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Prediction of the Fate of Oxytetracycline and Oxolinic Acid in a Fish Pond Using Simulation Model – A Preliminary Study

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The fate of two popular antibiotics, oxytetracycline and oxolinic acid, in a fish pond were simulated using a computational model. The VDC model, which is designed based on a model for predicting pesticide fate and transport in paddy fields, was modified to take into account the differences between the pond and the paddies as well as those between the fish and the rice plant behaviors. The pond conditions were set following the typical practice in South East Asia aquaculture. The two antibiotics were administered to the animal in the pond through medicated feed during a period of 5 days as in actual practice. Concentrations of oxytetracycline in pond water were higher than those of oxolinic acid at the beginning of the simulation. Dissipation rate of oxytetracycline is also higher as it is more readily available for degradation in the water. For the long term, oxolinic acid was present at higher concentration than oxytetracycline in pond water as well as pond sediment. The simulated results were expected to be conservative and can be useful for the lower tier assessment of exposure risk of veterinary medicine in aquaculture industry but more data are needed for the complete validation of the model.

Keywords: Veterinary medicine, fate, risk assessment, VDC, model

INTRODUCTION

The behavior of veterinary drugs is receiving more and more attention of researchers because of their potential to pollute the environment. These drugs may be directly released to the environment with the discharge of excess feed pellets and animal wastes in aquaculture and land application of manure containing un–metabolized drugs from animal husbandry (Figueroa *et al*., 2004). Depending on their concentrations, veterinary antibiotics in aquatic environments may promote the development and spread of antibiotic–resistant bacteria or induce biological responses in non–target organisms.

Antibiotics are extensively used in aquaculture. These are applied through the feed or by simple addition to the water. Thus, these veterinary drugs are exposed directly to receiving water and pose higher risk to non–target aquatic organism. A parallel intake pathway results through excessive feed or excrements. Most of the unused drugs end up in the sediments where they are either degraded or slowly leach back into the surrounding water (Hirsch *et al*., 1999).

In order to ensure the safety of veterinary drugs, regulation authorities from several countries and regions in the world have joined and issued guidance for environmental impact assessment of medicinal products (VICH, 2004). One step in the assessment procedure is to predict the environmental concentration of those veterinary drugs. For this purpose, mathematical models for estimating the predicted environmental concentrations (PECs) of the drugs in the environment are necessary. However, while models for calculating the PECs of nutrients and pesticide are numerous, those can be used for veterinary drugs are very few.

With the purpose of developing a computational model for estimating PECs of veterinary drugs in fish pond by utilizing currently available models, the Veterinary Drug Concentration (VDC) model was developed by modifying a validated paddy rice pesticide model, PCPF–1, to adapt to the new environment conditions. The modified model is then tested with data collected from the literature for two popular veterinary drugs, oxytetracycline and oxolinic acid.

MATERIALS AND METHODS

Study veterinary drugs

Oxytetracycline is a widely used antibiotic in fish farming. It is administered in the form of medicated feed pellets, and calculations have shown that only 20–30% of the antibiotic given is actually taken up by the fish whereas the rest, 70–80%, reaches the environment. Most of the oxytetracycline is bound to particles and sediments under the farm. Detectable concentrations of oxytetracycline were also found in the sediment 3–6 months following feeding of the antibiotic. As well as affecting the nearby fauna, the presence of oxytetracycline in the sediment for such an extended period may increase the chance of bacteria developing resistance to

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the antibiotic (Samuelsen, 1989).

Oxolinic acid is also a popular antibiotic used in fish farming because of its high potency against Gram–negative bacteria. The administration route of oxolinic acid to fish is also medicated feed at a dosage rate of 10–20 mg kg^{-1} biomass day^{-1} for a period of 8–10 days. Similarly to oxytetracycline fate, a large fraction of the oxolinic acid administered to the fish is not absorbed or retained by the animal but is released to the environment by three routes. First, some of the medicated feed supplied is not ingested and, instead, falls directly to the bottom of the pond. Second, part of eaten oxolinic acid is not absorbed during passage through the gut and is released to the environment via the faeces. Finally, some of the absorbed oxolinic acid is excreted via the urine and bile in an unmetabolized and microbiologically active form. The amounts of oxolinic acid persisting in the pond water or in the effluent could affect microbial communities; this may affect the viability of continued fish culture if it alters the rate of degradation of organic matter or promotes the proliferation of antibacterial–resistant strains of pathogenic bacteria (Pouliquen *et al*., 1996).

Modeling concept of veterinary drugs in a fish pond

The general behavior of veterinary drug applied as additive in feed pellet in a fish pond is shown in **Fig. 1**. The flow of processes starts from applying feed containing veterinary drug to the pond. Then, the model simulation can be performed by considering the main processes: feed consumption of fish, dissolution of drug from the uneaten pellet into water, metabolism and excretion of drug by fish, sorption (adsorption and desorption), drainage/runoff, leaching, volatilization and degradation.

