (2018) and Le et al. (2020), in studies carried out in Brazil and Vietnam, respectively, concluded that the GPM IMERG product performs better for daily precipitation estimates compared to the TRMM TMPA product. Despite this, it is worth mentioning that the algorithms of the GPM, TRMM and GPCP satellites need additional improvements to carry out daily precipitation estimates (Reis et al. 2017; Tan and Santo 2018) in the Midwest Region of Brazil (Gadelha et al. 2019), because excellent results were not found for the indicators calculated on this time scale, as highlighted by Silva et al. (2019) and Pedreira Junior et al. (2021). According to Gadelha et al. (2019) this may be associated with the low density of in-situ gauges distributed in the Midwest Region and used as a reference on the surface.

3.3.2 Monthly Analysis

Figure 3 shows the results of *r*, *d*, MAE and RMSE of the precipitation estimates from the GPM, TRMM and GPCP satellites when compared to the precipitation data observed on the surface on a monthly scale. In general, monthly precipitation estimates have a strong correlation with surface observed data, since the *r* from the GPM, TRMM and GPCP satellites were 0.78, 0.74 and 0.71, respectively. These results corroborate with Reis et al. (2017), Torres et al. (2020) and Pedreira Junior et al. (2021) who found high correlations of the TRMM, GPCP and GPM monthly data, respectively, in relation to the precipitation data observed on the surface. Furthermore, Silva et al. (2019) and Pedreira Junior et al. (2021) concluded that the TRMM and GPM data present better correlations with the in-situ observed data than the GPCP estimated data on the monthly scale.

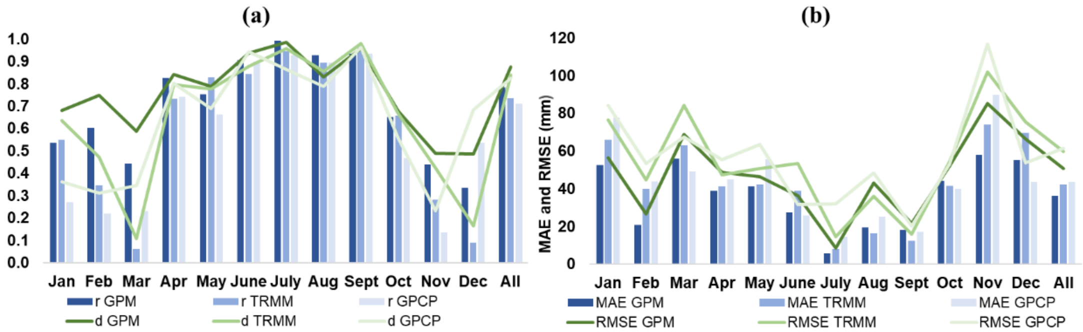

Fig. 3 Results of *r* and *d* **(a)** and MAE and RMSE **(b)** of GPM, TRMM and GPCP precipitation estimates in relation to precipitation data observed in surface on the monthly scale

The monthly precipitation estimates from April to September obtained the best results of correlation and agreement with the surface observed data in the three satellites analysed, with a slight advantage to the GPM ($0.75 < r < 0.99$ and $0.79 < d < 0.98$) when compared to others. By contrast the months from October to March were responsible for the worst monthly *r* and *d* results for GPM ($0.34 < r < 0.65$ and $0.49 < d < 0.75$), GPCP ($0.13 < r < 0.53$ and $0.23 < d < 0.68$) and TRMM ($0.06 < r < 0.66$ and $0.11 < d < 0.67$).

Regarding the MAE and RMSE, the GPM monthly precipitation estimates performed better in most months and in the overall analysis. The months from July to September presented the lowest MAEs for the three satellites (MAE $<$ 30.00 mm), while from November to March the highest MAEs occurred. The lowest RMSE occurred in the monthly estimates of February and from June to September, whereas the highest occurred from November to January and March.

In the general context, the monthly MAEs of the GPM, TRMM and GPCP satellites were 36.01 mm, 42.22 mm and 43.43 mm, respectively, while the monthly RMSEs were 50.79 mm for GPM, 59.88 mm for TRMM and 61.49 mm for GPCP. That is, higher monthly error linked to GPCP estimates and lower to GPM estimates, as verified by Pedreira Junior et al. (2021) in the state of Mato Grosso, Brazil (GPCP RMSE close to 60 mm, TRMM RMSE = 48.75 mm and GPM RMSE = 45.26 mm on the monthly scale). The RMSEs found in this work are close to the monthly RMSEs found by Amorim et al. (2020) for the GPM IMERG product (58.09 mm) and, especially, TRMM TMPA (59.61 mm), in a watershed located in the Midwest Brazilian. On the other hand, the TRMM monthly MAE in this work is lower than that identified in the Southeast Region of Brazil (MAE = 79.13 mm) by Reis et al. (2017).

