Stabilization and Complexities of Anopheles Mosquito Dynamics with Stochastic Perturbations

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***Abstract*—This paper investigates the complex effects of Anopheles Mosquito Model. The system of Anopheles mosquito in random noise has not been investigated so far. The present paper is a contribution in this unexplored area. Its been noticed that the system has been found with boundedness. The equilibrium points of the system are also found out. Global stability properties of the model are investigated by constructing Lyapunov function. Also we introduce the stochastic perturbations and suggest the deterministic model is robust with respect to stochastic perturbations. The analysis leads to the equilibrium of the stochastic perturbation wherein the total number of mosquito population and the biocontrollers remains stationary. Finally, the numerical examples are given and the diagrams are presented which support our results.**

***Index Terms*—Anopheles, Stochastic, Equilibrium points, Lyapunov.**

I. Introduction

THE Mosquito is one of the species that give nuisance to the public health of the world. It is very important to understand the lifecycle of the dangerous mosquito species in which can be controlled to manage the public health.

All mosquito pest will go through complete metamorphoses, from egg to larva, from larva to pupa, from pupa to adult. The cycle begins when a female mosquito obtains a blood meal from either a human-being or from other mammal to supply the required nutrients to produce approximately around two hundred and fifty eggs at a time [1]. She then seeks an aquatic location usually on the surface of stagnant water, or in a water filled in depression [2], or on the edge of a container, where rainwater was collected for the female mosquito to lay eggs [3]. Two days, after the eggs will get hatch into larvae [4]. The larvae live and feed on microorganisms in the water for seven to fourteen days and develop into pupae, which will not feed for more than fourteen days. The mosquito then emerges from the pupa shell as a fully developed adult after four days. The moment the body of the mosquito finishes moulting, it is hypersensitive to carbon dioxide exhaled from mammals, it has poor eyesight and very sensitive to mammal sweat scent ever from a half mile distance [5]; This enables it to locate a mammal to seek out for a blood meal by a suck on the animal or human skin. As the mosquito punctures the skin it injects its saliva into the flesh. If the mosquito is infected with any kind of disease [6]–[10]. it is transferred into the prey through the saliva.

There are about 2500 species of mosquitoes on the planet, of which 300 are well known disease carriers. Different species carry different diseases that are local to the area where they live. The disease Malaria is transmitted by the female Anopheles mosquito which feeds on human blood ([11]–[14]).

It is observed that as long as an environment is left uncared for, it will definitely become a breeding ground providing many mosquito hatcheries. When an environment is occupied with millions of mosquitoes [15], no preventive measures can cure or manage the mosquito pest [16]. The dynamics of Anopheles mosquito life cycle breaks-up by using backstepping control which was studied [17], [18] and it has been recommended that in addition to managing the environment and preventing it from becoming a breeding zone, a permanent control measure should be employed. This paper investigates the complex effects of Anopheles mosquito model. The system of Anopheles mosquito with random noise has not been investigated so far. The present paper is a contribution in this unexplored area. Much work has been done to control this species, but no work has been done so far with stochastic perturbations. This paper is organized as follows. In section 2, the system of differential equation is modelled. This differential equation represents the life cycle of Anopheles mosquito.In section 3, the boundedness and the local and global stability of the equilibrium points are analysed. In section 4, projects about the stochastic nature on this model. In section 5, present the diagrams and in section 6, is devoted to the conclusion.

II. The Mathematical Model

For modelling Anopheles mosquito life cycle, the following assumptions are made.

1) The total population of Anopheles mosquito life cycle consists of four forms, such as adult, egg, larva and pupa.
2) In every stage, the natural death rate μ is considered uniformly.
3) Let *bN* be the existing population, where *b* is natural birth rate at adult stage.
4) x_5 is the controller in egg stage at the rate α .
5) x_6 is controller in larva stage at the rate γ .

