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RESEARCH ARTICLE

Dynamical behavior and control strategy of a dengue epidemic model

Comportamiento dinámico y estrategia de control de un modelo de epidemia de dengue

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RESUMEN

Aedes mosquitoes, specifically the *Aedes aegypti* or *albopictus* species, has the potential of transmitting illness such as Zika, Dengue, Chikungunya, and Yellow Fever. The movement of people and increasing population density have led to the emergence of diseases such as dengue, which have become a major global health problem in recent years. Developers of vector control campaigns and medical professionals are currently investigating methods to anticipate the dengue outbreak's apex and to identify the factors that influence the climate to the expansion of mosquito populations. The primary variables that have been identified are weather, precipitation, temperature, and epidemiological week. The initial phase of an investigation is the model that is designed to create an instrument that can simulate dengue outbreaks using system dynamics methodology. This instrument will function as a foundation for the forecasting of dengue transmission.

KEYWORDS: System Dynamics (SD); conceptual model; dengue virus; mosquito control.

ABSTRACT

Los mosquitos *Aedes*, específicamente la especie *Aedes aegypti* o *albopictus*, tienen el potencial de transmitir enfermedades como el Zika, el dengue, el Chikungunya y la fiebre amarilla. El movimiento de personas y el aumento de la densidad de población han llevado al surgimiento de enfermedades como el dengue, que se han convertido en un problema de salud mundial importante en los últimos años. Los desarrolladores de campañas de control de vectores y los profesionales médicos están investigando métodos para anticipar el apogeo del brote de dengue e identificar los factores que influyen en el clima para la expansión de las poblaciones de mosquitos. Las variables primarias que se han identificado son el tiempo, la precipitación, la temperatura y la semana epidemiológica. La fase inicial de una investigación es el modelo que está diseñado para crear un instrumento que puede simular brotes de dengue utilizando la metodología de dinámica del sistema. Este instrumento servirá de base para la predicción de la transmisión del dengue.

PALABRAS CLAVE: Dinámica de Sistemas (DS); modelo conceptual; virus del dengue; control de mosquitos.

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I. INTRODUCTION

The *Aedes aegypti* mosquito goes through four stages throughout its life cycle, which are as follows: egg, larval, chrysalis, and adult [1]. These organisms are capable of inhabiting metropolitan regions at altitudes lower than approximately 1.367 miles above sea level. They deposit their eggs cells in sanitary water reservoirs such as swimming pools, vases, aquatic plants, tires, and outdoor containers that can hold water [2], [3].

Research on the flight range of most females suggests that most insects choose to remain throughout their lives in or near the houses where they were born. On average, they usually fly approximately 400 meters [4], [5].

Dengue is prevalent in areas where more than fifty percent of the world's human population resides, resulting in its rapid spread. The disease has a mortality rate of over 2% per year and is present in more than one hundred nations [2], [6].

In humans, the illness is caused by the bite of a female vector infected with the virus, the most common species being *Aedes aegypti*. Following an incubation period of 4 to 10 days, a mosquito infected with the virus can transmit it throughout its life. Mosquitoes typically acquire the illness by feasting on the blood of infected individuals, whether they show symptoms. Humans are the exclusive source of the virus for unaffected mosquitoes [7].

In the years before 1970, severe dengue epidemics were limited to only nine nations. Today, however, dengue is prevalent in more than 100 countries in the World Health Organization (WHO) regions. These nations account for nearly 70% of the total global burden of disease caused by dengue. Every year, an estimated 390 million dengue infections occur, with 96 million of them presenting clinically, approximately 70% of the global disease burden is localized in Asia, while America, Southeast Asia, and Western Pacific regions are the most severely afflicted [8].

