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Using Machine Learning to Improve Vector Control, Public Health and Reduce Fragmentation of Urban Water Management

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Abstract: Urban waters (UW) are complex environments, and their definition is related to water systems in urban zones, whether in a natural system or an urban facility. The health of these environments is related to public health and the quality of life because public health is the focal point of environmental and anthropic impacts. Infrastructure is paramount for maintaining public health and social and economic development sanitation. Insufficient infrastructure favors disease vectors. The population and environment suffer from deficient urban water infrastructure in Brazil despite government efforts to manage the existing systems. In this work, machine learning (regression trees) demonstrates the deficiency of sanitation and UW management fragmentation on public health by using the *Aedes aegypti* infestation index (HI) and water supply, wastewater, stormwater and drainage indicators (SNIS data). The results show that each Brazilian region faces different problems. The more infested regions were Northeastern, Northern and Southeastern. Moreover, municipalities with better SNIS data have lower infestation rates. Minimizing problems related to sanitation through the integrated management of water and urban areas is extremely important in developing countries. UW governance is connected to public health. Water management fragmentation leads to more complex issues, and managers must confront them to improve the quality of life in urban zones.

Keywords: urban waters management; indicators; *Aedes aegypti* infestation index; machine learning

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1. Introduction

Urban waters (UW) are complex environments, and their definition is related to water systems in urban environments, whether in a natural system or an urban facility. The health of these environments is related to public health and the quality of life in different aspects. The water-sensitive planning management concept (WSP) must be integrated and considered as proposed by [1]. In addition to that, it is necessary to generate urban waters systemically and integrate the urban administrative and environmental quality issues and public health to reduce risks in diverse fields, expanding the WSP concept by seeking adaptation and resilience. Public health is the focal point of environmental and anthropic impacts, and economic consequences from insufficient public health generate further problems unfolding in several areas and impacting the entire society [2]. Risks and challenges increase in urban areas in developing countries. In this way, urban and health issues are intertwined and reflect the prevalence of communicable diseases [3], insufficient infrastructure and deficiencies in public policies. The interconnection between health and urbanization is emphasized by the United Nations [4,5] and the operation of the sanitation service chain and health [6]. It is only possible to maintain public health and social and economic development through the basic sanitation infrastructure of a community [7].

There is no adequate wastewater collection or treatment for almost half of the population in Brazil. There is "some type" of water treatment in 70% of all collected wastewater [8]; the remainder is discharged into the stormwater drainage network or directly into rivers. It reflects two problems: insufficient domestic wastewater treatment and surface runoff contamination in the stormwater drainage network and rivers. The incorrect destination and increasing generation of urban water (UW) flow, associated with the high cost of treatment, resulted in swelling volumes of untreated accumulated UW, producing severe environmental and public health problems. This kind of water management is fragmented [9]; it hinders governance and prevents a broader view of the connections in this coupled human–water system. In fact, there is deficient UW management and standing water observed throughout Brazil, consequently; diseases such as dengue, yellow fever, Zika and chikungunya are spread by the *Aedes aegypti* mosquito, breeding in aquatic habitats [10] that provide a favorable environment for their dissemination.

Ref. [11] reported that dengue fever cases exceeded the American continental record in 2019. There were 2,070,170 cases notified in Brazil, the highest number of cases in the world [11]. *A. aegypti* is typical in tropical and subtropical climate regions; its population is associated with climate variations and changes [10,12,13], and dengue fever cases are impacted by accidents [14] and natural and socioeconomic factors [15]. *A. aegypti* is an insect found in all Brazilian states, and it is responsible for the proliferation of successive dengue fever, Zika virus, chikungunya and yellow fever epidemics in Brazil [16–18]. The mosquito infestation is measured using the *A. aegypti* Infestation Index Rapid Survey—LIRAa, a sampling method for monitoring the populations of *A. aegypti* larvae that indicates regions with the most expressive number of mosquito reproduction habitats by providing infestation indexes. The House Infestation Index (HI), which corresponds to the proportion of infested houses [18], was employed in this work. [11] endorses HI use to compare mosquito–city infestation around the world [19–22].

Brazil has been trying to improve its sanitation management processes and started to collect data for developing indicators in 1995. Indicators are parameters that provide evidence about or describe an environment, area or phenomenon with a significance exceeding the associated parameter value [23]. They are useful for simplifying relevant information on complex phenomena, decision making, or verifying goal achievements [24,25]. The use of indicators is important, but in developing countries, there is a scarcity and poor quality of relevant and available information [26], affecting its use [27] and the decision-making process [26]. Indicator quality presents the mentioned problems in Brazil [27]. Even when data are available, data series are not complete. Hence, complex analysis, like machine learning methods, must be used.

Machine learning can be used specifically to make prediction models from data. Regression trees are machine learning methods for creating prediction models. The models are found by recursively partitioning the data space and fitting a simple prediction model within each partition [28]. As a result, the partitioning can be represented graphically as a decision tree. Classification trees are designed for dependent variables that take a finite number of unordered values, as the prediction error is measured in terms of misclassification cost. Regression trees are used for dependent variables that take continuous or ordered discrete values, as the squared difference between the observed and predicted values typically measures a prediction error. Boosted regression trees were used by [29] to predict environmental variables influencing global mosquito distribution.

The influence of sanitation on public health is known, but data need to be included in the literature reporting urban water management indicators on *A. aegypti* infestation; so, this work is innovative, and its purpose is to fill this gap by using Brazilian data.

2. Materials and Methods

Brazil spans an area of 8,510,418 km^2 in South America and it has the sixth largest population globally, with 203 million inhabitants [30]. It is divided into 26 states and subdivided into 5570 smaller administrative municipalities or counties. There are five geographic regions in Brazil; Figure 1 shows different characteristics based on their geographic position, economy, biome, climatological regimes, population, cultural aspects, standards of living and other factors. The analyses were performed by comparing regions separately.

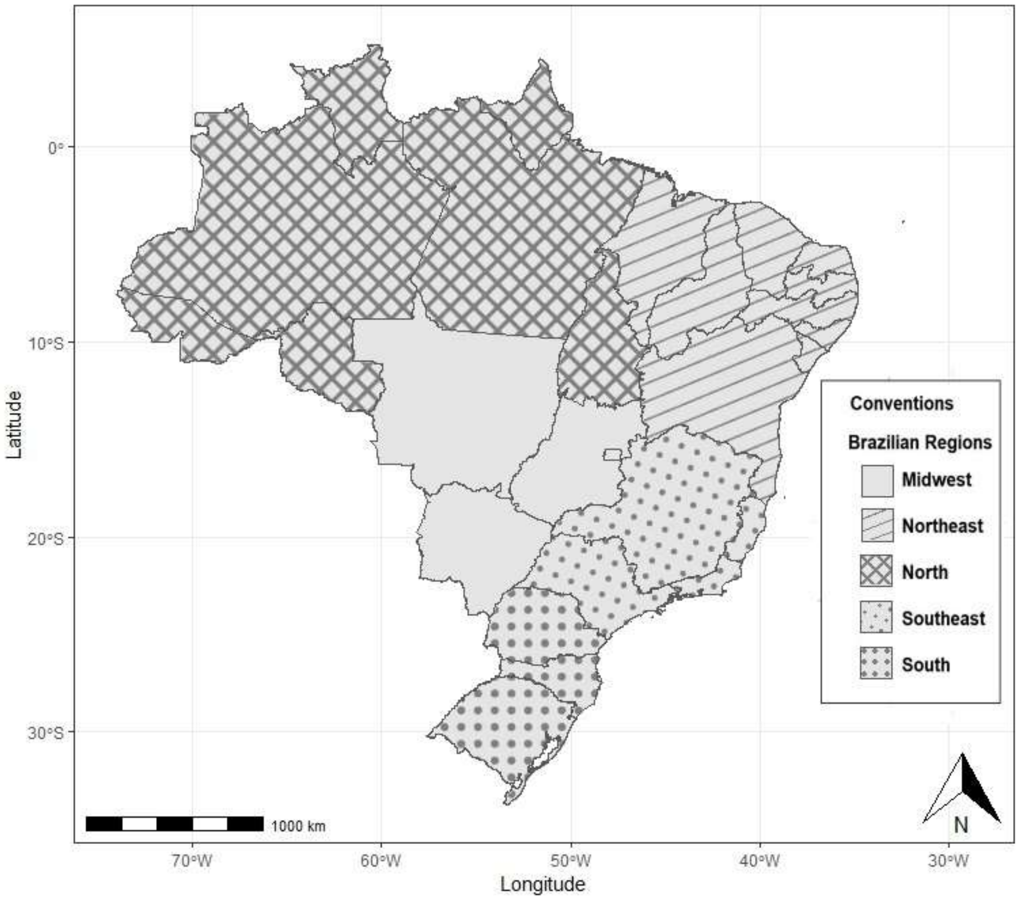

Figure 1. Brazilian regions.

The UWM data were obtained from the Brazilian Information System on the Sanitation (SNIS) platform (http://app4.mdr.gov.br/serieHistorica/), accessed on 22 September 2022. Initially, the researchers used all indicators, but due to missing data, indicators were excluded when there were more than 75% incomplete data. The SNIS indicator data provided by the Brazilian government provide information on urban waters (UW), which are quantitative on services provided in each municipality. These indicators include a series of 11 economic/financial and administrative, 18 water operations, 7 sewerage operations and 11 quality indicators (water and wastewater) for water supply and wastewater–wastewater collection and treatment. The stormwater drainage indicators had one general data item, seven financial data items and six infrastructure data items for services provided in each municipality.

