

# Study on Bird Flu Infection Process Within a Poultry Farm

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# Study on Bird Flu Infection Process within a Poultry Farm with Effects of Spatial Diffusion

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**Abstract** We describe an ODE model and a PDE model. A nonlinear diffusion system of partial differential equations is analyzed for investigation of bird flu transmission process within a poultry farm. Effect of threshold number that gives measure of infectious intensity is investigated. It depends on three factors: removal of infected birds, vaccination, and capacity of the farm. Our analysis shows that the transmission of bird flu within a poultry farm is expressible in terms of traveling wave solutions. It also shows a spatial significance of diffusivity.

**Keywords** Nonlinear Diffusion System, Transmission Process, Infectious Intensity, Traveling Wave Solutions, Numerical Results

## 1 Introduction

Bird flu is a highly infectious and fatal disease for domestic birds. The disease is caused by virus types H5N1 carried by wild birds such as wild ducks. Most highly pathogenic strain (H5N1) has been spreading throughout Asia since 2003, before it reached Europe in 2005 and Middle East, as well as Africa in 2006. Cases of infected poultry farms were reported from several provinces of Indonesia including Bali, West Java, West Java and West Kalimantan in January 2004. Several cases of bird flu-to-human infection have also been reported. Those include cases found in 12 provinces in Indonesia. Any human-to-human infection of bird flu has not yet been reported so far. However, bird flu is now endemic to some region (Table 1) and it is inevitable for the virus to acquire the ability unless the contact between hosts and human is reduced in frequency.

Poultry farms are contact points between carriers of bird flu virus and human. The infection with highly pathogenic form transmits rapidly over a poultry farm and causes domestic birds serious symptoms that eventually lead to death. In current practice, even if infection is detected from only

**Table 1.** Bird Flu Cases in West Sumatra 2011-2015

Year	Infected (per case)	Susceptible (per case)
2011	31,508	841
2012	1,164	1,073
2013	11,038	-
2014	2,170	338
2015	3	7

Source: Department of Animal Husbandry, West Sumatra, Indonesia

one bird, the entire population in the farm are culled, which have been causing immense damage to the poultry industry. Vaccination is an effective measure against bird flu because vaccinated chickens produce up to 100 thousands times less virus when infected. While vaccinating chickens is effective, it affects export trade. Some countries even set a non-vaccination policy [1]. Now techniques to control outbreaks in a poultry farm must be developed.

In this study, infection processes of bird flu within a poultry farm is analyzed with mathematical techniques. Various mathematical models have been applied to problems that relate to bird flu infection. A mathematical model to interpret the spread Avian Influenza from the bird world to the human world with autonomous ordinary differential equations was analyzed [3,7] and the stability analysis is carried out. The transmission dynamics and spatial spread rate by the size of the susceptible poultry birds were studied [4]. A disease transmission model with diffusive terms to investigate spatial spread of Avian Influenza among flock and human were studied [9]. A diffusive epidemic that describes the transmission of Avian Influenza among birds and humans is investigated [2]. Mathematical models for bird flu infection process within a poultry farm were also proposed in previous study [5,8,10].

Bird flu transmission processes within a poultry farm involve three essential factors: influenza virus as source of disease, domestic birds as host, the environment as medium. The population of domestic birds in a poultry farm is maintained at the manageable capacity for efficient production with supply of new healthy birds for vacancies. Once bird

flu intrudes into a poultry farm, some infected birds die at an early stage of infection, and some others live longer. Regardless of being alive or dead, infected birds are the hosts of virus, unless they are completely removed from the population. In a typical poultry farm in Indonesia, there are ten houses each of which contains 1250 chickens. Each chicken in a house is placed in 25x50 [cm] wire net cages. Groups of each of which consists of four cages placed on each side are line up in one direction which amount total length approximate 40 [m] (Figure 1).



Figure 1. Typical of Poultry Farm in Indonesia (Gunung Nago Group Farm, Padang City, West Sumatra).

