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Studying the Dynamical Network of Malaria at the Local Level with the Effect of *Plasmodiums'* Incubations

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ABSTRACT

Anopheles mosquito is the epidemic vector of Malaria. This disease is usually found in Thailand for many years because the physical features of the land in Thailand is suitable for breeding of *Anopheles* mosquitoes. Four types of *Plasmodiums* (*Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae* and *Plasmodium ovale*) are related with this disease. The incubation rates of four *Plasmodiums* are difference. The people who work in the border of Thailand are at a higher risk to infection with this disease. In this study, we formulate and analysis the dynamical equations for the transmission of Malaria with the effect of *Plasmodiums*' incubations when there is the movement of population at the local level. The analysis of each parameter is given to point the way for decreasing the outbreak of this disease.
KEYWORDS: *Anopheles* mosquito, dynamical equations, incubation, local level, movement, Malaria, *Plasmodiums*.

INTRODUCTION

In each year, there are about 300 to 500 million Malaria cases. There is 1.5 to 2.7 million deaths worldwide due to this disease. This disease can transmit between the people by biting of the female *Anopheles* mosquito. Birds, mammals and lizards are also the host of Malaria parasite. Protozoa parasite of the genus *Plasmodium* can cause the Malaria disease. There are four types of malaria parasites: *Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae* and *Plasmodium ovale*. These four types have the different incubation periods. The incubation periods of *Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae* and *Plasmodium ovale* are 12 days, 13 days, 28 days and 17 days, respectively. There are about 60 different species belonging to the genus *Anopheles* [1]. *Anopheline* mosquitoes are the only known vectors of malaria in human that perform this function throughout the world. These mosquitoes undergo an aquatic larval stage, pupate and then hatch into flying adults. *Anopheline* mosquitoes are insects of the order Diptera, and genus *Anopheles*. The male *Anopheles* feeds on nectar and fruit juices while the female takes both plant products and blood [2]. The females' mosquitoes require a meal of blood to produce fertile eggs. The female mosquito ingests the malaria parasite by biting a human who was already infected with the parasite. There is four phases; egg, larva, pupa and adult for the life cycle of mosquitoes. The adult vectors copulate within a day or so, usually in flight and after one or two blood meals, the first batch of several hundred eggs are laid at the breeding site. Lifetime of female mosquitoes may lay several batches of eggs. During two to three days, the eggs will hatch and release the larvae into the water, the larvae will transform into the non-feeding pupae. Over a period of 2-4 days, within the pupae, metamorphosis takes place, terminating in the materialization of the adults [2]. The symptoms of Malaria cases are chills, fever, nausea, vomiting, back pain, increased sweating anemia, splenomegaly (enlargement of the spleen). Temperature and humidity are most important environmental factors for developing of *Plasmodiums* in mosquitoes. If temperature is below 16 ^{0}C, then parasites will stop developing in mosquitoes. The average temperature between 20 – 30 ^{0}C and the average relative humidity about 60% are the best condition for the development of this disease [3]. Most Malaria cases are from Southeast Asia and the Western Pacific, although a significant number also be found in Africa and South America [4]. The dynamical model of Malaria was first explained by Ross [5], the equations were constructed between human and vector populations but the incubation period of *Plasmodium* did not included into the model. In 2009 [6], we formulated the transmission network dynamics of only one *Plasmodium*; *Plasmodium Vivax*, and the analysis of time distribution for the different situations were given. In 2012 [7], we presented the mathematical model for the transmission of *Plasmodium Falciparum* Malaria by separating the human into juvenile and adults populations. Standard dynamical modeling method was used for analysis our model. Recently [8], mathematical model of Malaria was developed by inclusion age of human and season. Analysis of the model was given. From the previous studies, the effects of incubations of four *Plasmodiums* (*Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae and Plasmodium ovale*) were not considered for constructing the model. But in reality, all four *Plasmodiums* have the different behaviors. The human behaviors, social contacts and travel between cities should be included in the model [9-10]. In this study, we construct and analyze the dynamical equations for the transmission of Malaria with the effect of four *Plasmodiums'* incubation when there is the movement of population at the local level (village).

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DYNAMICAL EQUATIONS

We study the transmission of Malaria with *Plasmodiums'* incubations**.** The dynamical changes of human and mosquito populations are considered. The human population is separated into five groups; susceptible, exposed, infectious, dormant and recovered groups. The mosquito population is separated into three groups; susceptible, exposed and infectious groups because the vector never recover from infection. The movement of people is considered to see the distribution of this disease. Suppose that there are K persons and M houses in each village. The persons move to any houses in this village by random process. We random the 1st person to the K^{th} person go to each house. The uniformly distribution is used for random processing. Each day, one person can go only one time in one house of this village. The probability for each person to visit each house is equivalent. Nobody come from the other villages.

In each house, the persons who stay at the first day will come back to their houses at the ending time. At the first day, there is only one infected human in one house, no infected human stay in the other houses in the village.

The considered variables are defined as follows:

$S_{h_{t,j}}$ is the number of susceptible persons in j^{th} house after visited at day t ,

$E_{h_{t,j}}$ is the number of exposed persons in j^{th} house after visited at day t ,

$I_{h_{t,j}}$ is the number of infectious persons in j^{th} house after visited at day t ,

$D_{h_{t,j}}$ is the number of dormant persons in j^{th} house after visited at day t ,

$R_{h_{t,j}}$ is the number of recovered persons in j^{th} house after visited at day t ,

$S_{v_{t,j}}$ is the number of susceptible vector in j^{th} house after visited at day t ,

$E_{v_{t,j}}$ is the number of exposed vector in j^{th} house after visited at day t ,

$I_{v_{t,j}}$ is the number of infectious vector in j^{th} house after visited at day t .

