GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

Urban occupation and surface runoff in cities: a study case in Piracicaba - SP

Leonardo da Silva Granziera
Master, Pontifical Catholic University of Campinas, Brasil

Marcius Fabius Henriques de Carvalho
Doctor, Pontifical Catholic University of Campinas, Brasil
marcius.carvalho1951@gmail.com

Lia Toledo Moreira Mota
Doctor, Pontifical Catholic University of Campinas, Brasil
lia.moreira.mota@gmail.com

Cláudia Cotrim Pezzuto
Doctor, Pontifical Catholic University - SP - Brasil
claupezzuto@gmail.com

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

ABSTRACT

This study analyzes how uncontrolled human occupation can negatively impact surface runoff conditions in urban environments. For this purpose, the study assesses the correlation between rainfall, Piracicaba River flow and the urban occupation growth regarding the incidence of floods in Piracicaba-SP. To address the research question: Is the increase in flooding caused by the increased population density? The following data was used: flow and precipitation data in the urban perimeter, obtained from the Piracicaba Water and Electricity Department; population and density data from five neighborhoods based on the "Google Earth Pro" software, covering sixteen years of study. The findings indicate that three districts experienced increased flooding, while two other well-established districts did not encounter significant changes in flood frequency.

KEYWORDS: Runoff, urban occupation, flooding.

1 INTRODUCTION

As cities expand their perimeters, the demand for housing, infrastructure, sanitation, health services and education services increases, leading to a greater complexity of problems and challenges in urban management. This study explores how uncontrolled human occupation can negatively impact surface runoff conditions in urban environments. Specifically, the study aims to examine the correlation between precipitation, Piracicaba River flow, urban development and the incidence of floods in downtown areas of Piracicaba-SP. The main research question seeks to determine whether population density contributes to downtown flooding. The research analyzed flow and precipitation data within the city limits, population data, and neighborhood density using "Google Earth Pro" software over sixteen years. The results indicate that three districts have experienced an increase in flooding, while two other well-established districts did not experience significant changes in flood frequency. Consequently, new spaces are incorporated into cities and, when there are no studies and planning that recognize the potential and weaknesses of the environment, these new spaces can result in environmental degradation (BRASIL, 2016).

Streams and lakes are filled in without planning, rivers and natural areas are occupied and irregular subdivisions emerge, contributing to increased waterproofing of surfaces, causing the progressive degradation of watershed areas and influencing surface runoff conditions. Consequently, urban areas experience peak flows and stormwater pollution increases (LIMA; LOPES; FAÇANHA, 2019; SALVIANO; GROPPO; PELLEGRINO, 2016).

Effective urban planning should consider the physical alterations in the most superficial soil layers, vegetation coverage, and topography to safeguard the soil's infiltration capacity and vegetation retention. It is also significant to acknowledge that the density of urban occupation directly impacts the increase in water-resistant areas, causing modifications in surface runoff, drainage systems and resulting in larger and more frequent floods in urban centers.(HOLANDA; SOARES; OLIVEIRA, 2020).

An aspect to be examined in regards to the incidence of floods is the increase in precipitation during rainy seasons, with an assessment of whether there is an upsurge in the occurrence of intense rainfalls, with a consequent increase in the flow of watercourses and the overloading of urban drainage systems, which may contribute to an increased risk of material damage (DE SABÓIA et al., 2017). (MURARA; and MENDONÇA, 2019) state that the greater the intensity of precipitation in urban areas, the greater the damage and losses in these areas.

ISSN 2318-8472, v. 12, n. 85, 2024

Considering all the references consulted within the context of this study, the research questions arise:

(1) Is the increase in precipitation relevant to the increase in the occurrence of flood events in the areas considered for this study in the urban center of Piracicaba?

(2) Is progressive urbanization the primary cause of flooding?

In answering these questions, this research seeks to understand how phenomena such as floods and flooding are related to a combination of natural factors and human actions. The study includes an analysis of natural factors such as precipitation, river behavior, and morphometry among natural factors.

Occupation of urban areas by impoverished people is a significant issue in developing nations. This challenge arises due to a scarcity of resources, leading to suboptimal practices. Such practices are regarded as inappropriate and are recurrent in nature.

2. METHODOLOGY

This study aims to evaluate the impact of urban development and precipitation on surface runoff and its relationship with flood risk in five areas of the city center of Piracicaba. It requires gathering and examining rainfall and pluviometric data that is obtainable within the boundary of the local authority, coupled with past data from 2002 until 2020. Population growth, density and urbanization levels will be studied by collecting data from databases of the Brazilian Institute of Geography and Statistics (IBGE, 2022) and State Data Analysis System (SEADE, 2021) during the study period. The contribution of the urban growth will be evaluated through photointerpretation analysis of historical images of the municipality. Based on the acquired data, this research questions the impact of increased soil sealing on the frequency of floods in the urban area of Piracicaba. The analysis concludes that the urban areas of Piracicaba experienced flooding during the study period. The following section presents the study area's characterizations, along with identifying the data collection points for flow and precipitation.

2.1 Characterization of the study area

The study object of this research is the urban perimeter of the municipality of Piracicaba, crossed by the Piracicaba River, which is located at Longitude: -47.64685° and Latitude: - 22.72372°, with a total territorial area of 1,378.069 km², an urbanized area of 110.83 km2, and a population estimated at 423,323 inhabitants (IBGE, 2022). The municipality's population density is 293.18 inhabitants per km², with a degree of urbanization of 98.20% and a geometric annual growth rate between 2010 and 2021, of 0.66 (SEADE, 2021).

