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Exposure risk assessment and evaluation of the best management practice for controlling pesticide runoff from paddy fields. Part 2: Model simulation for herbicide pretilachlor

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Complete List of Authors:	Thai, Phong; Kyushu University, Department of Bioproduction Environmental Sciences

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Exposure risk assessment and evaluation of the best management practice for controlling pesticide runoff from paddy fields. Part 2: Model simulation for herbicide pretilachlor

Thai Khanh Phong[1], Son Hong Vu[2], Satoru Ishihara[3], Kazuaki Hiramatsu[1], Hirozumi Watanabe[4*]

[1]Department of Bioproduction Environmental Sciences, Faculty of Agriculture, Kyushu University, Higashi-ku, Fukuoka 812–8581, Japan.

[2]Department of Science and Technology, Ministry of Agriculture and Rural Development, 2 Ngoc Ha Street, Hanoi, Vietnam

[3]Agricultural Chemicals Inspection Station, Food and Agricultural Materials Inspection Center, Kodaira-shi, Tokyo 187-0011, Japan.

[4]Tokyo University of Agriculture and Technology, Graduate School of Agriculture. 3-5-8 Saiwaicho, Fuchu, Tokyo 183-8509 Japan.

Abstract:

BACKGROUND: Monitoring studies revealed high concentrations of pesticides in the drainage canal of paddy fields. It is important to have a tool to predict those concentrations in different management scenarios as an assessment tool. A simulation model for predicting pesticide concentration in a paddy block (PCPF-B) was evaluated and then used to assess the effect of water management practices for controlling pesticide runoff from paddy fields.

RESULTS: PCPF-B model achieved acceptable performance. The model was applied to constrained probabilistic approach using Monte Carlo technique to evaluate the Best

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Management Practices for reducing runoff of pretilachlor into canal. The probabilistic model predictions using actual data of pesticide use and hydrological data in the canal showed that the water holding period (WHP) and the excess water storage depth (EWSD) effectively reduced the loss and concentration of pretilachlor from paddy fields to the drainage canal. The WHP also reduced the time span of pesticide exposure in the drainage canal.

CONCLUSIONS: It is recommended that: 1) Applying the WHP as long as possible but at least 7 days depending on the pesticide and field conditions; 2) Maintaining a EWSD greater than 2 cm to store substantial rainfall to prevent paddy runoff especially during the WHP.

Key words: paddy block, drainage canal, PCPF, rice pesticide.

** Correspondence to: Hirozumi Watanabe, Tokyo University of Agriculture and Technology, Graduate School of Agriculture, 3-5-8 Saiwaicho, Tokyo 183-8509, Japan*

E-mail: pochi@cc.tuat.ac.jp

1 INTRODUCTION

In the companion paper[1] we have described the monitoring of pesticide runoff in a small paddy watershed in Central Japan. The monitoring results showed that the problem of pesticide contamination caused by paddy fields effluent is still imminent. High concentrations of pesticides were found in the outlets of main and secondary drainage canals. Nakano *et al.*[2] also reported pesticide concentrations of 10 – 90 μg L^{-1} at the outlet of a paddy drainage canal. An estimated considerable percentage of applied pesticides were reportedly lost through surface drainage/runoff water to the drainage canal.[1] Therefore, controlling pesticide runoff from paddy fields to the environment is still an important aspect of sustainable rice cultivation.

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Some management practices such as the water holding practice (WHP), the period during which no water is intentionally released from paddy plots and the excess water storage depth (EWSD), the extra depth obtained by the high boundary of a paddy plot to accommodate excess precipitation, have proved effective in controlling pesticide runoff from paddy plots by experiments as well as simulations.[1,3,4] However, it is also necessary to evaluate the effectiveness of those practices at larger scale such as paddy block or paddy watershed. At this large scale, experimental evaluation would be costly and the use of simulation model would be a good alternative for this purpose.

Few simulation models for pesticide behavior in a rice paddy field system have been developed for assessing the potential exposure of a pesticide. For a paddy plot scale, RICEWQ,[5] PADDY,[6] and PCPF-1[7] has been used for simulating pesticide concentration in paddy water and surface soil under different paddy conditions. RICEWQ and PADDY models also have their corresponding models for river system, RIVWQ and PADDY-Large.[8,9] However, the algorithms used for pesticide application in those models were either based on a simultaneous and homogeneous application or a normal distribution application, which makes them inapplicable for paddy blocks where the number of pesticide application events is limited and is totally dependent on farmers' schedules. An extended version of PCPF-1, namely PCPF-B, has been developed to deal with this issue[10] and thus could be used to evaluate the management practices of a paddy block.

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Probabilistic approaches to environmental risk assessment for pesticides are widely accepted as they can quantify the uncertainty associated with model prediction and generate meaningful outputs for decision-making processes.[11] It is increasingly recognized that the uncertainty in model input parameters should be taken into account in regulatory decision-making at higher tiers. However, until now only few probabilistic risk assessments have been done for rice pesticides used in the monsoon Asian region.[12,13]

The objectives of this paper were to evaluate a block scale model for predicting rice pesticide concentration in the drainage canals with monitoring data and to apply this model to evaluate the Best Management Practices for reducing pesticide runoff from paddy blocks using a constrained probabilistic approach. Pretilachlor, a commonly used rice herbicide in Japan, was the target compound in this study.