The researchers used the House Infestation Indicator (HI) as a dependent variable in this article, which corresponds to the percentage (%) of Ae. Aegypti-infested houses compared to the total number of surveyed ones studied (Equation (1)). The municipalities inform the infestation index annually to the Health Ministry. Data were accessed from the Brazilian Health Ministry through the Brazilian Government Transparency Portal (https://www.portaltransparencia.gov.br).

$$\mathrm{HI} = \frac{\text{number of positive properties}}{\text{total number of surveyed properties}} \times 100 \tag{1}$$

The classification of the municipality compared to mosquito infestation is carried out based on three categories of HI values: satisfactory (HI $\leq$ 0.99), warning (1.0 $\leq$ HI $\leq$ 3.99) and hazardous (HI $\geq$ 4.0) (Health Ministry, 2017). The chosen analysis period was 2017 for this research.

2.1. Statistics Analysis

The UWM indicators in this work were water supply and wastewater (AEIN) and stormwater (DREIN) urban display was the dependent variable from the analyzed municipalities. Initially, an exploratory analysis was performed to characterize the sampling. The statistical analysis encompassed both descriptive statistics and correlation analysis. Linear relationships, correlations and collinearity issues were evaluated between UWM (AEIN and DREIN) and HI indicators.

2.2. Regression Trees

Following the computation of descriptive statistics and correlation analysis, regression trees were modeled to identify the relationship [2]. This analysis technique fits well due to data complexity. Decision trees are nonparametric techniques used to model complex relationships between the input and output of a classification or regression problem without assuming any prior hypotheses [31]. According to [32], the decision tree enables database classification into finite groups by utilizing hierarchical rules for its branches and organizing the data in a way to compress it to provide an understanding of the process. Regression trees are decision trees for continuous quantitative response variables and can be easier to interpret than other regression models [33,34]. This model is suitable even when the data do not meet regression assumptions like normality distribution, linearity, homogeneity of variance and independence among predictors [35]. R software, version 4.0.3 [36] was used to perform all the analyses.

There are various algorithms for decision trees, and we use the Classification and Regression Trees (CART) algorithm in this article, as developed by [31] Breiman. The process of the CART algorithm for regression trees involves splitting the data set into smaller subgroups and fitting a constant to each observation in each subgroup.

The tree was constructed using binary recursive partitioning, which involved splitting the predictions into binary partitions ranging from the largest to the smallest. After that, the tree was pruned, applying the complexity parameter as a pruning criterion [37]. Pruning is a technique used to calculate the optimal number of splits to balance explanatory variables and complexity parameters. The complexity parameter is a number between 0 and α and measures the 'cost' of including an additional variable in the model [37].

Cross-validation was applied to evaluate and test the model performance. The rpart function performs a 10-fold cross-validation so that the error associated with a complexity parameter value is calculated on the hold-out validation data [37]. ME (mean error) and MAE (mean absolute error) were employed to assess the model's accuracy. ME and MAE units are the same as the original data and can be easily interpreted.

By using R software [36], assisted by rpart [37] and rpart.plot packages [38], regression trees were generated using the rpart function [31]. The level of significance adopted in correlation analysis was α = 5%.

3. Results

The results were organized as follows: first, we will present the House Infestation Index (HI) analysis results concerning the water supply and wastewater indicators (INs). Then, we will introduce the results for the stormwater drainage indicators (DREIN). Each analysis presents descriptive statistics, a selection of indicators, each regional regression and a discussion of results.

3.1. Water Supply and Sanitary Wastewater Service Indicators

3.1.1. Characterization of the Sample and Descriptive Statistics

The SNIS UWM data showed that 5570 municipalities (100% of all municipalities) supplied at least one indicator of the qualitatively selected indicators (47 indicators) for water supply and wastewater in the first step; only 217 municipalities submitted data on all these indicators. A total of 5353 municipalities presented just some indicators (at least one). Regarding HI, 5482 municipalities presented the following data (Table 1). The final sample comprises 5482 municipalities that presented SNIS and HI data.

Table 1. Descriptive statistics of the House Infestation Index (HI); N is sample size.

	N	Minimum	First Quartile	Median	Average	Third Quartile	Maximum	Standard Deviation
Brazil Region	5482	0.00	0.00	0.40	1.415	1.60	100.00	4.550
Midwest	454	0.00	0.00	0.20	0.787	0.80	34.40	2.038
Northeast	1783	0.00	0.40	1.40	2.574	3.20	100.00	5.925
North	433	0.00	0.00	0.30	1.349	1.60	100.00	5.113
Southeast	1636	0.00	0.00	0.30	0.816	0.80	100.00	4.414
South	1176	0.00	0.00	0.00	0.756	1.00	9.00	1.371

Descriptive statistics show HI values in Table 1 from the analyzed municipalities, the country and the regions, considering the sample.

3.1.2. Water Supply and Wastewater Indicators—AEIN

Table 2 presents indicators by group, as well as descriptions, units and codes.

Table 2. Summary of the selected indicators for the regression trees.

Indicator Group	Code	Indicator Description	Unit
ECONOMIC/FINANCIAL AND ADMINISTRATIVE	AEIN005	Average water tariff	USD/m^3
	AEIN006	Average wastewater tariff	USD/m^3
	AEIN007	Incidence of personnel and third-party services costs in the service total expenditure	%
	AEIN008	Average annual expenditure per employee	USD/employee
	AEIN012	Financial performance index	%
	AEIN018	Equivalent amount of personnel	employee
	AEIN029	Revenue evasion index	%
	AEIN041	Wastewater direct operational revenue participation in total operational revenue	USD/inhabitants/year
	AEIN048	Productivity index: own employees per 1000 connections of water and wastewater	employees/1000 connections

Table 2. *Cont.*

Indicator Group	Code	Indicator Description	Unit
WATER OPERATIONS	AEIN001	Water economy density per connection	economy/connection
	AEIN009	Hydrometric Index	%
	AEIN010	Index of micro-metering related to available consumption	%
	AEIN020	Extension of water network per connection	meters/connection
	AEIN022	Average water consumption per capita	liters/inhabitants/day
	AEIN023	Urban water supply index	%
	AEIN043	Residential water consumer units' participation in total water units	%
	AEIN044	Index of micro-metering related to consumption	%
	AEIN052	Water consumption index	%
	AEIN053	Average consumption of water per economy	m^3/month/economy
	AEIN055	Total water supply index	%
SEWERAGE OPERATIONS	AEIN021	Extension of sewerage network per connection	meters/connection
	AEIN046	Index of treated wastewater related to water consumption	%
	AEIN047	Urban sewerage supply index on the attended municipalities	%
QUALITY—WATER AND WASTEWATER	AEIN072 *	Average duration of interruptions in water supply	hours/interruptions
	AEIN074 *	Average duration of intermittence	hours/intermittence
	AEIN077	Average duration of wastewater overflow repair	hours/overflows

* Interruptions and intermittences differ in the magnitude of hours; interruptions are based on an hour scale and intermittences on a day scale.

3.1.3. Regression Trees

Midwestern Region

The Midwest region regression tree in Figure 2 indicates a relation between economic/financial and administrative indicators and the HI Index.

HI data are associated with AEIN012 (financial performance index) and AEIN005 (average water tariff). We observed that 98% of municipalities present an AEIN012 lower than 229%, and the average HI is at a satisfactory level (0.67), Figure 2. This demonstrates that higher income does not contribute to reducing mosquito proliferation. In 2% of the analyzed municipalities, the average HI reaches the risk status (5.5), whereas AEIN012 is higher than 229%, meaning the revenue is 2.29 times higher than expenses.

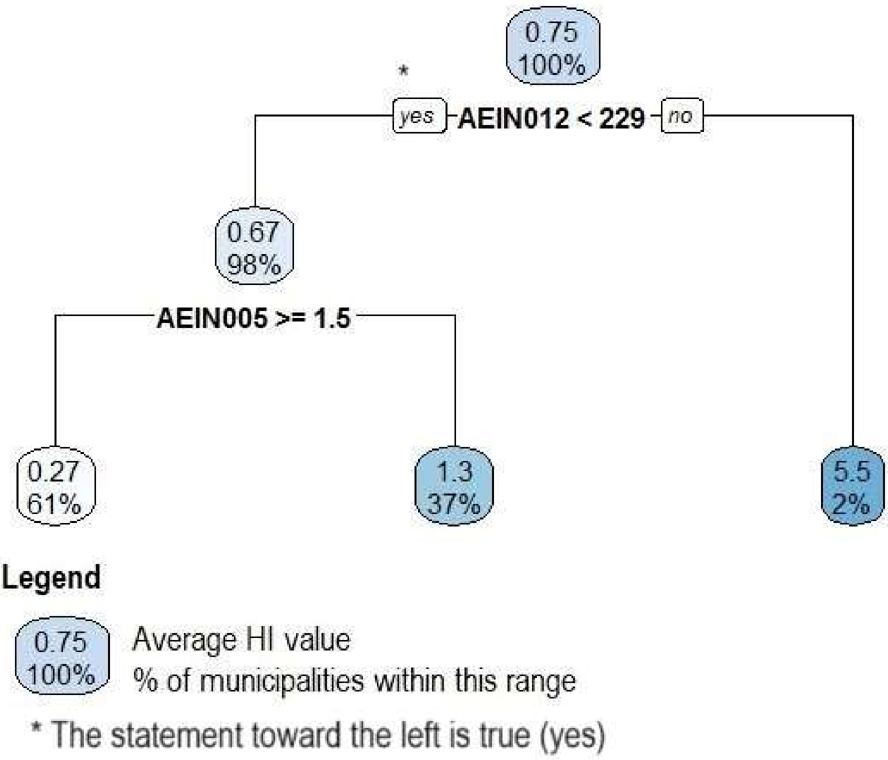

Figure 2. Regression tree modeling the relationship between HI index and water supply and wastewater (AEIN) indicators for Midwestern region.

Also, in 61% of municipalities (257), an average water tariff (AEIN005) of 1.5 USD/m^3 or higher maintains the HI at a satisfactory level, reducing the average HI from 0.67 to 0.27. However, in 37% of cases (154), if the AEIN005 is lower than 1.5 USD/m^3, the average HI increases to 1.3 and reaches the warning status.