The dynamical equations of human and vector populations are given by

$$\Delta S_{h_{t,j}} = -(\gamma_{h_f} + \gamma_{h_v} + \gamma_{h_m} + \gamma_{h_o})I_{v_{t,j}} Sh_{t,j} + (r_{1_f} + r_{1_v} + r_{1_m} + r_{1_o})Eh_{t,j} - \alpha(r_{1_v} + r_{1_o})I_{h_{t,j}}$$
$$+ (r_{3_v} + r_{3_o})D_{h_{t,j}} + (r_{4_v} + r_{4_o})R_{h_{t,j}} + (r_{6_f} + r_{6_v} + r_{6_m} + r_{6_o})I_{h_{t,j}}$$

$$\Delta E_{h_{t,j}} = (\gamma_{h_f} + \gamma_{h_v} + \gamma_{h_m} + \gamma_{h_o})I_{v_{t,j}} S_{h_{t,j}}(t) - (r_{1_f} + r_{1_v} + r_{1_m} + r_{1_o})E_{h_{t,j}}(t) - (\lambda_{h_f} + \lambda_{h_v} + \lambda_{h_m} + \lambda_{h_o})E_{h_{t,j}}(t)$$

$$\Delta I_{h_{t,j}} = (\lambda_{h_f} + \lambda_{h_v} + \lambda_{h_m} + \lambda_{h_o})E_{h_{t,j}} - (r_{5_f} + r_{5_v} + r_{5_m} + r_{5_o})I_{h_{t,j}} + (r_{2_v} + r_{2_o})D_{h_{t,j}}$$
$$- (r_{6_f} + r_{6_v} + r_{6_m} + r_{6_o})I_{h_{t,j}}$$

$$\Delta D_{h_{t,j}} = \alpha(r_{1_v} + r_{1_o})I_{h_{t,j}} - (r_{3_v} + r_{3_o})D_{h_{t,j}} - (r_{2_v} + r_{2_o})D_{h_{t,j}}$$

$$\Delta R_{h_{t,j}} = (r_{5_f} + r_{5_v} + r_{5_m} + r_{5_o})I_{h_{t,j}}(t) - (r_{4_v} + r_{4_o})R_{h_{t,j}}$$

$$\Delta S_{v_{t,j}}(t) = C - (\gamma_{v_f} + \gamma_{v_v} + \gamma_{v_m} + \gamma_{v_o})I_{h_{t,j}}(t)S_{v_{t,j}}(t) - \mu_v S_{v_{t,j}}(t)$$

$$\Delta E_{v_{t,j}}(t) = (\gamma_{v_f} + \gamma_{v_v} + \gamma_{v_m} + \gamma_{v_o})I_{h_{t,j}}(t)S_{v_{t,j}}(t) - (\lambda_{v_f}(t) + \lambda_{v_v}(t) + \lambda_{v_m}(t) + \lambda_{v_o}(t))E_{v_{t,j}}(t)$$
$$- \mu_v E_{v_{t,j}}(t)$$

$$\Delta I_{v_{t,j}}(t) = (\lambda_{v_f}(t) + \lambda_{v_v}(t) + \lambda_{v_m}(t) + \lambda_{v_o}(t))E_{v_{t,j}}(t) - \mu_v I_{v_{t,j}}(t)$$

The parameters are defined as follows

Parameters	Definition
γ_{h_f}	Transmission rate of *P.falciparum* from mosquitoes to human
γ_{h_v}	Transmission rate of *P.vivax* from mosquitoes to human
γ_{h_m}	Transmission rate of *P.malariae* from mosquitoes to human
γ_{h_o}	Transmission rate of *P. ovale* from mosquitoes to human
γ_{v_f}	Transmission rate of *P.falciparum* from human to mosquitoes
γ_{v_v}	Transmission rate of *P.vivax* from human to mosquitoes

γ_{v_m}	Transmission rate of *P.malariae* from human to mosquitoes
γ_{v_o}	Transmission rate of *P. ovale* from human to mosquitoes
α	Percentage of infected humans in whom some hypnozoites remain dormant in the liver
r_{1_f}	Rate at which the exposed human change to be the susceptible human with *P.falciparum*
r_{1_v}	Rate at which the exposed human change to be the susceptible human with *P.vivax*
r_{1_m}	Rate at which the exposed human change to be the susceptible human with *P.malariae*
r_{1_o}	Rate at which the exposed human change to be the susceptible human with *P.ovale*
r_{2_v}	Rate at which the dormant human change to be the infected human with *P.vivax*
r_{2_o}	Rate at which the dormant human change to be the infected human with *P.ovale*
r_{3_v}	Rate at which the dormant human change to be the susceptible human with *P.vivax*
r_{3_o}	Rate at which the dormant human change to be the susceptible human with *P.ovale*
r_{4_v}	Rate at which the recovered human change to be the susceptible human with *P.vivax*
r_{4_o}	Rate at which the recovered human change to be the susceptible human with *P.ovale*
r_{5_f}	Rate at which the infectious human who be infected with *P.falciparum* change to be the recovered human
r_{5_v}	Rate at which the infectious human who be infected with *P.vivax* change to be the recovered human
r_{5_m}	Rate at which the infectious human who be infected with *P.malariae* change to be the recovered human
r_{5_o}	Rate at which the infectious human who be infected with *P.ovale* change to be the recovered human
r_{6_f}	Rate at which the infectious human change to be the susceptible human with *P.falciparum*
r_{6_v}	Rate at which the infectious human change to be the susceptible human with *P.vivax*
r_{6_m}	Rate at which the infectious human change to be the susceptible human with *P.malariae*
r_{6_o}	Rate at which the infectious human change to be the susceptible human with *P.ovale*
λ_{h_f}	Incubation rate of *P.falciparum* in human
λ_{h_v}	Incubation rate of *P.vivax* in human
λ_{h_m}	Incubation rate of *P.malariae* in human
λ_{h_o}	Incubation rate of *P.ovale* in human
λ_{v_f}	Incubation rate of *P.falciparum* in mosquitoes
λ_{v_v}	Incubation rate of *P.vivax* in mosquitoes
λ_{v_m}	Incubation rate of *P.malariae* in mosquitoes
λ_{v_o}	Incubation rate of *P.ovale* in mosquitoes
μ_v	Death rate of mosquitoes
C	Constant recruitment rate of mosquitoes
K	The total population
M	The number of house
E	The ending time

Table 1. Definition of parameters in our model.

