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HSPF-Paddy Development for Simulating Pollutant Loadings from Paddy Fields

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Abstract

The Hydrological Simulation Program - FORTRAN (HSPF) was modified to simulate nonpoint pollutant loadings from paddy fields using a field experimental data collected during 2001~2002. The concept of a "dike height" was added in a modified HSPF code, named HSPF-Paddy, to consider the function of retaining water by a weir at the field outlet. The effect of fertilization on the variances of nutrients on the soil surface and shallow soil layer was described mathematically with a *Dirac delta* function (or first-order kinetics). As confirmed through model verification, the HSPF-Paddy modifications were shown to represent the function of retaining water, varied ponded water, and surface runoff by forced drain during both rainy and non-rainy seasons and reasonably predicted the water balance and nutrients behavior in paddy fields. It is a distributed watershed model which, with the paddy modifications, can now simulate nonpoint pollutant loadings where paddy fields are dominant, and it can be used to evaluate the effects of paddy fields on the water quality at a basin scale, and assess the impacts of proposed BMPs applied to paddy fields.

Keywords : HSPF, Watershed model, Paddy fields, Nitrogen, Phosphorus, Fertilizer, Nonpoint source pollution

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I. Introduction

The hydrologic and environmental conditions of paddy fields are somewhat different from those of other land uses. Human activity on paddy fields strongly influences the behavior of the water and nutrient runoff from the fields. Significant amounts of irrigation water and fertilizer are applied to paddy fields. The irrigation water during the growing season may vary from 500~800 mm to more than 3,000 mm (De Datta et al., 1973; Hukkeri and Sharma 1980). The function of retaining water in a large paddy field might work like a shallow reservoir that reduces surface runoff on wet days and releases drainage water on dry days. The water retention capacity of paddy fields during the flood period in Korea was estimated to be 237.8 mm (Eom, 2001) and

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it was influenced by weir height (Mishra et al., 1998).

Development and dissemination of fertilizer-responsive cultivars of rice have encouraged a steady increase in the use of fertilizer in developing countries. As a result, substantial amounts of nutrients are lost from those paddy fields receiving fertilizers (Yoon et al., 2003). Some studies were reported that the nonpoint source contribution from paddy fields was a major pollution source. Kawara et al. (1996) reported that loadings from paddy fields occupy most of the pollutant loads to Lake Biwa. Therefore, accurate simulation of paddy fields is a very important component of developing watershed management strategies, especially in the Asian monsoon area.

The Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 2001) is a comprehensive model developed under the sponsorship of the United States Environmental Protection Agency (U.S. EPA) for simulating many processes related to water quantity and quality in watersheds of almost any size and complexity. HSPF has been widely used for watershed management to simulate: (1) various hydrologic conditions (Albek et al., 2004), (2) transport of various nonpoint source pollutions, including contaminated sediment (Donigian and Love, 2003), and (3) land use management and flood control scenarios (Donigian et al., 1997). However, application of HSPF is limited in watersheds where paddy fields are predominant because the original HSPF cannot accurately simulate paddy fields behavior. Paddy fields often dominate the landscape in Korea, and intensive culturing in large area has raised concerns about the nonpoint source pollution potential from paddy fields. The mechanisms of hydrology and water quality in paddy fields are different from normal farmland. In this study, the original HSPF model was modified, and re-named HSPF- Paddy, to simulate the paddy fields and verified using field experiment data.

Ⅱ. Materials and Methods

1. Overview of Hydrological Simulation Program - Fortran (HSPF)

In HSPF terminology, a land segment which experiences infiltration is named a "*pervious land segment*". In HSPF, the PERLND module simulates the water quality and quantity processes which occur on a pervious land segment. The primary modules within PERLND simulate snow and ice (SNOW), the water budget (PWATER), sediment (SEDMNT), and water quality constituents (PQUAL and RQUAL). The auxiliary module of PERLND corrects air temperatures (ATEMP) and simulates soil temperatures (PSTEMP). In a similar manner, a land segment which does not allow infiltration (e. g. a parking lot, road/highway, rooftops connected to driveways, etc.) is named an "*impervious land segment*" and is simulated by the IMPLND module in HSPF. Many of IMPLND module sections are similar to the corresponding sections in the PERLND module, but are less complex due to the absence of infiltration and subsurface flows processes. The RCHRES module simulates the various processes which occur in a single reach of open or closed channel, or a completely mixed lake, including hydraulic behavior (HYDR), inorganic sediment (SEDTRN), general quality constituents (GQUAL), and biochemical constituents (RQUAL). Within a module section, simulation of physical processes (longitudinal advection, sinking, benthal release) is always performed before simulation of biochemical processes.

