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# Climate, social vulnerability, and dengue occurrence in Pernambuco, Brazil

## Clima, vulnerabilidade social e ocorrência da dengue em Pernambuco, Brasil

*Sara Nasário Tenório Alves*[1], *Camila Portela Marinho do Rego Barros*[2], *Edivan Rodrigues da Silva*[1], *Ricardo Brauer Vigoderis*[1], *Romero Luiz Mendonça Sales Filho*[1], *Werônica Meira de Souza*[1]

## ABSTRACT

Dengue remains one of the main public health challenges in Brazil. This study aimed to analyze the relationship between rainfall and dengue incidence in the state of Pernambuco, as well as to understand how socioeconomic indicators explain the heterogeneity of the disease's seasonal risk. Historical rainfall series from the National Institute of Meteorology (1961–2024), dengue notifications from the Department of Informatics of the Brazilian Unified Health System (2007–2024), and basic sanitation and Municipal Human Development Index (MHDI) indicators from the Brazilian Institute of Geography and Statistics (2010–2022) were used for municipalities in the Sertão, Agreste, and the Metropolitan Region of Recife. Climatology and mean values were calculated to characterize seasonality, and Poisson regression was applied to estimate climatic effects and simulate scenarios with rainfall increases of 10, 50, 100, and 200 mm. Rainfall was identified as the main trigger, with lags of one to three months. No trends were observed in the time series; however, the frequency of notifications increased after 2014. The model indicated that monthly increases of 50 mm raised cases by 56%, and 100 mm by 113%, particularly in Recife. The Sertão and Agreste regions, with lower MHDI and insufficient sanitation, showed higher risks; in the Metropolitan Region of Recife, unequal urbanization sustained elevated levels. In the absence of effective sanitation policies and under irregular rainfall patterns, outbreaks tend to evolve into regional epidemics. An integrated approach is recommended, including investments in water supply, sewage, and solid waste management, health education, entomological surveillance, climate monitoring, and preventive actions during the rainy season.

**Keywords:** *Aedes aegypti*; seasonality; rainfall; epidemiology; Poisson regression.

## RESUMO

A dengue permanece um dos principais desafios de saúde pública no Brasil. Este estudo teve como objetivo analisar a relação entre a precipitação pluviométrica e a ocorrência de dengue no estado de Pernambuco, bem como compreender como indicadores socioeconômicos explicam a heterogeneidade do risco sazonal da doença. Utilizaram-se séries históricas de precipitação do Instituto Nacional de Meteorologia (1961–2024), notificações de dengue do Departamento de Informática do Sistema Único de Saúde (2007–2024) e indicadores de saneamento básico e do Índice de Desenvolvimento Humano Municipal (IDHM) do Instituto Brasileiro de Geografia e Estatística (2010–2022), para municípios do Sertão, Agreste e Região Metropolitana do Recife. Calculou-se a climatologia e médias para caracterizar a sazonalidade, aplicando-se regressão de Poisson para estimar os efeitos climáticos e simular cenários com aumentos de precipitação de 10, 50, 100 e 200 mm. A precipitação foi o principal gatilho, com defasagens de um a três meses. Não se observaram tendências na série, porém a frequência de notificações aumentou após 2014. O modelo demonstrou que incrementos de 50 mm mensais elevaram os casos em 56%, e de 100 mm em 113%, sobretudo em Recife. Sertão e Agreste, com menores IDHM e saneamento insuficiente, apresentaram maiores riscos; na Região Metropolitana do Recife, a urbanização desigual sustentou níveis elevados. Sem políticas eficazes de saneamento e diante de chuvas irregulares, surtos tendem a evoluir para epidemias regionais. Recomenda-se uma abordagem integrada, com investimentos em água, esgoto e resíduos sólidos, educação em saúde, vigilância entomológica, monitoramento climático e ações preventivas no período chuvoso.

**Palavras-chave:** *Aedes aegypti*; sazonalidade; precipitação; epidemiologia; regressão de Poisson.

[1]Universidade Federal do Agreste de Pernambuco – Garanhuns (PE), Brazil.

[2]Universidade Católica de Pernambuco – Recife (PE), Brazil.

Corresponding author: Sara Nasário Tenório Alves. Avenida Bom Pastor, s/n – Boa Vista – CEP: 55292-270 – Garanhuns (PE), Brazil.
E-mail: saranasario@gmail.com

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## Introduction

Climate exerts a determining influence on the occurrence of arboviral diseases and, consequently, on human health. In recent decades, the climate-health interface has gained prominence within the scientific community, supported by substantial evidence demonstrating how climatic conditions play a critical role in population health and well-being worldwide (Mills and Donnelly, 2024; WHO, 2025).

Dengue is one of the most significant arboviral diseases in the global epidemiological scenario, representing a persistent public health problem in tropical and subtropical countries. It is estimated that more than 3.9 billion people are at risk of contracting the disease across more than 120 countries, particularly in the Americas and Southeast Asia (Olson et al., 2021). Recent studies indicate that, in the context of climate change, epidemiological modeling has projected an intensification of risk across different continents, reinforcing the need to integrate health and climate policies (Zhang et al., 2024; Childs et al., 2025).

From an epidemiological perspective, transmission is strongly seasonal, with annual epidemics that tend to coincide with periods of higher temperature, humidity, and precipitation, which favor the survival of the Aedes mosquito and shorten the virus incubation period. Epidemiological seasonality refers to the annual, and sometimes multiyear, pattern of epidemics influenced by climate, serotypes, and social factors (Ni et al., 2024; Xu et al., 2024). This pattern presents a well-defined time lag between the onset of favorable conditions, such as rainfall, and the peak of reported cases. Conceptually, this temporal lag corresponds to the time required for a sequence of events: formation of breeding sites, mosquito development, infection and viral incubation within the vector, transmission, incubation in humans, and finally, case detection and notification (Silva et al., 2016).

Brazil, due to its territorial extent, climatic diversity, and social inequalities, presents favorable conditions for maintaining the transmission cycle, with recurring epidemics recorded since the 1980s (Mesquita et al., 2021; Barcellos et al., 2024; Heath et al., 2025). Over the past two decades, the country has experienced large-scale epidemics characterized by the simultaneous circulation of different dengue virus serotypes and an increase in severe cases and deaths.

In 2024, Brazil recorded one of the largest epidemics in its history, with more than five million probable cases and over three thousand deaths reported by May. This scenario has been attributed to the reintroduction of serotypes, climate change, and structural deficiencies in sanitation and urbanization (Brasil, 2024; Lima-Camara, 2024). This pattern aligns with projections indicating the uneven expansion of mosquito-borne diseases under scenarios of global warming and increasing urbanization, particularly elevating risks in tropical countries (Colón-González et al., 2021; Nakase et al., 2024).

In the state of Pernambuco, dengue has been recorded since the 1980s, showing successive epidemic cycles and a significant burden of morbidity. Due to its geographic and climatic diversity, Pernambuco exhibits substantial spatial variation in disease occurrence. While the Sertão and Agreste regions are characterized by a semiarid climate with scarce and irregular rainfall (Rodrigues et al., 2018; Assis et al., 2021; Silva et al., 2025), the Metropolitan Region of Recife (MRR) and the Zona da Mata present high rainfall levels, exceeding 1,500 mm annually (Souza and Azevedo, 2012; APAC, 2023).

Precipitation stands out among the environmental factors that modulate dengue dynamics. Intense rainfall promotes the formation of breeding sites and accelerates the life cycle of the vector *Aedes aegypti*, while drought periods may lead to domestic water storage practices that also favor mosquito proliferation (Lima et al., 2016; Borges et al., 2024). Thus, both excess and scarcity of precipitation can influence outbreak occurrence, especially in areas with deficient urban infrastructure (Almeida et al., 2020).