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2 MATERIALS AND METHOD

2.1 Model description

The PCPF-B model (Fig. 1) was developed to simulate rice pesticides concentration in the drainage canal of paddy blocks. The paddy block can comprise a dozen paddy plots of different areas. A description of the PCPF-B model can be found elsewhere.[10] Compared to river scale models like RIVWQ, PCPF-B can simulate different pesticide application scenarios (application dates and areas) such as using normal distribution or uniform distribution or using specific dates. The model simulates pesticide fate and transport in a paddy block, which ranges from a few ha to few tens of ha.

In the PCPF-B model, paddy water is considered directly released into major canals/tributaries and the length of the canals within the block is relatively short (about a few hundred meters for a block of less than 10 ha), the pesticide residence time in the canal or the time needed for transporting pesticide from paddy plots to the outlet of the block is short. Hence, it is assumed that the process of pesticide dissipation in canal water can be neglected in the model.

The water balance data used for simulation is fed during model execution using monitoring data from the field. The water balance can also be calculated automatically in case monitoring data is not available.

The PCPF-B model's program is coded using Visual Basic for Applications in Microsoft Excel as for the PCPF-1 model. The Excel file includes a Macro program of PCPF-B, datasheets for input parameters, and daily water balance and daily UV-B radiation received on paddy water.

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2.2 Observed data for model evaluation

To evaluate the PCPF-B model before any application, monitoring data presented in the companion paper1 was used. A paddy block (block 2) located inside the monitored watershed in Sakura river basin, Ibaraki prefecture, Japan was selected with detailed monitoring data. Total paddy area of the target block is 5.32 ha with 17 paddy plots (5.06 ha) and 1 upland plot (0.26 ha) as shown in Fig. 2. The monitoring data of 2004 was used as it came with the information on pesticide use including pesticide products, application rate, application dates as well as applied areas in block 2 in the year of 2004, which were collected from farmers using questionnaires. Water samples were taken at different dates at the outlet of the canal to measure pesticide concentration in canal water by gas chromatography. Details about the monitoring and sample analysis were presented in the companion paper.[1]

2.3 Statistics evaluation

Model performance was assessed by statistical indices, including root mean square error (RMSE) and modeling efficiency (EF) in equations (1) and (2):

$$RMSE = \frac{100}{\overline{O}} \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \quad (1)$$

$$EF = \frac{\sum (O_i - \overline{O})^2 - \sum (P_i - O_i)^2}{\sum (O_i - \overline{O})^2} \quad (2)$$

where P_i and O_i are the predicted and observed values, respectively, $\overline{O}$ is the average of the observed values and n is the number of observations. In general, the lower the RMSE, the higher is the agreement between the measured and the predicted data. In contrast, the optimal value for EF is 1; thus, the closer to 1 the values of EF, the greater is the correspondence between measured and predicted data.[14]

2.4 Application of model to evaluate the Best Management Practices

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For the evaluation of the Best Management Practices to reduce pesticide runoff from paddy fields, different scenarios for water management practice were established, in which the main factors of water management such as WHP and EWSD were considered. The field condition (area, number of plots, number of applied plots) of block 2 were used as a realistic scenario for this evaluation. The relationship between management factors (WHP, EWSD) with the pesticide concentrations in canal and cumulative pesticide losses via surface drainage was established in order to evaluate appropriate field management for reducing pesticide runoff from paddy fields.

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The target compound, pretilachlor [2-chloro-2',6'-diethyl-N-(2-propoxyethyl)acetanilide], is a popular herbicide in Japan and in the world. Pretilachlor is widely used in transplanted and direct seeded rice for the control of several grasses, broad-leaved weeds and sedges. In block 2, pretilachlor, as active ingredient of one commercial product (Sparkstar), was applied to 4 plots (Fig. 2). Therefore, the application rate was the same in all applied plots. The application dates were acquired through questionnaires and fed to the model. Properties of this herbicide were determined and used previously for simulation[15] and will be used in this study as deterministic values.

The PCPF-B simulation was applied using probabilistic approach incorporating the variability in rainfall pattern as rainfall is the main cause of runoff from paddy plots during water holding period.[1,16] For this purpose, meteorological data including rainfall and solar radiation were collected from a 26-year archive (1984-2009), which is all data available from the meteorological station in Tsukuba, Ibaraki, Japan, which is close to the study site. Evapotranspiration (ET) was estimated using FAO-56 method[17] with corresponding meteorological data. Sets of rainfall, ET and solar radiation during the month of May would be used as input values for probabilistic simulations since it is the time of pesticide application and thus has the highest risk of pesticide runoff to the environment.

