Water quality modeling to evaluate BMPs in rice paddies

J.H. Jeon*, C.G. Yoon, H.S. Hwang*** and K.W. Jung****

*Research Division, Korea Environment Institute, 613-2 Bulgwang-dong, Eunpyeong-gu, Seoul 122-706, Korea (E-mail: *jihongjeon@hanmail.net*)

**Department of Environmental Science, Konkuk University, 1 Hwayang-dong, Kwangjin-gu, Seoul 143-701, Korea (E-mail: *chunyoon@konkuk.ac.kr; jungkw@konkuk.ac.kr*)

***National Institute of Environment Research, Ministry of Environment, Kyeongse-dong, Seo-gu, Inchen 404-170, Korea (E-mail: *undersun@me.go.kr*)

Water Science & Technology **Vol 53 No 2 pp 253–261** © IWA Publishing 2006

Abstract A water quality model applicable to rice paddies was developed using field data from 1999–2002. Use of the Dirac delta function efficiently explained the nutrient-concentration characteristics of ponded water. The model results agreed reasonably well with the observed data. The ponded-water quality was influenced primarily by fertilization; nutrient concentration was especially high during early cultivation periods. Reducing surface drainage during the fertilization period may substantially reduce nonpoint source loading from paddies. Increased weir heights and shallow irrigation methods were evaluated by the model as practical methods for reducing nutrient loading from paddies. These methods were effective in reducing surface drainage and are suggested as "best management practices" (BMPs) if applied based on site-specific paddy conditions.

Keywords Model development; paddy management; shallow irrigation; water quality; weir height

Introduction

Rice grown in paddies requires certain water-layer depths. Field water-layer depths during the growing season may vary from 500–800 mm (De Datta *et al.*, 1973) to more than 3,000 mm (Hukkeri and Sharma, 1980). In South Korea, paddy water levels are approximately 1,250 mm, and water is supplied primarily by irrigation (Chae, 1998). The hydrological and water quality characteristics of paddies differ slightly from those of other land-use types. The water retentiveness of paddies can reduce surface runoff, while paddy drain-off can produce surface runoff without a rainfall event. Therefore, the ridge height of diked rice fields and operational drain-off during the rice cultivation period can change the hydrologic pattern. Rice, like other crops, needs 16 essential elements, and all of these must be present in optimum amounts and in forms available to rice plants for proper growth. Among these elements, nitrogen, phosphorus, and potassium are most commonly applied as fertilizers, and major portions of these nutrients are used by rice plants throughout the growth cycle (Lee, 2001). However, a significant portion of these nutrients can be lost from paddies through surface drainage, seepage, and percolation. This loss might result in excessive nutrient supply to receiving water bodies and eutrophication problems (Cooke *et al.*, 1993).

In South Korea, paddies cover approximately 1 million ha, and irrigation for paddy rice culture ranks first among water uses and accounts for over 50% of the nation's total water consumption. Paddies are thus important to studies of water resources and watershed management. This paper describes a field experiment performed during the 1999–2002 growing seasons to analyze water and nutrient balances in rice paddies; a water quality model was developed to evaluate best management practices (BMPs) for paddies.