Liyanage et al. (2022), in a study conducted in the Kalutara district in Sri Lanka—a region with significant geographic diversity ranging from coastal areas to tropical forest zones and with an estimated population of approximately 1 million inhabitants and a demographic density of 662 people per km²—demonstrated that variables such as unplanned urban growth, precarious housing conditions, and deficiencies in solid waste management services are key determinants in the proliferation of *Aedes aegypti*.

Social and urban inequalities play a decisive role in the spatial distribution and severity of dengue and are often intensified by rainfall. In this context, social vulnerability is a multidimensional concept based on physical, social, economic, and environmental factors that determine the degree of susceptibility of a population to adverse conditions. It acts as a risk amplifier, highlighting the interaction between environmental and social determinants in epidemiological dynamics (Almeida et al., 2020; Ashokan et al., 2024).

Despite advances in the literature, gaps remain in local studies addressing the climate-dengue relationship in Pernambuco, particularly regarding the integration of socioeconomic variables and the updating of regional time series. This study contributes by combining historical climate data, reported dengue cases, and socioeconomic indicators such as the Municipal Human Development Index (MHDI) and sanitation conditions, as well as by simulating precipitation scenarios, thereby generating updated and applicable evidence for the Pernambuco context.

Given this context, the present study aims to analyze the association between precipitation and dengue occurrence in Pernambuco from 2007 to 2024, discussing how socioeconomic indicators help explain the spatial heterogeneity of risk during the rainy season.

## Materials and Methods

### Study area

The study was conducted in the state of Pernambuco, in Northeastern Brazil, encompassing five mesoregions: the Metropolitan Region

(MR), Zona da Mata, Agreste, Sertão, and Sertão do São Francisco (Figure 1). To represent this heterogeneity, eight municipalities were selected based on the availability of historical data series and epidemiological relevance: Recife (MR); Garanhuns and Pesqueira (Agreste); Arcoverde, Cabrobó, Ouricuri, Petrolina, and Triunfo (Sertão). This selection enabled the comparison of humid and semiarid areas, with distinct urbanization and sanitation profiles, forming a consistent statewide panel for analysis.

## Data

Monthly historical rainfall series were obtained from the National Institute of Meteorology (INMET) meteorological stations, covering the period from 1960 to 2024. After consistency analysis of the datasets, priority was given to series with fewer missing values. Occasional gaps in Petrolina, Arcoverde, and Recife were filled using records from other stations within the same municipalities provided by the Pernambuco Water and Climate Agency (APAC). Monthly data on reported dengue cases were obtained from the Department of Informatics of the Brazilian Unified Health System (DATASUS/Ministry of Health) for the period from 2007 to 2024. Temporal assessment of the datasets indicated that official dengue records are only available from 2007 onward.

Considering the temporal overlap between rainfall series and arboviral notification data, eight municipalities were selected with compatible time series covering the same period and representing the mesoregions of Pernambuco. Of these, five are located in the Sertão (Arcoverde, Cabrobó, Ouricuri, Petrolina, and Triunfo), two in the Agreste (Garanhuns and Pesqueira), and one in the MRR (Recife). These municipalities are highlighted in Figure 1.

For socioeconomic contextualization, descriptive indicators extracted from the 2010 and 2022 Demographic Censuses (Brazilian Institute of Geography and Statistics — IBGE) were considered, including population, population density, average household income, access to piped water, sanitation services, solid waste collection, and availability of exclusive household bathroom facilities.

## Methodological procedures

Monthly rainfall climatology (1961–2024) was calculated using monthly averages to identify seasonal patterns. According to the World Meteorological Organization (WMO, 2017), the climate of a region is defined based on historical series of at least 30 years. For dengue, monthly and annual averages were calculated, and time series from 2007 to 2024 were constructed to identify regions with higher incidence and epidemic peak months and years.

To assess the influence of socioeconomic indicators on dengue spread, based on IBGE Census data from 2010 and 2022, the following indicators were considered: population, population density (PD), number of occupied households, average income (R$), and the percentage of sanitation-related indicators, including access to piped water supply, sanitation systems (connected to the public network, drainage system, or septic tank), waste collection, exclusive household bathroom facilities, and dengue records.

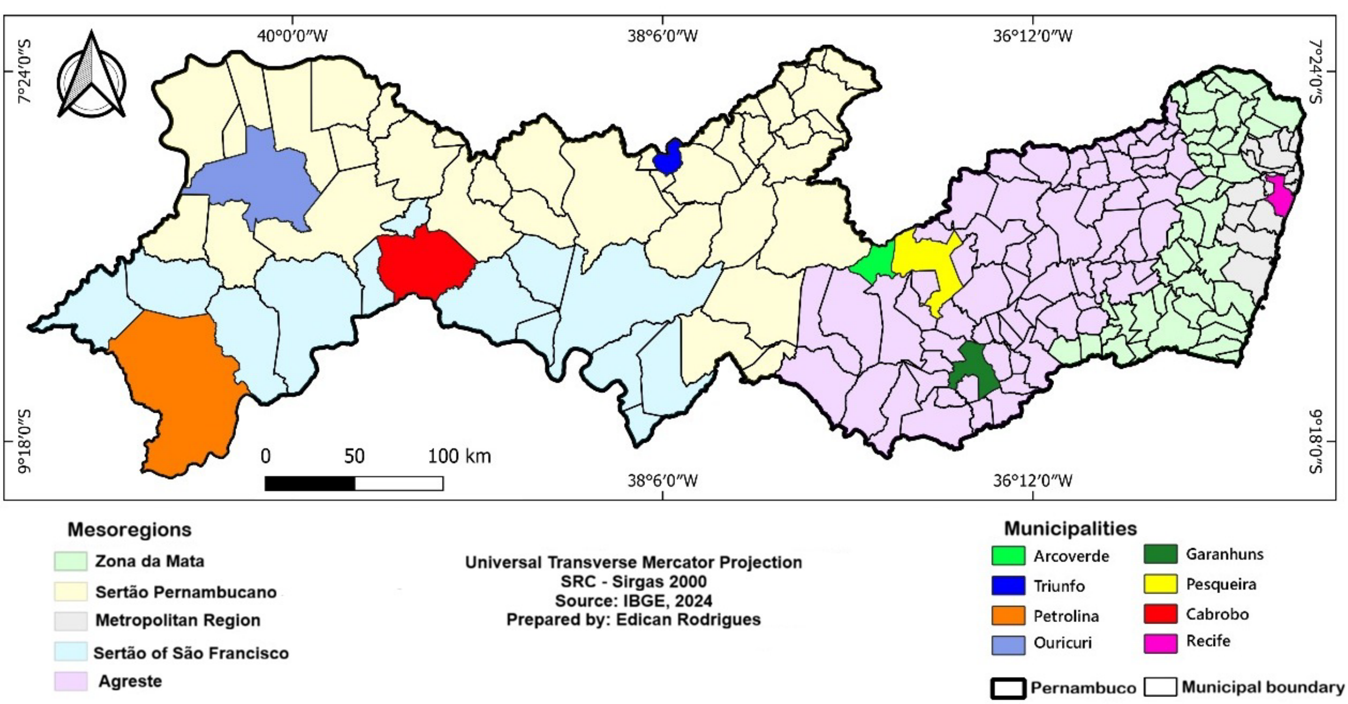
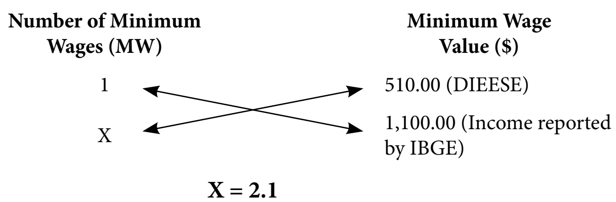



**Figure 1 – Location of the studied municipalities in the mesoregions of Pernambuco.**

Average income (R$) was converted into the number of minimum wages (MW) based on the official values provided by the Inter-Union Department of Statistics and Socioeconomic Studies (DIEESE, 2025), corresponding to R$ 510.00 in 2010 and R$ 1,212.00 in 2022. For example, if a household had an income of R$ 1,100.00 in 2010 (IBGE Census), the number of minimum wages was calculated using the following relationship:




Where:
X: 2.1 indicates that, in 2010, the household received 2.1 minimum wages.