For modeling purpose, a conceptual model for the behavior of drug in fish ponds is described in the form of compartmental system (**Fig. 2**). In order to simplify the calculation, the following assumptions were made in the development of VDC model:

(1) The feed consumption is instantaneous after feed application.
(2) The excretion of drug starts after feed consumption with a fixed interval depending on fish species and the excretion process is also instantaneous.
(3) Both water and sediment compartments are completely mixed reactors having uniform, unsteady chemical concentration. Although presented as a separate compartment in **Fig. 2**, the fish compartment is included in the water compartment.
(4) The thickness of the sediment compartment is 1 cm (active soil layer), and the pore water is included in the pond water.

The VDC model was developed based on the PCPF–1 model (Watanabe and Takagi, 2000; Watanabe *et al*., 2006), which is used for predicting pesticide concentrations in paddy fields.

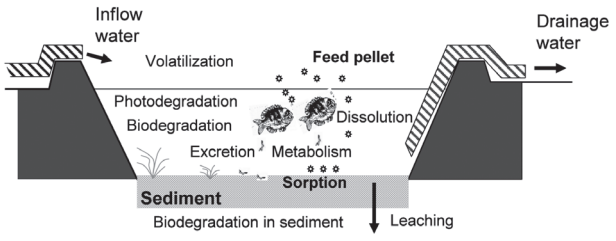

Fig. 1. Fate and transport of veterinary drugs in fish pond.

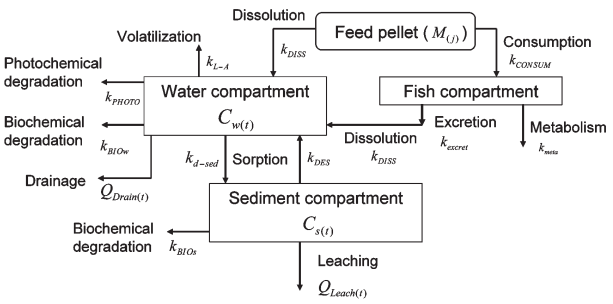

Fig. 2. Compartmental system for modeling drug fate in fish pond.

Water balance in the pond

Because in the fish pond water is the compartment from which drug can be easily discharged to the open environment, water balance calculation is important in the simulation process. The water balance within pond water compartment is considered with precipitation, irrigation, drainage, percolation and evapotranspiration as given below:

$$A\frac{dh_{PW}}{dt} = A^{*}[RAIN+IRR-DRAIN-PERC-ET] \quad (1)$$

where h_{PW} is the depth of water in the pond (L), t is time (T), A is the area of the pond (L^2). *RAIN* is the average rainfall rate ($L\ T^{-1}$), *IRR* is the rate of water supply ($L\ T^{-1}$), *DRAIN* is the surface drainage or overflow rate ($L\ T^{-1}$), *RERC* is the rate of percolation ($L\ T^{-1}$), *ET* is the rate of evapotranspiration ($L\ T^{-1}$) during dt. In the Equation (1), precipitation, percolation and evapotranspiration are assumed homogeneous over the area and the seepage though levee is not considered in the model.

Mass balance in the pond

1) In the water compartment

As mentioned in the earlier section, the fish compartment is included in the water compartment. Therefore, mass balance concerning the fish will be discussed together in the water compartment section.

Processes affecting concentrations of drug in the pond water compartment include: 1) dissolution of the drug from uneaten feed after feed application, 2) desorption of the adsorbed drug from the pond sediment layer (PSL) into pond water, 3) dissolution of the drug excreted by fish, 4) offsite drug discharge by surface drainage, 5) drug transport below pond water compartment with percolation, 6) drug volatilization from pond water to atmosphere, and 7) drug dissipation by photochemical and biochemical degradation. Each process is assumed to occur independently and their effects on the drug con-

centration are assumed to be additive without any interaction. The drug mass balance in the pond water compartment is expressed considering above processes as given below,

$$\frac{dM_{PW}}{dt} = \dot{M}_{PW-DISS} + \dot{M}_{PW-DES} + \dot{M}_{EXCRET} + \dot{M}_{OF} + \dot{M}_{PW-PERC} + \dot{M}_{VAP} + \dot{M}_{PW-DEG} \quad (2)$$

where, M_{PW} is the total drug mass in pond water (M), $\dot{M}_{PW-DISS}$ is the mass rate of drug dissolution of uneaten applied drug in pond water (M T^{-1}), $\dot{M}_{PW-DES}$ is the mass rate of drug desorption from the PSL into pond water (M T^{-1}), $\dot{M}_{EXCRET}$ is the mass rate of drug excreted by the fish (M T^{-1}), M_{OF} is the mass rate of drug outflow by drainage and overflow (M T^{-1}), $\dot{M}_{PW-PERC}$ is the mass rate of drug transport below pond water compartment with percolation (M T^{-1}), $\dot{M}_{VAP}$ is the mass rate of drug volatilization from pond water to atmosphere (M T^{-1}), and $\dot{M}_{PW-DEG}$ is the mass rate of drug dissipation by photochemical and biochemical degradation (M T^{-1}).