Northeastern Region

The Northeastern region regression tree in Figure 3 indicates a connection between the economic/financial and administrative indicators, water and sewerage operations and quality indicators. We can observe that municipalities with AEIN074 (average duration of intermittence) values lower than 1333 h/interruption present an average HI of 2.6 (warning status). Among these, the municipalities with AEIN006 (wastewater tariff) of 0.6 USD/m^3 or higher (77% of the cases) have an average HI of 2.4—warning status. This indicator is associated with the AEIN023 (urban water supply index). Municipalities with higher values of duration of intermittences present a higher HI average value. Similarly, higher wastewater tariffs are related to the increased use of sanitary sewer services. The locations for mosquito proliferation decrease, as well as the HI, when wastewater is treated.

If the AEIN074 equals 1333 h/interruption or more, the average HI rises to 17 (risk status). This result can be associated with domestic water storage [39], meaning periods longer than 1333 h/interruption can result in water accumulation and mosquito proliferation. The value of 1333 h/interruption corresponds to 56 days/interruption, equivalent to almost 2 months. Considering that the *Aedes aegypti* mosquito takes 7 days to reach the adult phase, has a 30-day life cycle and the female lays 40 eggs every 3 days [18], this is a considerable amount of time not only for proliferation but also for disease transmission. Based on these results, we can observe the need for a continuous water supply to end improper storage and avoid habitats for mosquito development.

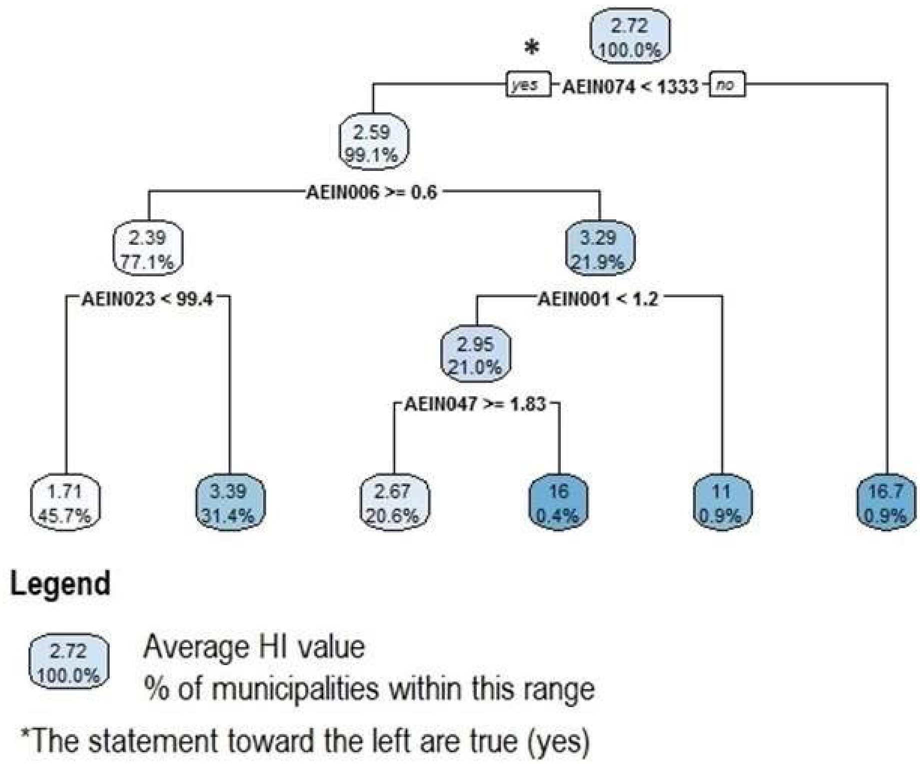

Figure 3. Regression tree modeling the relationship between HI index and water supply and wastewater (AEIN) indicators for Northeastern region.

Also, it is important to highlight the AEIN047 index (percentage of residencies supplied with sanitary sewer services). According to collected data from the regression tree, in seven municipalities (0.0043% of the 1614 studied municipalities) where less than 1.8% of the population is supplied with sanitary sewer services, the average HI reaches 16 (risk status). This means there is no correct destination for 98.2% of wastewater in these municipalities.

Northern Region

In this region, according to Figure 4, the most important indicators for HI are AEIN074 (average duration of intermittence) and AEIN044 (index of micro-metering related to consumption).

We can observe that 97.9% of the cases (328 municipalities) with an average duration of intermittence (AEIN074) equal to or over 0.75 h/interruptions present a decrease in the average HI from 1.42 to 1.14 (warning status), close to the satisfactory level. However, when this index is lower than 0.75 h/interruptions, for 2.1% of the cases, we can observe that the increase in the average HI to 14.7 is in a risk status category. This could indicate that these intermittences are happening in insufficient time to fix the problems in the network because 0.75 h/interruptions correspond to 45 min, which is a short time to verify the problem and fix it. Without the appropriate repair, the networks will continue with leakage problems, pipeline ruptures and supply shortages for the population. In all these cases, it is possible for the presence of stagnant water or wastewater that is an easily habitable location for the *A. aegypti* mosquito.

Regarding the index of micro-metering related to consumption, we can observe that for values of 99.9% or higher, the average HI is 0.206 (satisfactory), which occurs in 39.1% of municipalities (131). But, when the AEIN044 is lower than 99.9%, the average HI is 1.76 (warning), which occurs in 58.8% of municipalities.

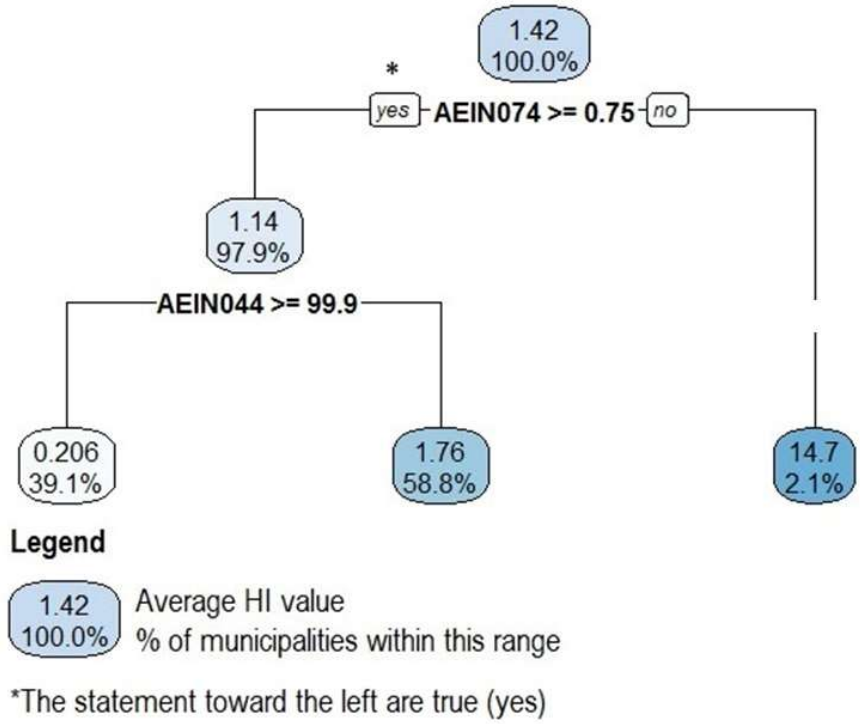

Figure 4. Regression tree modeling the relationship between HI index and water supply and wastewater (AEIN) indicators for Northern region.

Southeastern Region

In the Southeastern region, HI is related to the AEIN021 (extension of sewerage network per connection) and the AEIN074 (average duration of intermittence) indicators, according to Figure 5.

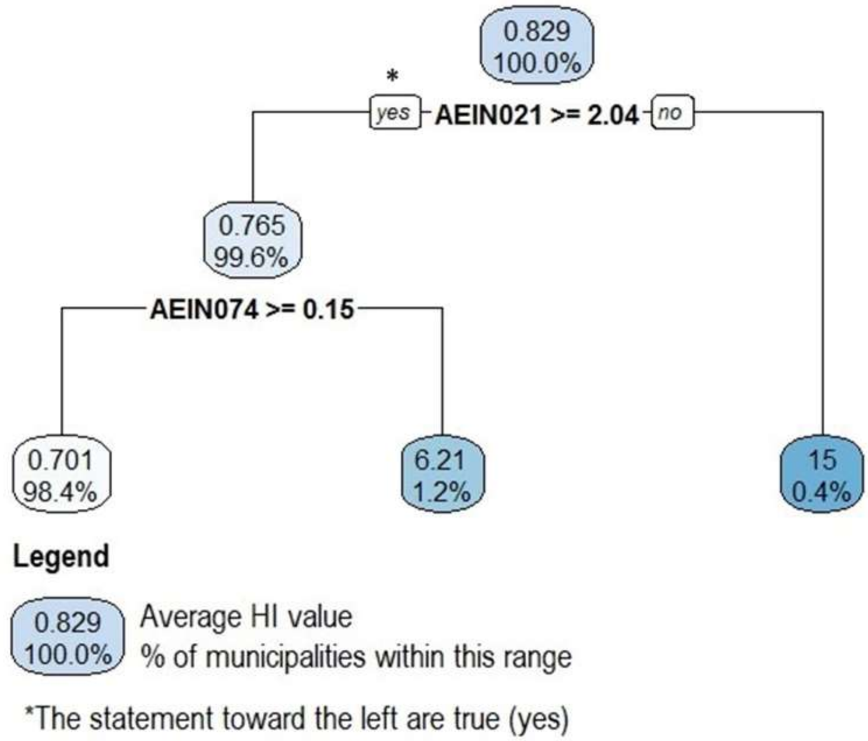

Figure 5. Regression tree modeling the relationship between HI index and water supply and wastewater (AEIN) indicators for Southeastern region.