There is a 122% increase in the Americas between 2021 and 2022, and a 23% increase between 2022 and 2023, the year in which the highest number of dengue cases was recorded. There were 4.5 million cases in the WHO Americas region, of which 2,300 of them were fatal. A significant number of cases were registered in Asia, specifically in Bangladesh (321 000), Malaysia (111 400), Thailand (150 000), and Vietnam (369 000). Figure 1 illustrates the chronological evolution of dengue cases and fatalities (a), the incidence of dengue by country in Latin America until 2022 (b), and the incidence of dengue deaths in Latin America until 2022 (c) [9]. The data is entered into the Health Information Platform for the Americas (PLISA, PAHO/WHO). The utilization of tools that simplify the processing of patient estimates simplifies the development of public policies for vector control, allows the evaluation of economic impact, assists in the formulation of health policies within the Health Institution and prepares for the provision of technology, availability of laboratory tests and human resources for the population. Figure 1b illustrates the progression of the disease in Latin America.

The annual costs for outpatient and fatal cases of dengue amounted to US$ 54 million and US$ 8 million, respectively, while the expenditure related to hospitalized patients was US$ 25 million. The economic burden of dengue is substantial and impacts health systems and economies worldwide. Furthermore, the expenses associated with monitoring and controlling vectors contribute to 48.9 of the whole economic burden that dengue has by country, which amounts to US$ 83 million yearly [10]. The projected average annual expenditure on pesticide products per family was US$ 31 million [11]. Nevertheless, vector management only achieves partial success in decreasing the impact of dengue sickness, which emphasizes the need of preventive [6]. In 2015, the expense of dengue in eighteen nations resulted in US$ 3.3 billion in Purchasing Power Parity. This confirms that the economic burden of dengue is significant in countries with shared socioeconomic characteristics and health systems [11].

The results of a technology surveillance that was carried out using the keywords “dengue” and “simulation” in the databases ScienceDirect, Scopus, Web of Science, and IEEE, which were published between the years 1993-2023, are displayed in Figure 2. The study identified a total of 1.360 articles; 132 were excluded because they were duplicates, 190 items were excluded because they did not meet the inclusion criteria by referring to aspects of patient care and treatment or mosquito ecology.

A total of 48 full-text articles were evaluated; 11 of them were found to use system dynamics, the same technique that was suggested because it allows the underlying causes of the system to be analyzed and understood, examining various scenarios without affecting the actual system. However, this research used only seven of the 48 articles evaluated as references, since they allowed the identification of the critical variables necessary for the creation of a causal diagram.