According to DIEESE (2025), the minimum income required to support a household in 2010 and 2022 was R$ 1,987.26 (3.9 minimum wages) and R$ 5,997.14 (4.9 minimum wages), respectively. The analysis also considered the school enrollment rate of the population aged six to 14 years (%) and the number of healthcare facilities linked to the Brazilian Unified Health System (SUS), with data obtained from IBGE for the years 2010 and 2009, respectively. In addition, the MHDI, including its sub-indices (income, longevity, and education), was obtained from the Atlas Brasil platform (http://www.atlasbrasil.org.br/consulta) based on the year 2010. These indicators have not yet been updated by government agencies, limiting access to more recent data on the socioeconomic conditions of the analyzed municipalities.

To assess the MHDI, classification thresholds established by Atlas BR (2025), in accordance with the United Nations Development Programme (UNDP), were used. The MHDI ranges from 0.000 to 1.000, with values closer to 1.000 indicating higher human development at the state, municipal, or metropolitan level. The classification adopted was: 0.000–0.499 (Very Low); 0.500–0.599 (Low); 0.600–0.699 (Medium); 0.700–0.799 (High); and 0.800–1.000 (Very High).

Based on this information, three tables were constructed to evaluate household access to basic services—such as treated water, sanitation, and solid waste collection—in relation to dengue case records. Municipal indicators were also considered, including MHDI, MHDI-Income, MHDI-Longevity, MHDI-Education (2010), school enrollment rate for ages 6–14 (2010), number of SUS healthcare facilities (2009), and annual dengue case records from 2007 to 2024, aiming to understand the relationship between these indicators and their impact on disease dissemination.

A conceptual model was developed as a theoretical framework based on the organization of socioeconomic indicators (Hagenlocher et al., 2013; Louis et al., 2014), considering three hypothetical scenarios: Current Scenario, Ideal Scenario, and Critical Scenario. These scenarios were defined based on MHDI, average income, and sanitation indicators (access to piped water supply, sanitation services, waste collection, and availability of exclusive household bathroom facilities). The simulations were applied to the Sertão, Agreste, and MRR to assess potential variations in socio-structural contexts and their implications for dengue vulnerability.

For the Current Scenario, the arithmetic mean of the selected indicators was calculated and normalized on a scale from 0 to 1 to facilitate comparison among variables. Regarding income, the minimum wage required to support a household (R$ 5,997.14, equivalent to 4.9 minimum wages) was considered based on DIEESE (2025) for the year 2022, although the official minimum wage at that time was R$ 1,212.00.

Sanitation indicators were expressed as percentages (%). For simulation purposes, these data were normalized based on the Ideal Scenario, which assumes 100% coverage (or 1 on the scale) for each service. The MHDI, by definition, already ranges from 0 to 1. For the Critical Scenario, an MHDI value of approximately 0.550 was adopted, corresponding to municipalities with the lowest recorded indices in Brazil, according to the Atlas of Human Development in Brazil (Atlas BR, 2013; PNUD, 2013). Thus, the three scenarios—Current, Ideal, and Critical—were simulated for the three mesoregions of Pernambuco.

The association between precipitation and dengue occurrence was investigated using a Poisson regression model, commonly applied in epidemiology to assess the relationship between exposure to a risk factor and disease occurrence (Sriklin et al., 2021), as described in Equation 1:

$$\ln(Y) = \beta_0 + \beta_1 X_1 \qquad (1)$$

Where:
Y: the dependent variable (number of dengue cases);
$X_1$: the independent variable (precipitation);
$\beta_0$ and $\beta_1$: the regression coefficients representing the effect of each independent variable on the dependent variable; and ln denotes the natural logarithmic function.

The precipitation and dengue case time series were standardized for the period from 2007 to 2024, and the coefficients $\beta_0$ and $\beta_1$ were estimated using the Poisson model for each municipality.

A model with log-transformed precipitation was also fitted (Equation 2) for scenario simulation:

$$\hat{Cases} = \exp[\beta_0 + \beta_1 \cdot \mathrm{Log}(rainfall)] \qquad (2)$$

Based on the estimated coefficients ($\beta_0$ and $\beta_1$), hypothetical precipitation scenarios (10, 50, 100, and 200 mm) were simulated for each municipality, allowing the prediction of dengue incidence under different rainfall conditions.

The selection and validation of the final model were based on deviance analysis and the Akaike Information Criterion (AIC), ensuring a balance between goodness of fit and model parsimony. Statistical analyses were conducted using R software (version 4.4.1), including the generation of graphs, time series, and municipal-level simulations.

## Results and Discussion

### Seasonality of rainfall and dengue cases

The analysis of monthly climatology for the period 1961–2024 revealed distinct precipitation patterns across the mesoregions of Pernambuco, and showed that dengue incidence follows rainfall seasonality with a short time lag.

In the Sertão (Figure 2), the main rainy season occurs between January and April, with rainfall ranging from 80 to 130 mm, with March being the wettest month. The dry season lasts from six to eight months, with rainfall below 20 mm and often close to zero. An exception is Arcoverde (Figure 2a), where the rainy season extends from March to July due to its proximity to the Agreste region, and Triunfo (Figure 2e), which presents a humid period from January to July, with rainfall between 110 and 180 mm, influenced by local altitude. These results are consistent with previous studies (Silva et al., 2017; Assis et al., 2021; Silva et al., 2025).

Regarding the average dengue incidence, in Cabrobó, Petrolina, and Triunfo (Figures 2b, 2d, and 2e), peak cases occur 2–3 months after the rainfall maximum (January to March). In Arcoverde (Figure 2a), a lag of 1–2 months (April–May) is observed following the rainiest months (March–April), as well as an off-season outbreak (October–November), suggesting the influence of local determinants. In Ouricuri (Figure 2f), peaks occurred from February to April, possibly influenced by rainfall from the end of the previous year and/or temperature.

This temporal lag is consistent with studies demonstrating that water availability prolongs the survival and competition between *Aedes aegypti* and *Aedes albopictus*, allowing transmission to persist even after the immediate end of rainfall (Butakka et al., 2022). Scientific evidence also confirms that environmental changes, such as pollution and pesticide use in urban water bodies, can increase the risk of arboviral diseases by altering vector habitats (Rico et al., 2022).

In the Agreste region, Garanhuns presents its wet period from March to August, with rainfall ranging from 85 to 145 mm, with the highest values occurring during the May-June-July quarter (Barbosa et al., 2018; Rodrigues et al., 2018). Dengue cases, however, occur from January to May, peaking in May, suggesting a short lag of zero to two months. In Pesqueira, although precipitation occurs between February and June, the average dengue notifications are concentrated between March and May, with an off-season outbreak in December, suggesting additional influences such as water storage during dry periods, inadequate sanitation, and surveillance limitations.

In Recife (MR), rainfall occurs from March to July, and dengue reaches its peak between March and June, indicating a lag of zero to one month, while maintaining elevated levels throughout the year. Although the association with rainfall is evident, high humidity and population density sustain residual transmission even during the less rainy season. This regularity in precipitation ensures a continuous availability of breeding sites for mosquitoes (Reinhold et al., 2018). Recent studies project that, under climate change and increasing urban density, Aedes aegypti populations are likely to intensify in Brazilian metropolitan regions, making them future transmission hotspots (Heath et al., 2025).

These results regarding rainfall distribution in Pernambuco corroborate the findings of Barbosa et al. (2018), who reported that precipitation varies significantly across its mesoregions: the semiarid regions (Sertão and Agreste) exhibit strongly seasonal regimes with prolonged dry periods, whereas Zona da Mata and the MRR present moderate to strong seasonality but with a shorter dry season.