Mathematical model based on those factors and situation in a poultry farm that illustrated in Figure 1 were proposed in previous studies on bird flu infection processes within a poultry farm. A mathematical model was formulated in a study of the population of susceptible birds and the population of infected birds [5], and it was reformulated by taking the virus concentration into consideration [6] and spatial effects were incorporated into formulation of infection process. In recent studies, mathematical model was proposed based on the assumption that vacancies due to infection are replaced instantly, so that the total population always balances with the capacity of the farm [8]. The model was reformulated with consideration of spatial effect, and existence of traveling wave solutions in a singular limit was established [10]. Those traveling wave solutions correspond to progressive infection in a poultry farm. In this paper, analysis in the previous studies is continued. In the following sections, a mathematical model is described, and numerical techniques are illustrated. Numerical results are introduced and their significance is interpreted.

## 2 Mathematical Model of Bird Flu Infection Process And Stability Analysis

Let  $X$ ,  $Y$ , and  $Z$  be the population of susceptible birds, the population of infected birds, and the virus concentration in the medium, respectively. The number of transformation

from susceptible birds to infected birds due to infection per unit time is proportional to the virus concentration in the medium  $Z$  and the number of susceptible birds  $X$ . The decreasing rate of susceptible birds due to infection is  $\sigma XZ$ , where  $\sigma$  is a positive constant. The decreasing rate in the population of susceptible birds due to infection is the increasing rate in the population of infected birds. The number of infected birds removed from the population is proportional to the number of infected birds itself. Infected birds are hosts of virus. The increasing rate of the virus concentration is proportional to the number of infected birds because virus grow inside the hosts. The decreasing rate of virus concentration is proportional to the virus concentration itself. The foregoing disquisition leads to the following system of equations [5,6]

$$\begin{aligned} \frac{dX}{dt} &= a\{c - (X + Y)\} - \omega r X Z, \\ \frac{dY}{dt} &= \omega r X Z - m Y, \\ \frac{dZ}{dt} &= p(Y - r Z), \end{aligned} \tag{1}$$

where  $a$  is the rate of supply of new healthy birds for vacancies,  $c$  is the capacity of the farm,  $m$  is the removal rate,  $p$ ,  $r$ , and  $\omega$  are positive constants. Note that  $\sigma = \omega r$ . When vacancies due to infection are replaced instantly, the total population always balances with the capacity of the farm. Under the situation,  $X + Y = c$  and

$$\frac{dX}{dt} = -\frac{dY}{dt} = \omega r X Z + m(c - X) \tag{2}$$

holds. Now, the system (1) becomes the following system of equations for the population of the susceptible birds  $X$  and the virus concentration  $Z$  [8]

$$\begin{aligned} \frac{dX}{dt} &= m(c - X) - \omega r X Z, \\ \frac{dZ}{dt} &= p(c - X - r Z). \end{aligned} \tag{3}$$

Denote by  $X = X(t, X_0, Z_0)$ ,  $Z = Z(t, X_0, Z_0)$  the solution of system (3) that satisfies initial conditions  $X(0, X_0, Z_0) = X_0$ ,  $Z(0, X_0, Z_0) = Z_0$ . Let  $\Gamma = \{(X, Z) | 0 \leq X \leq c, Z \geq 0\}$ . The  $\Gamma$  is invariant under the flow generated by the system (3) in the sense that  $(X(t, X_0, Z_0), Z(t, X_0, Z_0))$  belongs to  $\Gamma$  for  $t \geq 0$  whenever belongs to  $\Gamma$ . Invariance of region  $\Gamma$  under the flow generated by the system (3) is illustrated in Figure 2. Solutions of the system (3) for different values of the removal rate  $m$  were illustrated in Figure 3. There are two states that are categorized according to stability of steady state solutions, infection free state and endemic state. There are two steady state solutions of system (3). One steady state solution is  $A(c, 0)$  that corresponds to the state where no birds in the population is infected. The other steady state solution is  $B(m/\omega, (\omega c - m)/(\omega r))$  that corresponds to the endemic state. The steady state solution  $A$  is asymptotically stable and the steady state solution  $B$  is unstable for  $\omega c - m < 0$ . The steady state solution  $A$  is unstable and the steady state solution  $B$  is asymptotically stable for  $\omega c - m > 0$  [8].