2. HSPF-Paddy Development

The infiltration distribution is focused around the two lines which separate the moisture available to the land surface (MSUPY) into what infiltrates and what goes to interflow (Fig. 1). A number of the model parameters are used to determine the location of lines I and II. The potential direct runoff, which is over line I, and the potential surface runoff (PSUR), which is the difference between MSUPY and line II, are calculated. Quantity of PSUR actually runs off (surface runoff; SURO) is determined. However, not all of the PSUR is truly potential surface runoff, due to the dike in the paddy rice field. Surface runoff can take place only when the height of the PSUR is higher than that of the dike. The DIKE was added and the SSUPR (the rate of supply to the overland flow surface) is calculated by the difference between PSUR and DIKE (the weir height) in the HSPF-Paddy. The SURSM (mean surface detention storage) is equal to the DIKE when PSUR is greater (higher) than the DIKE. It is equal to the PSUR, if PSUR is less than or equal to the DIKE height. Fertilization can be represented by an impulse load, and mathematically the *Dirac delta* function (or first-order kinetics) $\delta(t)$ can be used to represent it (Chapra, 1997).

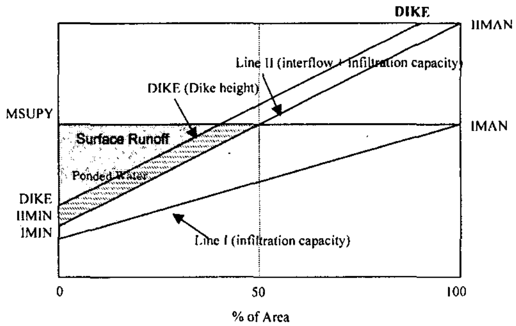
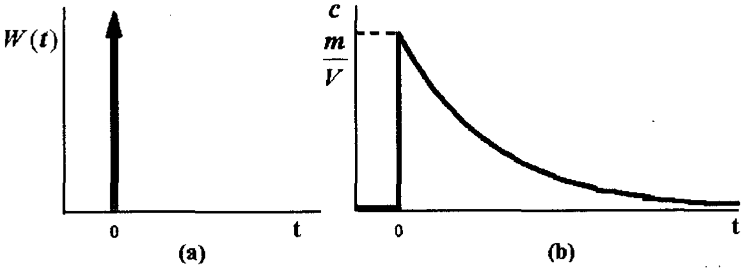


Fig. 1 Infiltration capacity, interflow, and potential surface runoff diagram in HSPF-Paddy (unit is mm/h or in/h).

Loading. The delta function can be visualized as an infinitely thin spike centered at t = 0 and having unit area. It has the following properties (Fig. 2):

$$\delta(t) = 0 \quad t \neq 0 \quad \cdots\cdots (1)$$

$$\int_{-\infty}^{\infty} \delta(t)dt = 1 \quad \cdots\cdots (2)$$



(a) (b)

Fig. 2 Conceptual expression of the effects of fertilization.

The load of mass to a water body can be represented in terms of the delta function as

$$W(t) = m\delta(t) \quad \cdots\cdots(3)$$

Outflow. The outflow mass flux can be represented by

$$Outflow = Qc \quad \cdots\cdots (4)$$

Reaction. Although there are many different ways to formulate reactions that purge pollutants from natural water, the most common by far is a first-order representation, as follows;

$$Reaction = km = kVc \quad \cdots\cdots (5)$$

where, k = a first-order reaction coefficient (T^{-1}).

Settling. By multiplying the flux times area, a term for settling in the mass balance is developed, as follows:

$$Settling = vA_s c \quad \cdots\cdots (6)$$

where, v = apparent settling velocity (LT^{-1}) and A_s = surface area of the sediments (L^2). Because volume is equal to the product of mean depth H and surface area A_s, Eq. 5 can also be formulated in a fashion similar to the first-order reaction, as in

$$Settling = k_s Vc \quad \cdots\cdots(7)$$

where, k_s = a first-order settling rate constant = v/H.