During rainy periods, water accumulation promotes the proliferation of *Aedes aegypti*, increasing transmission risk. Recent studies indicate that variations in rainfall patterns and urban conditions not only enhance the proliferation of *Aedes aegypti* but also favor the adaptation of *Aedes albopictus*, enabling species coexistence and increasing transmission risks in urban environments (Butakka et al., 2022; Sarker et al., 2024). During dry periods, although natural water bodies decrease, breeding sites may persist in containers and accumulated waste (Reinhold et al., 2018).

Thus, rainfall acts as the main trigger for vector proliferation, with lags of 1–3 months consistent with mosquito development and infection cycles. This highlights the need to anticipate control actions four to eight weeks before the onset of the rainy season and maintain them during the initial months thereafter, as well as to intensify surveillance in areas with off-season outbreaks.

### Dengue cases (2007–2024)

The time series of dengue cases revealed the occurrence of successive epidemic cycles in Pernambuco from 2007 to 2024 (Figure 3), following the national trend described by Brazil (2024). The years 2010, 2015, 2019, and 2024 stood out as those with the highest incidence, with records exceeding the state average across nearly all mesoregions.

In the Sertão (Figure 3a, 3b, 3c, 3d, and 3e), although no clear increasing or decreasing trend in dengue incidence was observed, there are indications of an increased frequency of the disease from 2014 onward, with alternating annual peaks among municipalities. Notably, Petrolina recorded approximately 27,000 dengue cases in 2024, and Arcoverde reported 1,700 notifications in 2015. In the other municipalities (2010 — Ouricuri; 2012 — Triunfo; 2019 — Cabrobó), case numbers did not exceed 300. These results are consistent with the strong regional hydrological seasonality and the short lags between rainfall and transmission. The prolonged dry season reduces natural breeding sites; however, domestic water storage and inadequate sanitation sustain residual transmission chains and create conditions for episodic outbreaks, a pattern commonly observed in semiarid climates (Barbosa et al., 2018; Reinhold et al., 2018).

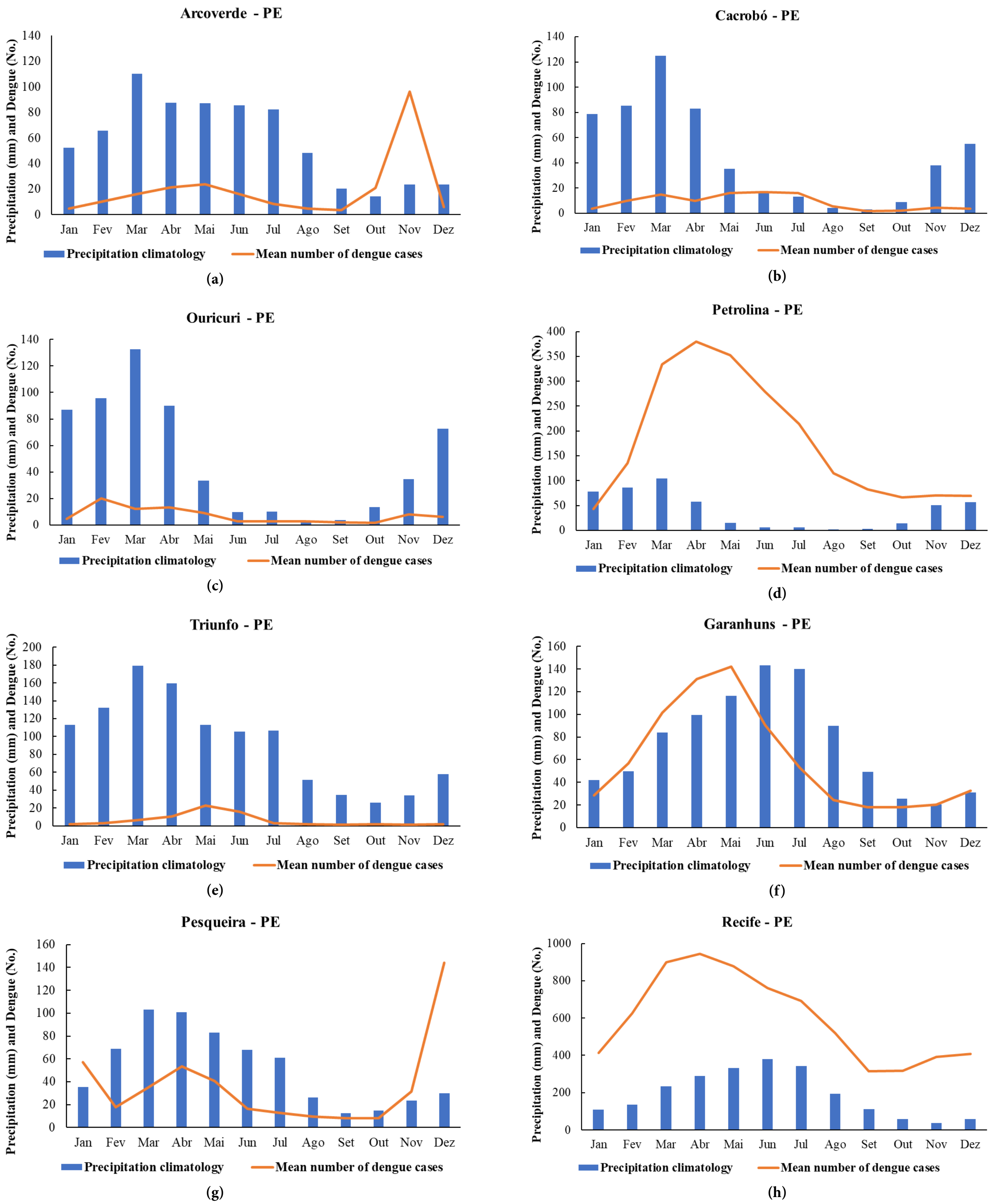



**Figure 2 – Monthly distribution of rainfall climatology (mm) and the average number of dengue cases in municipalities located in the (a, b, c, d, e) Sertão, (f and g) Agreste, and (h) the Metropolitan Region of Recife, Pernambuco.**