The highest average HI occurs when the extension of the sewerage network per connection is lower than 2.04 m/connection (0.4% of the cases—seven municipalities). This enables us to infer that the less the population is supplied with sanitary sewer services, the higher the mosquito proliferation is. When the AEIN021 is 2.04 m/connection or higher (99.6% of cases), the average HI changes from 0.829 to 0.765, remaining at satisfactory status, and is associated with the AEIN074. In cases where AEIN074 is 0.15 h/interruption (9 min) or higher, the average HI remains at the satisfactory status, which occurs in 1533 municipalities (98.4%). However, if the AEIN074 contains a value lower than 0.15 h/interruption, the HI average alters to 6.21, classified as a risk status, which happens in 1.2% of municipalities (18). Like the Northern region, these results demonstrate that shorter intermittences do not solve the problem. There is not enough time to fix the network; therefore, there is water and/or wastewater accumulation, transforming these locations into vector proliferation places, such as for A. aegypti. For this reason, in the Southeastern region, we can observe how the extension of the sewerage network and the total connections contribute to the HI.

Southern Region

The regression tree (Figure 6) for the Southern region indicates that values of AEIN048 (productivity index: company employees per 1000 connections of water and wastewater) of 1.8 employees/1000 connections or higher happen in 54% of municipalities (226) and present an average HI of 0.52.

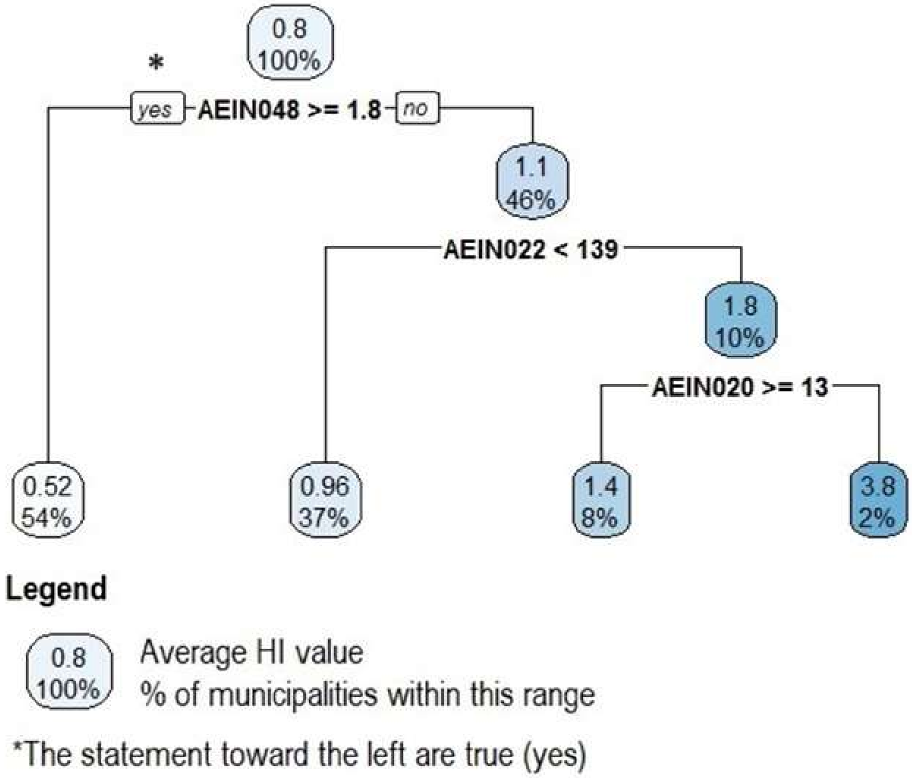

Figure 6. Regression tree modeling the relationship between HI index and water supply and wastewater (AEIN) indicators for Southern region.

We can also observe that lower AEIN048 values are associated with AEIN022 (average per capita water consumption) and present an average HI in the warning status (1.1). When AEIN022 is lower than 139 L/inhabitant/day in 37% of the cases (155 municipalities), the average HI is 0.96 (satisfactory status). If the AEIN022 is 139 L/inhabitant/day or higher, 10% of the cases (40 municipalities), the HI average values increase to warning status. This can be associated with increased water storage in residences, increasing the number of possible habitats for mosquito proliferation.

Also, when the AEIN022 is 139 L/inhabitant/day or higher, it is associated with the AEIN020 (extension of water network per connection). The AEIN020 indicator reaches an average HI of 1.4 (warning) in 8% of municipalities when the extension of the water network per connection is equal to or higher than 13 m/connection. For values lower than 13 m/connection, the HI level reaches the hazard status in seven municipalities (2%). This could be related to distant locations that need a larger network extension for supply or lower pressure on distant networks. These two situations contribute to water storage, which could increase the HI due to a higher number of habitats for mosquitoes. There will be physical water loss if the system presents any problems in its extension. These situations can be responsible for stagnant water accumulation, resulting in a higher number of locations for mosquito proliferation.

Comparison of Regional Results

We calculated the values of the mean errors (ME) and mean absolute errors (MAE) of prediction. Table 3 presents the errors obtained from each region. The ME values are close to zero, and the MAE values vary from 0.755 to 2.32. The highest error values are in the Northern and Northeastern region models. The obtained errors are larger in a more complex tree, considering that more variables are involved. Also, these regions have the highest standard deviation values in HI data (Table 1), which means more data variability.

Table 3. Errors obtained in the regional trees of water supply and sewerage.

Metrics	ME	RMSE	MAE
Midwest	0.077	1.827	0.755
Northeast	−0.051	5.607	2.320
North	−0.152	4.777	1.567
Southeast	−0.001	4.220	0.983
South	−0.240	1.744	1.153

The model regression trees demonstrate that it is important to analyze regions separately. According to their geographical location, the indicators have a stronger or weaker relation with the HI.

Table 4 and Figure 7 present the results in a simplified form obtained from each region regarding the water supply and sewerage indicators and their relations to the HI.

Table 4. Summary of regional results impacting the HI regarding the water supply and sewerage.

Region	Regional Results
Midwest	A higher income itself does not reduce HI. A continuous water supply is necessary to end improper storage and avoid mosquito development based on these results.
Northeast	Intermittences in the public network contribute to mosquito proliferation. Insufficient sanitary sewer services contribute to the increase in HI.
Northern	More effective maintenance in the network decreases HI.
Southeast	More effective network maintenance combined with the sewerage network extension and the number of connections of wastewater decreased HI.
South	Water storage and physical loss that occur in the extension of networks contribute to increased HI.

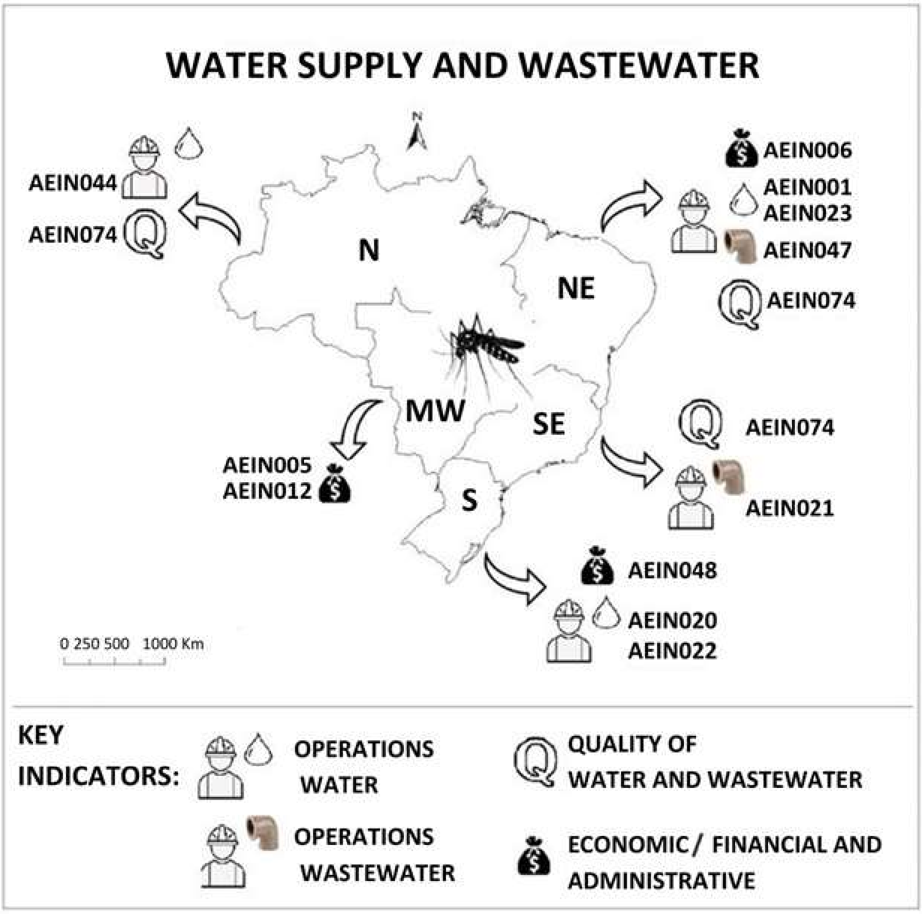

Figure 7. Summary of regional results impacting HI regarding the water supply and sewer system.

The main factors contributing to the increase in HI are related to economic/financial and administrative indicators in the Midwestern region. Mosquito proliferation is associated with water and sanitary sewer service management, and a higher revenue would not be enough to control this problem. Ref. [40] confirms that the participation of all spheres of society and institutions must act cooperatively in the decision-making process. Management must seek strategies for preventive health, hygiene and environmental education, the universalization of basic and environmental sanitation and the characteristics of each region to control and combat arbovirus diseases [41]. The Midwestern region tree illustrates this concept. Financial resources are insufficient to supply the demand and shortage because water resource availability is limited in this region, and the governing authorities need to adopt an action plan to provide efficient service to the entire population.