From the analysis of all statistical indicators on the monthly scale, it is possible to conclude that the GPM precipitation estimates are more reliable than the TRMM and GPCP estimates in the study area of the present work, corroborating with results found by Pedreira Junior et al. (2021) in the state of Mato Grosso, Brazil, Amorim et al. (2020) in the Midwest of Brazil, Rozante et al. (2018) throughout Brazil and Su et al. (2019) in China. Furthermore, it is important to note that the GPM, TRMM and GPCP satellites estimated precipitation more accurately on the monthly scale than on the daily scale, as observed by Melo et al. (2015), Reis et al. (2017), Silva et al. (2019), Gadelha et al. (2019), Amorim et al. (2020) and Pedreira Junior et al. (2021) in Brazil. Huffman et al. (2007) asserts that better results are expected on a monthly time scale, because both IMERG and TMPA are corrected with surface precipitation data to remove monthly bias.

3.3.3 Seasonal Analysis

Figure 4 shows the results of *r*, *d*, MAE and RMSE of the products of the GPM, TRMM and GPCP satellites in relation to the data observed on the surface on a seasonal scale: December – February (DJF), March – May (MAM), June – August (JJA) and September – November (SON) between the years 2012 and 2019. The GPM *r* ranged between 0.54 (SON) and 0.68 (JJA) with higher values for all periods compared to TRMM and GPCP, with the exception of TRMM in the JJA quarter (r = 0.73). As well as the GPM *d*, which varied between 0.50 (MAM) and 0.74 (DJF) with higher values for all periods compared to TRMM and GPCP, with the exception of TRMM in the JJA quarter (d = 0.73).

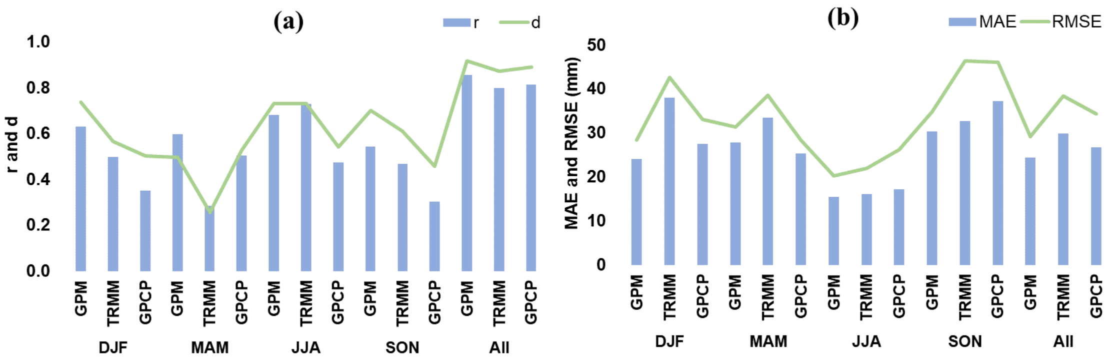

Fig. 4 Results of *r* and *d* **(a)** and MAE and RMSE **(b)** of the GPM, TRMM and GPCP precipitation estimates in relation to the precipitation data observed in surface in the seasonal scale

Regarding the MAE and RMSE, it is possible to highlight that the smallest errors occurred in the GPM estimates (15.48 mm < MAE < 30.26 mm and 20.17 mm < RMSE < 34.82 mm) in practically all analysed periods, with the exception of the GPCP in MAM (MAE = 25.27 mm and RMSE = 28.41 mm). The highest correlations/agreement and lowest errors between the estimated and observed datasets occurred in the JJA period, that is, the driest period in the Midwest Region of Brazil. On the other hand, the lowest correlations/agreements and the highest errors between the data occurred in the other periods, especially SON and DJF, the rainiest periods in the study area. Although Reis et al. (2017) found higher values of *r* among the TRMM and observed data in the same quarters in the Southeast Region of Brazil (0.75 < r < 0.87), there was a similar behaviour of the results, because the best performance of the TRMM data occurred in the JJA period and the worst in the SON and DJF periods, as observed by Saldanha et al. (2015) in a study carried out with GPCP data in South Brazil.