Total balance. The terms can now be combined into the following mass balance equation for well-mixed water body system:

$$V\frac{dc}{dt} = m\delta(t) - Qc - kVc - vA_s c \quad \cdots\cdots (8)$$

Before solving this equation, we can divided it by volume to yield

$$\frac{dc}{dt} = \frac{m\delta(t)}{V} - \frac{Q}{V}c - kc - \frac{v}{H}c \quad \cdots\cdots (9)$$

Collecting terms gives

$$\frac{dc}{dt} + \lambda c = \frac{m\delta(t)}{V} \quad \cdots\cdots (10)$$

Where

$$\lambda = \frac{Q}{V} - k - \frac{v}{H} \quad \cdots\cdots (11)$$

In which λ is called an eigenvalue (that is, a characteristic value). The particular solution for the *Dirac delta* function is:

$$c = \frac{m}{V}e^{-\lambda t} \quad \cdots\cdots (12)$$

where, c is concentration (mg/L) in ponded water, m is mass (kg), V is volume (m^3), λ is coefficient, and t is time (h). This solution indicates that the fertilizer is instantaneously distributed throughout the water body of the paddy field, resulting in an initial concentration of m/V. Thereafter, the result follows a general solution where concentration decreases exponentially at a rate dictated by the magnitude of λ (Fig. 2b). The types of nitrogen and phosphorus assumed for the fertilizer forms are ammonium and dissolved phosphorus. Nitrogen and phosphorus fertilizations to the surface layers were incorporated by the SPEC-ACTIONS block in HSPF, and included in the UCI (HSPF Users Control Input) file as solution ammonium storage (SAMSU) and solution phosphate storage (SP4SU) in the surface soil layer, respectively. *A Dirac delta* function was added in subroutines NITR and PHOS which respectively simulate the nitrogen and phosphorus balances for a pervious land segment. Mean solution ammonium in surface layer storage (SN (3)) and mean solution phosphate in surface layer storage (SP (3)) are calculated as the surface layer storage of nutrients in a paddy fields. If surface runoff occurs, nutrient loading is named mean surface water outflow of solution ammonium (TSAMS 1, 1) and of solution phosphate (TSP4S 1, 1) from the surface soil layer.

3. Experimental Paddy Fields

The study area irrigated with groundwater is a Konkuk University agricultural research farm in Yeoju (37°14′N, 127°33′E), located approximately 45 km southeast of Seoul (Fig. 3).

Table 1 summarizes the agricultural activities during the study period. The fertilization rate was that recommended by the National Institute of Agricultural Science and Technology of Korea. Ponded water depth in the experimental plot was measured continuously by an automatic water level recorder, and inflow and outflow were measured using weirs installed at the inlet and outlet of the plot, respectively. Rainfall was recorded by a tipping bucket rain gauge at the site, and evapotranspiration was estimated by the Penman-Monteith equation (Allen et al., 1998).

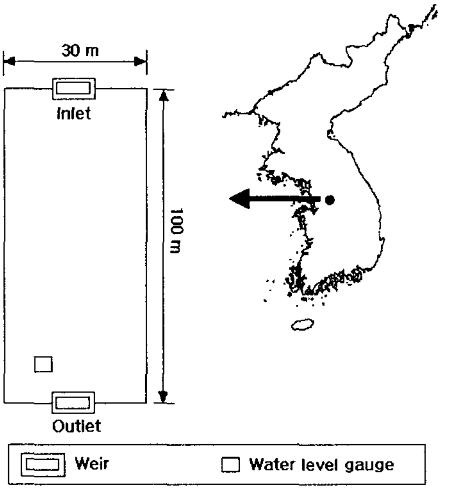


Fig. 3 The experimental study area.

Table 1 Agricultural activities during the study period.

Time		Agricultural activity	Remark
2001	2002		
20 May	17 May	Plowing and basal fertilization	Phosphorus (19.64 Kg P/ha) Nitrogen (55 Kg N/ha)
29 May	27 May	Rice transplanting	15×30 cm, four plants/hill
09 June	07 June	Tillering fertilization	Nitrogen (33 Kg N/ha)
17 July	26 July	Panicle fertilization	Nitrogen (22 Kg N/ha)
07 Oct.	12 Oct.	Harvest	-

Water samples were analyzed by Standard Methods (APHA, 1995) for conventional parameters including T-N and T-P.

Statistical analyses were performed to test the model performance by calculating the average error (AE), root mean square error (RMSE), and model efficiency (EF). The equations representing these relationships are as follows (Chanasykl et al., 2003; Nash and Sutcliffe, 1970):

$$AE = \frac{\sum_{i=1}^{n} P_i - O_i}{n} \quad \text{……………………………… (13)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \quad \text{…………………… (14)}$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - \bar{P})^2} \quad \text{……………………… (15)}$$

where P_i and O_i are predicted and observed values, respectively, and n is a number of values.