doi: 10.2166/wst.2006.059

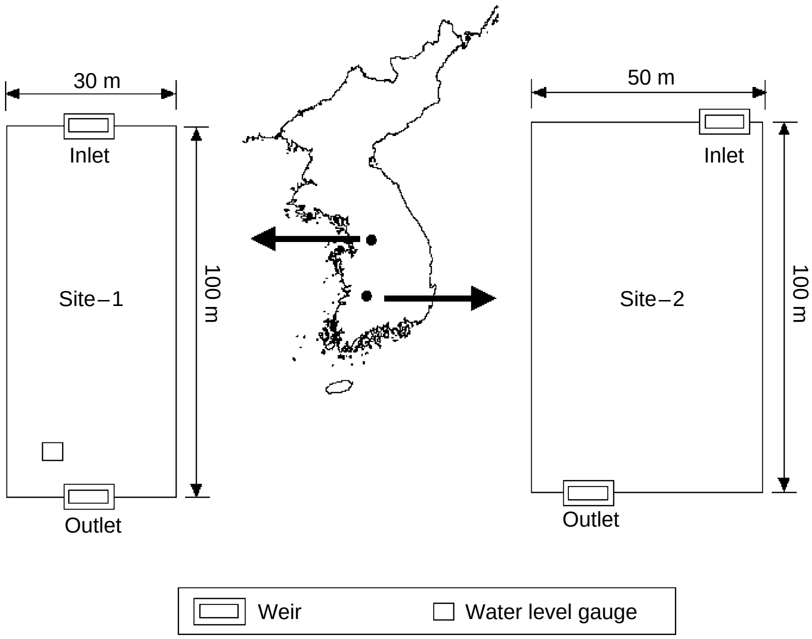


Figure 1 Study area and sampling points

Study area

The field experiment was performed at two separate sites in Korea as shown in Figure 1. Site-1 was a Konkuk University agricultural research farm in Yojoo (37°14′N, 127°33′E) irrigated with groundwater; experiments were performed here for two years (2001–2002). Site-2 was a field research farm in Jinan (35°37′N, 127°16′E) irrigated with surface water; experiments were performed here in 1999 and 2000.

Model development

The planning-level model PADDIMOD was developed to predict water and nutrient balances in rice paddies. Figure 2 illustrates the water balance concept for paddies and the model. The modeled inflow to a paddy consists of irrigation (IR_1), input from any upper paddies (IR_2), and rainfall (*PR*); the outflow consists of evapotranspiration (*ET*), infiltration (*INF*), and surface runoff (*DR*). Fertilization loading is presented as impulse loading, represented mathematically by the Dirac delta function (or impulse function) $\delta(t)$ (Chapra, 1997). The Dirac delta function can be visualized as an infinitely thin spike centered at $t = 0$ and having a specified unit area (Figure 3). The solution indicates that fertilizer is instantaneously distributed throughout the water body of the paddy, resulting in an

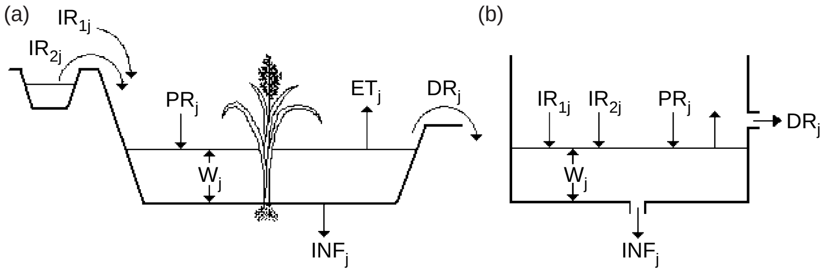


Figure 2 Water balance concept in a paddy (a) and the model (b)

initial concentration of *m*/*V*. Thereafter, the result is identical to the general solution, i.e. the concentration decreases exponentially at a rate dictated by the magnitude of λ.

Results

Model calibration and validation

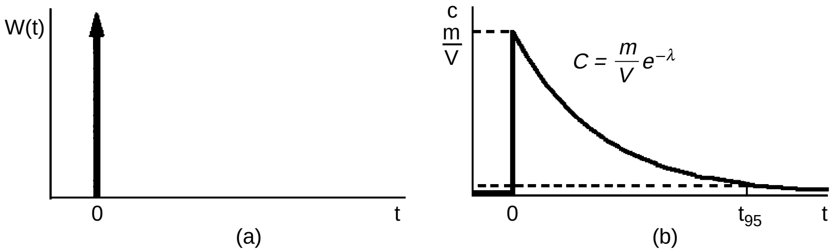
The model was calibrated and validated with two independent data sets from two separate sites. The simulation results of ponded-water depth (mm) and surface runoff (mm) are shown in Figure 4; data for ponded-water depth at Site-2 were not available. The ponded-water depth generally varied with rainfall and irrigation, except during two forced drainages for fertilization (tillering and panicle). Simulated nutrient concentrations of ponded water are shown in Figure 5. Nutrient concentration was mainly influenced by fertilization, and the total nitrogen (TN) and total phosphorus (TP) concentrations reached 50 mg/L and 5 mg/L, respectively, for the basal fertilization period. This result implies that control of surface drainage especially during May and June can substantially reduce nonpoint source loading from paddies. Table 1 summarizes the statistical analyses of model fitness; average error (AE) and root mean square (RMS) values were low, while model efficiency (EF) values were high, indicating that the model simulation results matched the observed data quite well.