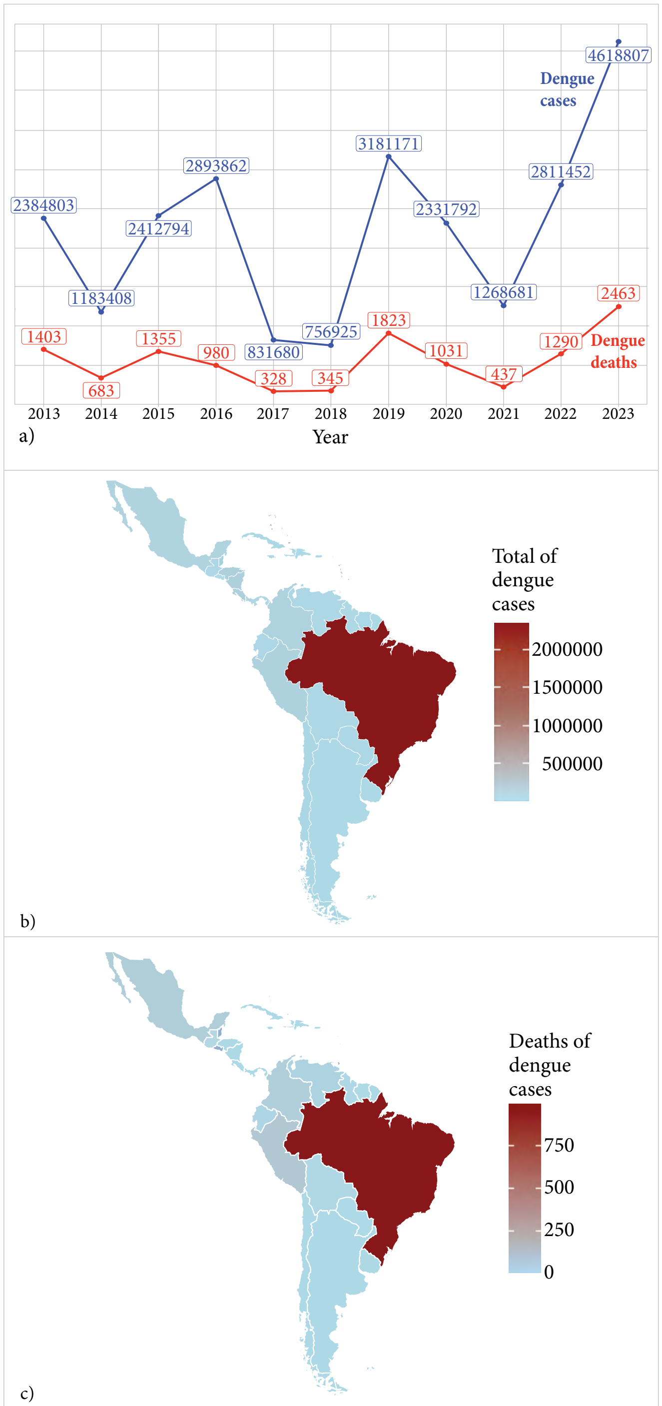

Figure 1. Total cases of dengue in Latin America by 2023: a) dengue cases and lethality over time, b) dengue incidence by country, and c) deaths by country. Source: PAHO/WHO.

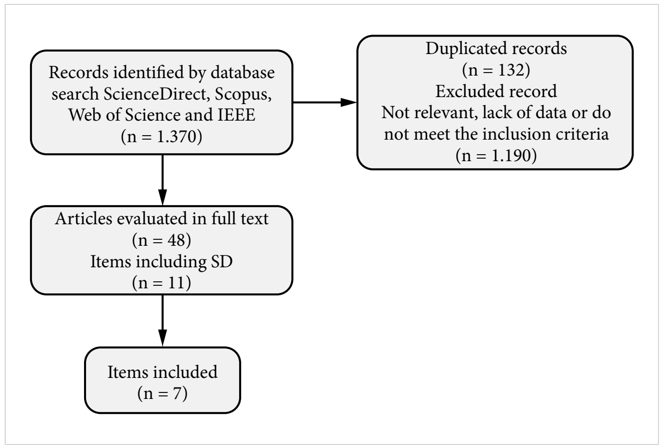

Figure 2. The results of a technology surveillance.

Various models of infectious disease transmission, including *Aedes aegypti* mosquitoes, have been identified. Among them, five papers have been recognized for their notable authors and citation impact. One such publication is an agent-based model that assesses the efficacy of dengue vaccine campaigns in Yucatan, Mexico [12]. *Wolbachia*-based mosquito control approaches offer a promising solution, with lower fitness costs and fewer ethical concerns in comparison to alternative genetic modification techniques [13]. The cost-effectiveness of the dengue vaccination is evaluated using a Markov simulation model that is based on decision analysis [14]. Morin *et al.* [15] analyzes the impact of meteorological factors on the transmission of dengue virus, including the dynamics of transmission, viral replication, and vector mosquito populations.

Figure 3 illustrates the distribution of articles by related to dengue infections by nationality. The main contributors to research are the United States and India. Among the countries of Latin America, Brazil, Colombia, and Mexico have the highest research on the topic and highest prevalence rates (Figure 2).

The model used the seasonality equations from the *Aedes aegypti* mosquito life cycle as a basis [16]. The selection of these equations was based on their ability to examine the influence of temperature and precipitation on eight regions in Mexico, as well as the function of diapause in seasonality growth. Another study [1] was also used to supplement certain parameters that were not fully described in the previous study [16], due to the similarity between the regions being studied and the specificity of the information.