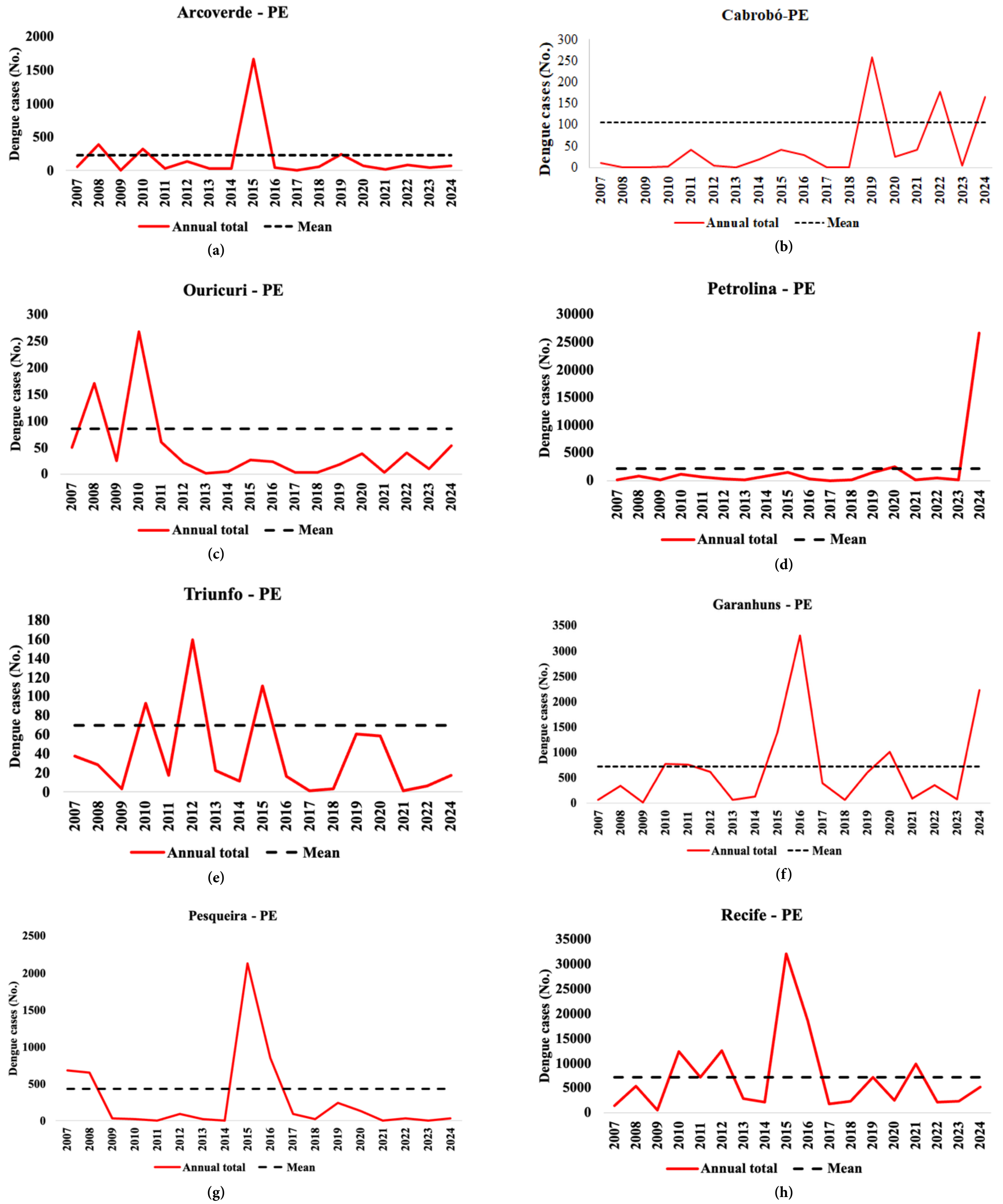



**Figure 3 – Distribution of the annual mean and total number of reported dengue cases from 2007 to 2024 in municipalities located in the (a, b, c, d, e) Sertão, (f and g) Agreste, and (h) the Metropolitan Region of Recife, Pernambuco, Brazil.**

In the Agreste and the MRR (Figure 3f, 3g, and 3h), no clear trends were observed over the analyzed period. However, from 2014 onward, an increase in the frequency of dengue notifications was identified, with the highest peaks recorded in 2015 in Recife, with nearly 32,000 cases; in 2016 in Garanhuns, with 3,300 cases; and in 2015 in Pesqueira, with approximately 2,300 reported cases.

In Recife, the elevated number of dengue cases, associated with water accumulation resulting from rainfall, high population density, and intra-urban heterogeneity, supports a nearly continuous transmission. This phenomenon has been described in tropical urban centers where structural factors reduce the dependence on rainfall (Reinhold et al., 2018; Herrmann et al., 2023).

The increase in the frequency of dengue cases from 2014 onward in Pernambuco is not solely associated with climatic conditions, but also with urban expansion, land-use changes, and socioeconomic inequalities, which favor mosquito proliferation, corroborating the findings of Rico et al. (2022). The persistence of these figures highlights the need for more effective, integrated, and continuous actions (Borges et al., 2024).

## Socioeconomic factors in dengue transmission

Dengue is an arboviral disease predominantly transmitted by *Aedes aegypti*, whose transmission dynamics are conditioned by environmental and socioeconomic determinants (Brasil, 2024). These socioenvironmental determinants directly impact individual and population health, as evidenced by the Dahlgren and Whitehead model (1991). This model organizes social determinants into concentric layers, demonstrating how individual, community, and structural factors shape health, underpinning the concept of socioenvironmental determinants as the interaction between societal organization and the physical environment that generates risks or protections to well-being.

In the context of dengue, this relationship becomes evident when rainfall—an environmental determinant at the macro scale in the outer layer of the model—acts as a key factor for egg hatching, combined with the third layer, in which inadequate sewage systems and poor solid waste management create the necessary physical breeding sites. Thus, the increase in cases is not solely a climatic phenomenon but rather the result of structural vulnerability, where deficiencies in basic sanitation and urban infrastructure transform natural rainfall cycles into severe epidemics. This highlights that health is determined by the unequal distribution of essential resources and services (Buss and Pellegrini Filho, 2007; Dahlgren and Whitehead, 2021).

To understand these linkages in the context of Pernambuco, Tables 1, 2, and 3 compile indicators of population, demographic density, income, education, Human Development Index (HDI), basic sanitation, and climatic variables. The pronounced territorial and social heterogeneity among municipalities provides a suitable framework for comparatively assessing how different structural and environmental conditions modulate vulnerability and disease spread.

Demographic density (DD), for instance, plays a crucial role in the dynamics of virus transmission (Lima-Camara, 2024). Cities with high population concentration, such as Recife—with a DD of 7,038.0 inhabitants/km² in 2010 and 6,803.60 inhabitants/km² in 2022 (Tables 1 and 2), facilitate rapid virus circulation and hinder vector control, particularly in densely occupied urban areas. Conversely, municipalities with low DD tend to present a lower risk of dissemination. However, this condition does not eliminate the need for continuous surveillance and coordinated preventive actions (IBGE, 2023).

There was a population increase in 50% of the municipalities studied—Arcoverde, Ouricuri, Petrolina, and Garanhuns—while the others showed a reduction in the number of inhabitants (Tables 1 and 2). This variation may be associated with different demographic and socioeconomic factors, including internal migratory movements observed in northeastern Brazil, such as "return migration", characterized by individuals who migrated to other regions of the country and later returned to their states of origin, not always settling in their municipalities of birth, as indicated by recent census data.

**Table 1 – Municipal indicators for 2010, including population, demographic density (DD), number of occupied households (HH), income (in minimum wages), and access to sewage (% of households with access to piped water supply, sewage systems, solid waste (SW), bathroom or toilet for exclusive household use), dengue cases.**

| Municipality | Pop. (inhab.) | DD (inhab./km²) | HH. (No.) | Income (No.) | Water (%) | Sewage (%) | SW (%) | Bathroom (%) | Dengue (No.) |
|---|---|---|---|---|---|---|---|---|---|
| Arcoverde | 68,793 | 196.1 | 20,191 | 0.9 | 85 | 86.4 | 90 | 95 | 325 |
| Cabrobó | 30,873 | 18.6 | 8,211 | 0.6 | 70 | 63.5 | 80 | 90 | 2 |
| Ouricuri | 64,358 | 26.6 | 16,591 | 0.6 | 80 | 65.5 | 85 | 92 | 269 |
| Petrolina | 293,962 | 64.5 | 80,503 | 1.1 | 95 | 72.7 | 98 | 97 | 1,155 |
| Triunfo | 15,006 | 78.6 | 4,345 | 0.8 | 60 | 31.7 | 75 | 88 | 93 |
| Garanhuns | 129,408 | 282.2 | 37,401 | 0.9 | 90 | 36.7 | 95 | 96 | 765 |
| Pesqueira | 62,931 | 63.2 | 18,429 | 0.6 | 75 | 89.87 | 88 | 93 | 25 |
| Recife | 1,537,704 | 7,038.0 | 471,210 | 2.2 | 98 | 60 | 99 | 98 | 12,439 |

Source: adapted from 2010 IBGE Census (2016) and DATASUS (Brazil, 2026).