Fig. 1 depicts the flow diagram of Anopheles mosquito life cycle. The Mathematical Model of Anopheles mosquito life cycle ([18]) is given below:

$$\begin{aligned}
\frac{dx_1}{dt} &= bN + \rho x_4 - (\eta+\mu)x_1 \\
\frac{dx_2}{dt} &= \mu x_1 + \mu x_5 - \rho x_2 - \mu x_2 \\
\frac{dx_3}{dt} &= \mu x_2 + \mu x_6 - \mu x_3 - \beta x_3 - \rho x_2 \\
\frac{dx_4}{dt} &= \mu x_3 - \mu x_4 - \rho x_4 \\
\frac{dx_5}{dt} &= c - \mu x_5 \\
\frac{dx_6}{dt} &= d - \mu x_6
\end{aligned} \tag{1}$$

where x_1 is the number of adult mosquito at time t, x_2 is the number of eggs at time t, x_4 is the number of pupa at time t,

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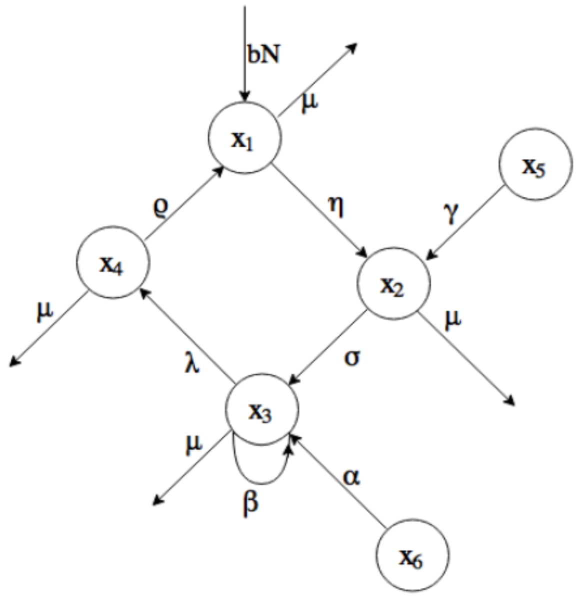

Fig. 1: Flow Diagram of Anopheles mosquito life cycle

x_5 is the controller in egg stag at time t,x_6 is the controller in larva stage at the rate of α. b is the natural birth rate at adult stage,c is the initial state population of x_5, d is the initial state population of x_6, η is the rate of adult mosquito ovisposit, ρ is the rate of pupa push to adult mosquito, μ is the normal death at all the stages, β is the death of larva eat-ups to larva and N is the total population. where x_1, x_2, x_3 and x_4 are number of adult mosquito, eggs, larva and pupa at time t respectively, x_5 and x_6 are the controllers in the stages of egg and larva at the rate of α and γ respectively.

III. The Modified Mathematical Model

The equation of the model can be written as

$$\begin{array}{rcl} \frac{dx_1}{dt} & = & bN + \rho x_4 - (\eta + \mu)x_1 \\ \frac{dx_2}{dt} & = & \mu(x_1 + x_5) - (\rho + \mu)x_2 \\ \frac{dx_3}{dt} & = & (\mu - \rho)x_2 + \mu x_6 - (\mu + \beta)x_3 \\ \frac{dx_4}{dt} & = & \mu x_3 - (\mu + \rho)x_4 \\ \frac{dx_5}{dt} & = & c - \mu x_5 \\ \frac{dx_6}{dt} & = & d - \mu x_6 \end{array} \tag{2}$$

Replacing
$a = \eta + \mu; r = \rho + \mu; q = \mu + \beta; s = \mu - \rho.$
The modified equation of (1) is

$$\begin{array}{rcl} \frac{dx_1}{dt} & = & bN + \rho x_4 - ax_1 \\ \frac{dx_2}{dt} & = & \mu(x_1 + x_5) - rx_2 \\ \frac{dx_3}{dt} & = & sx_2 + \mu x_6 - qx_3 \\ \frac{dx_4}{dt} & = & \mu x_3 - rx_4 \\ \frac{dx_5}{dt} & = & c - \mu x_5 \\ \frac{dx_6}{dt} & = & d - \mu x_6 \end{array} \tag{3}$$

IV. Analysis of the Deterministic Model

A. Boundedness

Assume that, $x_1(0) > 0, x_2(0) > 0, x_3(0) > 0, x_4(0) > 0, x_5(0) > 0$and $x_6(0) > 0$, are positive initial conditions. Let us consider the system (x_1) with these positive initial conditions for local existence, positiveness and boundedness of the solutions. As the right hand sides of (3) are smooth functions of$(x_1, x_2, x_3, x_4, x_5, x_6)$ parameters. The local existence and uniqueness properties hold within the positive quadrant .

