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   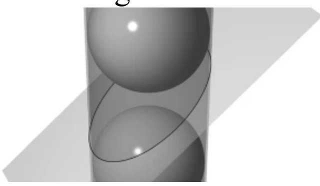

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   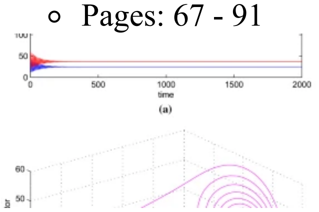

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   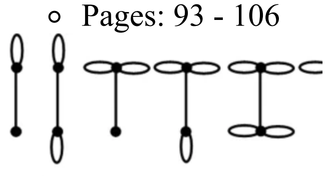

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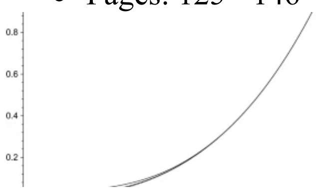

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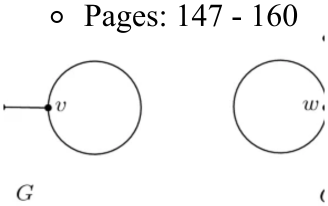

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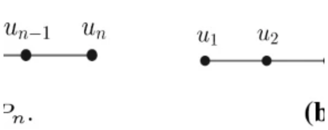

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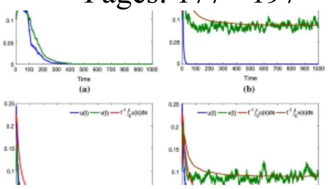

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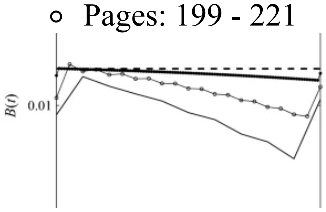

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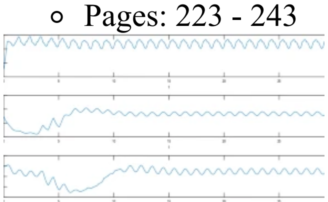

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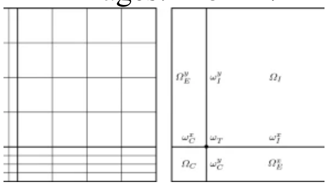

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.gorithm (forward Euler)

Initialize $\mathbf{u}_0^h$, p_0^h and φ_0^h, set $n := 0$ and $t_n := 0$.
Increase $n \to n+1$ and set $t_n := t_{n-1} + k$.
Make one forward Euler step (30) to determine φ_n^h.
Update mean density $\bar{\varrho}_n$ by (31).
Solve the linear problem (32) to determine p_n^h and
If $t_n \leq T$ goto 2.

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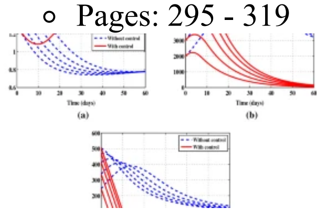

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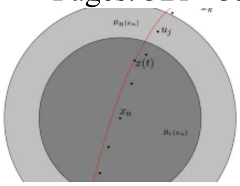

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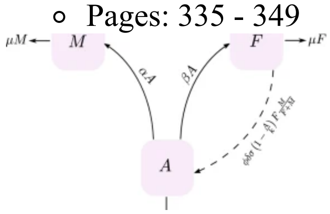

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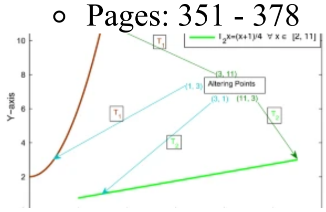

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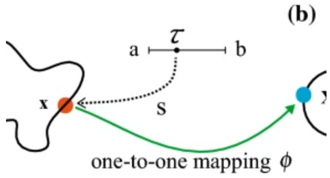

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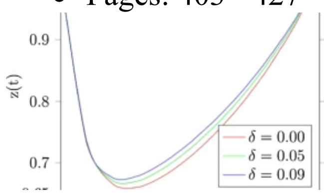