The change of drug mass in pond water, which is the left side of Equation (2), can be rewritten with the pond water depth and the drug concentration in the pond water as below since both the depth of pond water and the drug concentration in the pond water are variables,

$$\frac{dM_{PW}}{dt} = A\frac{d(h_{PW}C_{PW})}{dt} \quad (3)$$

where C_{PW} is drug concentration in pond water (M L^{-3}). Each component of the mass equation will be discussed in the following section.

Drug dissolution from uneaten medicated feed

After feed application, the fish will consume a portion of it instantaneously. The uneaten feed will remain in water and slowly settle down to the bottom of the pond. During this settling period the drug is released (dissolved) from the feed. The mass of drug dissolved from the feed is proportional to the uneaten feed amount and is calculated as

$$Uneaten_{(j)} = M_{(j)} \times (1 - k_{CONSUM}) \quad (4)$$

where $M_{(i)}$ is the mass of drug in one application at day No. j, and k_{CONSUM} is the consumption ratio of applied feed in one application.

Then the drug dissolves into the pond water following Equation (5)

$$\dot{M}_{PW-DISS} = A\left[\frac{d\,h_{PW}C_{PW}}{dt}\right]_{DISS} = A\left[h_{PW}\frac{d\,C_{PW}}{dt} + C_{PW}\frac{d\,h_{PW}}{dt}\right]_{DISS} \quad (5)$$

The dissolution of applied drug into pond water is assumed to follow the first order kinetics. The change of the drug concentration in pond water due to drug dissolution is given by,

$$\left[\frac{d\,C_{PW}}{dt}\right]_{DISS} = k_{DISS}(C_{SLB} - C_{PW}) \quad (6)$$

where k_{DISS} is the first order rate constant of drug dissolution in water (T^{-1}), C_{SLB} is the solubility of drug in water (M L^{-3}). The change of the drug concentration in pond water depends on the rate constant and the concentration differential between its solubility value and ambient drug concentration in pond water. Substituting Equation (6) into (5), the expression of the rate of mass transfer by drug dissolution is given by,

$$\dot{M}_{PW-DISS} = Ah_{PW}k_{DISS}(C_{SLB} - C_{PW}) + A\left[C_{PW}\frac{d\,h_{PW}}{dt}\right]_{DISS} \quad (7)$$

The dissolution process described will stop when the total dissolved mass exceeds the mass of drug available for dissolution.

Desorption from pond sediment layer

The desorption process is also assumed to occur following the first order kinetic. The change of the drug concentration in the PSL due to desorption is given by,

$$\left[\frac{dC_{S-PSL}}{dt}\right]_{DES} = -k_{DES}(C_{S-PSL}) \quad (8)$$

where C_{S-PSL} is the drug concentration in the sediment layer (M M^{-1} dry weight basis), k_{DES} is the first order rate constant for the drug desorption from the PSL (T^{-1}). Neglecting the effect of the initial variation of the PSL depth, the rate of drug mass transfer from the PSL into pond water is now expressed as;

$$\dot{M}_{PW-Des} = -Ad_{PSL}\,\rho_{b-PSL}\left[\frac{dC_{S-PSL}}{dt}\right]_{DES} = A\,d_{PSL}\,\rho_{b-PSL}k_{DES}C_{S-PSL} \quad (9)$$

where d_{PSL} is the depth of the PSL (L) and ρ_{b-PSL} is the bulk density of PSL (M L^{-3}).

Excretion from fish

After consumption, part of the consumed drug is excreted to the pond through feces or urine. The excretion is delayed compared to the time of consumption depending on fish species. The mass of drug excreted to the water for further dissolution is calculated as follows:

$$Excretion_{(j)} = M_{(j)} \times k_{CONSUM} \times k_{excret} \quad (10)$$

where k_{excret} is a the ratio of drug excreted to pond water.