Other data concerning water management used for water balance calculation was presented in Table 2. Management practices such as WHP and EWSD were set for each scenario. Then the water balance was automatically calculated. Water level in each plot was kept between the maximum and minimum paddy water depths (H_{max} and H_{min}). Irrigation was used to control the water level. It means that on days when the water level was below H_{min} irrigation water was added to raise the paddy water level to H_{max}. Other components such as rainfall, percolation, and evapotranspiration were included in the calculation. During the WHP, the height of the drainage gate (H_{gate}) was set equal to the sum of H_{max} and EWSD. Only when water level higher than H_{gate} did runoff occur.

However, after the WHP, daily drainage occurred at a rate similar to the average monitoring data reported previously.[1]

Meanwhile, the other input parameters concerning field conditions were fixed as deterministic values. It was intended for easy comparison of simulation results between management scenarios.

The Monte Carlo technique, a widely used method for probabilistic assessment and uncertainty analysis, was incorporated into the PCPF-B model. The method involves random sampling of inputs and successive model runs until a stable statistical distribution of outputs is obtained. In this study, Monte Carlo technique was run for 2500 iterations. The running of the PCPF-B model and the extraction of the relevant model outputs can be automated using the commercially available software package Crystal Ball 7 (Decisioneering Inc., US), which is suitable for a spreadsheet model in Excel environment like the PCPF-B.

3 RESULTS

3.1 Observed water balance for deterministic simulation

Major water balance components of the monitored block in 2004 including daily rainfall, irrigation and drainage as well as canal inflow and outflow were presented in Fig. 3. Daily drainage/runoff from the paddy fields was estimated from the balance of the drainage canal, being equal to the subtraction of the canal inflow from the canal outflow. Daily irrigation was calculated using the water balance equation of the paddy compartment with estimated percolation, seepage, evapotranspiration and paddy water depth (H_{pw}). Significant runoff occurred during large rainfall events (Fig. 3). During the early period of May, the increasing surface drainage was probably because farmers released paddy water during

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transplanting period to have optimum paddy water depth. However, this water balance estimation did not contain any information about the practice of water managements such as EWSD and WHP. Because the canal inflow consisted of water discharge from a irrigation pipe, it was intermittent and not corresponding to rainfall events. The canal outflow was responsive to rainfall events and surface drainage from the paddy plots in block 2.

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3.2 Model evaluation

Input parameters for the model execution are presented in Table 1. The estimated water balance of the monitored block (Fig. 3) was used for the deterministic runs. Pretilachlor was applied in several plots (Fig. 2) in three different dates. The total applied area of pretilachlor was 1.18 ha, corresponding to 22.1% of the block area.

The average flow velocity in the canal was about 0.06 m s^{-1}. With the length of the receiving canal of 320 m, the average residential time of pesticide in the canal was estimated as 1.5 hours. The bottom of the canal consists of heavy clay soil and a layer of small gravel. Therefore, the adsorption/desorption of pesticides may be negligible. And because of such short retention time, neglecting the processes of pesticide dissipation in canal water was considered reasonable.

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Fig. 4 shows the results of the deterministic model evaluation. Simulated pretilachlor concentrations with deterministic parameter indicated general trend and magnitude of pesticide concentrations in canal water. The simulated concentrations in the individual plots (data not shown) were similar with those reported in other study.[15] The simulated curves at the block outlet agreed with the observed data although slight over-estimation was observed. Since no drainage canal of upstream block flows through the studied block and the canal inflow was of irrigation water only, the observed pretilachlor concentrations in the canal water were not affected by the runoff of pretilachlor applied in other paddy blocks. Both simulated and observed data have concentration peaks corresponding to major application dates in the block but there were some minor peaks in the simulated curves due to the fluctuation of canal inflow, causing different dilution factors from day to day. The occurrence of the main peaks were close to the application dates when concentration of pretilachlor in the individual plots was high. And its occurrence also depends on the drainage rate of the block. It can be observed that during the early period after pesticide application a peak in drainage/runoff rate corresponded to a peak in pesticide concentration in the drainage canal.

The RSME and EF values calculated for PCPF-B from the simulated results were 87.5 and 0.72, respectively. The values of these two statistic indices in this study were slightly farther away from ideal values than those reported for paddy water but similar to those reported for paddy soil in plot-scale simulation.[5,14] Therefore, it was seen as acceptable considering much greater uncertainty in block-scale simulation.

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The overestimation observed in this simulation was probably due to the better-than-expected water management in the studied block, which resulted in less pesticide runoff amount from treated plots than what was estimated in our water balance calculation. With the fact that farmers, mostly part-time farmers, practiced water management as they wished, uncertainty in water balance was high for block-scale simulation. Our assumption of no pesticide dissipation and interaction in the canal may also contribute to the overestimation. Meanwhile, greater overestimation was reported for other pesticide models applied to block scale drainage canals.[18,19]

3.3 Model application

Having an acceptable performance, the PCPF-B model was used to evaluate the effectiveness of two water management practices, WHP and EWSD, in controlling pesticide runoff at paddy block scale. Mean predicted cumulative loss and 50 percentile predicted concentration of pretilachlor in the drainage canal were used as criteria for the evaluation.