BMPs evaluation by PADDIMOD

The effect of paddy BMPs on the nutrient loading from Site-1 was evaluated using the PADDIMOD simulation for the conditions in 2001. Increasing weir height from 100 to 200 mm retained more ponded water and reduced surface drainage especially during May when high nutrient concentration resulted from fertilization; Table 2 shows the marked reduction in nutrient loading that resulted. The reduction of TN and TP surface loadings was about 78 and 49%, respectively, attained by simply increasing the weir height by 100 mm (Figure 6).

The effect of shallow irrigation was also simulated, and the results are summarized in Table 2. The ponded-water depths of the field experimental sites were generally maintained at 100 mm; shallow irrigation was simulated with ponded-water depths of 10–30 mm and a weir height of 100 mm.

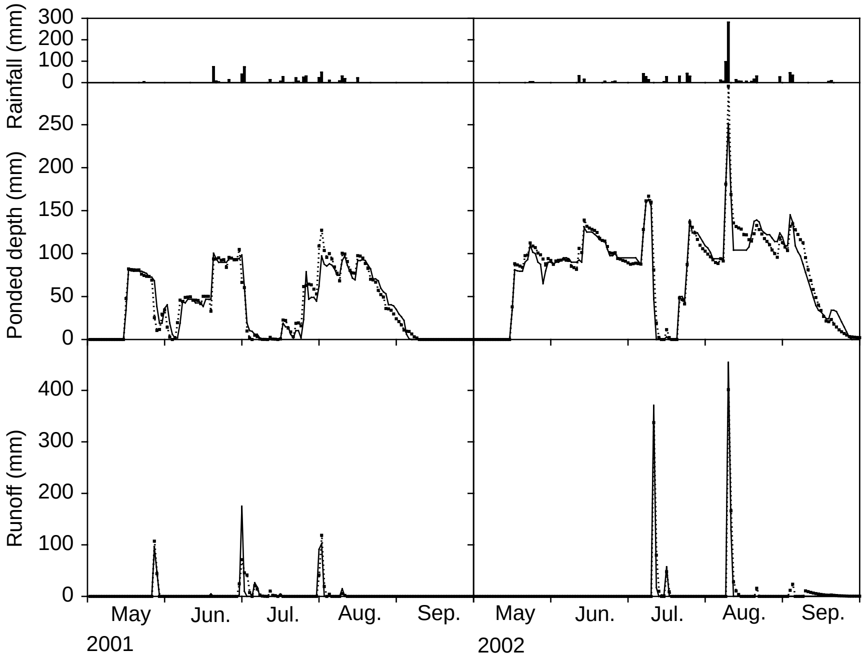
The model predicted that shallow irrigation can also substantially reduce nutrient loading from paddies. The shallow irrigation condition reduced modeled TN and TP surface loadings by approximately 74 and 47%, respectively, and the total irrigation depth from 296 to 130 mm. Note that while the reduction in nutrient loading was substantial, total surface runoff was reduced only slightly. Surface drainage was controlled during the initial stage of paddy preparation; this control likely contributed most to the nutrient-load reduction because of the high nutrient concentration of ponded water during the basal fertilization period.