Loss by overflow/drainage and percolation

The rate of drug discharge by drainage water is calculated with the drug concentration in the pond water and the rate of drainage as,

$$\dot{M}_{OF} = -A\,DRAIN\,C_{PW} \quad (11)$$

Also, the rate of the drug transport by percolation from the pond water into the pond sediment is expressed with the drug concentration in the pond water and the rate of percolation as,

$$\dot{M}_{PW-PERC} = -A\ PERC\ C_{PW} \quad (12)$$

Drug volatilization from pond water to atmosphere:

The volatilization of the drug from pond water to atmosphere is simulated by the drug mass transfer coefficient:

$$\dot{M}_{VOL} = -A\ k_{L-A}\ C_{PW} \quad (13)$$

where k_{L-A} is the drug mass transfer coefficient from pond water to atmosphere (L T^{-1}). The method developed by Mackay and Leinonen (1975) was used to estimate k_{L-A} , and it is given as,

$$k_{L-A} = \left[\left(K_L^{CO_2}\sqrt{\frac{M_{CO_2}}{M}}\ \right)^{-1} + \left(H\ K_G^{H_2O}\sqrt{\frac{M_{H_2O}}{M}}\ \right)^{-1}\right]^{-1} \quad (14)$$

where M is the relative molecular mass of the drug, M_{CO2} and M_{H2O} are the relative molecular masses of CO_2 and H_2O, $K_L^{CO_2}$ (4.75 m d^{-1}) is the mass transfer coefficient of the CO_2 in water, $k_G^{H_2O}$ (720 m d^{-1}) is the mass transfer coefficient of H_2O in air and H is the Henry's constant of the drug [27] and $H=16.04\ M\ VP\ /\ C_{SLB}\ T$, where VP is the vapor pressure of the drug (mm Hg), C_{SLB} is the water solubility of the drug (M L^{-3}), and T is the ambient temperature (K).

Drug dissipation by degradation processes:

Drug dissipation processes in pond water included in the model are photochemical degradation and biochemical degradation. Biochemical degradation may involve abiotic degradation but mainly biotic processes. The rate of drug dissipation by two dissipation pathways were assumed to be additive. Considering the variation of the pond water depth, the rate of drug dissipation by photochemical and biochemical degradation is given by,

$$\dot{M}_{PW-DEG} = A\left(\left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW-PHOTO} + \left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW-BIOCHEM}\right) \quad (15)$$

where $\left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW=PHOTO}$ and $\left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW=BIOCHEM}$ are the changes of the drug masses during dt in the pond water due to photochemical and biochemical degradation, respectively. Drug degradation by photochemical reactions is a complex phenomenon. However, in order to keep the simplicity of the model expression for complex reactions, the change of drug concentration due to photochemical degradation was assumed to be a function of the UV radiation received on the solute or pond water because most of photochemical reactions occur under the absorption of UV radiation. UV is also applicable for the experiments obtaining the required parameters as well as UV data can be available in some meteorological database. The rate of drug photolysis depends on the duration of UV irradiation and could be assumed to follow the first order kinetics (Jiao *et al.*, 2008). It is also advantageous to consider the photochemical degradation with respect to the amount of radiation instead of the time since the radiation from the sunlight is transient and dependent on the weather conditions in the field. We also neglected the light adsorption by pond water since it is difficult to evaluate wavelength–dependent underwater light field that depends on the highly variable absorption properties of water (Zafiriou *et al.*, 1984). Applying the first order rate law, the change of the drug concentration as a function of the cumulative UV radiation energy is given as below,

$$\frac{dC_{PW}}{dE_{UV-C}} = -k_{PHOTO}\ C_{PW} \quad (16)$$

where E_{UV-C} (kJ m^{-2}) is the cumulative UV radiation received on the solution body and k_{PHOTO} (m^2 kJ^{-1}) is the first order rate coefficient of photochemical degradation with respect to the cumulative UV radiation. Then, the change of the drug concentration in pond water as a function of time is obtained with the derivative of the cumulative UV radiation as a function of time by applying chain rule as,

$$\frac{dC_{PW}}{dt} = \frac{dC_{PW}}{dE_{UV-C}}\ \frac{dE_{UV-C}}{dt} \quad (17)$$

Applying the product rule and substituting Equation (17), now the change of the drug mass in pond water due to photochemical degradation as a function of time becomes,

$$\left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW-PHOTO} = -h_{PW}\ k_{PHOTO}\ C_{PW}\ \frac{d\ E_{UV-C} dt}{dt} + \left[C_{PW}\frac{dh_{PW}}{dt}\right]_{PW-PHOTO} \quad (18)$$