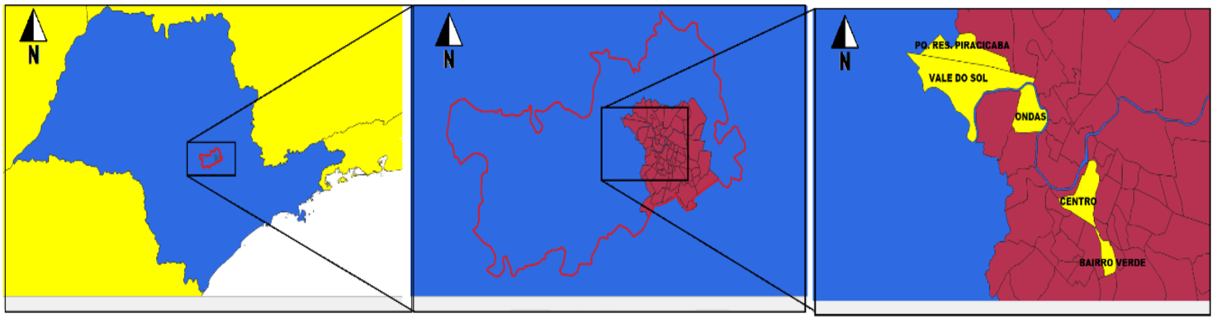
The municipality lies 152 km away from the State of São Paulo capital, belongs to the Campinas Administrative Region and is served by the SP 127, SP 147, SP304 and SP 308 highways. Situated on the border of the municipalities of Rio Claro, Limeira, Santa Bárbara D'Oeste, Laranjal Paulista, Iracemápolis, Anhembi, São Pedro, Charqueada, Rio das Pedras, Tietê, Conchas, Santa Maria da Serra, Ipeúna and, Saltinho (IPPLAP, 2022).

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

Five districts were selected for analysis based on three criteria: proximity to the banks of the Piracicaba River, occupation evolution throughout the study period and potential vulnerability to flooding, as indicated in the Municipal Master Plan. Figure 1 displays the geography of the districts, while Figure 2 provides a detailed breakdown of their locations.

Figure 1: Location map of the study area.

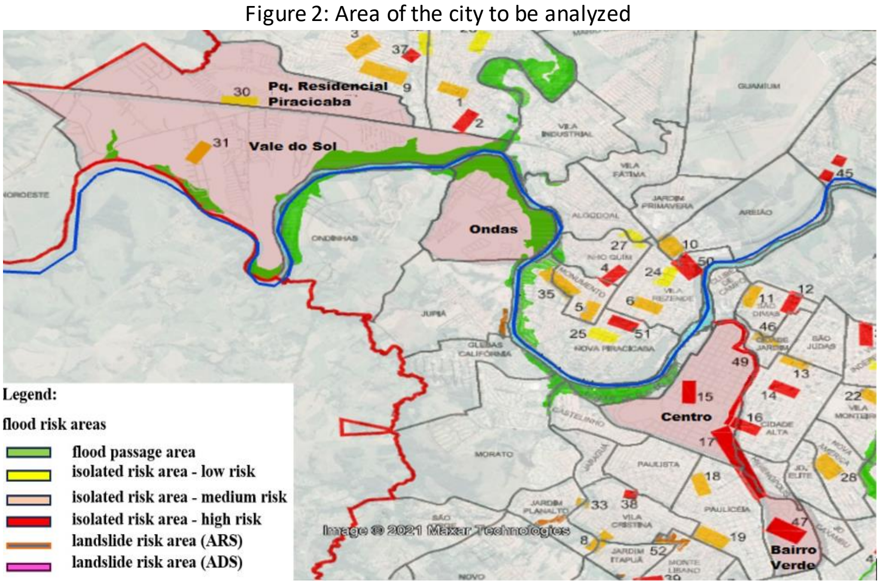


Source: Adapted from PMP (2023).

The left image in Figure 1 illustrates the location of the municipality of Piracicaba within the State of São Paulo. The central image denotes the area under investigation, while the image on the right illustrates the 5-districts considered in this research (Parque Residencial Piracicaba, Vale do Sol, Ondas, Centro and Bairro Verde).

The survey conducted by the State Department of Civil Defense highlights the regions in green and yellow colors, located on the banks of Piracicaba River, as shown in Figure 2 (GOVERNO SP, 2023).

Figure 2: Area of the city to be analyzed



Source: Adapted from PMP (2023).

ISSN 2318-8472, v. 12, n. 85, 2024

2.2 Sample points location

The collection of flow data from the Piracicaba River involves two specific points, as indicated in Figure 3. The first point is located upstream, and the second point is downstream of the city, respectively. Furthermore, the third point denotes the location for precipitation data collection. Notably, these three points are situated along the perimeter of the municipality of Piracicaba. From 2002 to 2018, the Department of Water and Electric Energy (DAEE, 2022) conducted telemetric monitoring and acquired data on daily rainfall and flow.

Figure 3: Location of points related to rainfall and flow data - Piracicaba, SP

Source: Adapted from GOOGLE-EARTH (2023).

3 CASE STUDY

This section provides an analysis of the data collected regarding river flows, precipitation, floods, and urban occupation during the study period from 2002 to 2018.