NUMERICAL ANALYSIS OF OUR DYNAMICAL EQUATIONS

We simulate our dynamical equations in the different situations to see the time distribution of exposed and infected humans. The results are as follows:

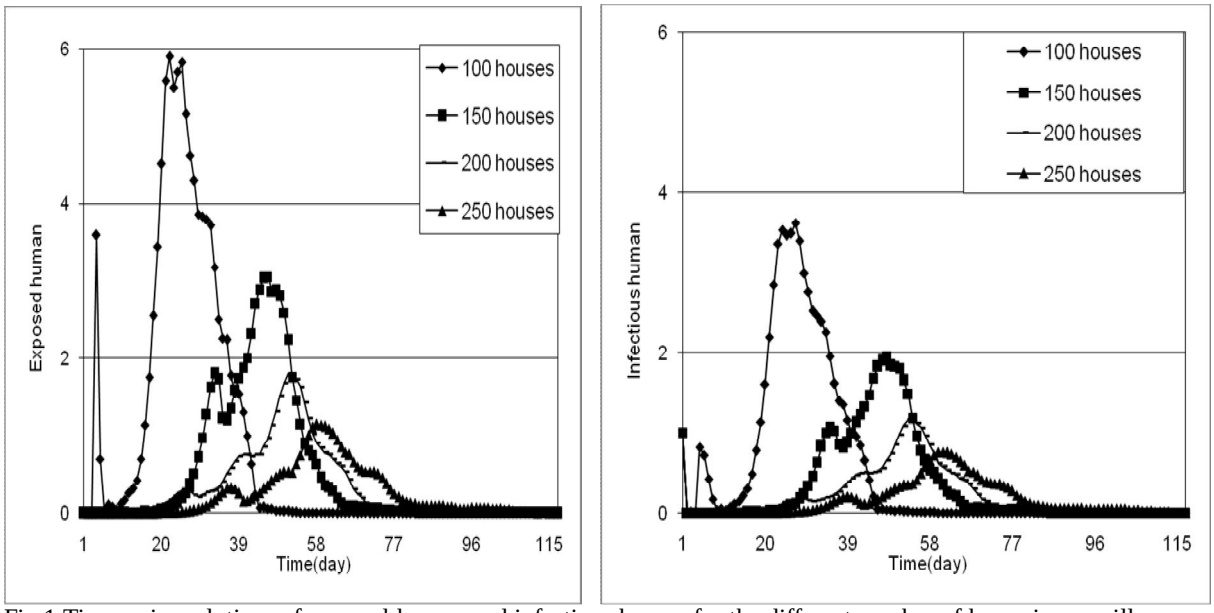

Fig.1 Time series solutions of exposed human and infectious human for the different number of house in one village.

The parameters are K = 10,000, $\gamma_{h_f} = 0.45$, $\gamma_{h_v} = 0.35$, $\gamma_{h_m} = 0.15$, $\gamma_{h_o} = 0.05$, $\gamma_{v_f} = 0.45$, $\gamma_{v_v} = 0.35$, $\gamma_{v_m} = 0.15$, $\gamma_{v_o} = 0.05$, $\alpha = 0.5$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$, $r_{6_v} = 1/120$, $r_{6_m} = 1/60$, $r_{6_o} = 1/100$, $\lambda_{h_f} = 1/12$, $\lambda_{h_v} = 1/13$, $\lambda_{h_m} = 1/28$, $\lambda_{h_o} = 1/17$, $\lambda_{v_f} = 1/12$, $\lambda_{v_v} = 1/13$, $\lambda_{v_m} = 1/28$, $\lambda_{v_o} = 1/17$, $\mu_v = 1/45$.

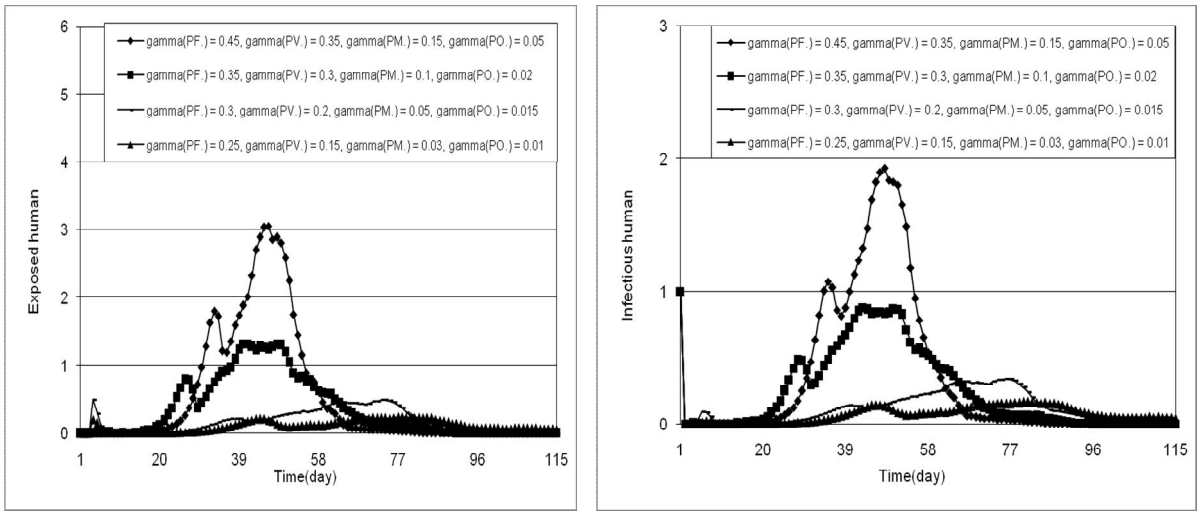

Fig.2 Time series solutions of exposed human and infectious human for the different transmission rate of four *Plasmodiums* in one village. The parameters are K = 10,000, M = 150, $\alpha = 0.5$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$, $r_{6_v} = 1/120$, $r_{6_m} = 1/60$, $r_{6_o} = 1/100$, $\lambda_{h_f} = 1/12$, $\lambda_{h_v} = 1/13$, $\lambda_{h_m} = 1/28$, $\lambda_{h_o} = 1/17$, $\lambda_{v_f} = 1/12$, $\lambda_{v_v} = 1/13$, $\lambda_{v_m} = 1/28$, $\lambda_{v_o} = 1/17$, $\mu_v = 1/45$.