Ref. [42] analyzed the performance of public and private sanitation providers from 2009 to 2016 in the Midwestern region of Brazil using correlations and cluster analysis. They found several correlations between the sanitation indicators. Among them, we reference the correlation between the AEIN012 (financial performance index) and the AEIN003 (total expense per invoiced m^3) indicators, AEIN003 and AEIN005 (average water tariff) and AEIN005 and GDP. The average water tariff was also associated with the service supply index, indicating that the greater the water supply, the higher the tariff is. The author also describes that the Midwestern region presents water supply (99.3%), average water tariff (0.9 to 1.22 USD/m^3) and GDP (USD 5123.27) above the national average, which is, respectively, 88.3%, 0.31 to 0.9 USD/m^3 and USD 2653.36. According to [42], the increased water supply results in a higher tariff for this service. So, in this region, a lower infestation of the *Aedes aegypti* mosquito can be associated with a more abundant water supply, considering that this results in decreased water pooling. It is also observed in the Southern region, where the HI proliferation can be related to increased water storage.

Ref. [43] studied the association among dengue and climate, sociodemographic and sanitation variables in the capital cities of the Brazilian Northeastern region from 2001 to 2012 using cluster analysis. The authors found connections between dengue and all the studied variables. Results were obtained linking the water supply and sewerage-associated dengue to the indicators AEIN006 (average wastewater tariff), IN009 (hydrometric index), AEIN021 (extension of sewerage network per connection), IN001 (water consumer unit density per connection) and AEIN015 (wastewater collection index). In the regression tree of the Northeastern region, we can observe the presence of three indicators presented by [43]. Although AEIN015 is not present, it is associated with the indicator AEIN047 (urban sewerage supply index on the served municipalities). The insufficient sanitary sewer services considerably increase the average HI. These issues relate to economic, financial, administrative and water and sewerage operation indicators.

Intermittences are interruptions in the water supply and sewerage network for solving problems related to pipeline ruptures, operating restrictions, distribution system shortcomings, weak governance and other issues [44]. The regression trees of the Northeastern, Northern and Southeastern regions indicate an association of HI to the AEIN074 quality indicator (average duration of intermittence). In Nicaragua, [45] demonstrated that residences with irregular water supply are almost twice as likely to have a positive HI and positive pupae of *A. aegypti* compared to residences with a regular supply. Also, proliferation control can only be re-established when the water supply is steady and economic, social and management factors support its effectiveness.

We analyzed that the average intermittence of 56 days increases the proliferation of the vector in the Northeastern region. According to [46,47], domestic water storage is necessary to supply the needs when the service is unavailable. This storage is usually implemented improperly and without regular cleaning of the containers, which becomes an ideal location for mosquito reproduction. In the Northern and Southeastern regions, shorter intermittences are responsible for increased HI. These issues could be associated with the quality and effectiveness of intermittent services, which means, in most cases, insufficient time to properly repair the sanitation system. The periods in the Northern and Southeastern regions are 45 min/interruption and 15 min/interruption, respectively. According to [48], the Northern region presents the highest index of decreased income (57%), distribution loss (55.14%) and loss per connection (648.91 L/day/connection). This information supports the presented idea regarding inefficient maintenance of the regional network, considering that 45 min/interruption is a short period to solve the number of problems related to water loss. Also, these physical losses result in water accumulation, which can be associated with mosquito proliferation.

According to [49], the losses in the water supply system arise from two factors: apparent and real water losses. Noticeable loss is related to covert connections to the system, and the real loss is the leakage in the distribution infrastructure. Although there is no system without water distribution losses, operational planning and management must focus on achieving the lowest possible value. SNIS highlights that the national index of water distribution loss is 39.2%. It means that in every 100 L of water supplied by the service providers, 60.8 are utilized by consumers. In addition to the Northern region, the other regions also present significant water distribution losses. The other regions in descending order are Northeastern (45.7%), Southern (37.5%), Southeastern (36.1%) and Midwestern (34.4%).

The indicators with higher relevance to HI are sewerage operations, water quality and wastewater in the Southeastern region. The extension of the sewerage network per connection (calculated according to the extension of the sewerage network and the number of wastewater connections) jointly with the average duration of intermittences impacts mosquito proliferation. Ref. [41] analyzed basic sanitation and arbovirus diseases in Natal/RN, Brazil. They demonstrated that the sanitary sewer services do not abide by the populational growth, causing data disparity. Also, they confirm a negative correlation between the mosquito proliferation index and sanitary sewer services. The lower the percentage of neighborhoods supplied with sewer services, the higher the mosquito proliferation percentage is. This situation, combined with the highest populational growth in the country [30], results in a considerable HI mosquito proliferation index in the Southeastern region. IBGE data [30] show that in 2022, Brazil reached a population of 203 million inhabitants. Considering the 5570 Brazilian municipalities, São Paulo and Rio de Janeiro comprise more than 9% of the population and have the highest population density in the country. These high and continuously growing indexes make sanitary sewer services unavailable to the entire population because the needed infrastructure is not supplied by the government.

Also, regions with higher wastewater production require larger collection and treatment networks. Treatment plants can also be locations for mosquito proliferation. Ref. [50] analyzed the development of mosquitoes in wastewater treatment plants in Cameroon, Central Africa, for a year. The authors observed that the mosquitoes could lay their eggs on macrophyte roots and this plant is a favorable location for mosquito proliferation, such as the *Aedes aegypti*. It is necessary to improve the monitoring of locations and implement continuous inspections to avoid these problems.

Water supply and sewerage systems provide general benefits to the population's health through direct and indirect effects, resulting mainly from the development level of the supplied location [51]. As observed by the results presented in this work, providing urban water infrastructure and integrating its management are important actions to meet sustainable development goals such as SGD 3, SGD6 and SGD11.

3.2. Stormwater Management Indicators

3.2.1. Descriptive Statistics

Regarding stormwater management indicators, 3667 municipalities (67.74% of all municipalities) supplied at least one indicator on the qualitatively selected indicators (14 indicators), and 76 municipalities submitted data on all these indicators (Table 5).

Table 5. Summary table of descriptive HI—stormwater drainage; N is sample size.

	N	Minimum	First Quartile	Median	Average	Third Quartile	Maximum	Standard Deviation
Brazil Region	3667	0.00	0.00	0.40	1.224	1.40	100.00	3.848
Midwest	329	0.00	0.00	0.20	0.827	0.90	34.40	2.260
Northeast	822	0.00	0.40	1.50	2.544	3.20	100.00	4.511
North	219	0.00	0.00	0.30	1.215	1.70	16.70	2.069
Southeast	1.291	0.00	0.00	0.30	0.854	0.80	100.00	4.920
South	1.006	0.00	0.00	0.00	0.761	1.00	9.80	1.362

Regarding the HI, of the 3667 analyzed municipalities, 2494 present satisfactory data, 912 are in warning status and 261 are at risk. The descriptive statistics of HI distribution per region are presented in Table 5. We can observe that 25% of municipalities in Brazil (first quartile) present an average HI of 0.00 (satisfactory status), and 75% of municipalities present an HI of 1.40 (third quartile, warning).

As observed in the AE analysis, the Northeastern region presents the highest HI, and more than 50% of its municipalities are in warning status ($1.0 \leq HI \leq 3.99$). The Southern region presents the lowest HI; nearly 75% of the analyzed municipalities are in satisfactory status ($HI \leq 0.99$). Most selected municipalities present HI in the warning status, lower than 3.99, and are considered to be in warning status.

3.2.2. Variable Selection

Regarding the stormwater drainage indicators, the correlation analysis did not identify any significant relationships but helped to detect many strongly correlated related indicators. In the end, six SWI sampling indicators remained, as described in Table 6.

Table 6. Summary of selected indicators for regression trees regarding stormwater management and drainage.

INDICATOR GROUP	CODE	INDICATOR DESCRIPTION	UNIT
GENERAL DATA	DREIN044	Housing density in urban areas	Houses/hectares
	DREIN001	Participation of company employees among all employees (including third-party) in urban stormwater management and drainage services	%
FINANCIAL DATA	DREIN010	Participation of the total expense in urban stormwater management and drainage services in the municipality's total expenses	%
	DREIN053	Investment disbursement per capita	USD/inhabitants/year
	DREIN054	Total investment disbursement in relation to the total investment retained	USD/inhabitants/year
	DREIN020	Ratio of paving and curb coverage in the municipality's urban areas	%
INFRASTRUCTURE DATA	DREIN021	Ratio of public streets covered by stormwater drainage underground networks in urban areas	%
	DREIN027	Percentage of perennial streams in storm drain tunnels	%

3.2.3. Regression Trees

The regression trees were modeled for the five regions of the country.

Midwestern Region

The regression tree of the Midwestern region (Figure 8) demonstrates that DREIN020 values (the ratio of paving and curb coverage in the municipality urban areas) are equal to or higher than 84% and occur in 110 municipalities (37% of the cases) and present an average HI of 0.36. For the other 63% of cases, the DREIN020 values are lower than 84%, and the average HI is 1, presenting a warning status. These results indicate that urban areas with a high infrastructure ratio contribute to decreasing mosquito proliferation.

We can also observe in Figure 8 that the municipality's ratio of paving and curb coverage represents 5% of the cases (15 municipalities) and averages a 3.3 HI. DREIN020 values lower than 81 are associated with DREIN021 values (the ratio of public streets covered by stormwater drainage underground networks in urban areas) and represent 58% of the cases. Lower HI values are associated with the ratio of paving and curb coverage and the ratio of stormwater drainage coverage, indicating increased control over the HI index when there is a complete urban stormwater drainage system.