**Table 2 – Municipal indicators for 2022, including population, demographic density (DD), number of occupied households (HH), income (in minimum wages), and access to sewage (% of households with access to piped water supply, sewage systems, solid waste (SW), bathroom or toilet for exclusive household use), dengue cases.**

| Municipality | Pop. (inhab.) | DD (inhab./km²) | HH. (No.) | Income (No.) | Water (%) | Sewage (%) | SW (%) | Bathroom (%) | Dengue (No.) |
|---|---|---|---|---|---|---|---|---|---|
| Arcoverde | 77,742 | 226.04 | 27,693 | 1.9 | 85.70 | 86.06 | 94.37 | 98.26 | 84 |
| Cabrobó | 30,294 | 18.26 | 9,997 | 1.5 | 89.50 | 69.87 | 69.76 | 96.20 | 178 |
| Ouricuri | 65,245 | 27.4 | 21,487 | 1.8 | 64.13 | 50.25 | 47.41 | 86.54 | 41 |
| Petrolina | 386,791 | 84.79 | 128,380 | 2 | 93.77 | 70.51 | 91.52 | 99.36 | 430 |
| Triunfo | 14,705 | 76.78 | 5,276 | 1.8 | 38.48 | 20.92 | 63.42 | 97.46 | 7 |
| Garanhuns | 142,506 | 310.77 | 49,029 | 1.6 | 85.87 | 59.57 | 91.55 | 98.70 | 352 |
| Pesqueira | 62,722 | 65.33 | 22,033 | 1.6 | 59.47 | 60.89 | 79.39 | 92.74 | 38 |
| Recife | 1,488,920 | 6,803.6 | 547,461 | 3.2 | 84.04 | 67.44 | 98.32 | 99.51 | 2,212 |

Source: adapted from 2022 IBGE Census (2023) and DATASUS (Brazil, 2026).

**Table 3 – Municipal indicators related to Human Development Index (HDI), HDI-Income, HDI-Longevity, and HDI-Education for 2010; school attendance rate (SAR) for children aged 6–14 in 2010; number of Unified Health System (SUS) health facilities (HF) in 2009; annual total of reported dengue cases (2007–2024).**

| Municipality | HDI (2010) | HDI – I (2010) | HDI – L (2010) | HDI – E (2010) | SAR (%) (2010) | HF (2009) | Dengue (2007–2024) |
|---|---|---|---|---|---|---|---|
| Arcoverde | 0.667 | 0.654 | 0.799 | 0.567 | 97.3 | 40 | 3,309 |
| Cabrobó | 0.623 | 0.581 | 0.773 | 0.539 | 97.6 | 21 | 842 |
| Ouricuri | 0.572 | 0.578 | 0.773 | 0.419 | 92.4 | 28 | 792 |
| Petrolina | 0.697 | 0.695 | 0.799 | 0.611 | 97 | 78 | 1,1605 |
| Triunfo | 0.67 | 0.624 | 0.817 | 0.591 | 98.4 | 8 | 653 |
| Garanhuns | 0.664 | 0.662 | 0.795 | 0.556 | 96.8 | 61 | 10,699 |
| Pesqueira | 0.61 | 0.597 | 0.751 | 0.506 | 97.4 | 38 | 5,175 |
| Recife | 0.772 | 0.798 | 0.825 | 0.698 | 97.1 | 274 | 126,843 |

Source: adapted from Atlas BR (2013), IBGE (2013), and DATASUS (Brazil, 2026).

These individuals may settle in capital cities or medium-sized urban centers, contributing to population redistribution dynamics and, in some cases, to population decline in smaller municipalities from which out-migration was traditionally higher. Another relevant factor is the process of "demographic deconcentration" in metropolitan areas, where growth shifts from the core city to surrounding municipalities. Thus, the population decline observed in half of the analyzed regions—Cabrobó, Triunfo, Pesqueira, and Recife—may be explained by this migratory process and its variability over time (IBGE, 2016).

In parallel, a temporal comparison of Tables 1 and 2 shows that all eight municipalities studied experienced a decline in at least one basic sanitation indicator in 2022, with some municipalities showing reductions across all indicators (water supply, sewage, solid waste collection, and bathroom access). It is well established that inadequate sanitation is closely associated with water accumulation and the formation of vector breeding sites, favoring the reproductive cycle of *Aedes aegypti*, the mosquito responsible for dengue transmission, making these findings particularly concerning (Lima-Camara, 2024). Similarly, Souza et al. (2024) highlight that regional variations in dengue case distribution are linked to socioeconomic inequalities, reinforcing that areas with limited access to basic services tend to exhibit higher epidemiological vulnerability.

Among the municipalities with declining sanitation indicators, Ouricuri and Pesqueira stand out, as they showed a deterioration in all indicators in 2022 compared to 2010. In the case of Pesqueira, the 52% increase in dengue cases, from 25 cases in 2010 to 38 in 2022, may also be associated with reduced access to basic sanitation, as observed in Tables 1 and 2, although this relationship does not allow for establishing a direct causal link between the analyzed variables.

These results demonstrate that municipal infrastructure—particularly regarding water supply, sewage, solid waste collection, and bathroom access—plays a significant role in sustaining disease transmission. However, it is important to emphasize that dengue prevalence is multifactorial, also being influenced by climate, education, the presence of effective public policies, and other factors beyond infrastructure. This helps explain, for instance, why Ouricuri showed a decrease in cases despite low sanitation indicators.

Table 3 presents municipal indicators related to the HDI, including HDI-Income, HDI-Longevity, and HDI-Education for 2010, the school attendance rate for children aged six to 14 in 2010, the number of SUS health facilities in 2009, and the annual total of dengue records from 2007 to 2024.

Socioeconomic inequalities among municipalities are also reflected in HDI, per capita income, and educational levels, which together directly affect communities' capacity to prevent and respond to outbreaks (Borges et al., 2024). Recife, with the highest HDI among the analyzed cities (0.772), and income levels of 2.2 minimum wages in 2010 and 3.2 in 2022 (Tables 1, 2, and 3), demonstrates better access to healthcare, education, and essential public services—key elements for dengue control.

In contrast, municipalities such as Triunfo (HDI 0.670) and Pesqueira (HDI 0.610) face significant structural limitations. In these areas, there is lower income, and reduced educational attainment hinder access to information and preventive practices, resulting in greater exposure to both the vector and the disease (IBGE, 2023).

Basic sanitation is another essential determinant in dengue control, as it directly influences the proliferation of the *Aedes aegypti* mosquito. Cities such as Petrolina (72.70%), Recife (69.20%), and Ouricuri (58.30%) present relatively high coverage levels (IBGE, 2023). However, these areas still face challenges related to system maintenance and coverage, particularly in socially vulnerable areas, where unplanned urbanization and irregular settlements compromise service efficiency.

Insufficient sanitation favors the formation of breeding sites, increasing the risk of epidemic outbreaks (Lima-Camara, 2024). A technical report by the World Health Organization reinforces that the nexus between climate and health has become increasingly central, demonstrating how structural deficiencies in sanitation, combined with climate extremes, amplify population vulnerability (WHO, 2025).

Climatic conditions in Pernambuco also significantly contribute to maintaining the vector's life cycle. The combination of high temperatures, elevated humidity, and frequent precipitation creates a favorable environment for mosquito reproduction (Borges et al., 2024). In this context, the presence of meteorological stations in the analyzed municipalities represents an important advancement, as it enables continuous monitoring of environmental variables that influence dengue dynamics.

The interaction among these factors reveals that high population density, combined with inadequate sanitation and low educational levels, creates a scenario of increased risk for dengue transmission. Conversely, municipalities with better urban infrastructure, higher income, and greater access to information tend to exhibit greater resilience to the disease. Furthermore, the availability of climate monitoring tools provides an advantage in anticipating outbreaks, allowing for coordinated responses by health authorities (Lima-Camara, 2024).

It is well established that outbreak anticipation is primarily based on the analysis of climatic patterns and their potential changes, as identified through monitoring systems. However, it is important to emphasize that the cyclical nature of dengue—driven by the alternation of serotypes—results in epidemic peaks approximately every three to five years, providing a certain degree of predictability for governments and enabling early preparedness for epidemic events (Brasil, 2024).

Dengue epidemics impose a significant burden on health systems, both in terms of increased demand for care and economic costs. Therefore, it is essential to highlight the role of the State in ensuring adequate living conditions, including universal access to basic sanitation, thereby reducing mosquito breeding and, consequently, decreasing the recurrence of cases and epidemics (Medeiros, 2024).