The state space for the system (3) is positive quadrant $\{(x_1, x_2, x_3, x_4, x_5, x_6) : x_1 > 0, x_2 > 0, x_3 > 0, x_4 > 0, x_5 > 0, x_6 > 0\}$ which is an invariant set.

Theorem 1: The system (3) is dissipative.

Proof: Let $x_i(0) > 0$, where $i = 1,\ 2,\ 3, ...,\ 6$ be any solution of the system with positive initial conditions.

Now we define the function

$$M(t) = x_1(t) + x_2(t) + x_3(t) + x_4(t) + x_5(t) + x_6(t) \tag{4}$$

Therefore, time derivative gives we get

$$\begin{array}{rcl} \dot{M}(t) & = & \dot{x}_1(t) + \dot{x}_2(t) + \dot{x}_3(t) + \dot{x}_4(t) + \dot{x}_5(t) + \dot{x}_6(t) \\ & = & bN + c + d + 2\mu x_5 - [(a-\mu)x_1 + (r-s)x_2 \\ & & +(q-\mu)x_3 + (r-\rho)x_4 + \mu x_5] \end{array} \tag{5}$$

$$\frac{dM}{dt} \leq 2\mu x_5 - \xi(x_1 + x_2 + x_3 + x_4 + x_5 + x_6) \tag{6}$$

where $\xi = min(2, a, r, q, 1, \mu, s, \rho)$. Which gives

$$\frac{dM}{dt} + \xi M \leq 2x_5 \tag{7}$$

Since $\frac{dM}{dt} \leq x_5$,

$$\frac{dM}{dt} \leq x_5 \tag{8}$$

by a standard comparison theorem we have,

$$\lim_{t\to\infty} sup\ x_5(t) \leq L$$

where $L = max\{x_5(0), 1\}$, which gives

$$\frac{dM}{dt} + \xi M \leq L \tag{9}$$

$$\frac{dM}{dt} + \xi M = L(say) \tag{10}$$

Now applying the theory of differential inequality (Birkoff and Rota, 1982), we obtain

$$0 \leq M \leq \frac{L}{\xi} + \frac{W(x_1(0), x_2(0), x_3(0), x_4(0), x_5(0), x_6(0))}{e^{\xi t}} \tag{11}$$

and for $t \to \infty$ we get

$$0 \leq M(x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6) \leq \frac{L}{\xi} \tag{12}$$

Thus, all the solutions of the system (3) enter into the region B where,

$$\begin{array}{rcl} B & = & \{(x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6) \in \mathcal{R}^6_+\} \text{ with} \\ & & 0 \leq M \leq \frac{L}{\xi} + \epsilon, \text{for any } \epsilon > 0 \end{array} \tag{13}$$

which acquires the proof.

B. Equilibria and Local stability Analysis

The boundary and interior equilibrium point are discussed below. Toward the end, equating the right hand side of (3) to zero, the following six equilibrium points are obtained. The boundary equilibrium states are

$$E_1 = (\frac{bN}{a}, 0, 0),\ E_2 = (0, \frac{\mu}{r}x_1, 0, 0, 0, 0)$$

$$E_3 = (0, 0, \frac{s}{q}x_2, 0, 0, 0),\ E_4 = (0, 0, 0, \frac{\mu}{r}x_3, 0, 0)$$

$$E_5 = (0, 0, 0, 0, \frac{c}{\mu}, 0),\ E_6 = (0, 0, 0, 0, 0, \frac{d}{\mu})$$

and the interior equilibrium points are

$$E^* = (x_1^*,\ x_2^*,\ x_3^*,\ x_4^*,\ x_5^*,\ x_6^*)$$

where,

$$x_1^* = \frac{qr^2P}{s\mu} - \frac{dr}{\mu} - \frac{c}{\mu},\ x_2^* = \frac{qrP}{s} - \frac{d}{s}$$

$$x_3^* = \frac{r}{P},\ x_4^* = \frac{\mu}{P},\ x_5^* = \frac{c}{\mu},\ x_6^* = \frac{d}{\mu}$$

and

$$P = \frac{ard + bNs\mu + acs}{aqr^2 - \rho\mu^2}$$

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C. Global Stability Analysis