3.3.1 Effect on cumulative loss

Fig. 5 presented the effect of combined WHP and EWSD practices to the mean cumulative loss of pretilachlor in the block. It is observed that the application of WHP and EWSD as Best Management Practices reduced the loss of pesticide. The decline in cumulative loss of pretilachlor was proportional with the increase of WHP. Simple linear regression resulted in equations with high correlation coefficient (Table 3). The slope of the equation is greater when higher EWSD was applied.

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The monitored cumulative loss through surface drainage in block 2 was about 15% of the applied mass of pretilachlor. An observed cumulative loss of 14.1% for pretilachlor in a small paddy watershed was also reported by Nakano *et al.*[2] Corresponding value obtained from the deterministic simulations was 25.5%. The difference between observed and simulated herbicide losses might be explained by the fact that calculation of observed herbicide loss using weekly sampling data might lead to significant errors because it may miss some considerable peak concentrations between sampling dates. A finer sampling schedule is preferred for accurate calculation of herbicide mass discharge.

3.3.2 Effect on concentration

The application of Best Management Practices not only reduced the cumulative loss of pretilachlor but also prevented the occurrence of high concentrations of pesticides in canal

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water. The 50 percentile simulated concentrations of pretilachlor ranged from about 60 µg L^{-1} when no Best Management Practice was applied to about 15 µg L^{-1} when a 14-day holding period was applied (Fig. 6). In Fig. 6, while WHP showed its effect, ESWD did not significantly influence the maximum concentration of pretilachlor in the drainage canal. It is because in general (50 percentile range), there was no runoff during the water holding period and pretilachlor only appeared in the drainage canal after WHP, when water was released daily from the block in form of drainage and no EWSD remained. Therefore, regardless of the applied EWSD, it had no effect on the concentrations of pretilachlor in the canal. Meanwhile, comparison of 90 and 100 percentile simulated concentrations of pretilachlor (data not shown) showed that ESWD of 2 cm or higher would reduce the occurrence of high concentration of pretilachlor during the water holding period in most of the cases except in large rainfall events. Maximum mean concentration of pretilachlor in canal water decreased exponentially with the increase of WHP as a consequence of the exponential degradation of pesticide inside the plot.

4 DISCUSSION

PCPF-B model was able to simulate the general behavior of pretilachlor in the drainage canal when estimated water balance was available. The simulation by PCPF-B is rather conservative due to its assumption of no dissipation in the drainage canal. It led to the overestimation of concentration in canal water although the predicted plot concentration was still comparable with observed data. However, the performance of the model was considered acceptable. Improvement could be made by including dissipation processes in the canal as well as seepage inflow from adjacent plots.

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The constrained probabilistic assessment for WHP and EWSD against meteorological data for a paddy block in Central Japan gained an encouraging result. Application of appropriate WHP and EWSD can reduce both pesticide loss and pesticide concentration in the drainage canal. Combination of 14-day WHP and 3-cm EWSD has the potential of reducing more than 60% of pesticide loss compared to no Best Management Practice applied scenario. However, as the current Japanese recommendation for WHP printed on pesticide labels is only 3-4 days for all rice pesticides and no practice of EWSD is mentioned for the rice crop spanning the monsoon season, significant loss and high concentration of pesticide in the drainage canal is still expected as in the monitored data. The extension of WHP and the implementation of appropriate EWSD altogether are thus necessary to reduce the discharge of pesticide to the drainage canal.

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Establishing an appropriate WHP is not new in rice cultivation. There have been reports on WHP as Best Management Practice to reduce the loss of pesticides. In California, depending on the pesticide, various WHP have been gradually applied and extended (up to 28 days for molinate and 30 days for thiobencarb).[20] But further extension of WHP was not recommended as it would affect other aspects of the crop such as problem of salinity or rice plant physiology.[20] In Japan, keeping the water inside paddy plots for a prolonged period is not welcome in shallow water rice cultivation where farmers want moving water to stimulate the growth of rice plants. Until 2005, a WHP of only 3-4 days had been recommended in pesticide label firstly to ensure high effectiveness of the product and secondly to protect the environment. But recent monitoring still showed that farmers drain their plots only 1 – 3 days after pesticide application.[21] An increase of WHP to 7 days was currently recommended for all rice pesticides[22] with complete stop of irrigation but the dissemination of information seems to be limited and there is no incentive for farmers to

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follow the WHP recommendation. However, in order to reduce the environmental pollution caused by rice pesticides previous monitoring studies suggested increasing the WHP to more than 10 days based on the 90% dissipation time (DT_{90}) of the studied pesticide.[1,23] Results from this study indicated that pesticide discharge after a 14-day WHP can still produce high concentration of pretilachlor in canal water and therefore the WHP should be extended to as long as possible but at least 7 days according to the Ministerial guideline.[22]

Holding water inside paddy plots can be managed relatively easy under Mediterranean climate by maintaining the target water depth with irrigation because significant rainfall during the crop season rarely occurs. However, under Asian monsoon climate rainfall often occurs during and after the pesticide application period, sometime causing considerable paddy runoff. There are in average 12 rainfall events in May in the study area with about 15% of them larger than 2 cm. And our simulations have shown that creating and maintaining an appropriate EWSD is effective to prevent runoff during rainfall events in this area. Therefore, we propose that a EWSD from 2 to 3 cm needs to be maintained for controlling pesticide runoff from paddy fields in regions like Central Japan where moderate rainfall is expected. For more intensive rainfall prone regions, higher EWSD may be necessary to contain the rainfall water.