For the change of the drug concentration in pond water due to biochemical degradation, the reaction is assumed to follow the first order kinetics. Similar to the above equation, the change of the drug mass in the pond water due to biochemical degradation is given as,

$$\left[\frac{d\ h_{PW} C_{PW}}{dt}\right]_{PW-BIOCHEM} = -h_{PW}\ k_{BIOCHEM-PW}\ C_{PW} + \left[C_{PW}\frac{dh_{PW}}{dt}\right]_{PW-BIOCHEM} \quad (19)$$

where $k_{BIOCHEM-PW}$ (T^{-1}) is the first order rate constant of biochemical degradation in pond water. Replacing Equations (18) and (19) into Equation (14) gives,

$$\dot{M}_{PW-DEG} = Ah_{PW}\left(-k_{PHOTO}\ \frac{dE_{UVB-C}}{dt}\ -k_{BIOCHEM-PW}\right)\ C_{PW}$$

$$+A\left[C_{PW}\frac{dh_{PW}}{dt}\right]_{PW-PHOTO}+A\left[C_{PW}\frac{dh_{PW}}{dt}\right]_{PW-BIOCHEM} \quad (20)$$

The Last two terms in the above equation are the drug mass contribution through variable pond water depth due to photochemical and biochemical degradation processes. These terms are difficult to estimate since all the reactions in the pond water occur simultaneously. However, the contribution from these two processes to the changes of the drug concentrations in pond water seems not significant as found in the sensitivity analysis. Therefore, we assume that the last two terms in Equation (20) could be neglected. Finally, the governing equation for the drug mass balance in pond water is given by;

$$\begin{aligned} &A\frac{d(h_{PW}C_{PW})}{dt} \\ &= Ah_{PW}k_{DISS}(C_{SLB}-C_{PW})+A\left[C_{PW}\frac{dh_{PW}}{dt}\right]_{DISS} \\ &+Ad_{PSL}\rho_{b-PSL}k_{DES}C_{S-PSL} \\ &+AIRRC_{W-IRR}-ADRAINC_{PW}-APERCC_{PW}-Ak_{L-A}C_{PW} \\ &+Ah_{PW}\left(-k_{PHOTO}\frac{dE_{UV-C}}{dt}-k_{BIOCHEM-PW}\right)C_{PW} \end{aligned} \quad (21)$$

2) In the sediment compartment

The fate and transport processes affecting drug concentration in the PSL considered in the model were: 1) drug adsorption in sediment and subsequent partitioning in sediment water in the PSL upon dissolution of applied drug, 2) drug transport into and out of PSL through percolation of pond water, 3) biochemical degradation in the PSL, and 4) drug desorption from the PSL into pond water. Similar to the pond water compartment, it is assumed that each process is independent and that their effects on the drug concentration in PSL are additive without any interaction. The drug mass balance in the PSL is expressed as,

$$\frac{dM_{PSL}}{dt}=\dot{M}_{PSL-DISS}+\dot{M}_{PSL-PERC}+\dot{M}_{PSL-DEG}+\dot{M}_{PSL-DES} \quad (22)$$

where M_{PSL} is the total drug mass in the PSL, $\dot{M}_{PSL-DISS}$ is the rate of drug mass transfer into the PSL upon drug dissolution process, $\dot{M}_{PSL-PERC}$ is the rate of drug mass transport into and out of PSL through percolation, $\dot{M}_{PSL-DEG}$ is the rate of drug mass dissipation by biochemical degradation process in the PSL, and $\dot{M}_{PSL-DES}$ is the rate of drug mass transfer by drug desorption process from the PSL into pond water.

During the dissolution of the drug, the depth of the PSL increases following the piston type movement of the percolation front until reaching the maximum depth of 2.0 cm. At the same time, the drug is partitioned into solid and liquid phase according to the soil adsorption coefficient of given drug. Therefore, the change in drug mass in PSL is described as below,

$$\frac{dM_{PSL}}{dt}=A\left(\frac{\theta_{Sat-PSL}}{k_{d-PSL}}+\rho_{b-PSL}\right)\frac{d(d_{PSL}C_{S-PSL})}{dt} \quad (23)$$

where $\theta_{sat-PSL}$ is the volumetric saturated water content of the PSL ($L^3\ L^{-3}$), k_{d-PSL} is the soil adsorption coefficient of the drug in the PSL ($L^3\ M^{-1}$), and C_{S-PSL} is the concentration of the drug in sediment in the PSL ($M\ M^{-1}$).

The drug mass transfer by partitioning of dissolved drug upon application:

In the PSL as defined earlier, the applied drug in pond water is assumed partitioned immediately upon its dissolution following the equilibrium soil adsorption coefficient. The rate of the drug mass transfer into PSL by the drug dissolution is expressed by considering the effects due to initial increase in PSL depth as,

$$\begin{aligned} \dot{M}_{PSL-DISS} &= A\theta_{Sat-PSL}\left[\frac{dd_{PSL}C_{W-PSL}}{dt}\right]_{PSL-DISS} \\ &+A\rho_{b-PDL}\left[\frac{dd_{PSL}C_{S-PSL}}{dt}\right]_{PSL-DISS} \end{aligned} \quad (24)$$