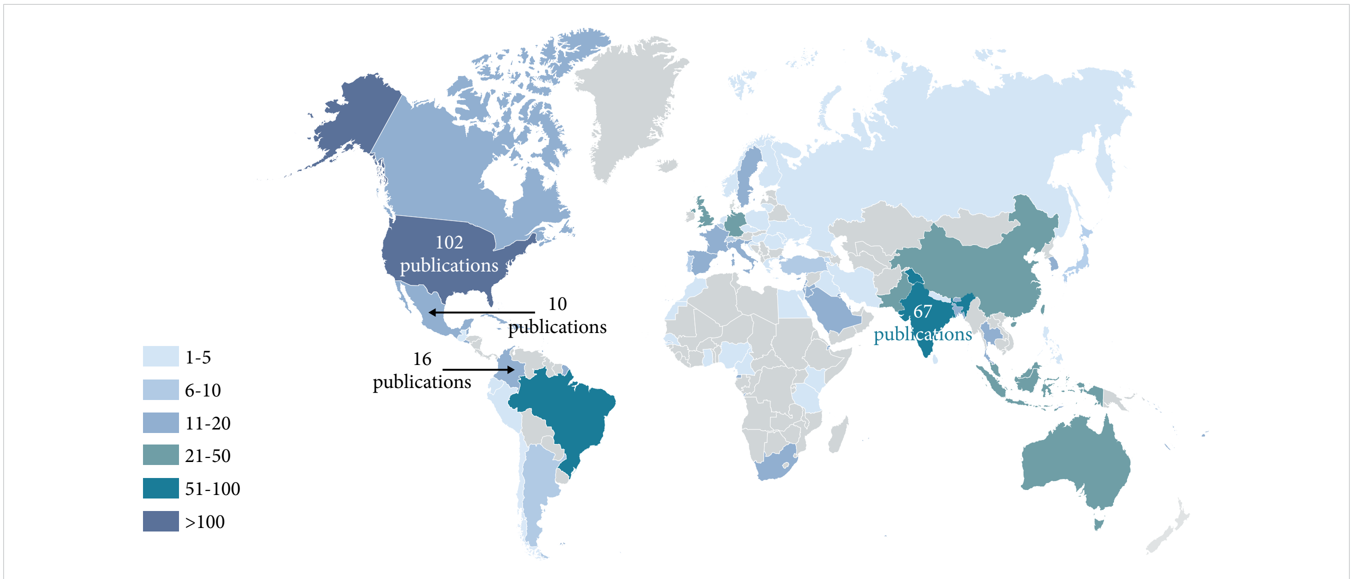

Figure 3. Articles related to dengue prevention or dengue infections by countries since 1993 up to 2023.

II. METHODOLOGY

The progress of studies to model mosquito behavior has been driven by the increasing need to predict and reduce dengue. In this study, the key variables presented in Table 1 that impact the spread of dengue were selected and defined to be included in the causal diagram (Figure 4), following the system dynamics methodology, was used in this study to address the complexity of dengue transmission.

System dynamics (SD) is a model-based approach that enables the understanding and simulation of the behavior of complex systems over time by considering the interactions between various variables and the feedback effects these variables generate. One of its main advantages is its ability to record both the short-term and long-term effects of various interventions [17].

The systemic approach allowed for modeling the complex interactions between factors such as environmental conditions, the number of male and female mosquitoes, larvae, pupae, and eggs, as well as mortality and transition rates at each stage, among others. Using a causal diagram, these relationships were represented to analyze how changes in one variable can influence others over time, allowing for a deeper understanding of epidemic behavior and the formulation of effective intervention strategies.