3.1 Analysis of the River Flow data over the study period

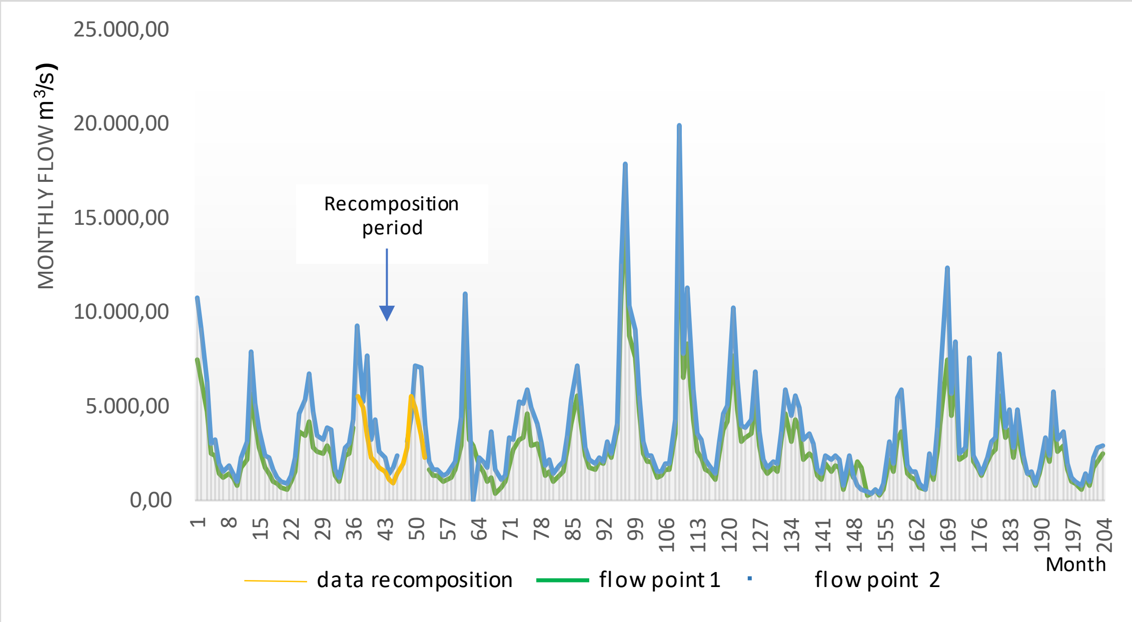
Statistical analyses were carried out to evaluate the consistency of the data, trends and to identify possible behaviors over the years. The lack of flow data at this point, for the months of 01/2005 to 04/2006 and the months of 2014 of the study period (2002 to 2018) was recomposed by applying the time series forecast model for seasonal data (LEVINE et al., 2012).

The flow rates during the study period for both stations are illustrated in Figure 4, which is identified in the blue line (Point 2) and green line (Point 1) in Figure 3. The flow rated during the recovery period for Point 1, from 36 to 56 months, is depicted in yellow.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

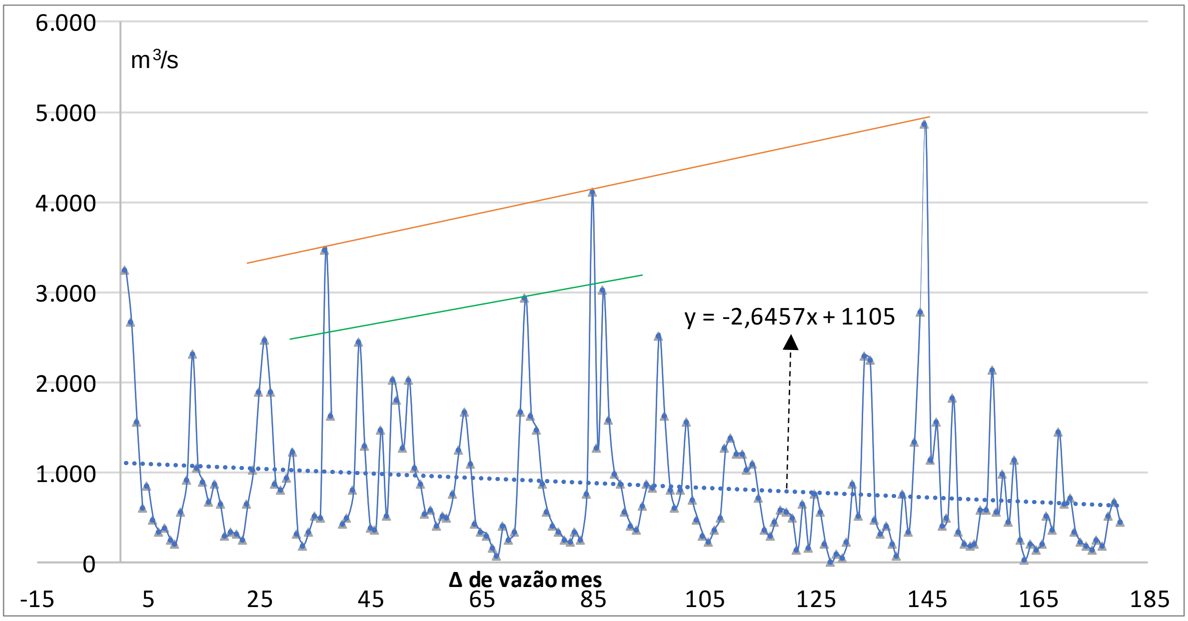
ISSN 2318-8472, v. 12, n. 85, 2024

Figure 4. Representation of the flow river behavior through the observation horizon.