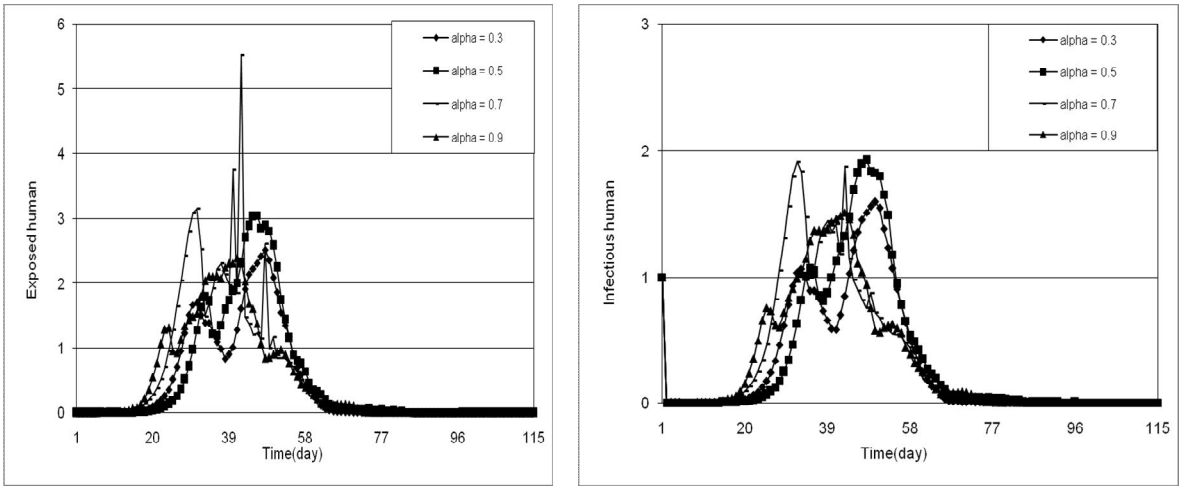

Fig.3 Time series solutions of exposed human and infectious human for the different percentage of infected humans in whom some hypnozoites remain dormant in the liver. The parameters are K = 10,000, M = 150, $\gamma_{h_f} = 0.45$, $\gamma_{h_v} = 0.35$, $\gamma_{h_m} = 0.15$, $\gamma_{h_o} = 0.05$, $\gamma_{v_f} = 0.45$, $\gamma_{v_v} = 0.35$, $\gamma_{v_m} = 0.15$, $\gamma_{v_o} = 0.05$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$, $r_{6_v} = 1/120$, $r_{6_m} = 1/60$, $r_{6_o} = 1/100$, $\lambda_{h_f} = 1/12$, $\lambda_{h_v} = 1/13$, $\lambda_{h_m} = 1/28$, $\lambda_{h_o} = 1/17$, $\lambda_{v_f} = 1/12$, $\lambda_{v_v} = 1/13$, $\lambda_{v_m} = 1/28$, $\lambda_{v_o} = 1/17$, $\mu_v = 1/45$.

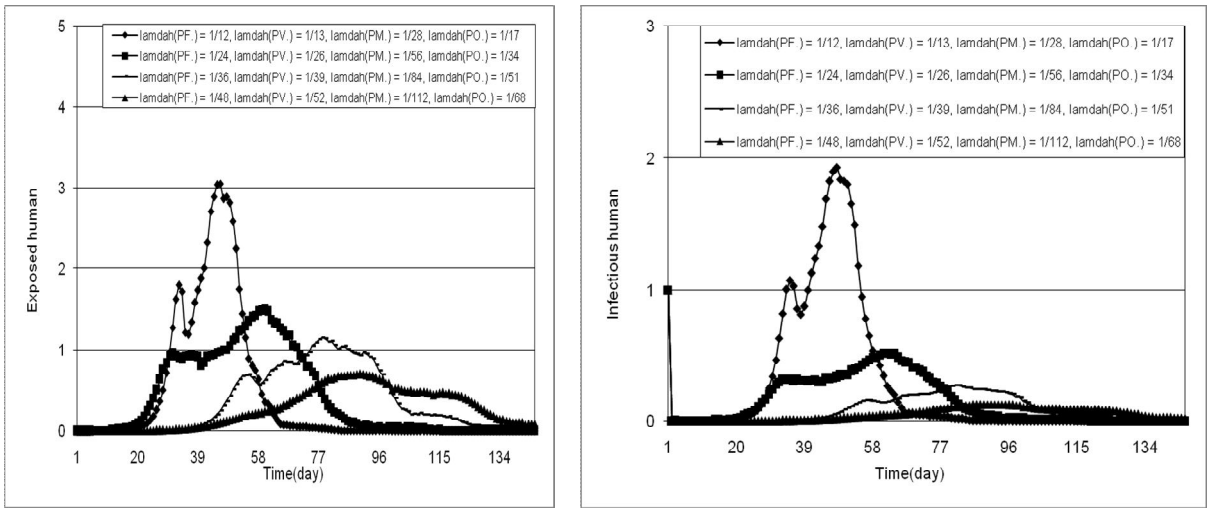

Fig.4 Time series solutions of exposed human and infectious human for the different incubation rate of four *Plasmodiums* in one village. The parameters are K = 10,000, M = 150, $\gamma_{h_f} = 0.45$, $\gamma_{h_v} = 0.35$, $\gamma_{h_m} = 0.15$, $\gamma_{h_o} = 0.05$, $\gamma_{v_f} = 0.45$, $\gamma_{v_v} = 0.35$, $\gamma_{v_m} = 0.15$, $\gamma_{v_o} = 0.05$, $\alpha = 0.5$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$, $r_{6_v} = 1/120$, $r_{6_m} = 1/60$, $r_{6_o} = 1/100$, $\mu_v = 1/45$.