More than a public health issue, dengue reflects multiple dimensions of social and urban inequality. Effective prevention therefore requires not only technical interventions but also a commitment to human dignity and collective well-being. This perspective aligns with studies examining the relationship between urbanization, climate, and dengue expansion, showing that transmission tends to concentrate in socially vulnerable urban areas (Sarker et al., 2024).

Given this context, addressing dengue in Pernambuco requires an intersectoral approach, with integrated public policies sensitive to regional inequalities. Prioritizing investments in health education, expansion of basic sanitation, strengthening of urban infrastructure, and the promotion of healthier environments are fundamental measures to contain the spread of the disease.

### Simulation of current, ideal, and critical scenarios

The increase in dengue cases in Pernambuco in recent years has highlighted not only the intensification of climate change and the adaptation of the vector to urban conditions, but also the persistent inequalities in sanitation conditions and human development across the regions of the state. Figure 4 presents a simulation model of three scenarios—Current, Ideal, and Critical—for the Sertão (Figure 4a), Agreste (Figure 4b), and MRR (Figure 4c), based on the analysis of HDI, average income, and access to sanitation services. The graphical representation reveals a concerning scenario, particularly in regions with lower indices, which directly contributes to increased population vulnerability to the spread of arboviruses such as dengue.

In the Sertão and Agreste regions (Figure 4a and 4b), HDI values (0.646 and 0.637, respectively) remain below both the state and national averages, reflecting more precarious living conditions. In these regions, indicators such as access to sewage systems (59% in the Sertão and 60% in the Agreste) and solid waste collection (73 and 85%) reveal deficiencies in basic infrastructure, which favor the proliferation of the *Aedes aegypti* mosquito, remaining far from the ideal scenario of full (100%) sanitation coverage. Environments with accumulated waste, exposed sewage, and inadequate water storage create ideal conditions for vector reproduction, increasing the risk of outbreaks.

Regions with lower average income, such as the Agreste and Sertão, below two minimum wages (Table 2), have a reduced capacity for individual and collective response to disease prevention and control, exacerbating the epidemiological situation. On the other hand, the MRR (Figure 4c), despite presenting better indicators (HDI of 0.772, 84% access to piped water, and 98% solid waste collection), is not immune to the spread of dengue.

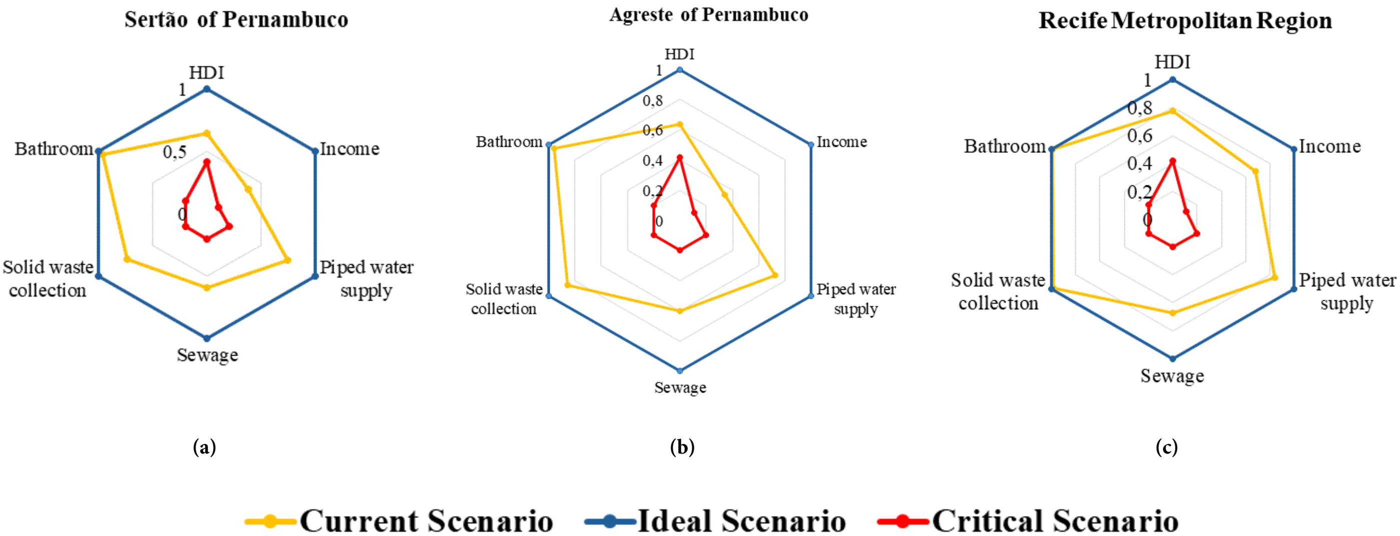



**Figure 4 – Representation of the Current, Ideal, and Critical scenarios in relation to Human Development Index (HDI), income, and sanitation indicators, including access to water supply, sewage systems, solid waste collection, and bathroom facilities in (a) the Sertão, (b) Agreste, and (c) Metropolitan Region of Recife, Pernambuco, Brazil.**

Rapid urbanization, combined with intra-urban inequality and population concentration, poses significant challenges for sanitation management, particularly in peripheral areas where services do not always keep pace with demographic growth.

The simulated scenarios demonstrate that, in the absence of effective public policies, all indicators may deteriorate significantly, with severe impacts on public health. Declines in water supply, sewage services, and solid waste collection, combined with rising temperatures and increasingly irregular rainfall—climatic factors that favor mosquito reproduction—may transform localized outbreaks into regional epidemics, corroborating findings by Colón-González et al. (2021) and Lima et al. (2024).

Thus, addressing dengue in Pernambuco requires more than emergency vector control actions; it demands structured and continuous investment in basic sanitation, reduction of social inequalities, and improvement of living conditions for the most vulnerable populations. Only through such measures will it be possible to break the cycle linking poverty, inadequate infrastructure, and disease. Furthermore, recent studies (Cheng et al., 2025; Dorigatti et al., 2025; Sant'Anna et al., 2025) emphasize the need for health policy planning to incorporate environmental and climate changes in order to address arboviral diseases in a sustainable manner.

## Observed dengue cases and cases predicted by the Poisson regression model

The statistical analysis confirmed a positive association between monthly precipitation and the occurrence of dengue cases in the eight municipalities studied. The Poisson regression model indicated that increases of 10 mm in precipitation were associated with an average increase of 3% in the number of reported cases at the state level. These findings are consistent with the literature demonstrating that the interaction between precipitation, environmental changes, and the simultaneous presence of different vector species intensifies the risk of arboviral diseases in urbanized areas (Butakka et al., 2022).

Figure 5 presents a comparison between observed dengue cases and those predicted by the Poisson regression model, considering the influence of rainfall on disease incidence across the three mesoregions of Pernambuco. The model showed good agreement with observed values during periods of higher precipitation, particularly between February and May, when monthly rainfall exceeded 80–150 mm in several locations. In years such as 2010, 2015, and 2022, this relationship becomes even more evident, with peaks in dengue cases coinciding with increased rainfall, reinforcing the strong link between water availability and the proliferation of *Aedes aegypti*. This relationship was also observed by Geraldini et al. (2024), who identified a direct correlation between rainfall events and increased larval density, followed by a rise in dengue cases.

In the Sertão, the model adequately captured peaks resulting from concentrated rainfall above 100 mm/month, although slight overestimation occurred in years of severe drought, such as 2012 and 2016, when low relative humidity (around 40%) limited vector survival.

In the Agreste, predictions closely matched observed values during both peak periods in March and April and seasonal declines, indicating that precipitation acts as the primary regulator of local dynamics. In the MRR, the model also showed good agreement, but with lower amplitude of variation due to a more evenly distributed rainfall regime throughout the year, which sustains transmission over longer periods.

The estimated coefficient for precipitation indicated that each additional 1 mm of monthly rainfall is associated with an approximate 0.9% increase in the disease incidence rate (IRR≈1.009).