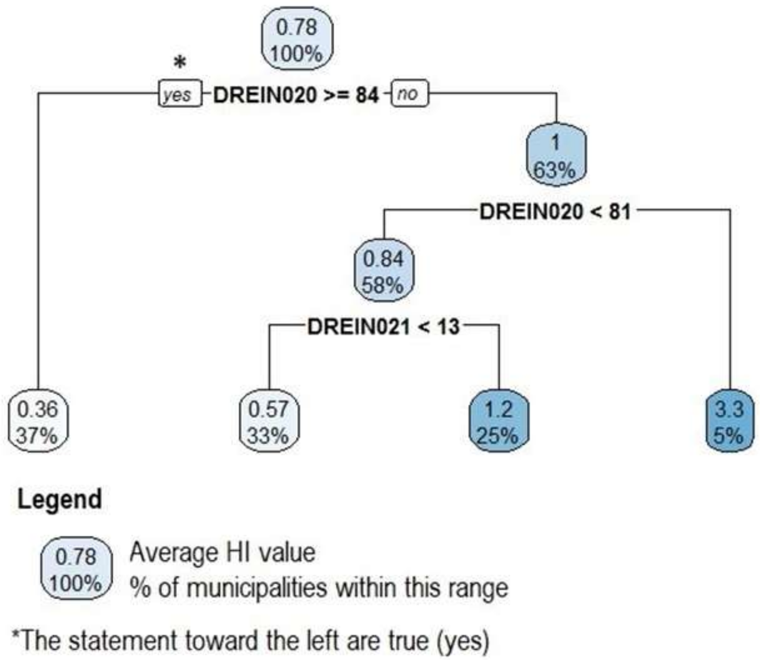

Figure 8. Regression tree modeling the relationship between HI index urban drainage (DREIN) indicators for Midwestern region.

Northeastern Region

Figure 9 (Northeastern region regression tree) demonstrates just one indicator related to HI. DREIN021 values (the ratio of public streets covered by stormwater drainage underground networks in urban areas) higher than 33% occur in 92 municipalities (11% of the cases), present an average HI of 5 and are associated with DREIN021 lower than, equal to or higher than 37%.

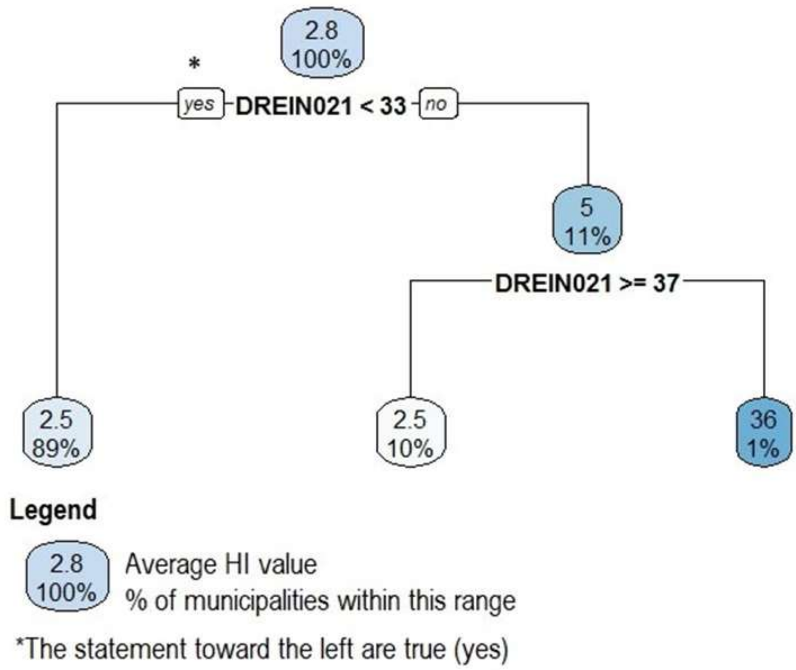

Figure 9. Regression tree modeling the relationship between HI index urban drainage (DREIN) indicators for Northeastern region.

We emphasize that municipalities with DREIN021 values from 33 to 37% present an average HI of 36 (risk status), occurring in 1% of the cases (36 municipalities). It means a stormwater pipe system is insufficient to reduce the HI. It is necessary to provide a complete system to improve this index.

Northern Region

The Northern region regression tree in Figure 10 also demonstrates that the infrastructure indicators present a larger impact on the HI. The low infrastructure index is remarkable compared to other regions in Brazil, represented by DREIN021.

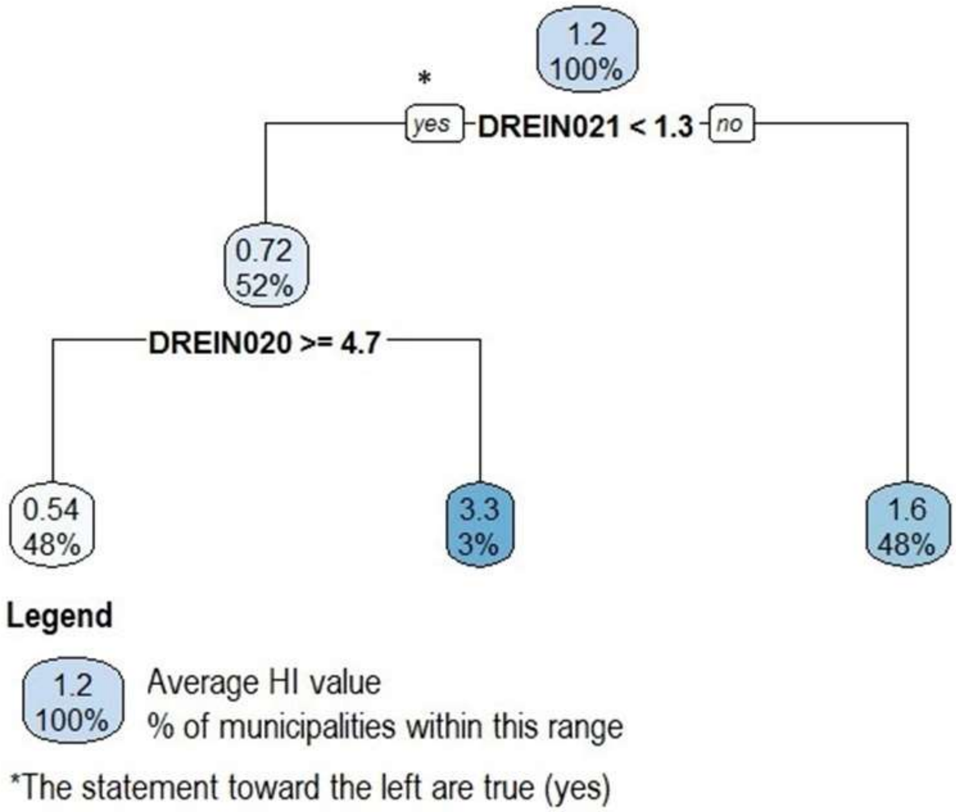

Figure 10. Regression tree modeling the relationship between HI index urban drainage (DREIN) indicators for Northern region.

In this region, cities with DREIN021 (the ratio of public streets covered by stormwater drainage underground networks in urban areas) values of 1.3% or higher present an average HI of 0.72, occur in 52% of the municipalities (110) and are associated with DREIN020 values (the ratio of paving and curb coverage in the municipality urban areas). DREIN021 values higher than 1.3% correspond to 48% of cases (103 municipalities). Lower HI values are associated with the ratio of paving and curb coverage and the ratio of stormwater drainage coverage, indicating that a higher control over the HI (House Infestation Index) of the *Aedes aegypti* occurs when there is a full urban stormwater drainage system.

Southeastern Region

According to the regression tree in Figure 11, the infrastructure indicators are also the most relevant in the Southeastern region. Figure 11 indicates that DREIN020 (ratio of paving and curb coverage in municipality urban areas) values of 76% or higher present an average HI of 0.68, occurring in 71% of the cases in 915 municipalities. DREIN020 values lower than 76% are associated with DREIN021 values (ratio of public streets covered by stormwater drainage underground networks in urban areas). DREIN021 values lower than 53% occur in 26% of cases (332 municipalities) and present a 0.7 average. DREIN021 values of 53% or higher correspond to 3% of the cases (37 municipalities). Lower HI values are associated with the ratio of paving and curb coverage and the ratio of stormwater drainage coverage, indicating increased control over the *Aedes aegypti* mosquito that occurs when there is a complete urban stormwater drainage system.

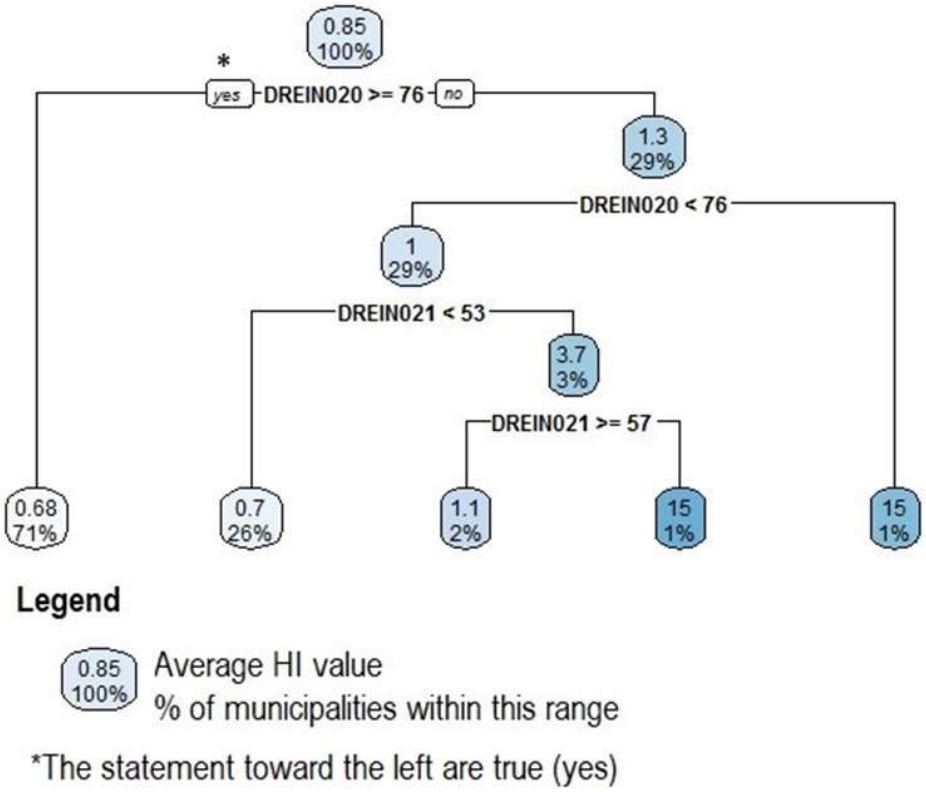

Figure 11. Regression tree modeling the relationship between HI index urban drainage (DREIN) indicators for Southeastern region.