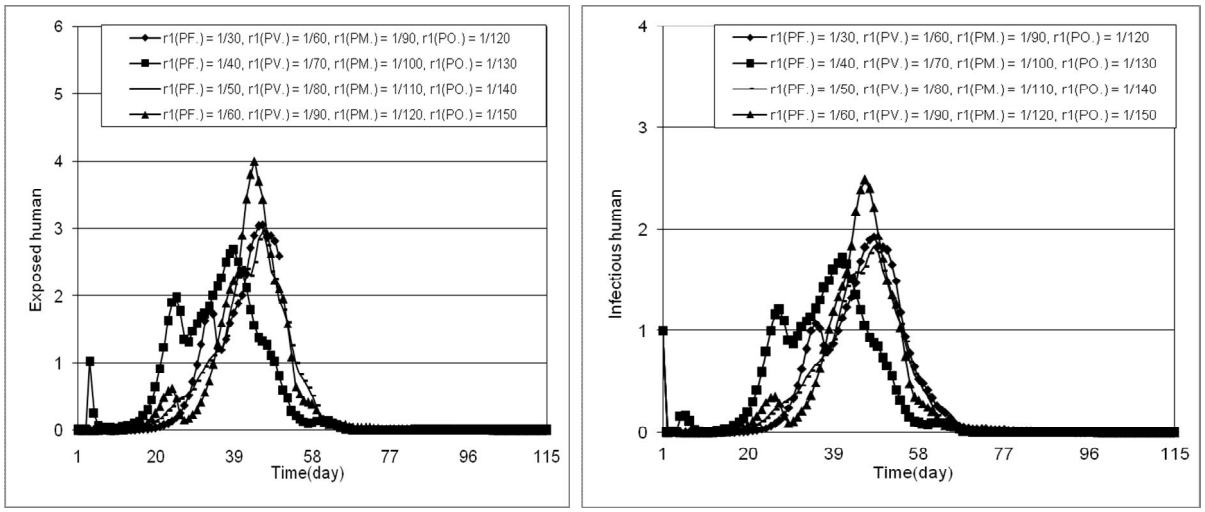

Fig.5 Time series solutions of exposed human and infectious human for the different rate at which the exposed human change to be the susceptible human in one village. The parameters are K = 10,000, M = 150, γ_{h_f} = 0.45, γ_{h_v} = 0.35, γ_{h_m} = 0.15, γ_{h_o} = 0.05, γ_{v_f} = 0.45, γ_{v_v} = 0.35, γ_{v_m} = 0.15, γ_{v_o} = 0.05, α = 0.5, r_{2_v} = 1/(5*30), r_{2_o} = 1/(5*30), r_{3_v} = 1/(3*30), r_{3_o} = 1/(6*30), r_{4_v} =1/(5*30), r_{4_o} = 1/(3*30), r_{5_f} = 1/30, r_{5_v} = 1/14, r_{5_m} = 1/7, r_{5_o} = 1/17, r_{6_f} = 1/90, r_{6_v} = 1/120, r_{6_m} = 1/60, r_{6_o} = 1/100, λ_{h_f} = 1/12, λ_{h_v} = 1/13, λ_{h_m} = 1/28, λ_{h_o} = 1/17, λ_{v_f} = 1/12, λ_{v_v} = 1/13, λ_{v_m} = 1/28, λ_{v_o} = 1/17, μ_v =1/45.

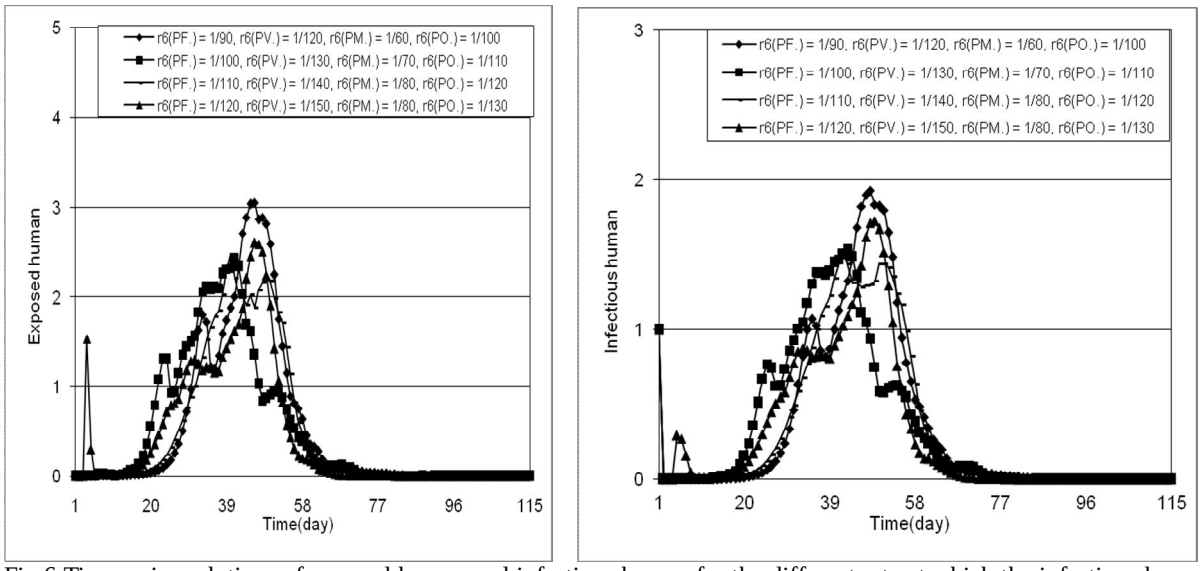

Fig.6 Time series solutions of exposed human and infectious human for the different rate at which the infectious human change to be the susceptible human in one village. The parameters are K = 10,000, M = 150, γ_{h_f} = 0.45, γ_{h_v} = 0.35, γ_{h_m} = 0.15, γ_{h_o} = 0.05, γ_{v_f} = 0.45, γ_{v_v} = 0.35, γ_{v_m} = 0.15, γ_{v_o} = 0.05, α = 0.5, r_{1_f} = 1/30, r_{1_v} = 1/60, r_{1_m} = 1/90, r_{1_o} = 1/120, r_{2_v} = 1/(5*30), r_{2_o} = 1/(5*30), r_{3_v} = 1/(3*30), r_{3_o} = 1/(6*30), r_{4_v} =1/(5*30), r_{4_o} = 1/(3*30), r_{5_f} = 1/30, r_{5_v} = 1/14, r_{5_m} = 1/7, r_{5_o} = 1/17, λ_{h_f} = 1/12, λ_{h_v} = 1/13, λ_{h_m} = 1/28, λ_{h_o} = 1/17, λ_{v_f} = 1/12, λ_{v_v} = 1/13, λ_{v_m} = 1/28, λ_{v_o} = 1/17, μ_v =1/45.