Together with the proposed management practices, extension work to disseminate the information to rice farmers is also important because of the low awareness on water management in pesticide runoff control in paddy fields as well as the complexity of the pesticide runoff process. However, further study is required for developing practical methods and apparatus for setting the appropriate EWSDs in the fields which complement farming practices and maintain healthy crop production.

5 CONCLUSIONS

A simulation model for predicting concentration of pesticide in the drainage canal of a paddy field block (PCPF-B) was validated and then applied to a constrained probabilistic approach for evaluating water management practices for controlling pesticide runoff from paddy fields. The proposed activities for reducing pesticide runoff from paddy fields in a monsoon region such as in Japan were as follow:

- Applying the WHP and extending the WHP from the current recommendation 7 days to as long as possible depending on field and plant conditions.
- Maintaining EWSD of about 2-3 cm in the paddy plot to store substantial rainfall amount in order to prevent paddy runoff during the WHP.
- Establishing a network of extension and enforcement so that farmers would be aware of and implement the proposed management practices.

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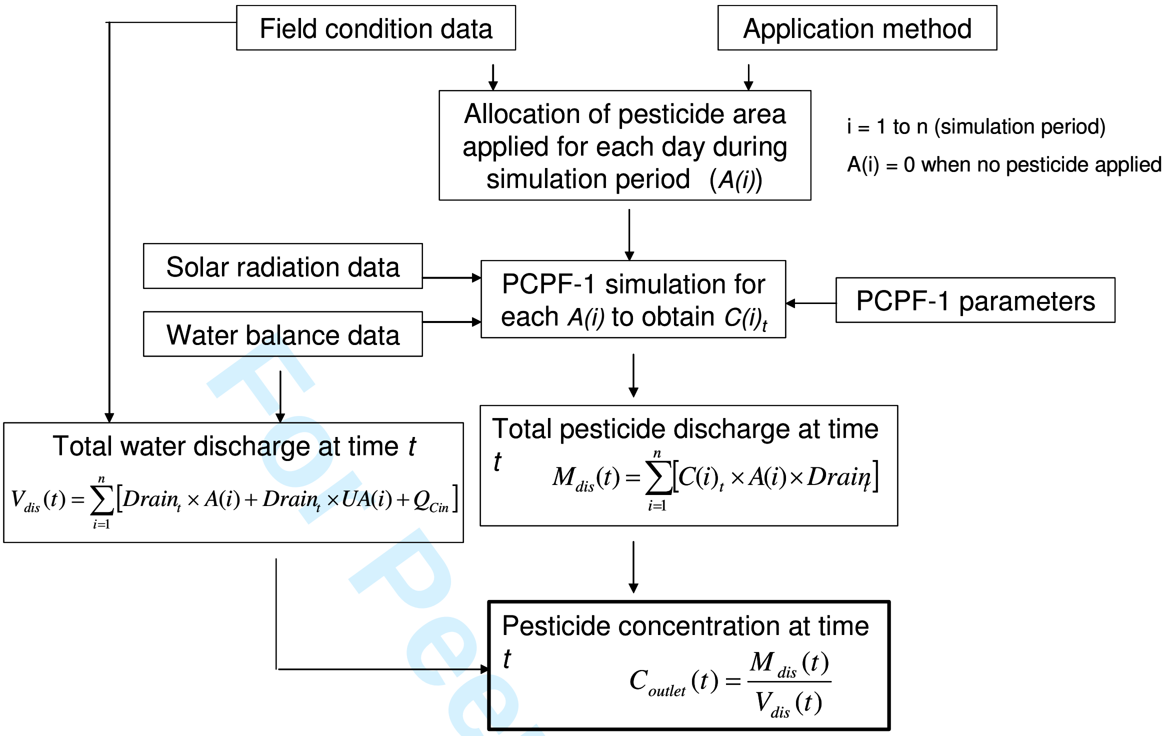

Figure 1. Diagram of the PCPF-B model.