Southern Region

The most relevant indicators in the Southern region are related to infrastructure, general and financial data, according to the regression tree in Figure 12. We can observe that cities with DREIN021 (ratio of public streets served by stormwater drainage underground networks in urban areas) values of 94% or higher, 5% of cases, present an average HI of 1.9 (warning status). DREIN021 values lower than 94 occur in 95% of cases (284 municipalities), present an average HI of 0.85 (satisfactory) and are associated with DREIN044 (housing density in urban areas). DREIN044 values lower than 3.5 houses/hectare correspond to 52% of the cases, occur in 156 municipalities and present an average HI of 0.65 (satisfactory). Cities with DREIN044 above 3.5 houses/hectare present an HI of 1.1 (warning status). It means that urbanization contributes to the proliferation of the *A. aegypti* mosquito [52–55].

We can also observe that the DREIN001 (participation of company employees among all employees in urban stormwater management and drainage services) also impacts the HI. In the Southern region, a high HI average occurs when the DREIN020 indicator (a paving and curb coverage ratio in the municipality's urban areas) is lower than 76%. Lower HI values are associated with the ratio of paving and curb coverage and the ratio of stormwater drainage coverage, indicating that improved control over the HI index occurs when there is a complete urban stormwater drainage system.

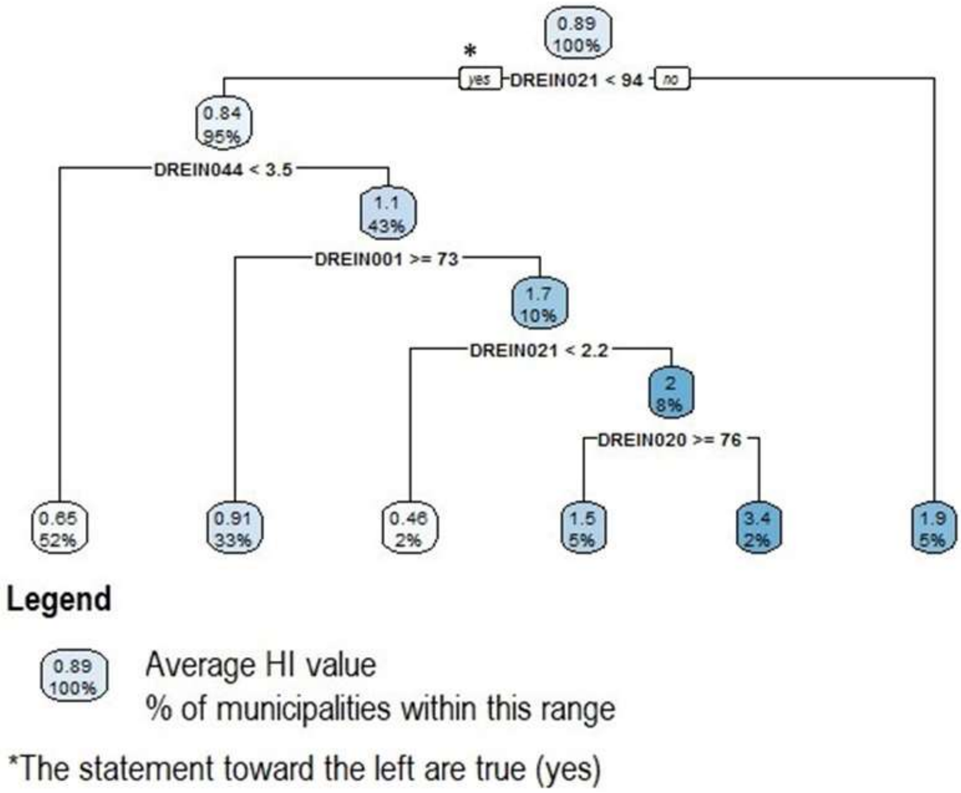

Figure 12. Regression tree modeling the relationship between HI index urban drainage (DREIN) indicators for Southern region.

3.2.4. Regional Errors

ME and MAE metrics of stormwater management and drainage are presented in Table 7. We can observe the ME values are close to zero (<0.001), and the MAE values vary from 0.893 to 2.700.

Table 7. Measure of errors obtained in the trees from each region regarding stormwater management and drainage.

Region	ME	RMSE	MAE
Midwestern	-5.196×10^{-17}	2.191	0.916
Northeastern	-1.812×10^{-15}	8.649	2.700
Northern	-4.312×10^{-16}	1.777	1.145
Southeastern	-2.164×10^{-16}	4.698	1.008
Southern	-1.23×10^{-17}	1.269	0.893

Just as in the standard deviation analysis of the HI variable in Table 7, the Northeastern region presents the highest values of errors in the models. At the same time, the trees of the Northeastern, Southeastern and Southern regions were not pruned because the overfitting was not large enough compared to the others. The obtained errors are larger in a more complex tree, considering that more variables are involved.

3.2.5. Inter-Regional Comparisons

Although the infrastructure indicators presented a stronger relationship with the regions' HI index, it is important to analyze the regional models. According to Figures 8–12, there are differences in the numeric range of indicators associated with HI, but the indicators are almost the same. Infrastructure indicator DREIN021 (ratio of public streets covered by stormwater drainage underground networks in urban areas) is related to HI in the studied regions. Except in the Northeastern region, indicator DREIN020 (ratio of paving and curb coverage in the municipality urban areas) is also related to HI in Brazilian regions. In the Southern region, financial and general indicators are also related to HI.

Table 8 and Figure 13 show that the general results obtained in the regression trees for every region are associated with infrastructure indicators. The exception is the Southern region of Brazil that, in addition to this indicator, is also influenced by general and financial indicators.

Table 8. Summary of regional results obtained in the regression trees regarding stormwater management and drainage.

REGIONS	DESCRIPTION OF REGIONAL INDICATORS IMPACTING HI
Midwestern	A full urban stormwater drainage system contributes to decreased proliferation of *Aedes aegypti*.
Northeastern	A stormwater pipe system is not enough to reduce the HI. There is a need for a complete system to improve this index.
Northern and Southeastern	A full urban stormwater drainage system contributes to decreased proliferation of *Aedes aegypti*.
Southern	A complete urban stormwater drainage system contributes to decreased proliferation of *Aedes aegypti*. Also, the population density and the participation of company employees among all employees in stormwater drainage services contribute to mosquito proliferation.

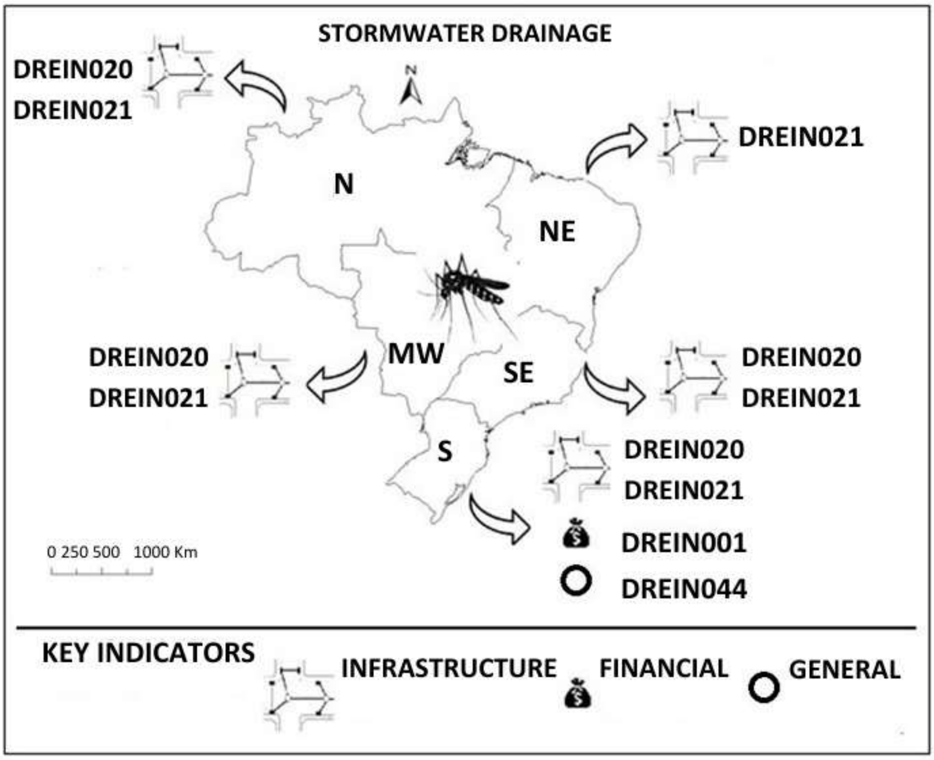

Figure 13. Summary of regional results impacting HI regarding stormwater management and drainage.

4. Discussion

The increasing complexity of urban environments [56], especially in issues related to urban water, encourages a series of studies [57], methodologies [58] and mechanisms capable of helping and improving stormwater systems [9]. Inefficient stormwater drainage management and unfinished stormwater drainage systems cause financial losses but also endanger the population with the propagation of waterborne diseases [59].