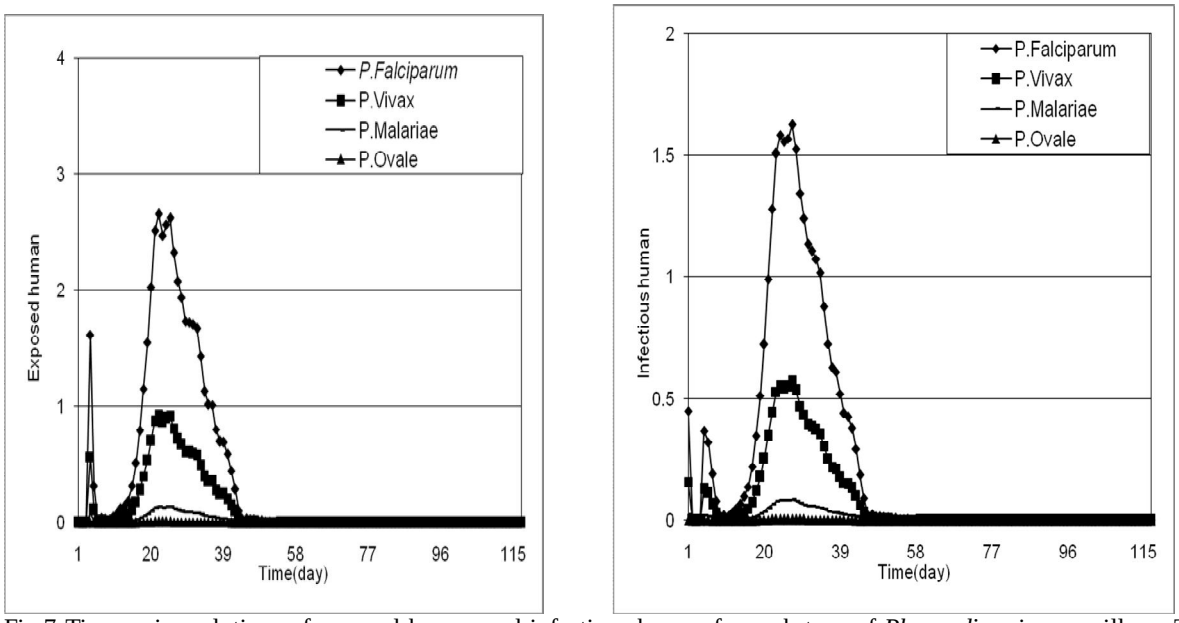

Fig.7 Time series solutions of exposed human and infectious human for each type of *Plasmodium* in one village. The parameters are K = 10,000, M = 100, $\gamma_{h_f} = 0.45$, $\gamma_{h_v} = 0.35$, $\gamma_{h_m} = 0.15$, $\gamma_{h_o} = 0.05$, $\gamma_{v_f} = 0.45$, $\gamma_{v_v} = 0.35$, $\gamma_{v_m} = 0.15$, $\gamma_{v_o} = 0.05$, $\alpha = 0.5$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$, $r_{6_v} = 1/120$, $r_{6_m} = 1/60$, $r_{6_o} = 1/100$, $\lambda_{h_f} = 1/12$, $\lambda_{h_v} = 1/13$, $\lambda_{h_m} = 1/28$, $\lambda_{h_o} = 1/17$, $\lambda_{v_f} = 1/12$, $\lambda_{v_v} = 1/13$, $\lambda_{v_m} = 1/28$, $\lambda_{v_o} = 1/17$, $\mu_v = 1/45$.

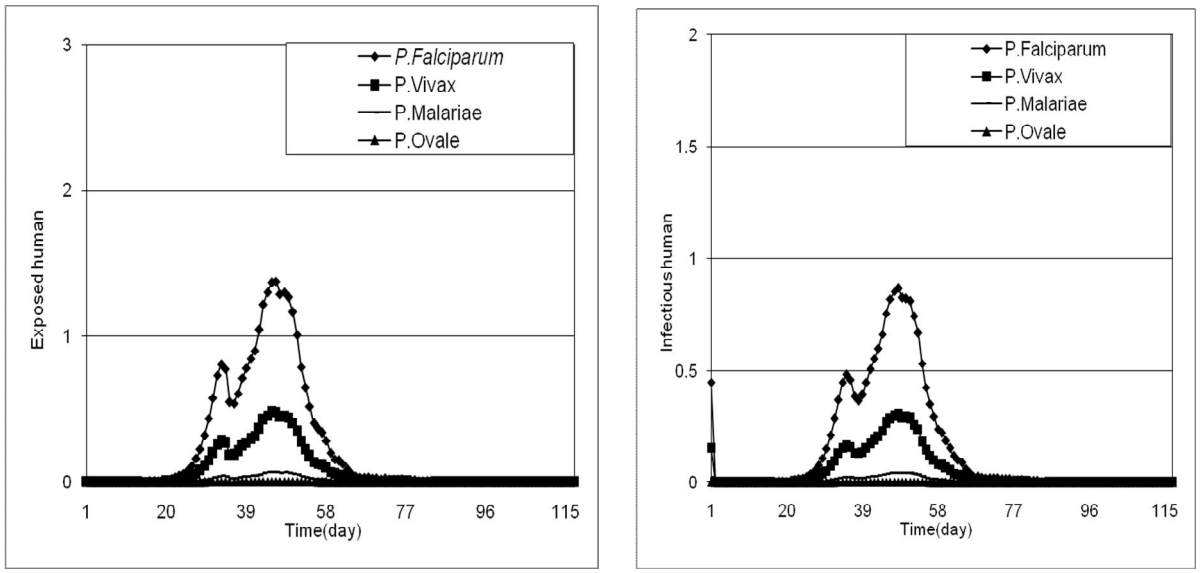

Fig.8 Time series solutions of exposed human and infectious human for each type of *Plasmodium* in one village. The parameters are K = 10,000, M = 150, $\gamma_{h_f} = 0.45$, $\gamma_{h_v} = 0.35$, $\gamma_{h_m} = 0.15$, $\gamma_{h_o} = 0.05$, $\gamma_{v_f} = 0.45$, $\gamma_{v_v} = 0.35$, $\gamma_{v_m} = 0.15$, $\gamma_{v_o} = 0.05$, $\alpha = 0.5$, $r_{1_f} = 1/30$, $r_{1_v} = 1/60$, $r_{1_m} = 1/90$, $r_{1_o} = 1/120$, $r_{2_v} = 1/(5*30)$, $r_{2_o} = 1/(5*30)$, $r_{3_v} = 1/(3*30)$, $r_{3_o} = 1/(6*30)$, $r_{4_v} = 1/(5*30)$, $r_{4_o} = 1/(3*30)$, $r_{5_f} = 1/30$, $r_{5_v} = 1/14$, $r_{5_m} = 1/7$, $r_{5_o} = 1/17$, $r_{6_f} = 1/90$,

r_{6_v} = 1/120, r_{6_m} = 1/60, r_{6_o} = 1/100, λ_{h_f} = 1/12, λ_{h_v} = 1/13, λ_{h_m} = 1/28, λ_{h_o} = 1/17, λ_{v_f} = 1/12, λ_{v_v} = 1/13, λ_{v_m} = 1/28, λ_{v_o} = 1/17, μ_v =1/45.