The dotted line in Figure 5 shows the difference between the downstream and upstream flow in the Piracicaba River, named Delta flow. This information enables us to evaluate the impact of the flow variations within the urban perimeter throughout the study period.

Figure 5. Assessment of the flow delta trend throughout the study period.



The analysis of the Delta flow variable is represented by the trend line defined by Equation 1.

$$Y = -2{,}6457 . X + 1105 \quad \text{Eq. 1}$$

ISSN 2318-8472, v. 12, n. 85, 2024

The initial coefficient of Eq.1, which represents the slope of the line, is negative, indicating that the delta is decreasing. That is, the difference between the downstream water flow at the end of the city, point 2, and the upstream point 1 in Figure 3 decreases over the study horizon. On the other side, the first-order Delta peak, represented by the orange line, and the second-order Delta peak, green line, increase significantly during the horizon period, which could contribute to the occurrence of flooding in the city.

3.2 Analysis of Precipitation in the Period.

Table 2 displays a stratum of monthly rainfall data for January and February from 2002 to 2018. During the analysis period, the highest monthly rainfall was recorded in January. Figure 6 displays the precipitation graph for January and February, and Eq.2 describes the precipitation behavior adjustment represented by a dotted trend line. In this adjustment, the variable (x) represents the year under examination and (y) depicts the precipitation value.

$$y = -3.2821X + 294.09 \qquad \text{Eq.2}$$

It is observed that Eq. 2 has a slightly negative slope (-3.2821). This result indicates the same direction of the Delta flow behavior throughout the study period, the decrease in precipitation. This finding is consistent with the result obtained by Salviano, Groppo & and Pellegrino (2016) when studying the southeastern region of Brazil, which indicates a slight decrease in precipitation.

Table 2 - Monthly precipitation data (mm) for the years 2002, 2007, 2011, 2016 and 2018, considering the summer period (December to March).

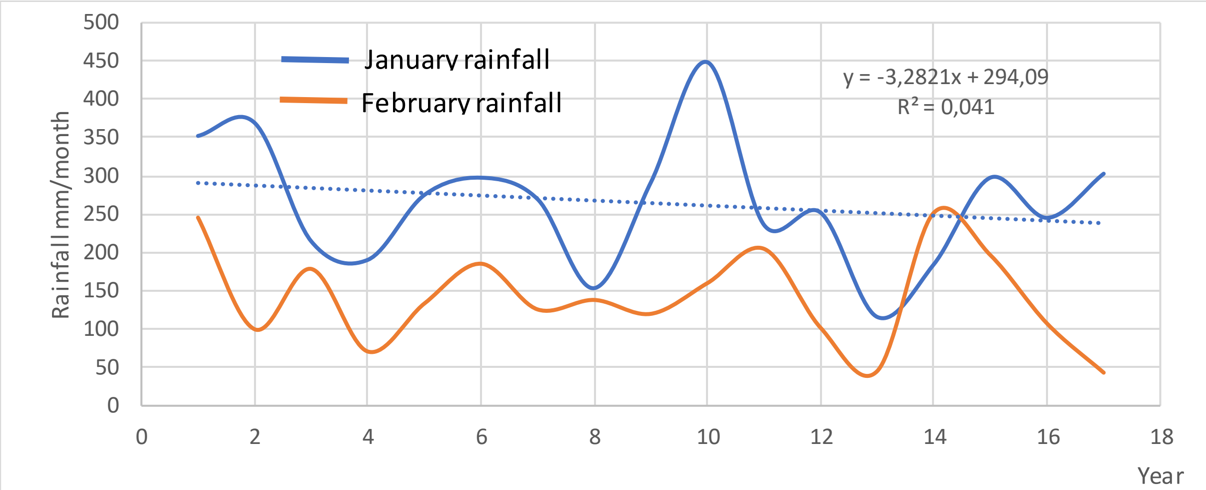
	Monthly precipitation (mm)			
Year	Dec.	Jan.	Feb.	Mar.
2002	150,4	352,2	245,6	323,3
2007	309,1	297,7	185,4	54,9
2011	145,4	448,4	160,1	245
2016	184,4	297,8	196,5	152,6

The slight decrease in precipitation over the study period contrasts with the trend of a sharp increase in the delta flow for the month of January, the flooding of part of the city, as shown in Figure 6.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

Figure 6 – Precipitation in the months of January and February, between 2002 and 2018.



3.3 Flow variation in the critical months

The first step in determining the occurrence of flooding in downtown Piracicaba was to assess whether there was a significant flow variation during the critical study period that could influence adverse events. The months of December, January, February, and March and the years 2002, 2007, 2011, 2016, and 2018 were selected for the study, as they represent the period of greatest flow within the urban perimeter of the city and, therefore, the most relevant for the assessment of flooding. Table 1 illustrates the flow disparity between the downstream and the upstream stations.