Although it represents prosperity, urban development and growth are accompanied by inevitable impacts on the local environment. Stormwater is one of the most concerning, considering that urbanization significantly changes the natural hydrological system, resulting in the increase in stormwater runoff followed by the peak flows of increasing water bodies, water quality degradation and sediment generation, among others [60].

In the Southern region, the DREIN044 indicator (housing density in urban areas) is associated with population growth, and, according to [61,62], the stormwater drainage systems are impacted by population density. The increase in the urban population intensifies the soil sealing, resulting in a larger peak flow [61]. Because of the urbanization process, the urban stormwater drainage systems had to deal with increasing quantities of water. Ref. [62] emphasized that the mosquito proliferation and the diseases transmitted by this arthropod are a consequence of the environmental condition associated with inefficient public health policies and the lack of appropriate urban infrastructure that, in many municipalities, does not correspond to the populational density. As pointed out by regional regression tree analysis, when the stormwater drainage system is made up of all its constituent parts, water can be drained quickly, reducing stagnant water accumulation, which is one of the main places for mosquito proliferation. The use of green infrastructure stormwater drainage systems could contribute to decreased mosquito habitats. Moreover, structures based on infiltration must be connected to the stormwater drainage networks to avoid the problem identified by [63].

Ref. [64] used a regression model in space and time to estimate the risk of dengue in Cali, Colombia. The authors describe that although urban populational growth is a consequence of the increase in the transmission of diseases by mosquitoes, the real effect of the populational density can vary in small spatial areas (for example, neighborhoods). In Cali, the public health authorities usually execute fumigation and education programs in neighborhoods with high populational density, resulting in insufficient intervention in areas with lower density but with populations of *Aedes aegypti*, such as sewers and green vegetation areas. These researchers evaluated the relationship between climate and HI; ref. [64] report that dengue cases exceeded the local average rate five weeks after short-duration rainfalls and three weeks after low-intensity rainfalls. Although the floods result in stagnant water, these events can also act as interferences by flooding and dislodging the eggs of these arthropods. In Jaffna, Sri Lanka, ref. [65] described that mosquitoes have become resistant to insecticides, and open drains for gray wastewater can be sources to select vector mosquitoes resistant to pyrethroid insecticides. In their conclusions, the authors present the importance of converting open drains into efficient underground drains and describe the importance of increased inspections in the stormwater drainage system. The company or outsourced employees perform these inspections in the stormwater drainage system. The Southern region's financial indicator refers to the employees' participation in stormwater drainage services. In this region, having more personnel in the stormwater drainage services contributes to decreased average HI.

Also, refs. [66,67] demonstrate the growing urbanization demands for increased stormwater drainage capacity and increased sections and slope of the conduit or channel. This result supports the study of [68] regarding the stormwater drainage systems in Salvador, Bahia, Brazil. They observed that rainfall lower or equal to 50 mm during 7 days increases the chances of proliferation of the *Aedes aegypti* by 28.3%, compared to the increased HI of 4.6% when rainfall is higher than 50 mm. Also, ref. [68] conducted two inspections in each of the 122 analyzed utility holes in 30 days. In 49% of the cases, the authors verified the presence of stagnant water, a favorable habitat for larval development, and adult mosquitoes. They concluded that in Brazil, the vector control campaigns usually focus on the residential environment. But, as pointed out by [69], for vector control in private areas, such as residences, cooperative behavior is not always observed. In public areas, ref. [65] recommend inspections and using larvicides as preventive measures to avoid mosquito breeding, especially in outside containers.

Supporting this, [68,70] conducted a study in Miami, Dade County, Florida, related to the main breeding sites of the *Aedes aegypti* mosquito. Ref. [70] observed that aquatic habitats such as utility holes, bromeliads and trash cans, respectively, present 45%, 33% and 17% fewer mosquito larvae when compared to tires, traditionally known as one of the main spots for the proliferation of vectors. However, these habitats are the most favorable for an immature mosquito to reach adulthood [70]. The control of vector mosquitoes in utility holes is challenging due to the difficulty of reaching all possible aquatic habitats inside the complex underground network. However, these authors demonstrated that modifications to the utility holes, e.g., raising them, allowed the stormwater drainage of stagnant water. Ref. [71] also observed that of the 67 habitats positive for *Aedes aegypti*, 53 were related to utility holes in stormwater drainage systems in Singapore.

The urban stormwater drainage density impacts increasing HI in Singapore [72]. Although an extensive stormwater drainage network reduces the risk of flooding, this hydraulic system can increase the number of dengue mosquito reproduction habitats. Clogging in the stormwater drainage network can result in water accumulation, contributing to mosquito proliferation. Ref. [72] emphasizes that the stormwater drainage network density must be the minimum required to avoid flooding, stormwater accumulation and mosquito reproduction to avoid these problems. Similar interpretations are observed regarding the relationships between HI and the stormwater system in Northeastern Brazil. But this is not only the case in Northeastern Brazil; an efficient stormwater system is necessary to avoid Ae. Aegypti habitats in general.

Generally, shortcomings in the stormwater drainage system result in economic, social and environmental problems. Therefore, the stormwater drainage master plan must be used for guiding stormwater management in the city [59]. Also, it is important to emphasize that this plan directs immediate actions in the short, medium and long term and it must consider the entire basin. Stormwater drainage is not an isolated action for managing channels and pipes, as seen classically. It is an instrument for planning and water governance [9,67], as observed by the results presented in this work on public health.

Ref. [67] affirms that urban stormwater drainage can cause other problems in basic sanitation. Among these problems are the obstruction of conduits, canals and streams due to an inefficient solid waste system and urban erosion that modifies the stormwater drainage system. It could lead to intermittences in the sewer and water supply systems. Furthermore, Brazil's stormwaters are not treated or used, and this causes an important pollution load [73], in addition to being an aquatic habitat for mosquitoes. This emphasizes the importance of water-sensitive urban design (WSUD) [73], nature-based solutions (NBS) [74] and health. In addition, this kind of solution can be used to enhance regional ecological networks [75], contributing to achieving different sustainable development goals such as SDG3, SDG11 and SDG15.

5. Conclusions

Diseases transmitted by vectors, such as *Aedes aegypti*, are considered one of the world's main causes of morbidity and mortality. Many factors have been associated with the increase in the number of diseases related to mosquitoes, such as yellow fever, dengue, chikungunya and Zika. This study clarifies one of the main points associated with public health and urban water management in a country with low levels of sanitation and, consequently, low urban security. Vector control is the best choice to control diseases transmitted by them. Regarding the analyzed regions with the highest and lowest rates of *Aedes aegypti* infestation, it was observed that the Northeastern region is the one with the highest HI, with more than half of its municipalities on warning. The Southeastern and

Midwestern regions have the largest number of municipalities in a satisfactory situation, and the South region has the largest number of municipalities with zero HI. It can be observed that public management is responsible for the systems studied here (water supply and wastewater and stormwater drainage). This proves that there is a great need for managers to be concerned with the sanitation infrastructure of cities. In Brazil, the water supply and sewer services results indicate many problems to be solved. These problems are associated with water distribution and wastewater, losses in the distribution system, network intermittences, poor user service, especially regarding sewerage and, above all, the management of governing authorities. We can also observe that in water and sewer supply analyses, the groups of indicators associated with the HI are economic/financial and administrative, water operations, water quality and wastewater. Although all of them are mentioned three times in the regional trees, we can notice that the water quality group is the most important, especially the IN074 (average duration of intermittences). It occurs because water quality and wastewater services impact the other indicator groups, such as insufficient supply and/or water quality and sewer services to the population, increased expenses on material and labor, connection density, network extension, physical water losses and urban supply index. From a regional point of view, in the Midwestern region, higher revenue in services related to water distribution does not imply a reduction in the HI, as there is a need for a continuous water supply. In the Northeastern region, intermittent water and wastewater networks and the lack of wastewater services contribute to the proliferation of the vector. For the Northern region, adequate maintenance in the distribution networks to solve the problems of physical losses contributes to a lower HI. In the Southeast, effective repairs (more effective network maintenance actions) and effective wastewater systems reduce the HI. In the Southern region, smaller water storage reduces mosquito proliferation. Although water storage is considered one of the proliferation causes of *Aedes aegypti*, it is necessary to increase inspection of the services provided to the population. The results indicate that the proliferation of the vector occurs mainly in the infrastructure of water supply and sewers or results from insufficient services, questioning the public management decisions for each region. At present, public vector control campaigns are focused on the residential environment. However, we can observe that public sanitation management indicators are associated with proliferation.

The results of the regional regression trees were more homogeneous regarding the urban stormwater system and HI data. The infrastructure indicators highlighted the HI proliferation in the Midwestern, Northern, Northeastern and Southeastern regions as most relevant. They indicate that a complete and well-designed stormwater drainage system decreases the proliferation of *Aedes aegypti*. The financial and general indicators are associated with the proliferation in the Southern region and the infrastructure indicators.

We can observe that the public management is responsible for the analyzed systems (water supply and sanitary sewer, stormwater management and drainage). It proves that there is a great need for the authorities to care about the sanitation infrastructure in cities, especially those related to urban waters. Vector control must be efficient, and sanitation indicators can be used as a tool. Regarding the information from SNIS (National System of Sanitation Information), it is important to warn and oblige the municipalities to complete the basic sanitation indicators correctly and to conduct accurate verifications of the local indicators associated with mosquito proliferation.

Therefore, public management must intervene in different causes to reduce the problem, adopting measures to increase awareness and control environmental conditions to reduce the mosquito population and the number of cases transmitted by *Aedes aegypti*. Also, sanitation policies only sometimes consider the local health situation and social and economic aspects and often apply similar solutions to different contexts.

Minimizing problems related to basic sanitation through the integrated management of water and urban areas and expanding the concept of water-sensitive planning (WSP) is extremely important in developing countries. Given that, urban water governance presents its importance and can help reach sustainable development goals. Governance is connected to public health and indicates problems managers must confront, proving that water management fragmentation results in even more complex issues.

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