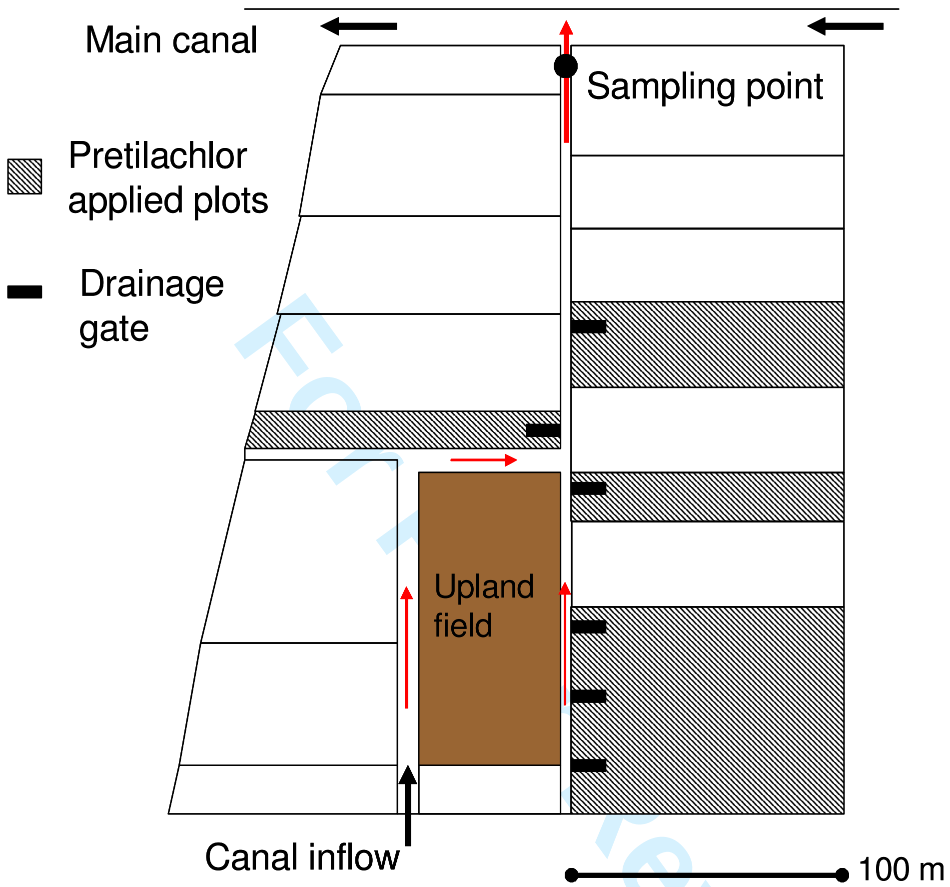

Figure 2. Description of the studied paddy block with pretilachlor applied plots.