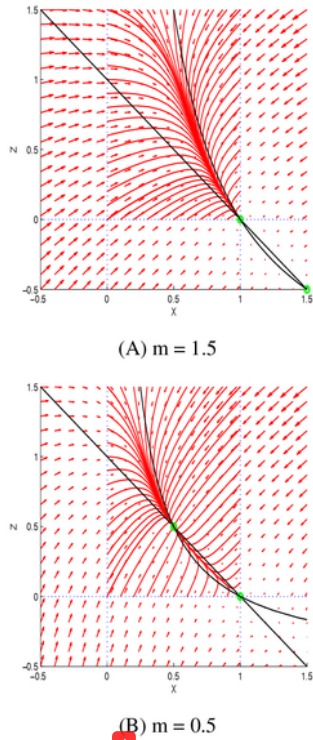


Figure 2. Invariant region  $\Gamma$ :  $c = 1, \omega = 1, p = 1,$  and  $r = 1$ . The invariant region  $\Gamma$  is shown for initial conditions  $(X_0, Z_0) = (1, 0)$  and different values of  $m$ .

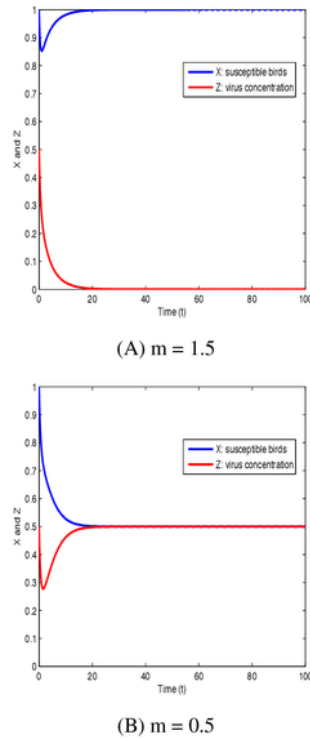


Figure 3. Solution of the ODE system (3):  $c = 1, \omega = 1, p = 1,$  and  $r = 1$ . (A) any solution converges to the infection free state for  $\omega c - m < 0$ , (B) any solution converges to the endemic state for  $\omega c - m > 0$ .

### 3 Mathematical Model with Spatial Virus Diffusion

Viruses transmit from one bird to another through media such as feed, dirt and air, so that spatial effects of virus transmission should be incorporated into formulation. It is appropriate to assume that a medium is one dimensional because bird cages are lined up in one direction. Let  $x$  be the one dimensional coordinate variable. When a diffusive term is added to the right hand side of the second equation, the system (3) becomes

$$\begin{aligned} \frac{\partial X}{\partial t} &= m(c - X) - \omega r X Z, \\ \frac{\partial Z}{\partial t} &= p(c - X - rZ) + d \frac{\partial^2 Z}{\partial x^2}, \end{aligned} \tag{4}$$

where  $d$  is the diffusion constant [10]. Traveling wave solutions of (4) are solutions expressed in terms of functions  $U$  and  $V$  as

$$X(x, t) = U(s), \quad Z(x, t) = V(s), \quad s = x - kt, \tag{5}$$

where  $k$  is the propagation speed of wave. Substituting (5) into (4) leads to the system of the ordinary differential equations

tions

$$\begin{aligned} U' &= -\frac{1}{k} \{m(c - U) - \omega r UV\}, \\ V' &= W, \\ W' &= -\delta W - \rho(c - U - rV), \end{aligned} \tag{6}$$

There are two stationary points for the system (6) in the  $(U, V, W)$  phase space. One stationary point is  $C(c, 0, 0)$ , and the other stationary point is  $D(m/\omega, \omega c - m/\omega r, 0)$ . A heteroclinic connection from the stationary point  $D$  to the stationary point  $C$  gives rise to a traveling wave solution of (4). Existence of such a heteroclinic orbit in a singular limit was established under the condition  $\omega c - m > 0$  in a previous study [10].

In the following, system (4) is focused on. The unknown variables  $X$  and  $Z$  of the system (3) are now functions of  $x$  and  $t$ , and they represent the population of susceptible birds and the virus concentration at location  $x$  and time  $t$ , respectively. Solutions  $X(x, t)$  and  $Z(x, t)$  are defined in the region in the  $xt$  plane  $\{(x, t) | 0 \leq x \leq l, t \geq 0\}$ . The system is associated with the initial conditions

$$X(x, 0) = X_0(x), \quad Z(x, 0) = Z_0(x), \quad (0 \leq x \leq l). \tag{7}$$

Note that constant solutions of the system (3) are constant solutions of the system (4).