TABLE 1
IDENTIFICATION OF VARIABLES FOR CAUSAL DIAGRAM DESIGN

AUTHORS	VARIABLES	DESCRIPTION
[1], [16], [18], [19], [20], [21]	Temperature	The temperature in Orizaba, Veracruz, is measured in Celsius degrees.
	Rainfall	Climate variability influences the seasonal patterns of infectious diseases by impacting the rates at which pathogens are transmitted.
[1], [7], [16], [20], [22]	Predators	Natural mosquito predators' rate.
	Food	Quantity of food that is available.
	Number of eggs	Number of eggs, beginning with one thousand.
	Egg mortality rate	The rate of egg mortality due to natural causes.
	Larvae	Number of larvae starts with zero
	Larvae mortality rate	Death rate of larvae coming from natural sources.
	Pupae	Number of pupae starts with zero.
	Pupae mortality rate	Death rate of pupae coming from natural sources.
	Female mosquitoes	It is estimated that the number of female mosquitoes accounts for 50% of the total population.
[16], [22]	Diapause eggs	Due to the low temperatures, eggs cannot be continuously developing.
	Egg mortality rate in diapause	Egg mortality rate in diapause

III. RESULTS AND DISCUSSION

For the second step, formulation, different mathematical techniques have been found that take into account the seasonality of the life cycle, among which vector modeling, multi-stage regression analysis and analysis stand out [1], [16], [20], [22], [23]. Some authors have used System Dynamics [20], [24] to organize the components and code that are necessary for the Stella® software. For simulating the behavior of temperature and precipitation, accessed information that is open from National Aeronautics and Space Administration (NASA) [25] over the past five years was used, the data were analyzed and with a 95% confidence level the normal distinction is adjusted, normal log, exponential and coordination. The Causal Diagram (Figure 4) was created after the variables were identified, which identifies the primary variables and the feedback circuits that connect them. Although these strategies are not within the scope of the paper, the contextualization of preventive and corrective control methods is highlighted in green color. The stages of the life cycle (egg, larva, pupae and adult) are represented by the red interactions and meteorology (temperature and precipitation).

Here is a description of the loops that are included in the Causal Diagram:

B1: The female mosquito population, the number of eggs, larvae and pupae make up the loop B1. If the number of larvae increases, the female mosquito population will increase, as will all the variables mentioned above. These circumstances are maintained in the absence of temperature fluctuations or control measures.

B2: The B2 loop, reflects the indirect relationship between these variables.

B3: the loop B3 demonstrate how corrective control is affected when vector surveillance and control are reduced.

The analysis of interactions in the causal cycle diagram suggests that temperature and precipitation are significant factors that influence the life cycle, mortality and diapause of mosquitoes. Furthermore, the number of mosquitoes at each stage will have a significant impact, and their future will be in danger if at least one is outside life-friendly values.

The objective of this research is to use system dynamics to simulate the behavior of the mosquito population. To predict the behavior of dengue-transmitting mosquitoes, it is essential to consider the total number of dengue cases per week, temperature, and precipitation. This is an archetype that can be implemented in any country and for any period, if provided with data from the region under study. Thus, the findings of this study have important implications for the public health and economics of dengue-affected communities. By better understanding the dynamics underlying the spread of the disease, public health authorities can design more effective and timely intervention strategies, which could significantly reduce the burden of dengue. In addition, it could have a positive economic impact by reducing the costs associated with medical treatment and lost productivity due to the disease.

In addition, it is important to consider factors such as population mobility and variability in immune response that could influence model projections.