Table 1 –Delta Flow for the period of study, (m3/s)

	Month			
Year	Dez.	Jan.	Feb.	Mar.
2002	910,74	3247,88	2672,10	1566,36
2007	513,12	3480,28	1628,14	3321,74
2011	837,71	4112,22	1270,16	3036,01
2016	591,67	4869,42	1142,71	1554,96
2018	453,37	1453,08	660,99	715,07

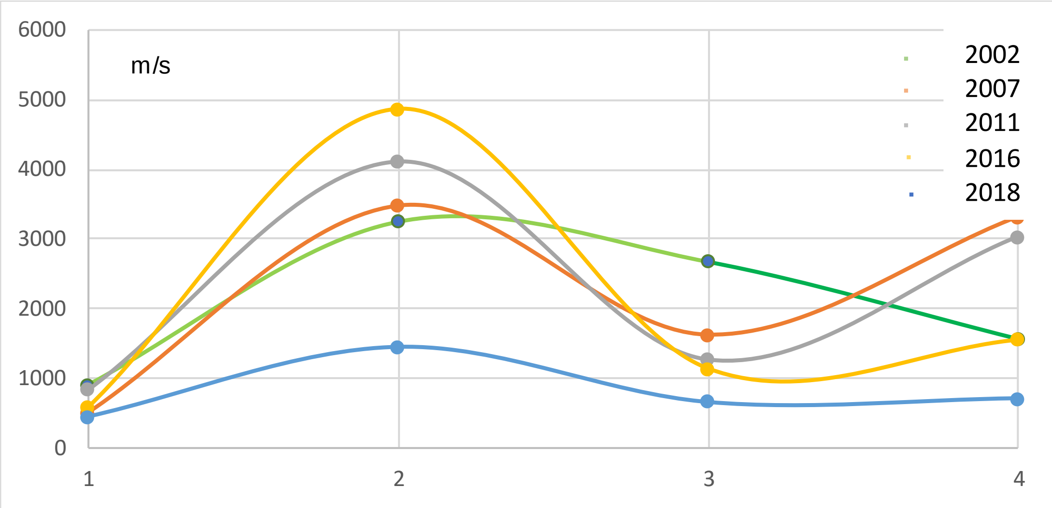
The flow increments behavior between upstream and downstream stations for the four months and five years considered in the study is depicted in Figure 7. According to the analysis, January exhibited the highest increase in flow during the study period, making it the most relevant period for

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

identifying floods in the city. Specifically, the flow increased from 3,247.88 m3/s in 2002 to 4,869.42 m3/s between 2002 and 2018, representing a 49% increase in volume.

Figure 7 – Monthly flow increments from 2002 to 2018. Period (December to March)



3.4 Precipitation Analysis in the period 2002 - 2018

Table 2 displays a stratum of monthly rainfall data for January and February during the period from 2002 to 2018. On average, monthly rainfall is highest in January. The rainfall graph for January and February, for all years from 2002 to 2018, is shown in Figure 8.

Table 2 - Monthly precipitation data (mm) for the years 2002, 2007, 2011, 2016, and 2018, considering the summer period (December to March)

	Monthly precipitation (mm)			
Year	Dez.	Jan.	Feb.	Mar.
2002	150,4	352,2	245,6	323,3
2007	309,1	297,7	185,4	54,9
2011	145,4	448,4	160,1	245,1
2016	184,4	297,8	196,5	152,6
2018	164,2	302,9	43,2	110,1

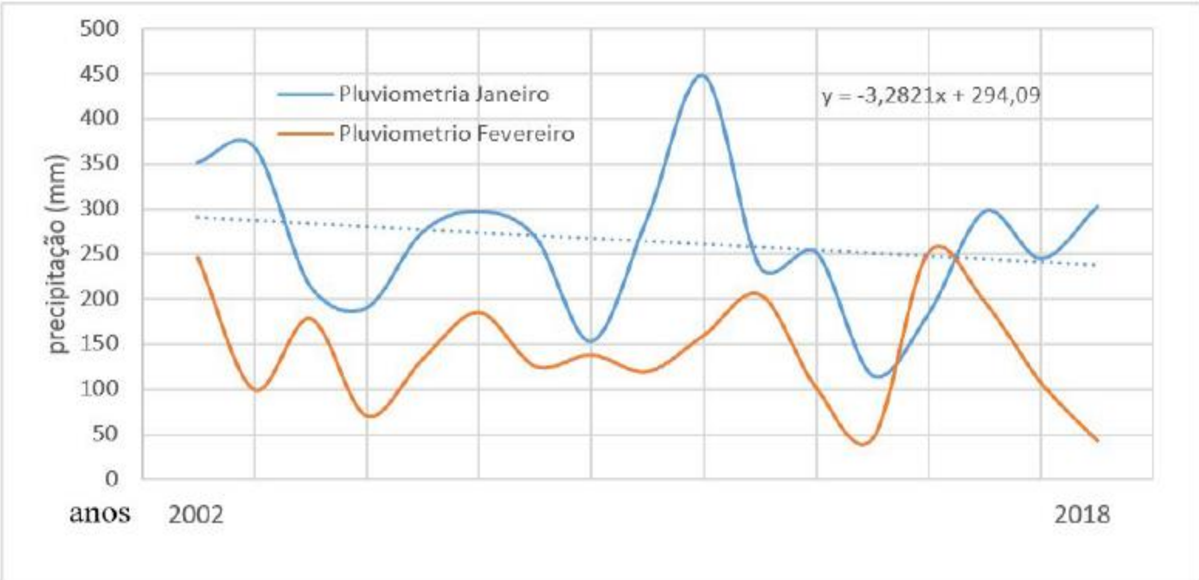
In this adjustment, the variable (x) represents the year under consideration and (y) represents the precipitation. The precipitation behavior over the period can be portrayed using a trend line described by Equation 3.

$$y = -3,2821x + 294,09 \quad \text{Eq.3}$$

ISSN 2318-8472, v. 12, n. 85, 2024

Equation 3 presents a negative slope (-3.2821). This result indicates a slightly decreasing behavior throughout the study period and is consistent with what was found by Salviano, Groppo and Pellegrino (2016), with a slight decrease in precipitation for the southeastern region of Brazil. The decrease in precipitation contrasts with the marked growth trend of the monthly flow for January throughout the study period, as shown in Figure 8.

