MASS BALANCE ANALYSIS AND WATER QUALITY MODEL DEVELOPMENT FOR LOADING ESTIMATES FROM PADDY FIELD

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ABSTRACT

Mass balance analysis and water quality model development for paddy field were performed using field experimental data during 2001-2002. About half (47 ~ 62 %) of the total outflow was lost by surface drainage, with the remainder occurring by evapotranspiration about 490 ~ 530 mm. Most of nutrient inflow and outflow were occupied by fertilization and plant uptake, respectively. Nutrient outflow by surface drainage runoff was substantial about 15% ~ 29% for T-N and 6% ~ 13% for T-P. However, the responses of yield and drainage outflow to fertilization were not significant in this study. Water quality model applicable to paddy fields was developed and it demonstrates good agreement between the observed and simulated. The nutrient concentration of ponded water was high by fertilization at early culture periods, so reducing surface drainage during fertilization period can reduce nutrient loading from paddy fields. Shallow irrigation, raising the weir height in diked rice fields, and minimizing forced surface drainage are suggested to reduce surface drainage outflow.

KEYWORDS: mass balance, water balance, nutrient loading, paddy field, water quality model

INTRODUCTION

Monsoon Asia's agriculture feeds 60% of the world's population by using only 30% of the arable land, and by approximately 40 years after World War , most Asia countries had achieved self-sufficiency in rice (Takase, 2003). It was relized recently that water quality improvement is hardly achieveable without proper control of nonpoint source pollution. The nonpoint source pollution is closely related with land use and rainfall events. The land use in Korea includes about 65 % of forest and 20 % of farmland, where runoff from forest is thought to be natural but drainage water from farmland is suspected as a key pollution source. Although urban area covers substantial portion of the country, much of urban runoff is collected by stormwater collection system and receives less attention. The rainfall of Asia monsoon region including Korea is concentrate and intensive during the crop growing season, therefore rural runoff including agricultural drainage water is particularly concerned in water quality perspectives.

Water is one of the most essential prerequisites for sustaining natural ecosystems and human development. Increasing human populations and economic development require more water and competition occurs among the water uses, furthermore, the available freshwater is not always satisfactory for intended water uses due to water quality problems. Therefore, not only securing water quantity but also water quality protection is important, and nitrogen and phosphorus are more concerned in this study because of their role in algal growth. A field experiment was performed during the 2001-2002 growing season to analyze water and nutrient balances in a paddy rice field, develop water quality model for paddy field, and suggestions are made to reduce nutrient loading and its resulting water quality impacts.

MATERIALS AND METHODS

Site and crop management

Field experiments were carried out at experimental farm of the Konkuk University Agircultural Research, Yojoo (37º14´N, 127º33´E, 70m elevation), Korea during growing season of 2001 to 2002. Fig. 1 shows the layout of study area and location of sampling station. Treatments included three fertilization rates, and the fertilization rate as recommended by the National Institute of Agricultural Science and Technology of Korea was applied to the standard fertilization plot (SF; 165N kg ha^{-1}, 15P kg ha^{-1}), excessive fertilization plot (EF; 110N kg ha^{-1}, 10P kg ha^{-1}), and reduced fertilization plot (RF; 77N kg ha^{-1}, 7P kg ha^{-1}). P and K were applied at transplanting, but N was applied at three different times (Table 1).

Measurements

Ponded water depth in each 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 each plot, respectively. The infiltration was measured by four infiltrometers, and percolation water was sampled via two ceramic porous cups. Water samples were conducted every two week, and analyzed by the Standards Methods(APHA, 1995). Rice plant samples were collected at harvest, and analyzed by the methods of Allen *et al.* (1986).

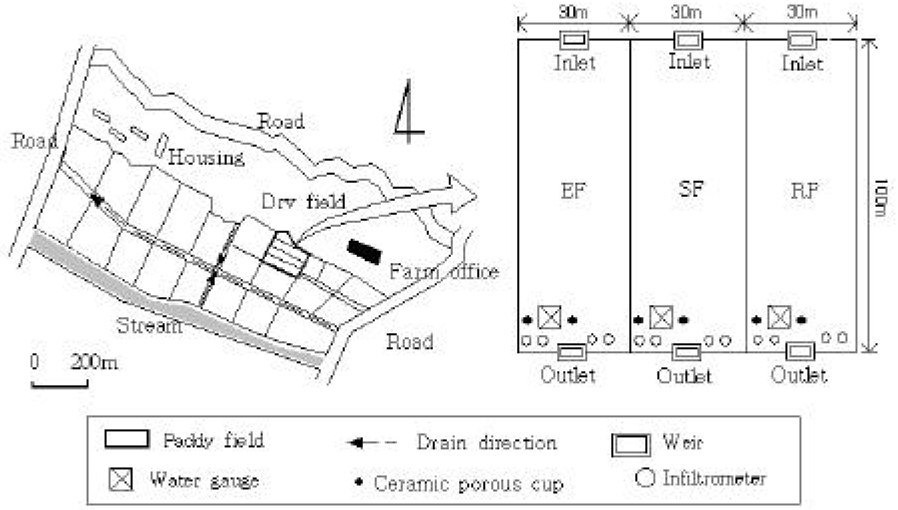


Fig. 1. Layout of the study area and location of sampling stations.

Table 1. Agricultural activities during the study period.