Theorem 2: The interior equilibrium point E^* is globally asymptotically stable if

$$\begin{array}{c} \rho = -\frac{x_1(x_1-x_1^*)-bN}{x_4};\ \mu = -x_2(\frac{x_2-x_2^*}{x_1+x_5}); \\ s = -\frac{x_3(x_3-x_3^*)-\mu x_5}{x_2};\ \mu x_3 + x_4(x_4 - x_4^*) = 0; \\ c = -x_5(x_5 - x_5^*);\ d = -x_6(x_6 - x_6^*) \end{array} \quad (14)$$

Proof: Define the Lyapunov function

$$V(x_i) = \sum_{i=1}^{6} l_i[(x_i - x_i^*) - x_i^* ln(\frac{x_i}{x_i^*})] \quad (15)$$

where $i = 1,\ 2,\ 3,\ 4,\ 5,\ 6$ are positive constants to be chosen later.

It is observed V is a positive definite function in the region except at E^* where it is zero.

Solving the rate of change of V along the solutions of the system (3), we get

$$\dot{V} = \sum_{i=1}^{6} l_i \frac{\dot{x}_i}{x_i}(x_i - x_i^*) \quad (16)$$

$$\begin{array}{rcl} \dot{V} & = & l_1(x_1 - x_1^*)(\frac{bN+\rho x_4}{x_1} + l_2(x_2 - x_2^*)(\frac{\mu}{x_2}(x_1 + x_5)) \\ & & +l_3(x_3 - x_3^*)(\frac{sx_2+\mu x_5}{x_3}) + l_4(x_4 - x_4^*)(\frac{\mu x_3}{x_4}) \\ & & +l_5(x_5 - x_5^*)(\frac{c}{x_5}) + l_6(x_6 - x_6^*)(\frac{d}{x_6}) \end{array} \quad (17)$$

Now choosing (14), we get

$$\begin{array}{rcl} \frac{dV}{dt} & = & -l_1(x_1 - x_1^*)^2 - l_2(x_2 - x_2^*)^2 - l_3(x_3 - x_3^*)^2 \\ & & -l_4(x_4 - x_4^*)^2 - l_5(x_5 - x_5^*)^2 - l_6(x_6 - x_6^*)^2 \end{array} \quad (18)$$

and hence $\dot{V}$ is negative definite.

Therefore, by Laselle's invariance principle, E^* is globally asymptotically stable.

V. Stochastic Stability Analysis of the Positive Equilibrium

Stochastic perturbations were introduced in some of the main parameters which were involved in this model.

In this paper, the stochastic perturbations of the variables $x_1,\ x_2,\ x_3,\ x_4,\ x_5,\ x_6$ are allowed with around the positive equilibrium E^*. In this case when it is feasible and locally asymptotically stable. Local stability of E* is implied by the existence condition of E^*. In Model (3), the stochastic perturbations of the variables around their value at E^* of white noise type, which are proportional to the distances of $x_1, x_2, x_3, x_4, x_5, x_6$ from values $x_1^*,\ x_2^*,\ x_3^*,\ x_4^*,\ x_5^*,\ x_6^*$

The equation (3) becomes

$$\begin{array}{rcl} dx_1 & = & [bN + \rho x_4 - ax_1]dt + \sigma_1[x_1 - x_1^*]d\omega_{t_1} \\ dx_2 & = & [\mu(x_1 + x_5) - rx_2]dt + \sigma_2[x_2 - x_2^*]d\omega_{t_2} \\ dx_3 & = & [sx_2 + \mu x_6 - qx_3]dt + \sigma_3[x_3 - x_3^*]d\omega_{t_3} \\ dx_4 & = & [\mu x_3 - rx_4]dt + \sigma_4[x_4 - x_4^*]d\omega_{t_4} \\ dx_5 & = & [c - \mu x_5]dt + \sigma_5[x_5 - x_5^*]d\omega_{t_5} \\ dx_6 & = & [d - \mu x_6]dt + \sigma_6[x_6 - x_6^*]d\omega_{t_6} \end{array} \quad (19)$$

where $\sigma_i,\ i = 1,\ 2,\ 3,\ 4,\ 5,\ 6$ are real constants, $\omega_{t_i} = \omega_i(t),\ i = 1,\ 2,\ 3,\ 4,\ 5,\ 6$ are independent from each other standard wiener process.The dynamical behavior of model (3) is robust with respect to a kind of stochasticity by investigating the asymptotic stability behavior of the equilibrium E^* .