Figure 8 - Monthly Precipitation in January and February for the years between 2002 e 2018.



3.5 Classification of the Urban Occupation

For the purposes of qualitative and quantitative land use analysis, a classification was conducted into three levels: high, medium, and low occupation, using the photointerpretation technique, based on historical images and following the proposal of Mattos, et al. (2009).

I - Low Occupancy Class – adopted in situations where there are trees in the streets, lawns in the passageways, and houses with gardens and backyards, the setbacks between buildings are wider and not connected, allowing greater ventilation. Furthermore, there is a smaller concentration of people.

II – Middle-Class Occupation – adopted when urbanization is less dense, but there is already a closer proximity between housing and a reduction in green areas.

III – High Occupancy Class – adopted when it is observed that the buildings are adjacent to each other, there is practically no green area, the sidewalks are narrow, the streets are paved and there are docks providing access to the riverbank. Additionally, this area experiences a greater concentration of people in the upper class, with typically little ventilation and a resulting increase in temperature.

This classification aims to associate urban occupation with the context of flooding.

ISSN 2318-8472, v. 12, n. 85, 2024

3.6 Population growth versus degree of urbanization

The municipality's urban growth rate was obtained from the Piracicaba Research and Planning Institute rate (IPPLAP, 2021) report. This information was then used to analyze the occupancy index of various districts including Vale do Sol, Residencial Parque Piracipaba, Ondas, Centro and Bairro Verde.

Regarding the development of urban occupation within the municipality and the degree of urbanization (quotient between the urban population and the total population of the municipality), there was a tendency of advance in the period from 2002 to 2018, as observed in Table 3.

Table 3 - Population Growth x Urbanization - Piracicaba- SP.

Year	Number of inhabitants	Degree of urbanization %
2002	336.473	96.21
2007	354.214	97.06
2011	367.004	97.91
2016	380.494	98.10
2018	400.949	98.51

3.8 Occupation classification in study areas

This item analyzes the behavior of five areas of occupation under study. The study employed image analysis based on the nomenclature proposed by Mattos et al. (2009), for the years 2007, 2011, 2016 and 2020, as shown in Table 4. Although flow and precipitation analyses were conducted and compared through 2018, the population growth assessment was extended through 2020. The purpose was to demonstrate that these data did not suffer a significant decrease or increase in percentages even when the analysis period was extended, as shown in Table 4.

ISSN 2318-8472, v. 12, n. 85, 2024

Table 4 – District occupancy rate

District	Occupancy	2007	2011	2016	2020
Ondas	Low	92,8%	90,41%	68,30%	66,9%
	Mean	7,2%	9,59%	23,97%	23,97%
	High	0,0%	0,0%	7,73%	9,04%
Parque Residencial Piracicaba	Low	77,7%	69,83	64,89%	64,89%
	Mean	0,0%	0,0	3,44%	3,44%
	High	22,28%	30,17	31,67%	31,67%
Vale Do Sol	Low	97,15%	89,23	88,6%	87,32%
	Mean	2,69%	4,85	6,12%	6,12%
	High	0,16%	5,92	6,55%	6,55%
Centro	Low	9,14%	8,79	8,1%	8,10%
	Mean	0,00%	0,0	0,0%	0,0%
	High	90,86%	91,21	91,9%	91,9%
Verde	Low	18,97%	18,97	18,97%	18,97%
	Mean	0,0%	0,0	0,0%	0,0%
	High	81,03%	81,03	81,0%	81,03%

3.9 Evolution of District occupation

The Ondas district, located in the western region of the municipality, has experienced a notable surge in occupancy since 2011. Occupancies between medium and high density increased by 25.74%.

The Parque Residencial Piracicaba district, situated in the northern region of the municipality, experienced a 9.39% increase in occupancy, contributing to a total of 12.84% occupancy, including medium density, by 2020. In the Vale do Sol neighborhood, also located in the northern region of the municipality, there was a less significant increase from 2007 between medium and high occupancy, with changes totaling 9.82% by 2020.

Centro district had the characteristics already classified as highly occupied since 2007, with little possibility of changes in study period. This result was expected, as it is the central area of the city, with occupancy already consolidated by many vertical buildings.