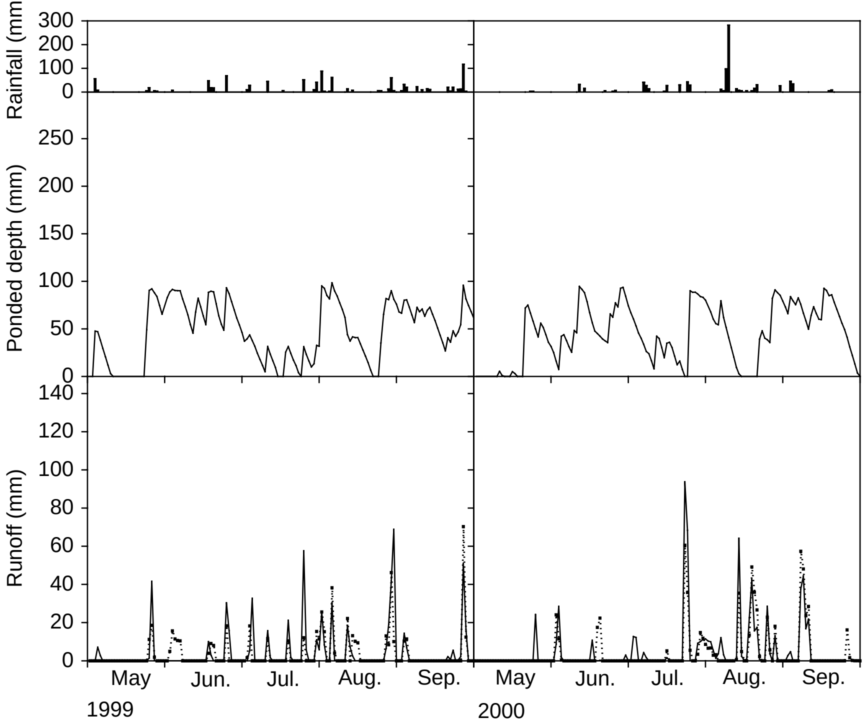
(a)

(b)

Figure 3 Loading and concentration plot of impulse loading

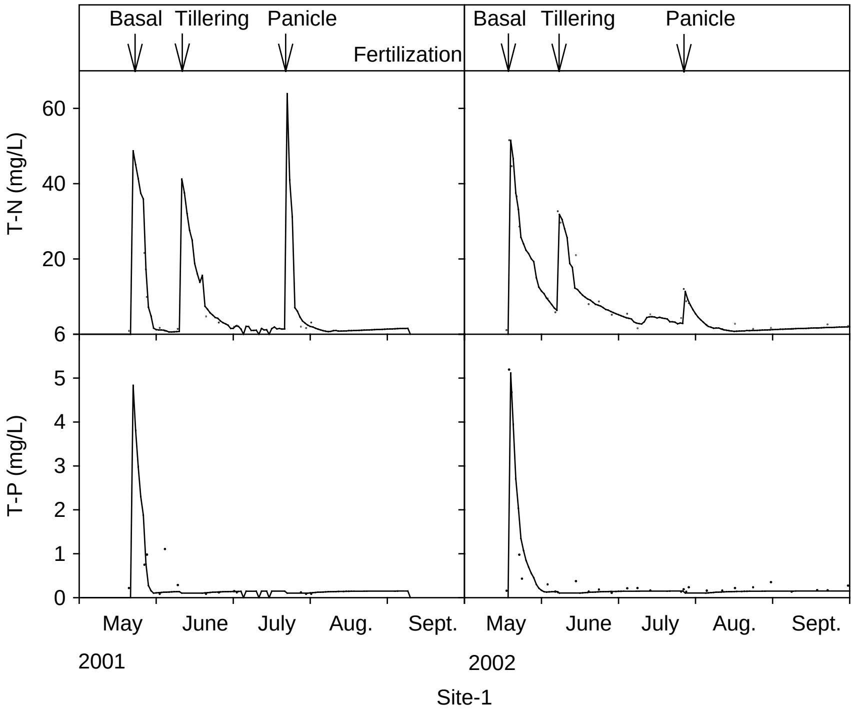


Site-1



Site-2

Figure 4 Observed and predicted ponded-water depth and surface runoff from the paddies