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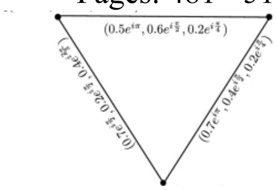

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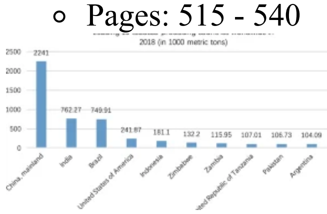

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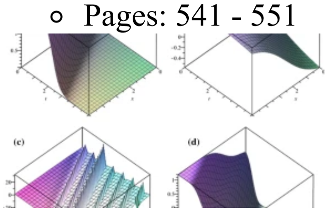

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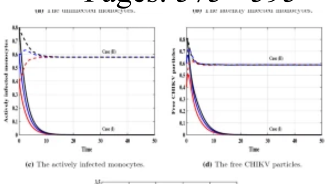

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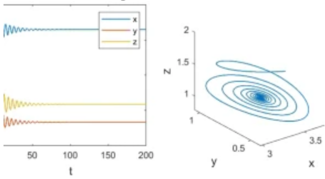

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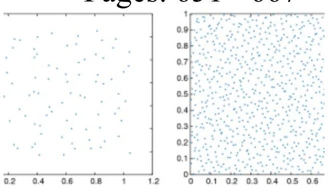

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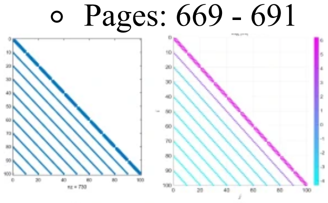

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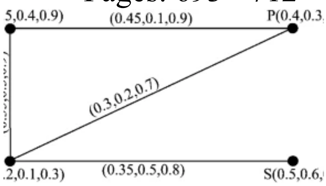

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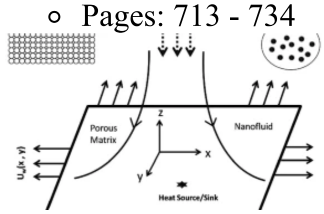

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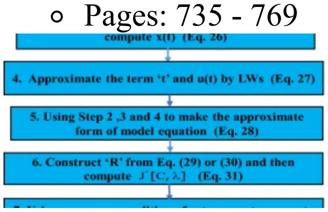

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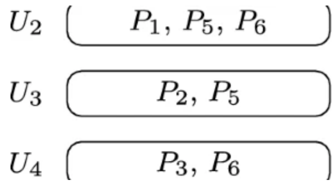

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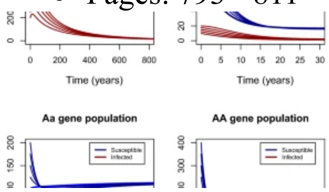

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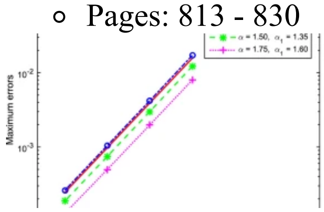

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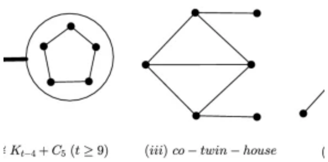

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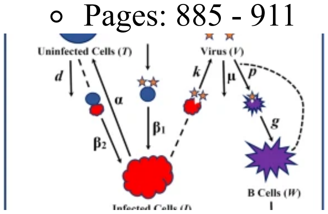

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Description and analysis of a mathematical model of population growth of Aedes aegypti

Ana María Pulecio-Montoya, Luis Eduardo López-Montenegro & Jeniffer Yinet Medina-García

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ORIGINAL RESEARCH

Description and analysis of a mathematical model of population growth of *Aedes aegypti*

Ana María Pulecio-Montoya[1] · Luis Eduardo López-Montenegro[2] · Jeniffer Yinet Medina-García[2]