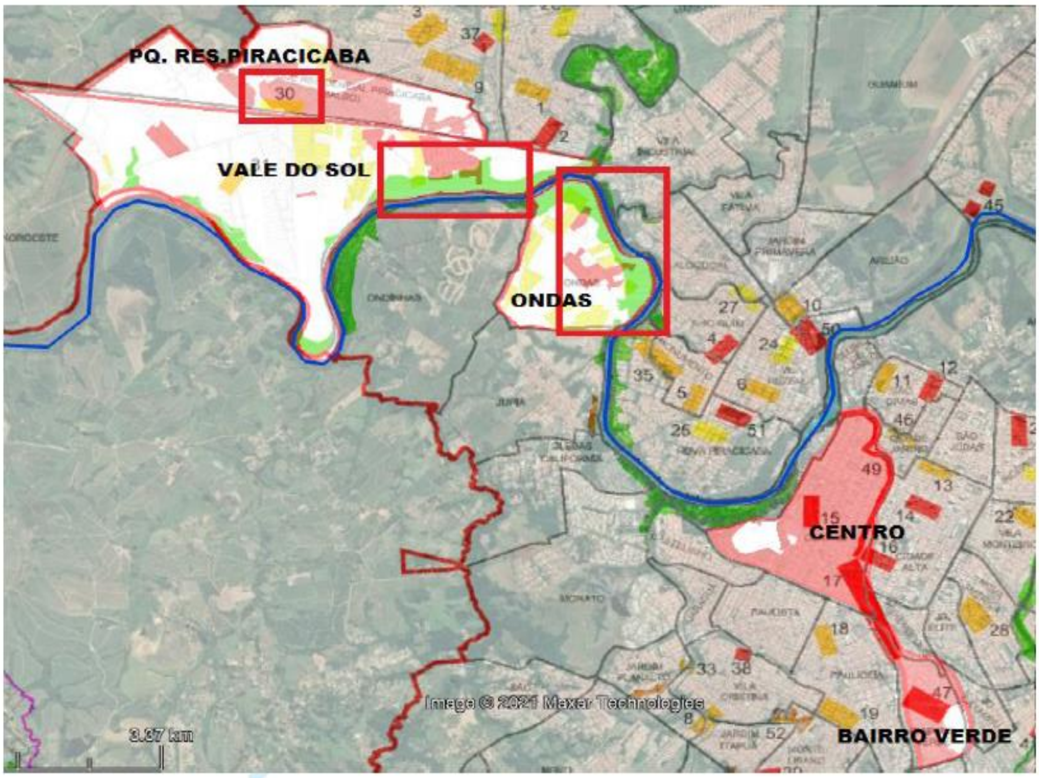
Verde district, located in the southern region of the municipality, the last district analyzed, was also characterized mostly as high occupancy, without intermediate characteristics of medium occupancy. This neighborhood has been fully consolidated since 2007, with approximately 81.23% of its territorial area maintaining a high occupancy density until 2020. However, 18,97% of its territorial area still has low occupancy density.

In conclusion, of the five districts, three had significant variations in population density (Ondas, Parque Residencial Piracicaba, Vale do Sol) and two did not (Centro and Bairro Verde). District risk areas are depicted in Figure 9, marked by red rectangles.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

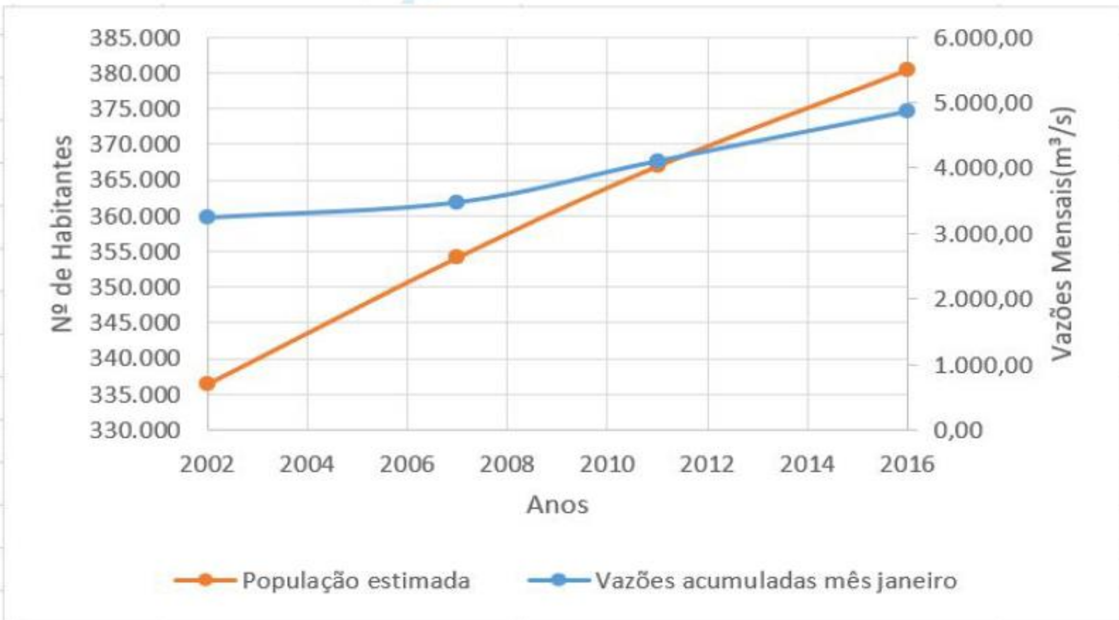
ISSN 2318-8472, v. 12, n. 85, 2024

Figure 9 – Occupation in flood risk areas.



Source: Adapted from PMP (2023).

Figure 10 - Flow for the month of January X Estimated population for the study period.