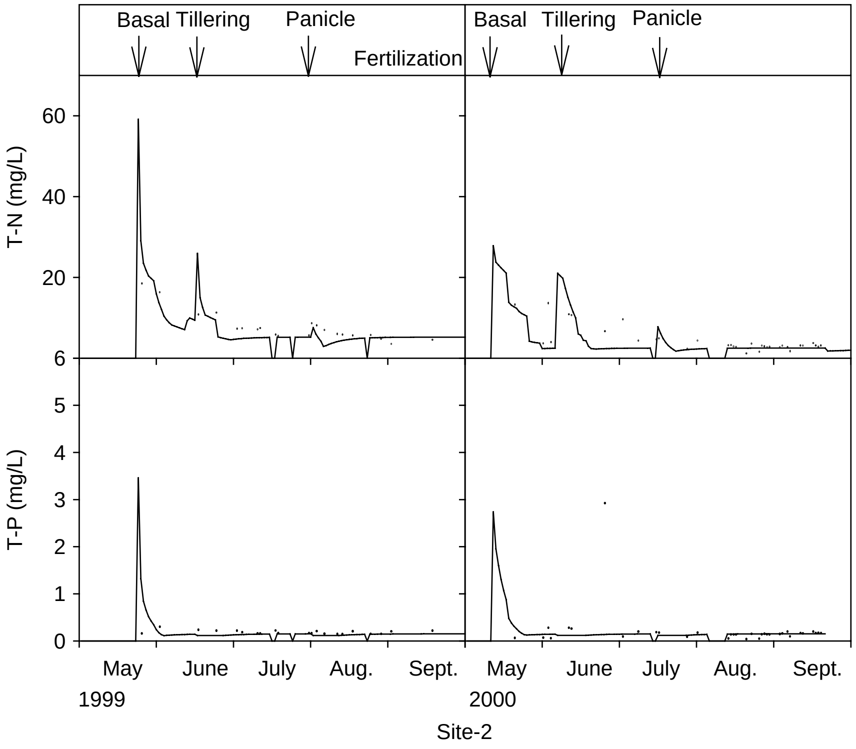


Figure 5 Observed and predicted nutrient concentrations of ponded-water in the paddies

Table 1 Results of the model fitness tests for the PADDIMOD model

	Ponded-water depth		TN		TP	
	Site-1	Site-2	Site-1	Site-2	Site-1	Site-2
AE (mm, mg/L)	0.81	–	− 0.11	− 0.53	− 0.06	0.02
RMS (%)	11.48	–	1.99	2.52	0.24	0.38
EF	0.93	–	0.98	0.99	0.95	0.70

Characteristics of surface drainage from paddies

Two sites were simulated using the PADDIMOD model with rainfall data from the last 10 years (1994–2004) to examine the general characteristics of surface loading from paddies. The average rainfall during the growing season was 978.8 mm, and average runoff coefficients for Site-1 and Site-2 were 0.55 and 0.59, respectively (Table 3). The average runoff coefficient for Korea is 0.60; thus, the simulation result was within the expected range. Site-2 showed higher loading than Site-1; more frequent drainage during the initial stage of paddy farming might explain the difference. The simulation results showed that surface nutrient loading was influenced mainly by rainfall amount and demonstrated a correlation between these two factors (Figure 7). Data from two other studies in Korea generally followed the pattern of the simulation results.

Discussion

Water quality in paddies is influenced by fertilization, and nutrient concentrations become especially high during fertilization periods (May–June). Surface runoff from paddies depends on rainfall and forced drainage. Paddy runoff during the fertilization period drains to outside water bodies and can cause eutrophication. Runoff early in the rice culture period can occur through agricultural activities such as forced drainage or lowered weir heights. Nutrient concentration during surface runoff caused by heavy rainfall events was similar to the background concentration, as shown in Figure 5. Therefore, compared to other land-use types, it may be possible to more effectively control nutrient loading from paddies using BMPs. Increased weir height and shallow irrigation were evaluated using the calibrated and validated PADDIMOD model; these measures were found to be effective in reducing surface nutrient loading. The increased weir height reduced TN and

Table 2 The effects of increased weir height and shallow irrigation on surface loading from paddy fields