Constant solutions of the system (4) includes the infection free equilibrium  $E_0(c, 0)$  which represents that there are no infected birds, and endemic equilibrium  $E_+(X^*, Z^*)$  where

$$X^* = \frac{m}{\omega}, \quad Z^* = \frac{\omega c - m}{\omega r}. \quad (8)$$

Let  $r_0 = \frac{\omega c}{m}$ . The parameter  $r_0$  gives measure of infectious intensity. If the condition

$$r_0 > 1 \quad (9)$$

is satisfied, then the endemic equilibrium  $E_+$  is realistic in sense that it lies in the first quadrant. In that case,  $E_+$  corresponds to an endemic state in which a part of the population remains infected. Those facts suggest that the parameter  $r_0$  depends on the capacity of farm  $c$ , the constant  $\omega$ , and the removal rate  $m$ .

Stability of constant solutions of nonlinear system such as system (4) has been studied by other authors [2]. Let  $\mu$  be the eigenvalue of the operator  $-\Delta$  with homogeneous boundary conditions on the interval  $[0, l]$ , that is,

$$Z'' + \mu Z = 0, \quad Z'(0) = Z'(l) = 0.$$

Those eigenvalues are  $\mu = \left(\frac{k\pi}{l}\right)^2$ ,  $k = 0, 1, 2, \dots$ . Furthermore, let

$$J = \begin{bmatrix} 0 & 0 \\ 0 & d\Delta \end{bmatrix} + \begin{bmatrix} -m - \omega r Z^* & -\omega r X^* \\ -p & -pr \end{bmatrix}, \quad (10)$$

where  $\Delta = \frac{\partial^2}{\partial x^2}$ . The linearization of the system (4) is  $u_t = Ju$ .  $\lambda$  is the eigenvalue of  $J$  if and only if it is an eigenvalue of the matrix

$$\phi = \begin{bmatrix} -m - \omega r Z^* & -\omega r X^* \\ -p & -d\mu - pr \end{bmatrix}, \quad (11)$$

that has characteristic equation

$$(\lambda + (m + \omega r Z^*))(\lambda + (d\mu + pr)) - \omega pr X^* = 0. \quad (12)$$

For the infection free equilibrium  $E_0$ , the characteristic equation is

$$\lambda^2 + (d\mu + pr + m)\lambda + (md\mu + pr(m - \omega c)) = 0. \quad (13)$$

If  $r_0 < 1$ , then  $pr(m - \omega c) > 0$ , eigenvalues are all negative for any non-negative value of  $\mu$  and  $E_0$  is asymptotically stable. It means that the number of virus concentration decrease as time elapses, so that the endemic state is insignificant. On the other hand, if  $r_0 > 1$ , then  $pr(m - \omega c) < 0$ , there is a possibility that eigenvalue is positive for some non-negative value of  $\mu$  and  $E_0$  is unstable. For the endemic equilibrium  $E_+$ , the characteristic equation is

$$\lambda^2 + (d\mu + pr + \omega c)\lambda + (\omega cd\mu + pr(\omega c - m)) = 0. \quad (14)$$

If  $r_0 > 1$ , then  $pr(\omega c - m) > 0$ , eigenvalues are all negative for any non-negative value of  $\mu$  and  $E_+$  is asymptotically stable. It means that endemic state is significant, and that there are some infected birds in the population. Otherwise, if  $r_0 < 1$ , then  $pr(\omega c - m) < 0$ , there is a possibility that eigenvalue is positive for some non-negative value of  $\mu$  and  $E_+$  is unstable.