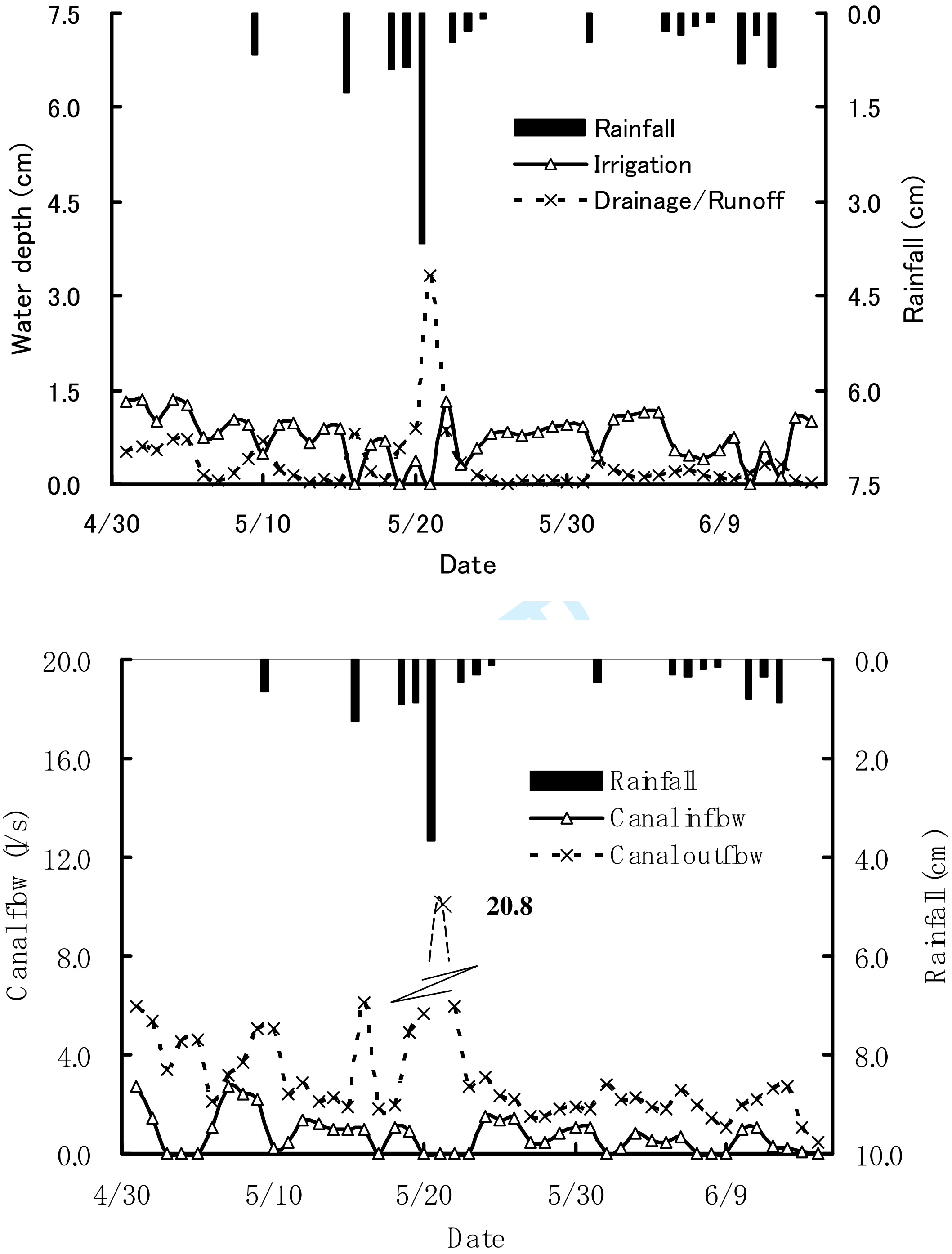

Figure 3. Main water balance components of block 2 during the monitoring period

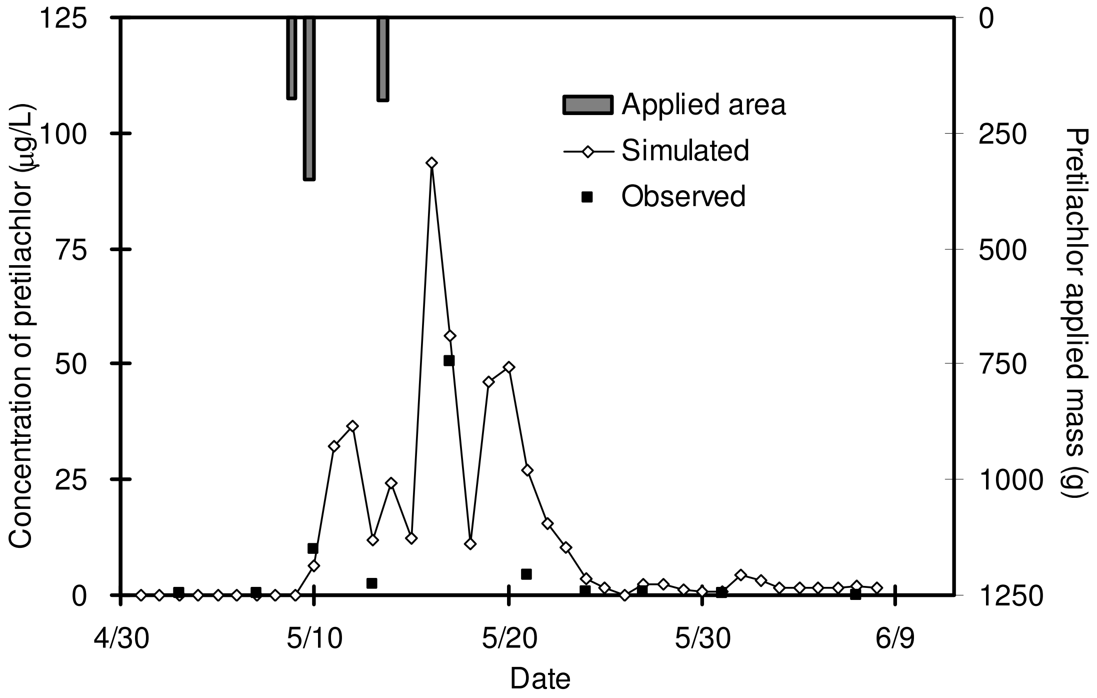

Figure 4. Herbicide concentrations in drainage canal water

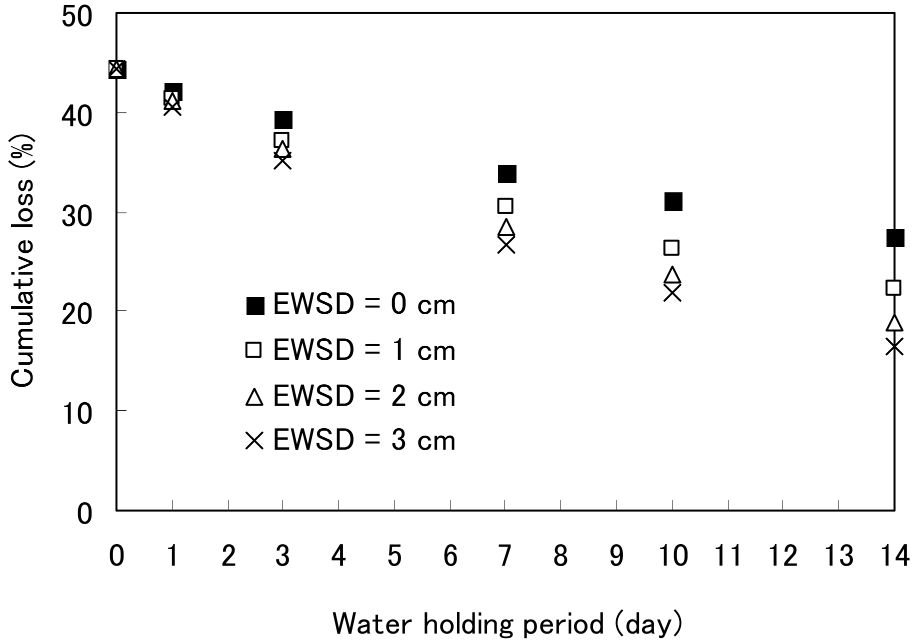

Figure 5. Mean cumulative losses of pretilachlor to the drainage canal under different water management scenarios