Applying the first order kinetic equation as in the Equation (6) and rearranging, the rate of the drug mass transfer into the PSL by the drug dissolution becomes,

$$\begin{aligned} \dot{M}_{PSL-DISS} &= Ad_{PSL}(\theta_{Sat-PSL}+\rho_{b-PSL}k_{d-PSL})(k_{DISS}(C_{SLB}-C_{PW}) \\ &+\frac{C_{PW}}{d_{PSL}}\frac{d\,d_{PSL}}{dt}) \end{aligned} \quad (25)$$

The drug transport by percolation:

Percolation process is among the main consuming factor of water in aquaculture pond, sometimes amounting to about 50% of water loss from a pond (Nath and Bolte, 1998). In the model, the drug transport process in PSL through the percolation is assumed such that drug mass equivalent to that in the percolating pond water enters, while the drug mass equivalent to that in the percolating soil water that equilibrium with adsorbed drug is leached from the PSL. Using the percolation rate and the equilibrium soil adsorption coefficient of the drug in the PSL, the rate of the drug transport through the percolation is given by,

$$\dot{M}_{PSL-PERC}=A\,PERC\,(C_{PW}-\frac{1}{k_{d-PSL}}C_{S-PSL}) \quad (26)$$

The drug dissipation by biochemical degradation:

Although numerous transformations occur in the homogeneous water and sediment phases as well as in the interface between phases, they are difficult to define or determine the absolute effect of the reaction. In order to simplify the model expression, the rate of the drug dissipation due to biochemical degradation in sediment is considered with the change in drug concentration in

sediment as given by,

$$\dot{M}_{PSL-DEG} = Ad_{PSL}\ \rho_{b-PSL}\left[\frac{dC_{S-PSL}}{dt}\right]_{BIOCHEM-PSL} \quad (27)$$

The changes of drug concentration in sediment due to biochemical degradation is also assumed to occur following the first order reaction similar to other rate constants discussed above, and the effects from the initial variations in PSL depth is assumed to be insignificant. Now, the equation for drug degradation in PSL becomes,

$$\dot{M}_{PSL-DEG} = -Ad_{PSL}\ \rho_{b-PSL}\ k_{BIOCHEM-PSL}\ C_{S-PSL} \quad (28)$$

where $k_{BIOCHEM-PSL}$ (T^{-1}) is the first order rate constant of the drug biochemical degradation in the PSL.

The drug transfer by desorption:

The desorption process from the PSL to pond water was described in earlier section. The rate of the drug transfer due to desorption from the PSL to pond water is expressed as,

$$\dot{M}_{PSL-DES} = -Ad_{PSL}\ \rho_{b-PSL}\ k_{DES}\ C_{S-PSL} \quad (29)$$

Finally, governing equation for the drug mass balance in PSL becomes;

$$A\left(\frac{\theta_{Sat-PSL}}{k_{d-PSL}} + \rho_{b-PSL}\right)\frac{d(d_{PSL}C_{S-PSL})}{dt}$$

$$= Ad_{PSL}\ (\theta_{Sat-PSL} + \rho_{b-PSL}\ k_{d-PSL})\ (k_{DISS}\ (C_{SLB} - C_{PW})$$

$$+ \left[\frac{C_{PW}}{d_{PSL}}\ \frac{d\ d_{PSL}}{dt}\right]_{DISS})$$

$$+ A\ PERC(C_{PW} - \frac{1}{k_{d-PSL}}\ C_{S-PSL})$$

$$-Ad_{PSL}\ \rho_{b-PSL}\ k_{BIOCHEM-PSL}\ C_{S-PSL}$$

$$-Ad_{PSL}\ \rho_{b-PSL}\ k_{DES}\ C_{S-PSL} \quad (30)$$

Numerical procedure

The model program calculating above equations is coded using Visual Basic for Applications in Microsoft Excel. The Excel file includes a Macro program of PCPF–1, datasheets for input parameters, daily water

Table 1. Input parameters for VDC model simulation

	Unit	Oxytetracycline	Oxolinic acid
General information			
Feed consumption rate	%	0.9	0.9
Excretion rate	%	0.6[1]	0.1[1]
Depth of sediment layer	cm	1	1
Simulation period	d	30	30
Initial concentration in water	mg/L	0	0
Input data for plot simulation			
Water compartment			
Application rate	g/m^2	4	2
Solubility of the drug	mg/L	1000[2]	4[2]
Dissolution rate	1/d	0.239	0.239
Desorption rate	1/d	1.96[2]	0.464[2]
Volatilization coefficient	m/d	0	0
Photolysis rate	1/d	0.462[3]	0.267[4]
Biochemical degradation rate	1/d	0.154[5]	0.001[4]
Fraction of UVB over Rs		0.001232[6]	0.001232[6]
Soil compartment			
Bulk density	g/cm^3	0.937[6]	0.937[6]
Saturated water content	cm^3/cm^3	0.603[6]	0.603[6]
Partitioning coefficient	L/kg	490[2]	116[2]
Degradation rate const.	1/d	0.014[7]	0.007[4]
On application date			
Consecutive application	Uniform distribution during application period		
Discrete application	Individual date is fed		