## 4 Numerical Results

In order to investigate the transmission process of bird flu within a poultry farm from  $x = 0$  to  $l = 100$ , nonlinear diffusion system (4) subject to boundary conditions

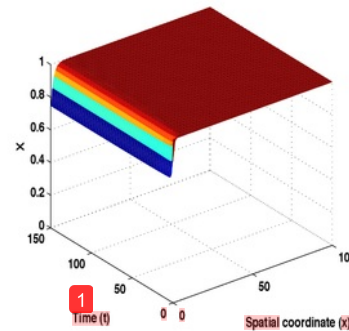
$$\begin{aligned} \frac{\partial X}{\partial x}(0, t) &= 0, \\ Z(0, t) &= 0.5, \\ Z(l, t) &= 0, \end{aligned} \quad (15)$$

$$\frac{\partial X}{\partial x}(l, t) = 0,$$

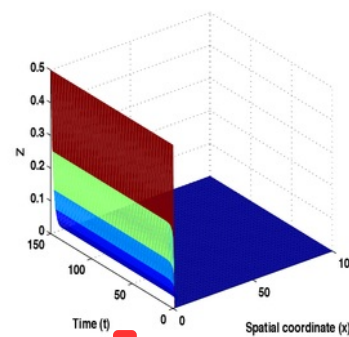
and initial conditions

$$\begin{aligned} X_0 &= \begin{cases} 1/2(1-x) & 0 \leq x < 1 \\ 1 & 1 \leq x \leq 100 \end{cases} \\ Z_0 &= \begin{cases} 1/2(1-x) & 0 \leq x < 1 \\ 0 & 1 \leq x \leq 100 \end{cases} \end{aligned} \quad (16)$$

was solved numerically. The values of the parameters are fixed at  $c = 1$ ,  $\omega = 1$ ,  $r = 1$  and  $p = 1$ . We will show numerical simulation for the susceptible birds ( $X$ ) and the virus concentration ( $Z$ ) for different values of the parameter  $m$  and  $d$ .



(A) X Component



(B) Z Component

Figure 4. Solution of the system (4):  $m = 1.5$  and  $d = 1$ . The state is free of infection. A solution approaches the infection free equilibrium  $E_0$ .

Let  $m = 1.5$ , then  $r_0 = 0.667 < 1$ , so that, the infection free equilibrium  $E_0$  of the system (4) is asymptotically stable, as shown in Figure 4. The figure depicts the persistence of the infection free state, in which the number of the virus concentration decrease as time elapses and population of the susceptible bird remains equal to capacity of farm. In this case, the endemic state is not significant. On the other hand, let  $m = 0.5$ , then  $r_0 = 2 > 1$ , so that, the endemic equilibrium  $E_+$  of the system (4) is asymptotically stable, as shown in Figure 5. It shows the stability of the endemic state in which a part of the population is always infected. The figure shows the decreasing value of  $X$  and the increasing value of  $Z$  with respect time  $t$  and distance  $x$ . Traveling wave solutions appear when  $E_+$  is asymptotically stable. The wave profile for the system (4) were illustrated in Figure 6 for  $m = 1.5$  and Figure 7 for  $m = 0.5$ . Progressive waves of bird flu infection were profiled for different of  $t$  and  $d$ . Note that the blue line in Figure 6 and 7 are solutions of the system (4) when  $t = 0$ .

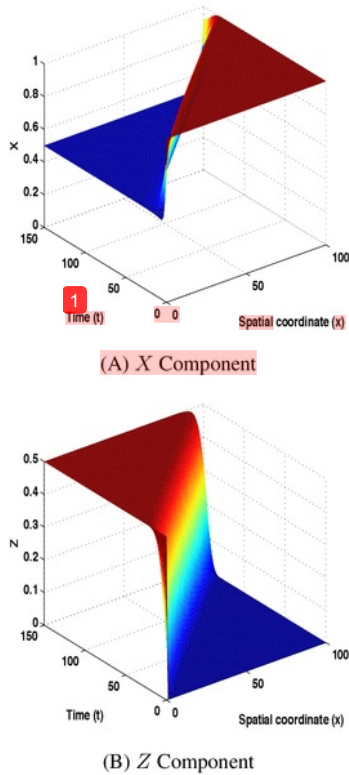


Figure 5. Solution of the system (4):  $m = 0.5$  and  $d = 1$ . The state is endemic. A solution approaches the endemic equilibrium  $E_+$ .