		Runoff (mm)		TN (kg/ha)		TP (kg/ha)	
		Observed	Simulated	Observed	Simulated	Observed	Simulated
Increased weir height							
2001	May	143.10	0.0	24.64	0.00	1.13	0.00
	June	182.42	182.4	0.15	1.55	0.01	0.11
	July	252.87	252.8	2.67	4.03	0.05	0.41
	Aug.	14.81	14.8	0.00	0.43	0.00	0.08
	Sept.	0.00	0.0	0.00	0.00	0.00	0.00
	Total	593.20	450.1	27.45	6.01	1.06	0.60
Shallow irrigation							
2001	May	143.10	0.00	24.64	0.00	1.13	0.00
	June	182.42	141.19	0.15	0.98	0.01	0.12
	July	252.87	281.72	2.67	5.86	0.05	0.39
	Aug.	14.81	11.30	0.00	0.42	0.00	0.04
	Sept.	0.00	0.00	0.00	0.00	0.00	0.00
	Total	593.20	434.21	27.45	7.26	1.06	0.56

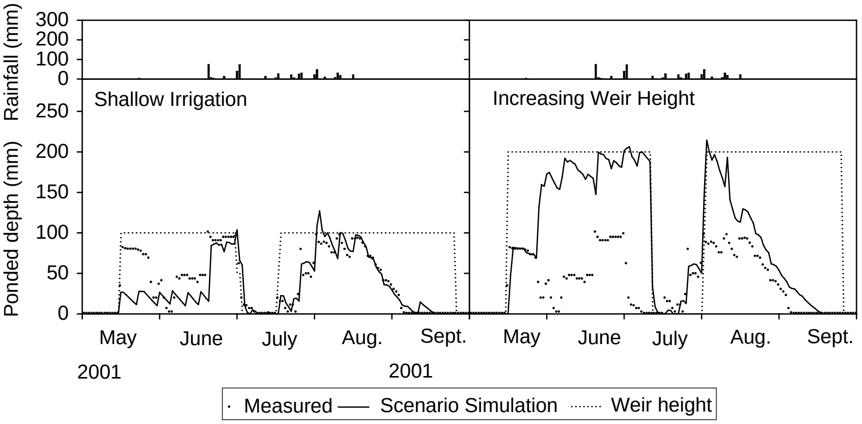


Figure 6 Simulation results for each scenario using PADDIMOD

TP surface loadings by approximately 78 and 49%, respectively. Results from shallow-irrigation modeling also suggested TN and TP surface loading reductions of approximately 74 and 53%, respectively. A three-year experimental study (Mishra *et al.*, 1998) in India with weir heights of 6 and 30 cm at 4-cm intervals revealed that about 56.75 and 99.5% of the rainfall could be stored in 6- and 30-cm weir-height plots, respectively, without a significant impact on grain yield. Bouman and Tuong (2001) reported that reducing ponded-water depths from 5–10 cm to the level of soil saturation did not reduce land productivity, and they found that 23% water savings caused only a 6% yield reduction.

Water-saving irrigation, raising the drainage weir height in diked rice fields, and minimizing forced surface drainage are suggested measures for reducing nutrient loading from paddies. The possible benefits may include reduced irrigation water use and more efficient water resource allocation; increased storage of rainwater, with resulting flood prevention and groundwater recharge effects; and reduced nutrient loss, i.e. reduced nutrient loading and better water quality. However, these practices affect only some aspects of the overall water environment and may have other effects. For example, excessively increased weir height may create submerging damage or cold-water damage to the rice crop, and shallow irrigation requires support for participation and irrigation facilities. Therefore, other various aspects and local conditions in addition to environmental concerns need to be considered when developing practical BMPs for paddies.

Table 3 Simulation results for the past 10 years using the PADDIMOD model

	Rainfall (mm)	Runoff (mm)	Runoff rate	TN (kg/ha)	TP (kg/ha)
Groundwater (Site-1)					
Avg.	978.8	533.48	0.55	10.23	0.77
Max.	1,468.8	991.91	0.68	18.36	1.39
Min.	668.0	276.63	0.41	5.31	0.40
S.D.	276.6	244.95	0.10	4.08	0.34
Surface water (Site-2)					
Avg.	978.8	581.39	0.59	15.09	0.94
Max.	1,468.8	961.04	0.68	22.77	1.54
Min.	668.0	392.77	0.47	8.72	0.49
S.D.	276.6	204.95	0.08	5.90	0.43