This analysis mainly represents the dynamics of the system around the interior equilibrium point E^* . For this purpose, we linearize the model using the following perturbation method, that is the stochastic differential system of (19) can be centred at its positive equilibrium E^* by the change of variables

$$u_i = x_i - x_i^* \quad (20)$$

where $i = 1,\ 2,\ 3,\ 4,\ 5,\ 6$ are positive constants. The linearized SDEs around E^* take the form

$$du(t) = f(u(t))dt + g(u(t))dw(t) \quad (21)$$

where $u(t) = [u_1(t)\ u_2(t)\ u_3(t)\ u_4(t)\ u_5(t)\ u_6(t)]^T$ and

$$f(u(t)) = \begin{bmatrix} -a & 0 & 0 & \rho & 0 & 0 \\ \mu & -r & 0 & 0 & \mu & 0 \\ 0 & s & -q & 0 & 0 & \mu \\ 0 & 0 & \mu & -r & 0 & 0 \\ 0 & 0 & 0 & 0 & -\mu & 0 \\ 0 & 0 & 0 & 0 & 0 & -\mu \end{bmatrix} u(t) \quad (22)$$

$$g(u(t)) = \begin{bmatrix} \sigma_1 u_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_2 u_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_3 u_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma_4 u_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_5 u_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_6 u_6 \end{bmatrix} \quad (23)$$

In (21) the positive equilibrium E^* corresponds to the trivial solution $u(t) = 0$. Let U be the set $U = (t\ \geq t_0) \times \mathcal{R}^+$. Hence $V \in \mathcal{C}_2^0(U)$ is twice continuously differentiable function with respect to u and a continuous functions with respect to t. Now the It$\ddot{o}$ stochastic differential is defined as

$$\begin{array}{rcl} \mathcal{L}V(t) & = & \frac{\partial V(t,u)}{\partial t} + f^T u(t)\frac{\partial V(t,u)}{\partial u} + \\ & & \frac{1}{2}trace[g^T(u(t))\frac{\partial^2 V(t,u)}{\partial u^2}g(u(t))] \end{array} \quad (24)$$

where

$$\frac{\partial V}{\partial u} = [\frac{\partial V}{\partial u_1}\frac{\partial V}{\partial u_2}\frac{\partial V}{\partial u_3}\frac{\partial V}{\partial u_4}\frac{\partial V}{\partial u_5}\frac{\partial V}{\partial u_6}]^T,$$

$$\frac{\partial^2 V(t,u)}{\partial u^2} = col(\frac{\partial^2 V}{\partial u_j \partial u_i}), i, j = 1, 2, 3, 4, 5, 6.$$

Theorem 3: Suppose the function exists as $V \in \mathcal{C}_2^0(U)$ satisfying the inequalities

$$\begin{gathered} V(t,u) \leq K_2 \mid u \mid^p \text{ and} \\ \mathcal{L}V(t,u) \leq K_3 \mid u \mid^p, K_i > 0, p > 0 \end{gathered} \tag{25}$$

Then the trivial solution of (19) is globally asymptotically stable.

Theorem 4: The zero solution of (19) is asymptotically mean square stable when

$$\begin{gathered} \sigma_1 > \sqrt{2a},\ \sigma_2,\ \sigma_4 > \sqrt{2r}, \\ \sigma_3,\ \sigma_5,\ \sigma_6 > \sqrt{2q} \end{gathered} \tag{26}$$

Proof: Now consider the Lyapunov function

$$V(u) = \frac{1}{2}[w_1u_1^2+w_2u_2^2+w_3u_3^2+w_4u_4^2+w_5u_5^2+w_6u_6^2] \tag{27}$$

where w_i are real positive constants are to be chosen in the following. It is easy to check that inequalities (25) hold with $p = 2$.