In the general context, when evaluating all quarters simultaneously from 2012 to 2019, the three groups of satellites obtained excellent performances in the results of the statistical indicators, especially the precipitation estimates from the GPM (r = 0.85, d = 0.92, MAE = 24.41 mm and RMSE = 29.21 mm). This result reinforces the good ability of the GPM IMERG-F product to adequately capture the seasonality of precipitation (Gaona et al. 2016; Rozante et al. 2018; Rodrigues et al. 2021), as well as the TRMM TMPA (Reis et al. 2017) and GPCPMON (Saldanha et al. 2015; Torres et al. 2020) products in Brazil. However, when analysing the periods separately, there were some relatively inferior results, especially in periods with higher temperatures (Higgins et al. 2010; Saldanha et al. 2015). This can be explained by the formation of isolated convective systems (Saldanha et al. 2015) and warm clouds over the region studied during these periods, which in turn generate worse satellite precipitation estimates (Rodrigues et al. 2021).

Finally, from the seasonal statistical analyses, it is possible to infer that the increase in the time scale improves the performance of the precipitation estimates of the GPM, TRMM and GPCP satellites (Pedreira Junior et al. 2021). Table 1 shows the general results of the *r*, *d*, MAE and RMSE indicators on the daily, monthly and seasonal scales of the three groups of satellites analysed. The values shown in bold represent the better performance and values in italic represents worse performance of that satellite when compared to the others, while the results in normal style symbolize intermediate performance or a tie with another satellite. In general, it is possible to conclude that the GPM estimates are more reliable than those of the TRMM and GPCP satellites in the municipality of Campo Grande, located in the Midwest Region of Brazil, as concluded by Pedreira Junior et al. (2021) in the state of Mato Grosso.

Table 1 General results of *r*, *d*, MAE and RMSE of the GPM, TRMM and GPCP precipitation estimates in relation to the surface observed precipitation data in the daily, monthly and seasonal time scales

Scale	Satellite	r	d	MAE (mm)	RMSE (mm)
Daily	GPM	0.67	0.79	3.08	7.55
	TRMM	*0.62*	*0.76*	*3.28*	*7.90*
	GPCPDAY	0.67	0.79	**3.00**	**7.36**
Monthly	GPM	**0.78**	**0.88**	**36.01**	**50.79**
	TRMM	0.74	0.84	42.22	59.88
	GPCPMON	*0.71*	*0.82*	*43.43*	*61.49*
Seasonal	GPM	**0.85**	**0.92**	**24.41**	**29.21**
	TRMM	*0.80*	*0.87*	*29.78*	*38.31*
	GPCPMON	0.81	0.89	26.78	34.32

The values shown in bold represent the better performance and values in italic represents worse performance of the satellite when compared to the others, while the results in normal style symbolize intermediate performance or a tie with another satellite

The limitation of this work is the use of a small study area compared to the entire municipality of Campo Grande and the state of MS. However, this is justifiable due to the lack of regularly distributed in-situ gauges with consistent and reliable data both in Brazil and in this region, as reported by Gadelha et al. (2019). Almagro et al. (2021) highlight that although Brazil is one of the most important countries for global water flows, it has scarce allocation of resources for hydrometeorological monitoring, which results in major challenges for the adequate knowledge of its water resources, including precipitation. According to Xavier et al. (2016) and Gadelha et al. (2019), the density of in-situ gauges in Brazil (1 per 720 km²) is below that recommended by the World Meteorological Organization (1 per 575 km²) (WMO, 1994), mainly in the North and Midwest Regions (Curtarelli et al. 2014).

It is important to highlight that the urban area of Campo Grande has been suffering from an increase in hydrological disasters in recent years. In this scenario, Almagro et al. (2021) concluded that the use of precipitation products from satellites improves the ability to mitigate extreme hydrological events, such as floods and droughts. Therefore, the estimates of precipitation via remote sensing can be an alternative for future studies that aim to alert the population in relation to periods and rainfall volumes more susceptible to flooding, as well as areas that require more mitigation actions on the part of the public administration, in order to minimize environmental, social and economic damage. Additionally, satellite-based precipitation products are valuable tools for data-poor regions due to their low latency and global reach, enabling continuous and high-quality monitoring of water resources (Almagro et al. 2021).