[1] Rigos *et al.*, 2004; [2] Tolls, 2001; [3] Jiao *et al.*, 2008; [4] Lai and Lin, 2009;
[5] Pouliquen *et al.*, 2007; [6] Watanabe and Takagi, 2000; 7 Blackwell *et al.*, 2005

balance and daily UV radiation, model calculations. The datasheet for input parameters consisting 18 parameters is shown in **Table 1**. It should be noted that although equations for calculating the volatilization coefficient is described this parameter was not fed into the model because it lacks supporting documents from the literature.

The datasheet for the daily water balance consists of daily rainfall, irrigation, drainage, percolation, evapotranspiration, paddy water depth and its differential during the day in centimeter. Data were recorded from the actual measurement in the field experiment or from the weather station if applicable. Similarly, the datasheet for the daily UV radiation received on paddy water was recorded from the field observation or from the weather station. Other input parameters can be taken by experimental measurement or by literature review.

Equations (21) and (30) after being rearranged were solved for C_{PW}, and C_{S-PSL}, respectively, by using the fourth–order Runge–Kutta method with given initial conditions. Since these equations depend on each other, the numerical solutions of C_{PW}, and C_{S-PSL} were simultaneously obtained using an iterative procedure. The iteration is carried out until the solutions of both equations converge within the given criteria (less than 0.1% of relative error) at each time step. The time interval for the calculation of above equations is 1 hour.

RESULTS AND DISCUSSION

Applicability of the model

The VDC model was run for oxytetracycline and oxolinic acid for one application period of 5 days (feeding one time a day). The simulated concentrations of two drugs in pond water and pond sediment are shown in **Fig. 3** and **Fig. 4**.

As observed from the figures, drug concentration increased from the start of the application until the end of application period. Due to the difference in input parameters (such as physico–chemical properties, excretion rate…) between two compounds, concentrations of oxytetracycline were higher than that of oxolinic acid in both water and sediment compartment. Maximum concentrations of oxytetracycline could be as 10 folds higher than the peak concentrations of oxolinic acid in water as well as in sediment. However, the dissipation of oxytetracycline is also rapid. There was almost no residue of oxytetracycline in the water and sediment at the end of the simulation (about 25 days after the application period) while oxolinic acid dissipated at slower rate.

The literature data for evaluating the newly developed model is limited because most of studies on the fate of veterinary drugs in fish farming are about the coastal/marine farming in temperate climate regions (Bjorklund *et al.*, 1991; Samuelsen et al., 1992) although inland aquaculture is an important food producing sector especially in Asia (Sapkota *et al.*, 2008). Only Bebak–Williams *et al.*, (2002) reported lower concentrations of oxytetracycline (less than 0.6 mg/L) in water of a recirculating fish tank because the sediment (fish feces and uneaten feed) containing very high concentrations of oxytetracycline (up to 2000 mg/kg) was removed from the pond by filters. For oxolinic acid, similar environmental concentration range was reported in shrimp ponds in mangrove area of Vietnam (Le and Munekage, 2004).

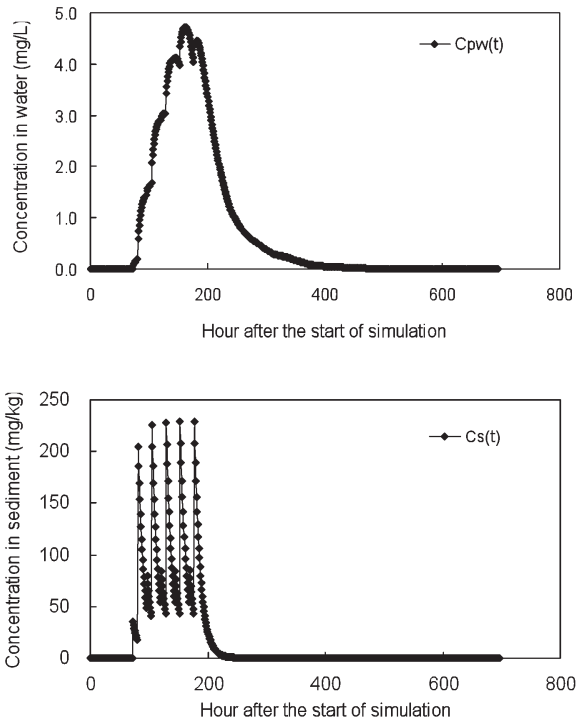

Fig. 3. Simulated concentration of oxytetracycline in pond water (above) and sediment.