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Abstract
This article proposes a mathematical model based on ordinary nonlinear differential equations that describes the dynamics of population growth of the mosquito *Aedes aegypti* throughout its life cycle. Then, a modification is made to the model by implementing a time delay, initially constant and then distributed over time. In addition, h, the population growth threshold, is established, the equilibrium points (trivial equilibrium, coexistence equilibrium) of the population are found and an analysis of local stability of the coexistence equilibrium is performed. If $h > 1$, this results in the population of adult aquatic mosquitoes persisting in the environment, approaching a equilibrium of coexistence, regardless of whether the time delay is considered or not. Finally, numerical simulations are carried out using Matlab software using the functions ode45 and dde23, with a value of $h > 1$, which allow the solutions of the initial model of ordinary differential equations to be compared to the solutions when the delay is implemented.

Keywords Smooth dynamical systems · Stability theory · Ordinary differential equations.

Mathematics Subject Classification 37Nxx

1 Introduction

Aedes aegypti is a short-flying mosquito, known as the main vector that transmits viruses that cause diseases such as yellow fever, dengue fever, zika, and chicungunya,

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among others [22]. Recently, the number of infected people has increased, especially among vulnerable groups or those with deficiencies in their immune system such as older adults, children and pregnant women. Mosquitoes become infected when they feed on the blood of a person already infected with a virus and, once infected, they can spread the virus by biting other people. Only female mosquitoes bite because they need blood to carry out their reproductive process. The mosquito's habitat is related to the human environment, since in homes there are many opportunities to reproduce and raise their larvae in containers that store wastewater [9].

The life cycle of the mosquito varies between approximately 7 and 14 days and consists of two phases: immature phase and mature phase. The first is divided into three stages: egg, larva and pupa. The second phase is the adult mosquito. The eggs measure approximately one millimeter in length and are initially white in color but after a while turn black [15]. They are deposited one by one in isolation by the females, who place around 400 eggs in containers subject to water retention. Eggs withstand all types of environment, such as the absence of water for several months (up to one year). They adhere to the walls of the container and begin their incubation process taking one day to hatch under favorable conditions [9,10,21].

The larvae represent the feeding and growth phase of the mosquitoes, which pass through four larval states and then become pupae. The larvae spend most of their time feeding on objects submerged in water and any other material accumulated on the walls and bottom of the container [9,15]. The duration of larval development depends on the temperature, food availability and the density of the larvae in the container. Under favorable conditions, the larval period from hatching to pupation may take 7 days [9].

The pupa is also aquatic, but does not feed. It is where the mosquitoes change from larval form to adult insects. This process under favorable temperature conditions may take 3 days. Pupae actively move throughout the hatchery and when inactive, float on the surface of the water [9].

The adult mosquito emerges from the pupal state, reaches up to 5 mm in size and on average lives for 2 to 4 weeks. This is an aerial phase and mainly represents the mating phase [19].

Because, during the bite, the female mosquito can transmit various viruses, public health entities often recommend control strategies [6]. Among these strategies are:

Environmental management, which consists of procedures to avoid or minimize vector propagation and contact between people and pathogenic vectors and making modifications to the environment to permanently or temporarily eliminate the habitat of the transmitters [16]. This includes proper disposal of containers such as buckets, tires, cans, etc., which are used by female mosquitoes as breeding grounds.

Biological control, which is based on the use of pathogenic organisms, parasites or predators, natural enemies of the mosquito such as larvivorous fish and predatory copepods *(Copepoda Cyclopoidea)* [16], bacteria like *Bacillus thuringiensis* that cause death of larvae, or the bacterium *Wolbachia* that alters the reproduction of the mosquito [11].

Chemical control, which consists of the application of insecticidal products such as Malathion and larvicides such as Temephos 1% to eradicate the mosquito [2].

Due to the diseases that this mosquito can transmit, there are several areas of science that seek to contribute ideas and results in some way in order to understand its population growth and thus determine which measures increase or decrease the number of mosquitoes that inhabit a certain region. Mathematical models that describe the variation in the number of mosquitoes are tools that seek to determine which parameters are highly sensitive in an environment under certain given conditions and thus introduce effective controls to decrease the population of the mosquito in the environment. These control strategies can be seen in several recent models [5,13,20].