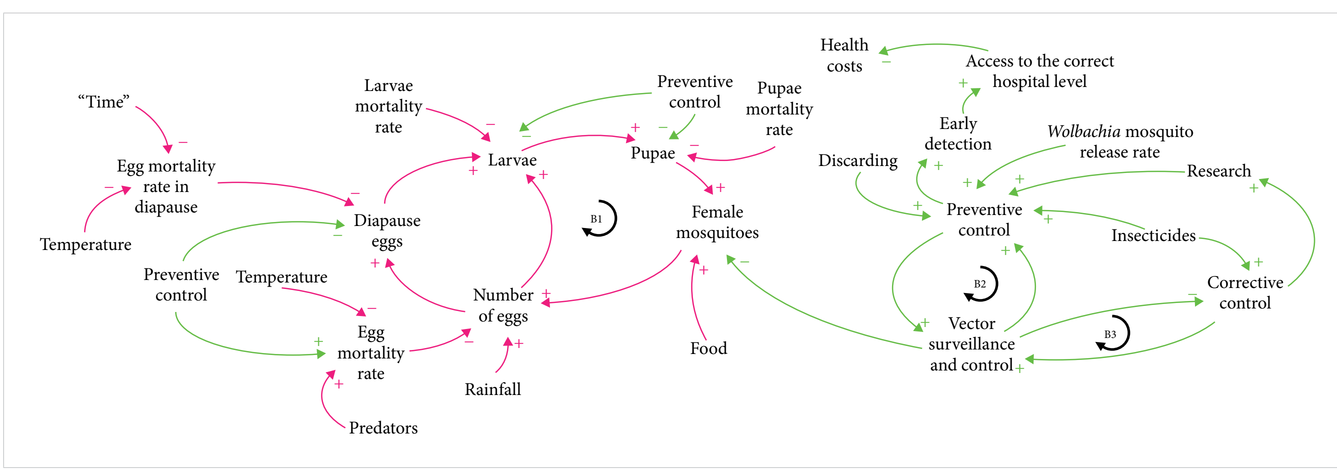

Figure. 4. Causal loop diagram.

IV. CONCLUSIONS

It is very helpful to have a deterministic model when dealing with big populations since it provides a useful tool for understanding the complexities of disease transmission. Deterministic models can help predict future trends and outcomes based on various scenarios, allowing for better decision-making in public health interventions. These models are particularly valuable in guiding resource allocation and response strategies during dengue disease outbreaks.

Through the utilization of a System Dynamics method and a causal loop diagram, this research presents a conceptual model with the objective of dissecting the biological processes that are responsible for mosquito reproduction. Additionally, the mortality rates that are associated with environmental conditions are taken into consideration. To conduct potential evaluations of the dynamics of dengue transmission and the impact of biological, chemical, or mechanical control measures, this model can provide valuable insights into the most effective strategies for controlling mosquito populations and reducing the spread of the disease. By incorporating various factors that impact mosquito reproduction and mortality, decision-makers can make more informed choices when implementing interventions to combat dengue outbreaks.

The life cycle of mosquitoes that transmit dengue is significantly influenced by temperature; at higher temperatures, the complete life cycle is completed more quickly, while at lower temperatures, the cycle is prolonged. The model proposes the identification of a mathematical distribution that explains the behavior of temperature and its influence on dengue transmission.

This model can be further extended to include variables like the stage at which a diagnosis is made, the capacity of the healthcare facility, the length of time that a disease progresses before a patient seeks medical attention, the accessibility of medical supplies, extra diagnostic tools, and vaccine development, to name a few. It is anticipated that this expanded framework will provide a more comprehensive and holistic perspective, as well as provide insights into potential areas for improvement. The importance of this discovery is underscored by ongoing investigations into healthcare procedures and vector control in Latin America. The conceptual model developed in this study has the potential to elucidate the life cycle of the *Aedes aegypti* mosquito and its correlation with the dengue virus's transmission. It is possible to comprehend the dynamics of dengue transmission and obtain guidance for its control by identifying critical intervention sites, such as the removal of mosquito breeding grounds or the application of insecticides. It also serves as a foundation for additional research on the dynamics of dengue virus transmission and its impact on the economies, healthcare systems, and supply chains of affected countries.

In summary, this conceptual model advances our knowledge of dengue and opens up new avenues for investigating how the disease affects different aspects of society and the environment. This will help with decision-making and lead to the development of more efficient dengue control measures.

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