Now the Itö process (24) becomes

$$\begin{aligned} \mathcal{L}V(t,u) \quad = \quad & w_1[-au_1 + \rho u_4]u_1 + w_2[\mu u_1 - ru_2 + \\ & \mu u_5]u_2 + w_3[su_2 - qu_3 + \mu u_6]u_3 + \\ & w_4[\mu u_3 - ru_4]u_4 + w_5[-\mu u_5]u_5 + \\ & w_6[-\mu u_6]u_6 + \\ & \tfrac{1}{2}trace[g^T(u(t))\tfrac{\partial^2 V(t,u)}{\partial u^2}g(u(t))] \end{aligned} \tag{28}$$

here

$$\frac{\partial^2 V}{\partial u^2} = \begin{bmatrix} w_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & w_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & w_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & w_6 \end{bmatrix} \tag{29}$$

and

$$\begin{aligned} \tfrac{1}{2}trace[g^T(u(t))\tfrac{\partial^2 V(t,u)}{\partial u^2}g(u(t))] \quad = \quad & \tfrac{1}{2}[w_1\sigma_1^2u_1^2 + w_2\sigma_2^2u_2^2 \\ & +w_3\sigma_3^2u_3^2 + w_4\sigma_4^2u_4^2 \\ & +w_5\sigma_5^2u_5^2 + w_6\sigma_6^2u_6^2] \end{aligned} \tag{30}$$

Use (30) in (28), we get

$$\begin{aligned} \mathcal{L}V(t,u) \quad = \quad & -w_1[a - \tfrac{1}{2}\sigma_1^2]u_1^2 - w_2[r - \tfrac{1}{2}\sigma_2^2]u_2^2 \\ & -w_3[q - \tfrac{1}{2}\sigma_3^2]u_3^2 - w_4[r - \tfrac{1}{2}\sigma_4^2]u_4^2 \\ & -w_5[\mu - \tfrac{1}{2}\sigma_5^2]u_5^2 - w_6[\mu - \tfrac{1}{2}\sigma_6^2]u_6^2 \end{aligned} \tag{31}$$

which is negative definite and it is asymptotically stable in mean square.

VI. Numerical Simulation and Discussion

In this paper the complex effects of Anopheles mosquito model is analyzed and It is observed that the boundary equilibrium point E^* is feasible. If the death rate of the mosquito population remains a certain threshold value then the positive equilibrium is feasible.

Moreover all the solution converges to the positive equilibrium. It is observed that the deterministic model is robust with respect to the stochastic perturbations. It is to be noted that when $x_1^*,\ x_2^*,\ x_3^*,\ x_4^*,\ x_5^*,\ x_6^*$ increases, the asymptotic mean square ability property is achieved.

For the numerical simulations, the fourth order Runge kutta method is used. The parameter values are taken as $a = 0.2;\ b = 0.9;\ c = 2000;\ d = 5000;\ q = 0.9;\ r = 0.5;\ s = 0.6;\ \rho = 0.7;\ \mu = 0.3$ and the initial densities are taken as $x_1 = 31759,\ x_2 = 13982,\ x_3 = 78366,\ x_4 = 39877$.

From this analysis, it is observed that the large value of *N* compared to the biocontrollers $x_5$and x_6, the system take a larger time to bring the mosquito population under short run.

In Fig. 2, depicts the stabilization of stochastic Anopheles mosquito model when the total population *N* = *100000000* and the biocontroller densities are $x_5 = 48346987$ and $x_6 = 6838987$.

In Fig. 3, depicts the stabilization of Biocontrollers when the total population *N* = *100000000* and the biocontroller densities are $x_5 = 48346987$ and $x_6 = 6838987$.

Fig. 4 depicts the stabilization of stochastic Anopheles mosquito model when the total population *N* = *10000* and the biocontroller densities are $x_5 = 48346987$ and $x_6 = 6838987$.

The analysis leads to the equilibrium of the stochastic perturbation where in the total number of mosquito population and the bio-controllers remain stationary.