Ⅲ. Results

Fig. 4 illustrates the simulation results of ponded water depth (mm) and surface runoff (mm). Initial irrigation water was applied to the dry experimental paddy sites for puddling, which was confined by dikes and an adjustable weir. Then the ponded water depth varied with rainfall and irrigation, except during forced drainage for fertilization of panicle period. Generally the model output closely followed the observed data and it predicted the water balance in the paddy rice fields during the growing season quite well.

Fig. 5 shows the simulation results for the amount of nutrient storage in the ponded water. These results also demonstrated that the nutrient model output also reasonably predicted the nutrient behavior in the paddy fields. The amount of nutrient storage was mainly influenced by fertilization, with a peak storage right after fertilization, and then decreasing with time; note the timing of the fertilizations shown at the top correspond with the peak storages, as expected. However, nutrient storages reaches background

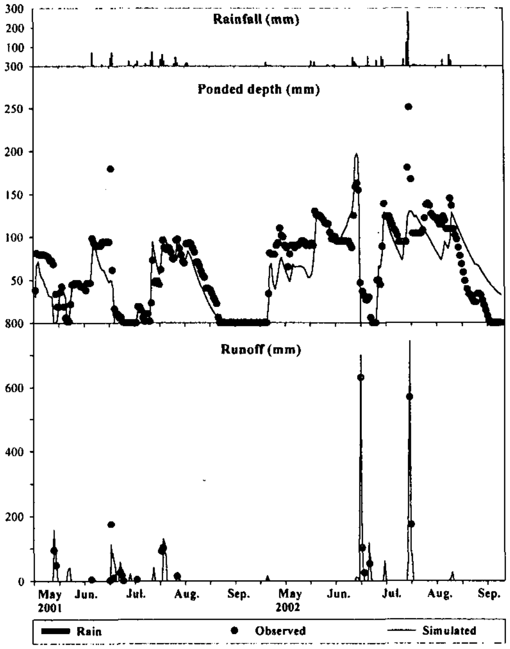


Fig. 4 Observed and predicted ponded water depth and surface runoff from the paddy fields.

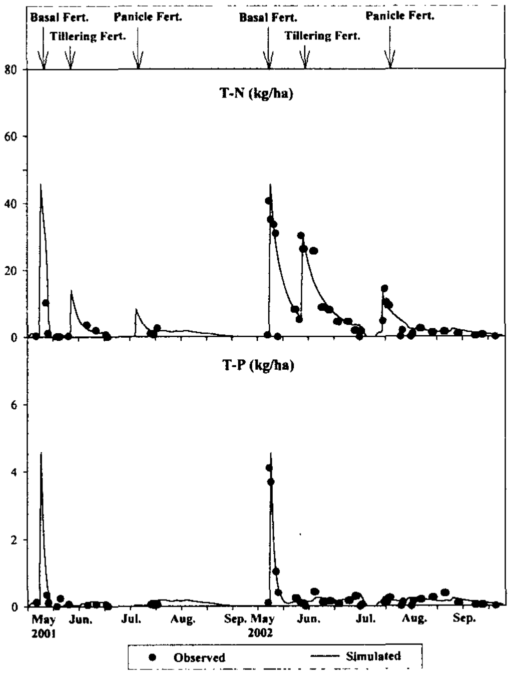


Fig. 5 Observed and predicted nutrient accumulation in the paddy fields.

Table 2 Result of the model fitness test

	AE	RMSE	EF
Ponded water depth (mm)	5.37	17.86	0.52
T-N (kg/ha)	-0.49	3.03	0.93
T-P (kg/ha)	-0.01	0.21	0.93

levels during the heavy rainfall season; thus fertilizer impacts do not extend beyond the growing season.

Table 2 summarizes the statistical analyses for model fitness or performance, where values of AE and RMSE were low and values of EF were high, indicating that the model simulation results matched the observed data quite well. Fig. 6 is a scatter plot of observed versus predicted data and most data are distributed along the 1:1 line except for a few outliers. Both the model fitness test and scatter plot showed that the HSPF-Paddy model results are sufficiently accurate to simulate the behavior of water and nutrients in the paddy fields system.