In this context, despite having been carried out outside the urban area and in a small study area, the present study sought to evaluate the performance of rainfall estimates from satellites based on available and reliable observed data close to the city, as a way of encourage the expansion of rainfall monitoring in the capital and state of MS, as well as contribute to future research with a larger study area. Finally, it is important to emphasize that one of the main advantages of using precipitation estimates via remote sensing is its temporal and spatial continuity (Melo et al. 2015). Nevertheless, it is necessary to continually update and expand the network of in-situ gauges in Brazilian municipalities in order to assess the reliability of satellite products as recommended by Melo et al. (2015).

3.4. Conclusions

The objective of this study was to compare the performance of precipitation estimates based on remote sensing of the GPM, TRMM and GPCP in relation to the data observed by in-situ gauges, in the daily, monthly and seasonal time scales, in the capital of the state of MS, Midwest Region of Brazil. On the daily scale, precipitation estimates by GPM and GPCP had similar performances and more satisfactory in relation to correlation, agreement, errors and detection of rainfall observed on the surface compared to TRMM estimates, with a slight advantage for GPCP estimates. Nevertheless, caution is needed before using daily precipitation data estimated via satellite, because no excellent statistical results were found, but moderate.

In monthly and seasonal scales, in general, the estimates from the IMERG-F product were more reliable than the estimates from the TMPA and GPCPMON products. Furthermore, it is possible to conclude that increasing the time scale considerably improves the correlation and agreement between the data estimated via remote sensing and those observed on the surface. Therefore, this study demonstrated that the estimates from the GPM, TRMM and GPCP satellites can be an alternative to the absence of surface precipitation measurements in a region close to the urban area of the municipality of Campo Grande - MS, especially the GPM estimates on longer time scales and drier periods.

In this way, it is expected that the results of this work will help in the planning of several socioeconomic activities that involve precipitation data, such as agriculture, livestock, energy generation and identification of risk areas for hydrological disasters in regions with climates characterized by dry winter and humid summer. Finally, it is recommended to increase the number of in-situ gauges and decrease their respective percentages of sampling failures, in order to allow new spatially and temporally more representative assessments between the estimated and observed precipitation data in Brazil.

Acknowledgements

To the Support Foundation for the Development of Education, Science and Technology of the State of Mato Grosso do Sul (FUNDECT) for the granting of the scholarship during the Doctorate. To UFMS and to the Postgraduate Program in Environmental Technologies (PPGTA) for the opportunity for the Doctorate. To the HEROS Laboratory and Giovanni portal of NASA for providing precipitation data from surface meteorological stations and satellites, respectively.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish All authors agree to publish.

Author Contributions Rafael Brandão Ferreira de Moraes: Writing, theoretical development, statistical analysis and making figures and tables. Fábio Veríssimo Gonçalves: Writing, analysis of results and reviews.

Funding This work is supported by Doctoral scholarship from the FUNDECT for the first author (Public Notice n.19/2019).

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Availability of Data and Materials Some of the data are publicly available and their references are provided in the manuscript. Other restricted data are available from the corresponding author upon reasonable request and with permission of the source department.

Code availability Not applicable.

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FINAL CONSIDERATIONS

The general objective of this work was to develop the Urban Hydrological Disasters Susceptibility Index (UHDSI) from indicators pertinent to different spheres (morphometry, land use and occupation, rainwater infrastructure and environmental), taking into account both infiltration and surface runoff of rainwater. As well as carrying out the application of the index developed in UHMs of a municipality located in the Midwest Region of Brazil and its validation from historical records of floods available in local information media. The indicators used in the composition of the UHDSI were average slope (Sa), coefficient of compactness (Kc), drainage density (Dd), demographic density (Ddem), degree of surface permeability (DSP), susceptibility to production of sediments (SPS), daily precipitation (Pd), degree of canalization of watercourses (DCW), condition of storm drains (CSD) and rainwater retention devices (RRD). This reinforces the concept that indicators pertinent to different spheres are crucial for analysing the hydrological susceptibility of UHMs and should be analysed together.

The main characteristics of UHMs classified with high to very high susceptibility to urban hydrological disasters according to UHSDI consist of higher soil sealing rates and population density than the other UHMs analysed, as well as insufficient and poor condition of the RRDs and crucial elements for the proper functioning of the drainage system, such as storm drains. The results of the UHDSI and historical records applied in each UHM obtained a strong correlation ($r > 0.80$), evidencing the reliability and validation of the developed index. The UHDSI is capable of assisting in the formulation of adequate political measures, guidelines and legal norms for the ordering of land use and occupation, as it indicates the UHMs that require more attention and mitigating actions from the public power for an adequate and sustainable socioeconomic development.