Fig. 5 depicts the stabilization of stochastic Anopheles mosquito model when the total population *N* = *10000* and the biocontroller densities are $x_5 = x_6 = 10000$.

VII. Conclusion

In this paper, the complex effects of Anopheles mosquito model is investigated. The boundedness of the model has been found and the equilibrium points of the system have been identified. Global stability properties of the model are investigated by using Lyapunov function.The stochastic perturbations is introduced and suggested the deterministic model is robust with respect to stochastic perturbations. It is showed that the interior equilibrium point of the Anopheles mosquito model is global asymptotically stable by constructing suitable Lyapunov function. Moreover all the solutions converge to the positive equilibrium. The stochastic perturbations is introduced to the system by using stochastic differential equations and Ito‘s process. It is showed that the zero solution of this stochastic system is asymptotically mean square stable through the construction of the Lyapunov function. Finally, numerical examples are given and diagrams are presented which support the results.

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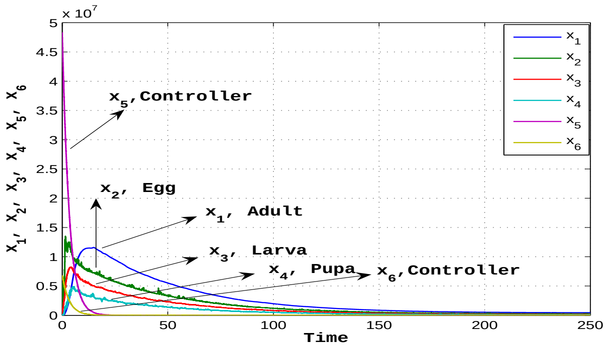

Fig. 2: Stabilization of stochastic Anopheles mosquito model when N = *100000000*

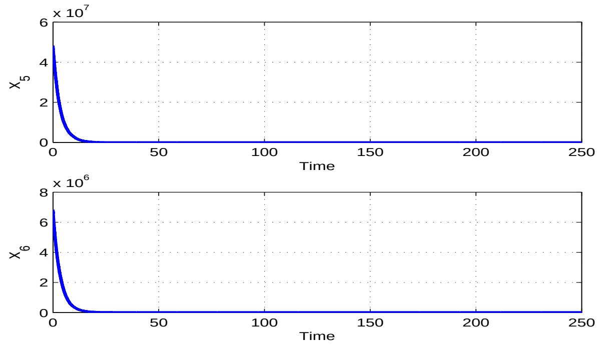

Fig. 3: Stabilization of Biocontrollers

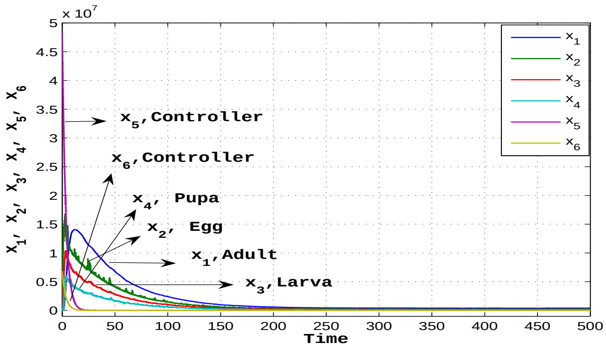

Fig. 4: Stabilization of stochastic Anopheles mosquito model when N = *10000*

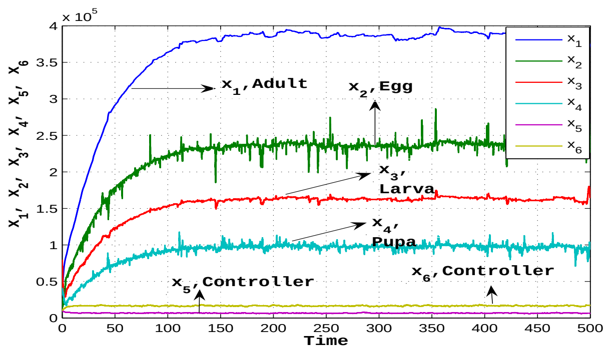

Fig. 5: Stabilization of stochastic Anopheles mosquito model when the total number of mosquito population and the bio-controllers remain stationary.

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