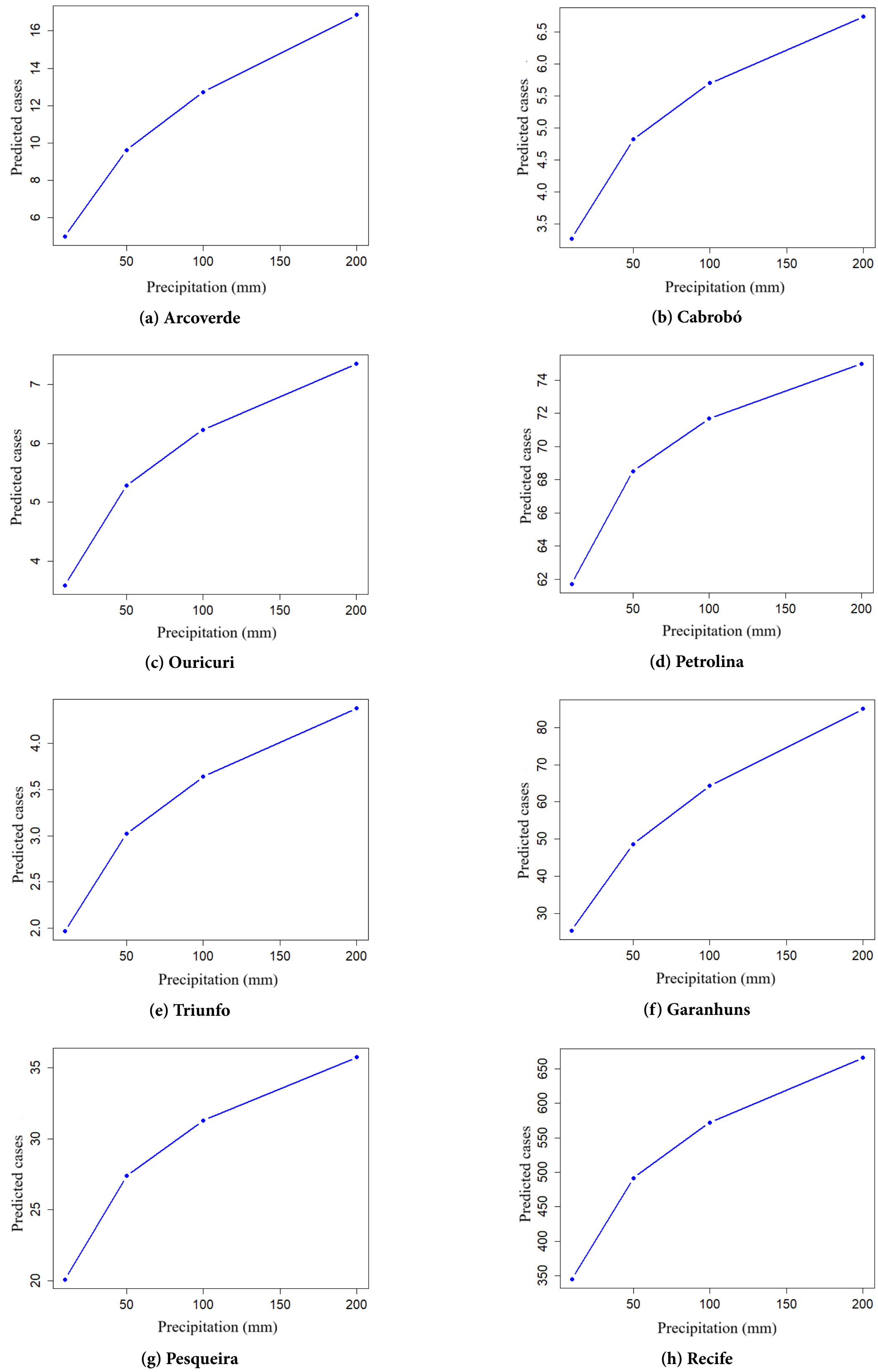



**Figure 5 – Predicted dengue cases based on increasing rainfall in municipalities located in the Sertão: (a) Arcoverde, (b) Cabrobó, (c) Ouricuri, (d) Petrolina, and (e) Triunfo; in the Agreste: (f) Garanhuns and (g) Pesqueira; and in (h) the Metropolitan Region: Recife, Pernambuco, Brazil.**

Thus, increases of 50 mm in monthly precipitation may result in an approximate 56% rise in the number of cases, while increases of 100 mm may more than double reported cases, with an increase of around 113%.

A recent study by Heath et al. (2025) in Brazil showed that the density of the *Aedes aegypti* mosquito is expected to increase nationwide, albeit unevenly, exceeding thermal limits in northern Brazil while increasing substantially in the South and Southeast. The study also highlights that climate change and rapid urban growth are likely to increase the risk of mosquito-borne disease outbreaks in the future.

Periods with rainfall volumes exceeding 150 mm/month, particularly between February and May, coincided with peaks in dengue cases, reinforcing the role of water availability as a key trigger for the proliferation of *Aedes aegypti*.

Thus, the model was able to predict with good accuracy the periods of higher risk of dengue transmission, serving as a key indicator for planning early preventive actions, especially at the onset of the rainy season. Codeco et al. (2022) point out that climate change is already affecting the transmission of arboviral diseases in Brazil, and that rising temperatures and changes in precipitation regimes have favored both the geographic expansion and intensification of dengue.

These results are consistent with studies such as Borges et al. (2024), which demonstrate that precipitation is one of the most consistent triggers for increased vector density. Furthermore, Silva and Scalize (2023) highlight that, in urban areas, the impact of rainfall may be amplified by factors such as inadequate drainage and the accumulation of solid waste, creating persistent breeding sites and sustaining transmission even outside peak rainy periods.

## Conclusion

This study demonstrated that precipitation is a central determinant of dengue occurrence in Pernambuco, directly influencing the seasonality and intensity of outbreaks. Peaks in cases coincided with the rainiest months, and statistical modeling confirmed a significant association, particularly with lags of one to three months, highlighting the role of rainfall as a trigger for vector proliferation.

No clear trend of increase or decrease in dengue cases was identified in Pernambuco; however, since 2014, an increase in the frequency of notifications has been observed in most of the municipalities studied.

The research also revealed how urban infrastructure and social inequalities influence dengue epidemiology. Municipalities with better economic conditions and greater access to essential services, such as Recife, demonstrated a higher capacity to cope with the disease. In contrast, regions such as the Agreste and Sertão, characterized by semiarid conditions, average incomes below two minimum wages, and limited access to basic services, showed greater susceptibility to virus transmission. The high population density in Recife also favors virus circulation, making epidemiological control more challenging.

The simulated scenarios indicate that, in the absence of effective public health policies, environmental changes may significantly impact epidemiological indicators, with more severe consequences in highly urbanized regions such as Recife and Petrolina.

The Poisson regression model indicated that increased precipitation directly contributes to the proliferation of *Aedes aegypti*. In this sense, increases of 50 mm in monthly rainfall may result in an approximate 56% rise in the number of cases, while increases of 100 mm may more than double notifications, with an increase of around 113%, particularly in the MRR.

Finally, addressing dengue requires an intersectoral and continuous approach to prevent setbacks in sanitation and social development indicators, as well as increases in case numbers in Pernambuco. It is also recommended to integrate urban management, environmental policies, and social protection, with a territorial focus, in order to break the cycle linking inadequate infrastructure, inequality and disease.


## Authors' Contributions

**Alves**, S. N. T.: conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft; writing – review & editing; **Barros**, C. P. M. R.: conceptualization; data curation; formal analysis; writing – review & editing; **Silva**, E. R.: data curation; software; **Vigoderis**, R. B.: conceptualization; investigation; writing – review & editing. **Sales Filho**, R. L. M.: conceptualization; data curation; statistical analysis; software; writing – review & editing; **Souza**, W. M.: conceptualization; data curation; formal analysis; funding acquisition; methodology; project administration; resources; supervision; validation; visualization; writing – review & editing.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