Population growth during the given period was 13.1%, whereas the growth rate of flow for January of the same period was 49.9%. The results illustrate significant growth and indicate that the

ISSN 2318-8472, v. 12, n. 85, 2024

flow in January demonstrated more substantial growth within the urban perimeter, as presented in Figure 9. Additionally, non-uniformities were present in the population's growth pattern, as depicted in the following analysis.

4. FINAL CONSIDERATIONS

The Delta flow, which represents the difference between the flow of water collected downstream and upstream of the urban center of Piracicaba, experienced a significant increase of 49.91% between 2002 and 2016. However, during the same period, rainfall data in January, the month with the highest rainfall and flow, showed a slight decrease based on its trend line.

In contrast, the data on the population evolution of the municipality demonstrated an increase of 13.1% between 2002 and 2020. This was most pronounced in the Ondas district, as well as the Vale do Sol and Parque Residencial Piracicaba districts which represent risk and environmental protection areas, with the Ondas district being the most affected.

The historical occupation analysis from 2002 to 2018 indicates that precipitation rates, according to the collection points, did not suffer significant variations, with a slight decrease being observed. Notably, there was a significant increase in river flows between upstream and downstream.

This study is expected to contribute to municipal managers proposing a plan to mitigate the adverse effects observed today in terms of urban drainage through the implementation of successful experiments with the rain garden, which aims to reduce the speed of water, directing it through the land through afforestation and expansion of soil infiltration capacity, among other actions, desilting water courses.

REFERENCES

BRASIL, J. L. S. **Eventos Pluviais Extremos e Risco de Inundações na Cidade de Aracaju / SE**. 2016. Universidade Federal de Sergipe (UFS), 2016.

DAEE. **Departamento de Águas e Energia Elétrica: Sistema Integrado de Bacias Hidrográficas**. [s.l: s.n.]. Disponível em: <http://sibh.daee.sp.gov.br>.

DE SABÓIA, M. A. M.; DE SOUZA FILHO, F. de A.; DE ARAÚJO JÚNIOR, L. M. de; SILVEIRA, C. da S. Avaliação do impacto das mudanças climáticas no sistema de drenagem urbana em localidades situadas em baixas latitudes: Um estudo de caso em Fortaleza-CE. **Revista Brasileira de Recursos Hidricos**, v. 22, 2017.

GOOGLE-EARTH. **Mapa**. Disponível em: <https://www.google.com.br/intl/pt-PT/earth/>. Acesso em: 19 mar. 2023.

GOVERNOSP. **Governo do Estado de São Paulo São Todos. Cartas Geotécnicas de Suscetibilidade , Aptidão à Urbanização e Risco**. [s.l: s.n.]. Disponível em: <http://www.defesacivil.sp.gov.br/instrumentos-de-identificacao-de-riscos/>.

HOLANDA, M. A. C. R. de; SOARES, W. de A.; OLIVEIRA, D. B. C. de. Predição do escoamento superficial e consequentes alagamentos em centros urbanos. **Revista Ibero-Americana de Ciências Ambientais**, v. 11, n. 5, p. 1–11, 2020.

IBGE. Cidades e Estados. **Ibge**, p. https://www.ibge.gov.br/cidades-e-estados/mt/cuiab, 2022. Disponível em: <https://www.ibge.gov.br/cidades-e-estados/ac/.html%0Ahttps://www.ibge.gov.br/cidades-e-estados/pa/santarem.html>.

IPPLAP. **Instituto de Pesquisas e Planejamento de Piracicaba. Piracicaba em Dados.** [s.l: s.n.]. Disponível em: <https://ipplap.com.br/site/piracicaba-em-dados/>. Acesso em 12-2021

LEVINE, D. M.; STEPHAN, D. F.; KREHBIEL, T. C.; BERENSON, M. L. **Estatística: teoria e aplicações**. [s.l: s.n.]752 p.

LIMA, S. M. S. A.; LOPES, W. G. R.; FAÇANHA, A. C. Desafios do planejamento urbano na expansão das cidades: entre planos

ISSN 2318-8472, v. 12, n. 85, 2024

e realidade. **urbe. Revista Brasileira de Gestão Urbana**, v. 11, p. 1–16, 2019.

MURARA, P.; MENDONÇA, M. Variabilidade e Tendências das Precipitações Pluviais em Rio do Sul – SC. **Revista Brasileira de Geografia**, v. 06, p. 1996–2007, 2019.

PMP. **Prefeitura do Município de Piracicaba. Plano Diretor de Desenvolvimento de Piracicaba - Revisão do Plano Diretor**. [s.l: s.n.]. Disponível em: <http://planodiretor.piracicaba.sp.gov.br/plano-diretor-de-desenvolvimento-de-piracicaba/>.

SALVIANO, M. F.; GROPPO, J. D.; PELLEGRINO, G. Q. Análise de tendências em dados de precipitação e temperatura no Brasil. **Revista Brasileira de Meteorologia**, v. 31, n. 1, p. 64–73, 2016.

SEADE. **Fundação Sistema Estadual de Análise de Dados. Produtos**. [s.l: s.n.]. Disponível em: <https://www.seade.gov.br/lista-produtos/>. Acesso em 11-2021.

TARGA, M. dos S.; BATISTA, G. T.; DINIZ, H. N.; DIAS, N. W.; MATOS, F. C. de. Urbanização e escoamento superficial na bacia hidrográfica do Igarapé Tucunduba, Belém, PA, Brasil. **Revista Ambiente e Agua**, v. 7, n. 2, 2012.