However, most of models consider only the female mosquito population, often involving their interaction with humans. This is the case of [18], where the population growth model of the mosquito considers the aerial and aquatic stages and the influence on them of climatic changes, but in which the role of the male mosquito in the reproductive stage is minimized. In [26] the interaction of the mosquito with the human population is considered, with attention focused on the transmission of diseases.

Another difficulty that can arise in adding reality to a mathematical model of population growth of *Aedes aegypti* closer is the variation in the duration of the aquatic phase of the mosquito, due to adaptation of the mosquito to its environment. This allows it to accelerate or decelerate its development when the environmental conditions are not ideal. This process can be mathematically modelled as a time delay, such as in the models presented in [22] in which time delays are used to describe the duration of the stages of mosquito development in a temperature controlled environment.

This article presents a mathematical model that describes the population growth of the mosquito *Aedes aegypti*, which considers the immature phase and the population of female and male mosquitoes in the adult phase. A delay (at first constant and then distributed) over time is then introduced, in order to take into account the fact that the eggs take time to hatch. The change in the behavior of the solutions is then determined. The local stability of the model is analyzed and numerical simulations are shown that allow the analytical results to be visualized.

2 The model

Initially, we propose a model based on differential equations that describes how the population of the mosquito *Aedes aegypti* behaves in its life cycle, and then implements the constant and distributed delays over time. The model considers two phases of the mosquito: the immature phase and the mature phase. The immature phase identifies a single population, A, of immature states, while the mature phase distinguishes between two populations: M of male mosquitoes and F of female mosquitoes.

To establish the model, the following hypotheses are taken into account:

- The death rate of male mosquitoes is equal to that of females, but different from the death rate of the immature phase.

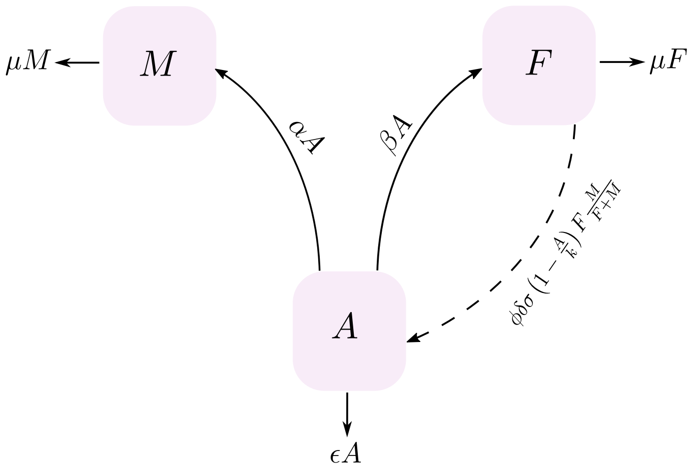

Fig. 1 Flow diagram of the model

Table 1 Variables and parameters of the model

Symbol	Description
M	Average number of adult males at time t
F	Average number of adult females at time t
A	Average number of immature mosquitoes at time t
α	Rate of male development
β	Rate of female development
μ	Natural death rate in the mature phase
ϕ	Proportion of female mosquitoes that lay eggs
ϵ	Natural death rate in the immature phase
δ	Average number of eggs laid by each female
σ	Breeding rate between males and females
k	Maximum number of immature mosquitoes that the medium supports

- The male mosquito development rate is different from the female mosquito development rate.
- In the immature phase a maximum number of containers is assumed. Therefore, there is a maximum number of immature mosquitoes k that the medium supports.

Taking into account the above hypotheses, the flow chart in Fig. (1) is presented. The variables and parameters involved in the dynamics of population growth are described in Table (1).

The flow diagram shows three populations where the variation of each population is represented by a differential continuity equation, that is, its variation is equal to the difference between the input flow and the output flow.

In the case of the variation of the population of male mosquitoes M, the inflow is αA, which represents the number of mosquitoes that develop to male adults per unit