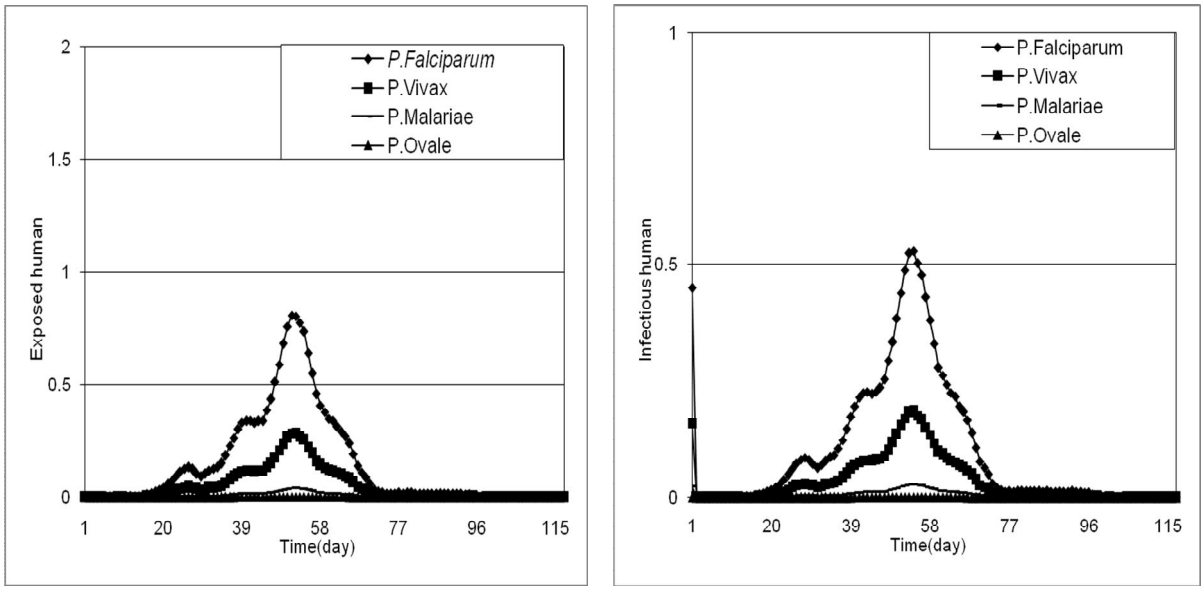

Fig.9 Time series solutions of exposed human and infectious human for each type of *Plasmodium* in one village. The parameters are K = 10,000, M = 200, γ_{h_f} = 0.45, γ_{h_v} = 0.35, γ_{h_m} = 0.15, γ_{h_o} = 0.05, γ_{v_f} = 0.45, γ_{v_v} = 0.35, γ_{v_m} = 0.15, γ_{v_o} = 0.05, α = 0.5, r_{1_f} = 1/30, r_{1_v} = 1/60, r_{1_m} = 1/90, r_{1_o} = 1/120, r_{2_v} = 1/(5*30), r_{2_o} = 1/(5*30), r_{3_v} = 1/(3*30), r_{3_o} = 1/(6*30), r_{4_v} =1/(5*30), r_{4_o} = 1/(3*30), r_{5_f} = 1/30, r_{5_v} = 1/14, r_{5_m} = 1/7, r_{5_o} = 1/17, r_{6_f} = 1/90, r_{6_v} = 1/120, r_{6_m} = 1/60, r_{6_o} = 1/100, λ_{h_f} = 1/12, λ_{h_v} = 1/13, λ_{h_m} = 1/28, λ_{h_o} = 1/17, λ_{v_f} = 1/12, λ_{v_v} = 1/13, λ_{v_m} = 1/28, λ_{v_o} = 1/17, μ_v =1/45.

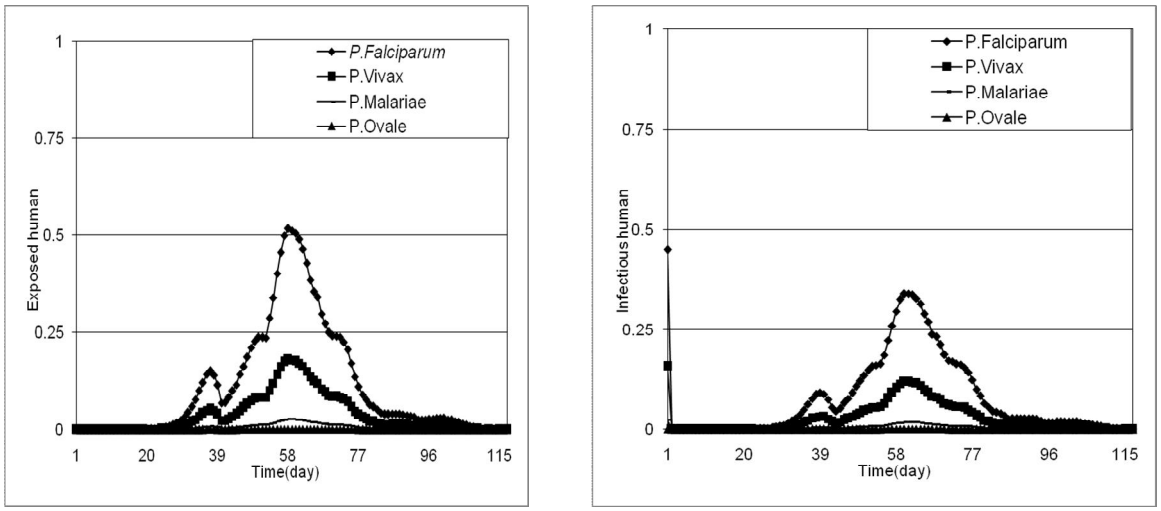

Fig.10 Time series solutions of exposed human and infectious human for each type of *Plasmodium* in one village. The parameters are K = 10,000, M = 250, γ_{h_f} = 0.45, γ_{h_v} = 0.35, γ_{h_m} = 0.15, γ_{h_o} = 0.05, γ_{v_f} = 0.45, γ_{v_v} = 0.35, γ_{v_m} = 0.15, γ_{v_o} = 0.05, α = 0.5, r_{1_f} = 1/30, r_{1_v} = 1/60, r_{1_m} = 1/90, r_{1_o} = 1/120, r_{2_v} = 1/(5*30), r_{2_o} = 1/(5*30), r_{3_v} = 1/(3*30), r_{3_o} = 1/(6*30), r_{4_v} =1/(5*30), r_{4_o} = 1/(3*30), r_{5_f} = 1/30, r_{5_v} = 1/14, r_{5_m} = 1/7, r_{5_o} = 1/17, r_{6_f} = 1/90,

r_{6_v} = 1/120, r_{6_m} = 1/60, r_{6_o} = 1/100, λ_{h_f} = 1/12, λ_{h_v} = 1/13, λ_{h_m} = 1/28, λ_{h_o} = 1/17, λ_{v_f} = 1/12, λ_{v_v} = 1/13, λ_{v_m} = 1/28, λ_{v_o} = 1/17, μ_v =1/45.

Furthermore, we consider the time distribution of infectious human when incubation rates of *Plasmodiums* do not included in our dynamical equations.