Ⅳ. Discussion

The major assumption of the HSPF-Paddy modifications is that the removal pattern of fertilizer accumulated in paddy fields follows an exponential equation. The validity of this assumption is supported by the comparisons between simulated and observed data as well as by other studies cited in the literature. The simulation results show that nutrient concentrations in the surface waters draining paddy fields increased significantly following fertilizer application, and subsequently declined sharply, then remained almost constant (Fig. 4). Takamura et al. (1977) reported that ammonia nitrogen concentrations reached about 25~100 mg/L after fertilization in paddy fields. However, ammonia volatilization losses in flooded soil ranged from negligible amounts to as high as 60% of the applied nitrogen (Ghosh and Bhat 1998). Chowdary et al. (2004) reported that volatilization follows first-other kinetics and the gaseous (volatilization) loss of N varies from 25 to 33% of the applied fertilizer in paddy fields. They also reported that about 75% of the total volatilization loss occurs within 7 days of urea application, and this process continues for about 15 days after fertilizer application. In this study, the high nitrogen concentrations due to fertilizer applications continue for about 20 days (Fig. 4).

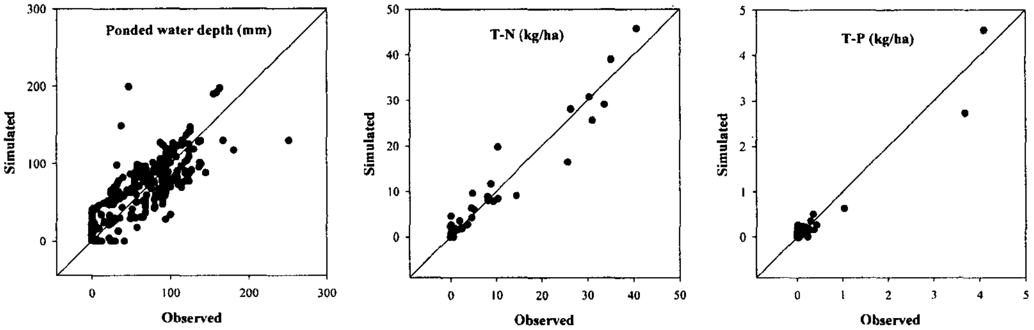


Fig. 6 Scatter plot of observed versus predicted data.

The chemical behavior of P in paddy rice field soil is largely controlled by the transformation of Fe oxides (Zhang et al., 2003). Substantial amounts of applied phosphorus were lost by adsorption/sedimentation as a form of Fe (II)-P in paddy rice fields (Kirk et al., 1990). Wang et al. (2001) reported that concentrations of both total P and dissolved P in the surface waters increased significantly following P application, which was higher with increasing rate of fertilizer P, especially during the first 2 weeks after application. P concentrations subsequently declined sharply for about 10 days, then declined steadily and remained almost constant after about 1 month following application.

Some studies were performed about model development for paddy fields; water balance (Wu et al., 2001); water movement in soil layer (Chen et al., 2002); and nutrient loading estimation (Chung et al., 2003). However, all of them were focused on simulation of just the paddy fields, not the entire watershed. The HSPF-Paddy model can simulate water and nutrient behavior in surface, subsurface and groundwater of paddy fields, along with the encompassing multiple land uses at a watershed scale (pervious/impervious land) and water quality in stream. The downstream impacts on waterbodies, as well as BMPs evaluation, of paddy fields practices, is important. The HSPF-Paddy model can be used for these types of comprehensive evaluations of both BMPs and water body impacts. However, field scale studies were necessary for estimate applicability of model.

V. Conclusions

A state-of-the-art watershed model, HSPF, was modified to simulate pollutant loadings from paddy fields, and re-named HSPF-Paddy. Nutrient storages in the surface waters increased significantly following fertilizer application, subsequently declined sharply within a few days, and then declined steadily and remained almost constant where after application. These variances of nutrient on the water surface by fertilizer follows first-other kinetics and can be explained using the *Dirac delta* function. The validity of this model is supported by the comparisons between simulated and observed data as well as by other studies cited in the literature. Dike-retained water and the variation of nutrient accumulation on the water surface by fertilizer can be simulated successfully in HSPF-Paddy. This model is applicable under a wide range of field, environmental and management conditions for the rice crops, and can provide a good representation of watershed hydrology, watershed pollutant loading, and in-stream water quality for complex land use conditions. Therefore, it can be useful for BMPs evaluations, irrigation water management for paddy fields itself, and the estimation of resulting effects on downstream water quality.

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