In view of the scarcity of consistent and reliable precipitation data in the municipality of Campo Grande-MS verified during the development of the UHDSI, new studies were carried out in order to statistically validate the TRMM precipitation estimates in the five geographic regions of the Brazil and to compare the performance of precipitation estimates based on remote sensing GPM, TRMM and GPCP in relation to data observed by in-situ gauges, on daily, monthly and seasonal time scales in the state capital from MS. On the daily scale, precipitation estimates by GPM and GPCP had similar performances and more satisfactory in relation to correlation, agreement, errors and detection of rainfall observed on the surface compared to TRMM estimates, with a slight advantage for GPCP estimates. Nevertheless, caution is needed before using daily precipitation data estimated via satellite, because no excellent statistical results were found, but moderate.

Furthermore, it is possible to conclude that increasing the time scale considerably improves the correlation and agreement between the data estimated via remote sensing and those observed on the surface. Therefore, this study demonstrated that the estimates from the GPM, TRMM and GPCP satellites can be an alternative to the absence of surface precipitation measurements in a region close to the urban area of the municipality of Campo Grande - MS, especially the GPM estimates on longer time scales and drier periods.

In this way, it is expected that the results of this work will help in the planning of several socioeconomic activities that involve precipitation data, such as agriculture, livestock, energy generation and identification of susceptible areas for hydrological disasters in regions with climates characterized by dry winter and humid summer. Finally, it is recommended to increase the number of in-situ gauges and decrease their respective percentages of sampling failures, in order to allow new spatially and temporally more representative assessments between the estimated and observed precipitation data in Brazil. Annex I display the manuscripts and articles that were developed during the Doctorate period.

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ANNEX I

- **ARTICLES PUBLISHED IN JOURNALS:**
    - **Moraes, R. B. F. de**; Gonçalves, F. V. (2021). Validation of TRMM data in the geographical regions of Brazil. *Revista Brasileira de Recursos Hídricos*, 26. https://doi.org/10.1590/2318-0331.262120210071
    - **Moraes, R. B. F. de**; Anache, A. A.; Gonçalves, F. V.; Bacchi, C. G. V. (2021). Construcción de indicadores e índice de accesibilidad en espacios públicos de Brasil. *Revista Pasajes*, v. 12, p. 1-21.
    - **Moraes, R. B. F. de**; Gonçalves, F. V. (2023). Comparison of the Performance of Estimated Precipitation Data Via Remote Sensing in the Midwest Region of Brazil. *Theoretical and Applied Climatology Journal*, p. 1-12. https://doi.org/10.1007/s00704-023-04523-z

- **MANUSCRIPT UNDER REVIEW IN JOURNAL:**
    - Manuscript "Development, application and validation of the urban hydrological disasters susceptibility index" in *Natural Hazards Journal*.

- **ARTICLES PUBLISHED IN CONFERENCES:**
    - **Moraes, R. B. F. de**; Gonçalves, F. V. *Correlação entre dados de precipitação estimados via sensoriamento remoto e observados em superfície*. In: 32° Congresso Brasileiro de Engenharia Sanitária e Ambiental (CBESA), 2023, Belo Horizonte – MG.
    - **Moraes, R. B. F. de**; Gonçalves, F. V. *Mapeamento de desastres hidrológicos na área urbana de Campo Grande - Mato Grosso do Sul*. In: 32° Congresso Brasileiro de Engenharia Sanitária e Ambiental (CBESA), 2023, Belo Horizonte – MG.
    - **Moraes, R. B. F. de**; Gonçalves, F. V. *Índice de susceptibilidade à produção de sedimentos em Microbacias Hidrográficas Urbanas*. In: XV Encontro Nacional de Engenharia de Sedimentos, 2022, Campo Grande – MS, p. 1-8.
    - **Moraes, R. B. F. de**; Gonçalves, F. V. *Comparação do desempenho de dados de precipitação estimados via sensoriamento remoto em Mato Grosso do Sul*.

In: 15° SILUSBA - Simpósio de Hidráulica e Recursos Hídricos dos Países de Língua Portuguesa e XVI SRHNE - Simpósio de Recursos Hídricos do Nordeste, 2022, Caruaru – PE, p. 1-10.