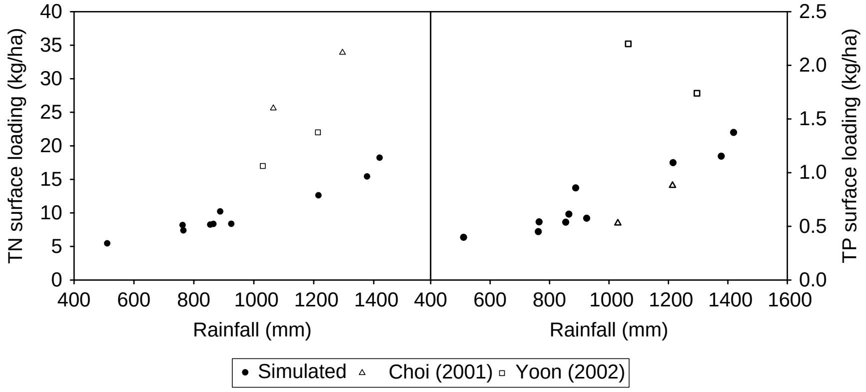


Figure 7 Relationship between rainfall amount and nutrient loading

Conclusions

The PADDIMOD model was developed using field data from two separate sites to simulate water and nutrient behavior in a paddy system. It was formulated with a few equations and simplified assumptions aimed at evaluating paddy BMPs for nonpoint source pollution control. The model produced realistic predictions and the simulated results reasonably matched the observed data. The model predicted daily ponded-water depth, surface drainage flow, and nutrient concentrations. As a simple and convenient planning model, the PADDIMOD can be used to evaluate BMPs for paddies alone or in combination with other complex watershed models.

Irrigated rice agriculture involves large amounts of water and nutrients, and substantial amounts of both inputs are lost through surface drainage. Nutrients lost by surface drainage flow into receiving water bodies and can cause eutrophication and other excessive algal growth problems. Nutrient loading from paddies occurs mainly by surface water flow, and surface drainage plays a key role in the movement of nutrients to receiving waters. Saving water by maintaining a shallow ponded-water depth and raising the drainage weir height in diked rice fields may be applicable BMPs to reduce surface drainage and associated nutrient loading. These BMPs were evaluated by the calibrated PADDIMOD model, which demonstrated their effectiveness. Model results showed that increasing the weir height from 100 to 200 mm could lead to greater water retention and reduced TN and TP surface loadings by approximately 78 and 49%, respectively. Shallow irrigation practices may also reduce TN and TP surface loadings by about 74 and 53%, respectively, and lower the total irrigation depth from 296 to 130 mm. The model demonstrated that controlling surface drainage during the initial stage may be the most critical factor in nonpoint source loading reduction from paddies because nutrient loads tend to be highest during the basal fertilization period.

References

Bouman, B.A.M. and Tuong, T.P. (2001). Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, **49**, 11–30.

Chae, J.C. (1998). Effect of tillage and seeding methods on percolation and irrigation requirement in rice paddy condition. *Korean Journal of Crop Science*, **43**, 264–268.

Chapra, S.C. (1997). *Surface Water-Quality Modeling*. McGraw-Hill, Inc., New York, NY, USA, pp. 47–87.

Cooke, G.D., Welch, E.B., Peterson, S.A. and Newroth, P.R. (1993). *Restoration and Management of Lakes and Reservoirs*, 2nd ed. Lewis Publishers, Boca Raton, FL, USA.

De Datta, S.K., Abilay, W.P. and Kalwar, G.N. (1973). Water stress effects in flooded tropical rice. In *Water management in Philippine Irrigation Systems: Research and Operations*. International Rice Research Institute, Los Baños, The Philippines, pp. 19–36.

Hukkeri, S.B. and Sharma, A.K. (1980). Water-use efficiency of transplanted and direct-sown rice under different water management practices. *Indian Journal of Agricultural Science*, **50**, 240–243.

Lee, B.W. (2001). Rice cultural practices in Asia. In *Rice Culture in Asia*, International Commission on Irrigation and Drainage, and Korean National Committee on Irrigation and Drainage, Seoul, Korea, pp. 36–54.

Mishra, A., Ghorai, A.K. and Singh, S.R. (1998). Rainwater, soil and nutrient conservation in rainfed rice lands in eastern India. *Agricultural Water Management*, **38**, 45–57.