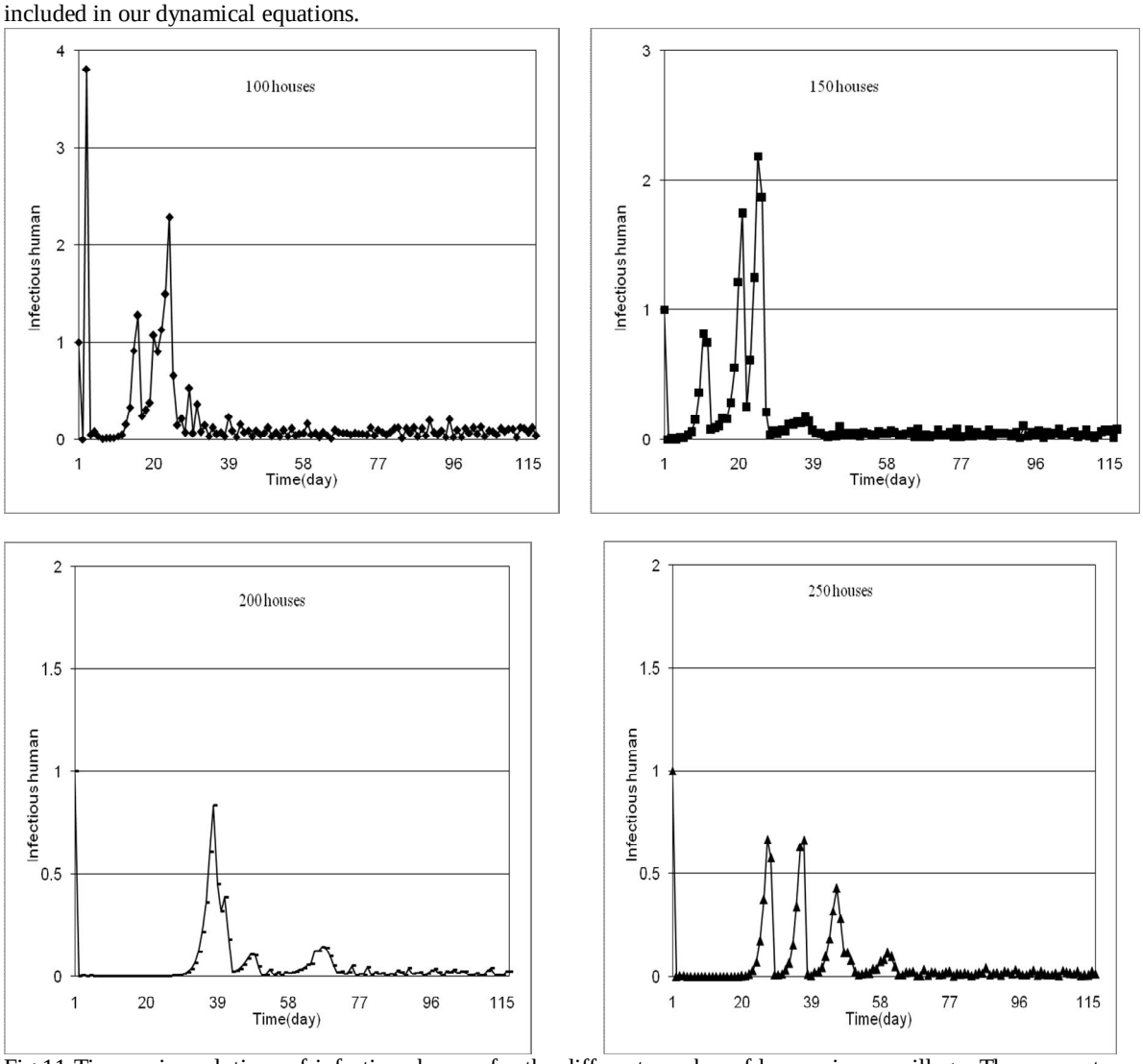

Fig.11 Time series solutions of infectious human for the different number of houses in one village. The parameters are K = 300, γ_{h_f} = 0.45, γ_{h_v} = 0.35, γ_{h_m} = 0.15, γ_{h_o} = 0.05, γ_{v_f} = 0.45, γ_{v_v} = 0.35, γ_{v_m} = 0.15, γ_{v_o} = 0.05, α = 0.5, r_{1_f} = 1/30, r_{1_v} = 1/60, r_{1_m} = 1/90, r_{1_o} = 1/120, r_{2_v} = 1/(5*30), r_{2_o} = 1/(5*30), r_{3_v} = 1/(3*30), r_{3_o} = 1/(6*30), r_{4_v} =1/(5*30), r_{4_o} = 1/(3*30), r_{5_f} = 1/30, r_{5_v} = 1/14, r_{5_m} = 1/7, r_{5_o} = 1/17, r_{6_f} = 1/90, r_{6_v} = 1/120, r_{6_m} = 1/60, r_{6_o} = 1/100, μ_v =1/45.

DISCUSSION AND CONCLUSION

We show numerical solutions of our dynamical equations. The different parameters are considered. Fig.1 show time series solutions of exposed human and infectious human for the different number of houses in one village. Fig.2 show time series solutions of exposed human and infectious human for the different transmission rate of four *Plasmodiums* in one village. Fig.3 show time series solutions of exposed human and infectious human for the different percentage of infected humans in whom some hypnozoites remain dormant in the liver. Fig.4 show time series solutions of exposed human and infectious human for the different incubation rates of four *Plasmodiums* in one village. Fig.5 show time series solutions of exposed human and infectious human for the different rate at which the exposed human change to be the susceptible human in one village. Fig.6 show time series solutions of exposed human and infectious

human for the different rate at which the infectious human change to be the susceptible human in one village. From the model outputs, we can see that the epidemic sizes are higher when the smaller number of households, the higher transmission rates, the smaller percentages of infected humans in whom some hypnozoites remain dormant in the liver, the higher incubation rates of *Plasmodiums*, the smaller rates at which the exposed human change to be the susceptible human and the higher rates at which the infectious human change to be the susceptible human. The epidemic outbursts are longer when the higher number of houses, smaller transmission rates and smaller incubation rates of *Plasmodiums*. Fig.7 to fig.10 show time series solutions of exposed human and infectious human for each type of *Plasmodium* when different number of households are considered. We can see that the most Malaria cases are infected with *Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae* and Plasmodium ovale, respectively. Moreover, we consider the time distribution of infectious human when the incubation rates of *Plasmodiums* are not considered. From fig.11, we can see that the epidemic outbursts are longer than when the incubation rate of *Plasmodiums* are included. The results of this study will point the way for controlling the transmission of this disease when there is the movement of populations.

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