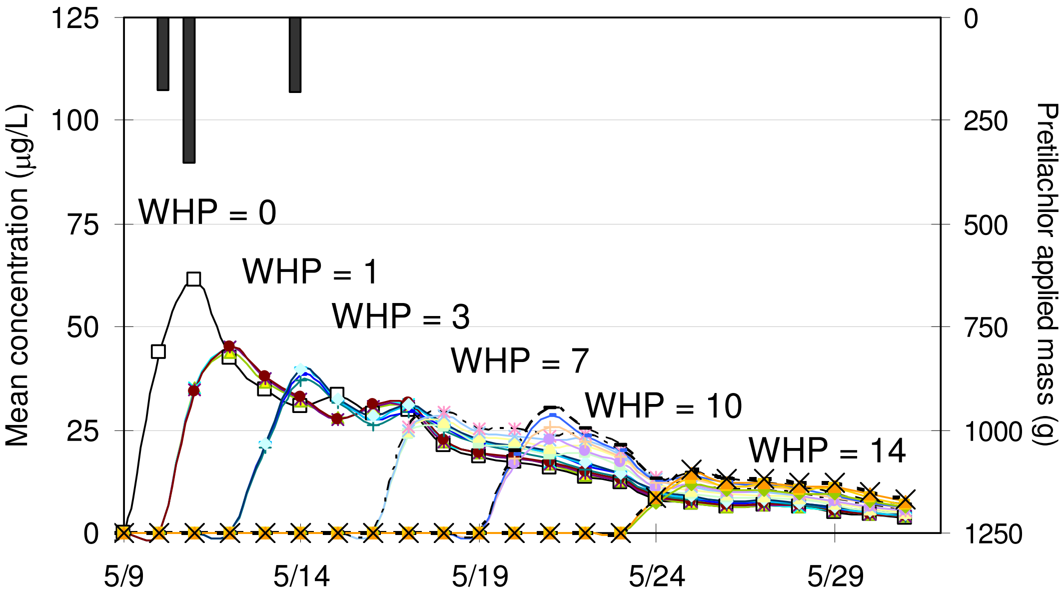

Figure 6. Mean concentrations of pretilachlor in the drainage canal under different water management scenarios

Table 1. Input parameters for PCPF-B model simulation

	Unit	Pretilachlor
General information		
Area of block	m^2	50600
Pesticide treated area	m^2	11820
Date to start simulation		2004/05/01
Simulation period	d	30
Input data for plot simulation		
Water compartment		
Application rate	$g\ m^{-2}$	0.06
Solubility of the pesticide	$mg\ L^{-1}$	50
Dissolution rate	d^{-1}	0.0631
Desorption rate	d^{-1}	0.1142
Volatilization coefficient	$m\ d^{-1}$	6.0×10^{-4}
Photolysis rate	d^{-1}	0.00083
Biochemical degradation rate	d^{-1}	0.0714
Factor of light attenuation by crop	d^{-1}	0.0162
Fraction of UVB over Rs		0.001232
Soil compartment		
Bulk density	$g\ cm^{-3}$	0.937
Saturated water content	$cm^3\ cm^{-3}$	0.603
Partitioning coefficient	$L\ kg^{-1}$	13.03
Degradation rate const.	d^{-1}	0.0368
On application date & amount		See Fig. 2

Table 2. Input water balance and management parameters used in Monte Carlo simulation for evaluation of WHP and EWSD

Parameter	Unit	Value	Distribution [a]	Comment
Climate condition				
Daily rainfall	cm day^{-1}		Randomly selected from archival data	26-year data
Evapotranspiration	cm day^{-1}		Corresponding to meteorological data	FAO-56 estimation
Water management scenarios				
Percolation	cm day^{-1}	0.15 – 0.4	Uniform	Monitoring
Surface drainage	cm day^{-1}	0.3	Point	Monitoring
$H_w$max	cm	5	Point	Assumption [a]
$H_w$min	cm	3	Point	Assumption [a]
EWSD	cm	0, 1, 2, 3	Point	
WHP	days	0, 1, 3, 7, 10, 14	Point	

[a]The assumption was made based on average value of field survey and the recommended value of agricultural cooperatives in the area.

Table 3. Regressed equations for the effect of WHP on cumulative loss of pretilachlor

	R^2	Regressed equation[a]
EWSD = 0	0.9846	y = -1.1841x + 43.287
EWSD = 1	0.9784	y = -1.5605x + 42.733
EWSD = 2	0.9819	y = -1.8115x + 42.703
EWSD = 3	0.9798	y = -1.974x + 42.384

[a] y is the cumulative loss (%) of pretilachlor, x is the water holding period (days)

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