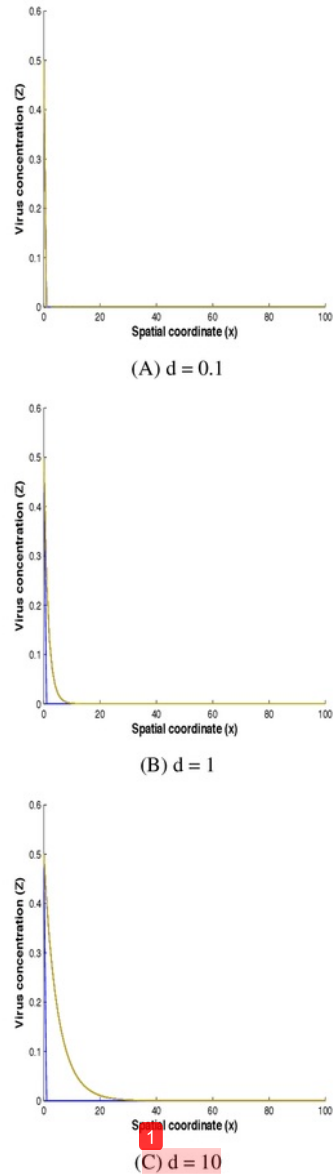


Figure 6. Profile of the virus concentration for  $m = 1.5$ .

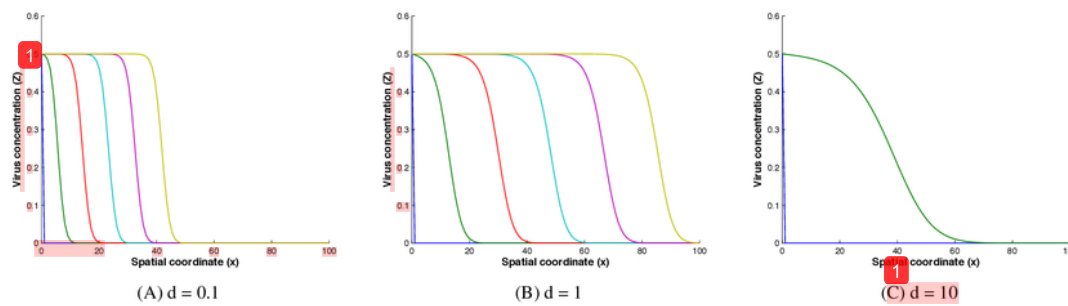


Figure 7. Profile of the virus concentration for  $m = 0.5$ .

## 5 Discussions

In the paper, we have considered analysis based on model (4) for bird flu infection process within a poultry farm. The parameter  $r_0 (r_0 = \omega c/m)$  gives measure of infectious intensity. Our analysis has shown that the infection is controllable for  $r_0 < 1$ , and that it is uncontrollable for  $r_0 > 1$ . Stabilities of infection free equilibrium and endemic equilibrium were analyzed. In absence of spatial diffusion, the infection free equilibrium  $E_0$  is asymptotically stable and the endemic equilibrium is unstable provided  $r_0 < 1$ . The infection free equilibrium is unstable and the endemic equilibrium  $E_+$  is asymptotically stable provided  $r_0 > 1$ .

Our numerical results have shown that transmission of bird flu within a poultry farm is expressible in terms of a progressive wave with a constant speed. Those waves appear when  $r_0 > 1$ , which implies that the bird flu prevails provided  $r_0 > 1$ , that is,  $\omega c$  is large or  $m$  is small. On the contrary, the traveling wave solutions do not seem to exist for  $r_0 < 1$ . It means that the bird flu is made controllable if  $\omega c$  is small or  $m$  is large. Existence of traveling wave solution in a singular limit was established in a previous study [10]. Our numerical results have also shown that the wave speed is proportional to the diffusivity, that is, the smaller the diffusivity is, the slower the propagation of virus infection.

Culling is the current practice even if only one bird is detected positive for infection of bird flu, which has given poultry farmers immense damages. Measures to control outbreaks of bird flu in poultry farms must be developed not only for economical effects but also for prevention of human-human infection. Outbreaks of bird flu in poultry farms must also be controlled for reduction of human contacts of infected birds. Our study has shown that bird flu infection within a poultry farm can be controlled with appropriate vaccination and proper removal of infected individuals.

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