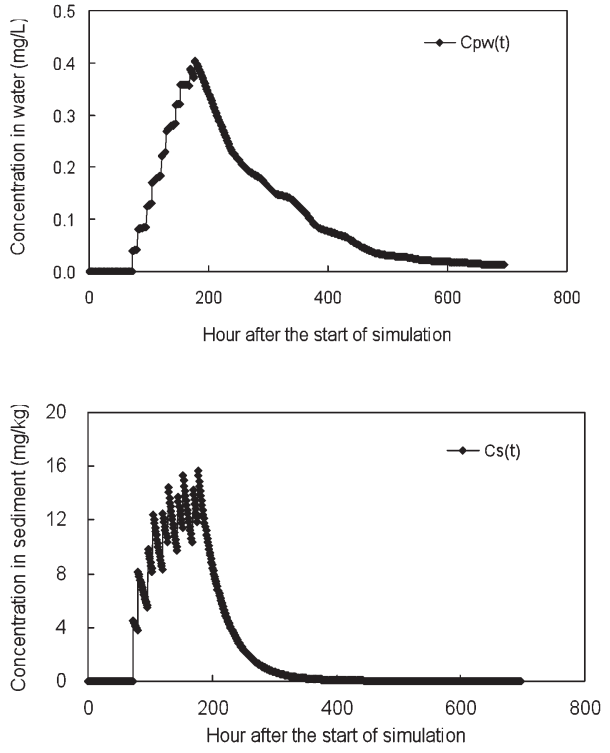

Fig. 4. Simulated concentration of oxolinic acid in pond water (above) and sediment.

In order to imitate the actual farming practice, another simulation with 2 application periods (10–day interval) was also carried out. The evolution curves of two compounds in pond water were shown in **Fig. 5**. Several application practice seems to have more effect on oxolinic acid than oxytetracycline since the former is more persistent in the environment than the latter.

The simulated results obtained from the new model were rather conservative. However, it can predict the general behavior of different kind of veterinary drug in a fish pond, thus can be used in the lower tier assessment of veterinary drugs.

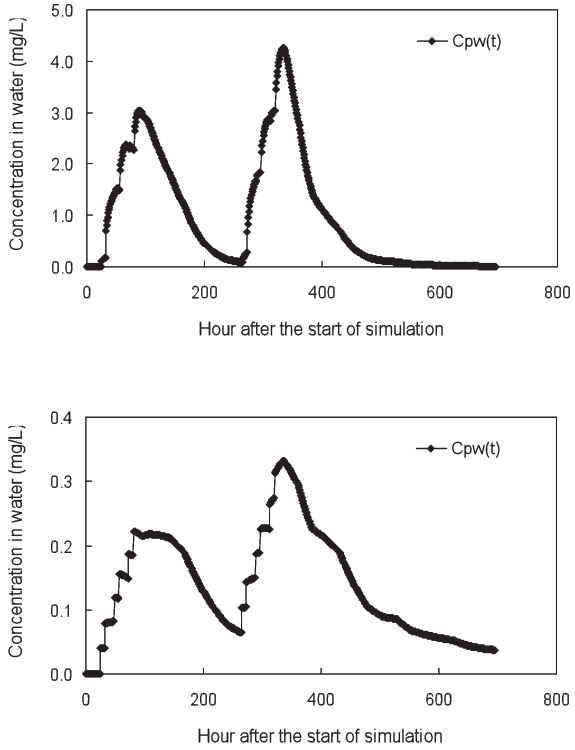

Fig. 5. Simulated concentrations of oxytetracycline (above) and oxolinic acid in pond water in case of two application spans with 10 days interval.

For future study

Actual data is required to calibrate and validate the model. Laboratory experiments are desired to determine the principal input parameters such as biochemical degradation rates in water and sediment, photodegradation rate (especially for photosensitive oxolinic acid) as well as sorption parameters. After that field study involving actual fish pond is needed to collect data for a complete validation of the model.

CONCLUSION

A Microsoft Excel based mathematical model, namely VDC model, was developed to predict the concentration of veterinary drug in a fish pond. The model algorithm was adapted from a paddy pesticide model (PCPF–1 model) with necessary modification to reflect the influence of the fish. Input parameters were selected from the literature to feed into the model. The simulated results showed the general behavior of two drugs, oxytetracycline and oxolinic acid, in pond water and pond sediment. Although limit data is available to accurately evaluate the model, preliminary judgment is that the model could be useful in lower tier risk assessment of veterinary drug in pond aquaculture. More experiments and possible adjustment are required for the model to be validated and applicable to actual scenarios.

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