2001	2002	Agricultural activity	Remark
May 20	May 17	Plowing and basal fertilization	Phosphorus, Nitrogen
May 29	May 27	Rice transplanting	15×30cm, four plants/hill
June 9	June 7	Tillering fertilization	Nitrogen
July 17	July 26	Panicle fertilization	Nitrogen
October 7	October 12	Harvest	-

Mass balance for water and nutrients

Water balance in paddy fields was estimated by the variation in ponded water depth (W), expressed in the form:

$$W_j = W_{j-1} + IR_{1j} + IR_{2j} + PR_j - (DR_j + ET_j + INF_j) \qquad (1)$$

where W_j is ponded water depth, W_{j-1} is ponded water depth on the previous day, IR_{1j} is amount of groundwater irrigation, IR_{2j} is amount of cascade inflow from upper paddy field, PR_j is rainfall, DR_j is surface drainage through weir, ET_j is evapotranspiration, and INF_j is deep percolation. The subscript j represents the j^{th} day and all parameters are expressed in millimeters.

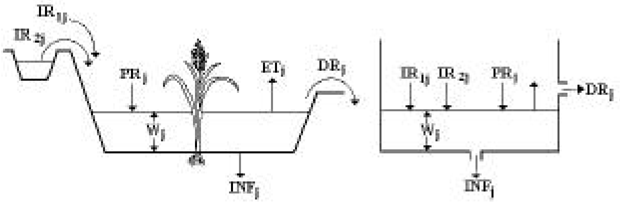
The nutrient inflow to the paddy fields was grouped into natural supply and fertilization, where natural supply included atmospheric deposition and irrigation water, and fertilization included mineral and organic sources. Nutrient outflow included surface drainage through the weir, deep percolation, and plant uptake. The general mass balance equation for both nitrogen and phosphorus was approximated in this study as:

$$I_{IR1} + I_{IR2} + I_{PR} + I_{FER} = O_{DR} + O_{INF} + O_{HRV} \qquad (2)$$

where I_{IR1} is inflow from groundwater irrigation, I_{IR2} is cascade inflow from upper paddy field, I_{PR} is inflow from rainfall, I_{FER} is inflow from fertilization, O_{DR} is outflow through surface drainage, O_{INF} is outflow through deep percolation, and O_{HRV} is outflow through plant harvest.

Model development

The water quality model for paddy field was daily continuous model assuming that paddy field is a completely mixed system, continuously stirred tank reactor (*CSTR*). The inflow to the paddy field consists of irrigation, input from upper paddy field and rainfall, and the outflow consists of evapotranspiration, infiltration and surface runoff (Fig. 2).



(a) (b)

Fig. 2. Water balance concept in paddy field (a) and this model (b).

Penman – Montheith equation and crop coefficient were applied for estimating actual evapotranspiration. Runoff and infiltration are calculated by ponded depth and coefficient function. Each equation is followed:

$$T = PET \times K_c \tag{3}$$

$$DR = (W - D) \times a_1 \tag{4}$$

$$INF = W \times a_2 \tag{5}$$

Where, PET is evapotraspiration by penman methods, K_c is a crop coefficient, D is depth of ridge, a_1 is coefficient for drainage and a_2 is coefficient for infiltration Fertilization can be represented as impulse loading. Mathematically the *Dirac delta function* (or *impulse function*) δ(t) has been developed to represent such impulse loading (Chapra, 1997). The particular solution for *Dirac delta function* is

$$c = \frac{m}{V} e^{-lt} \tag{6}$$

where, c is concentration, m is quantity of pollutant mass, v is volume of system, . is eigenvalue, and t is time (day).
If irrigation water inputs paddy field, nutrient concentration increase because of sediment release and reach certain concentration. Such behavior is given mathematical expression by the new continuous source (Chapra, 1997). The particular solution for this case is

$$c = æ\,(1 - e^{-lt}) \tag{7}$$

Model calibration and validation was conducted to the standard fertilization plot during 2001-2002.

RESULTS AND DISCUSSION

Water balance

Table 2 shows the water balance for each treatment. Total water inflow ranged from 1,014-1,964mm, about 44-50% supplied by rainfall and about 51-56% supplied by irrigation and input from upper paddy field. Total water outflow ranged from 1,071-1,865 mm and closed balanced with total water inflow. Infiltration and evapotranspiration were maintained regular amount about 80mm and 500mm, respectively. However, surface drainage runoff depended on amount of precipitation, and ranged from 507-1,255mm (47-67%) during study periods.

Table 2. Water balance summary in the treatment plots during the study period

	Plots	Inflow (mm)				Outflow (mm)			
		IR_1	IR_2	PR	Total	DR	INF	ET	Total
2001	EF	295.1	207.6	511.3	1,014.0	507.2	73.0	490.9	1,071.1
	SF	119.5	413.1	511.3	1,043.9	593.2	75.9	486.2	1,155.3
	RF	164.5	434.5	511.3	1,110.3	648.5	77.8	492.6	1,218.9
2002	EF	883.7	214.6	865.4	1,963.7	1,254.7	82.8	527.8	1,865.3
	SF	787.3	213.3	865.4	1,866.0	1,036.2	93.0	527.8	1,657.0

Mass balance

With a limited nutrient supply, there is maximum dilution of the nutrient in the plant, and uptake was replaced by other source such as rain or soil. Conversely, when the supply of a nutrient is large, the internal nutrient concentration is high, and there is maximum accumulation (Dobermann et al., 1998). In this study, because soil were still rich in these nutrients, and flooding was thought to increase their supply, yield responses to fertilizer N and P were small (Table 3). This situation was reported by other studies (De Datta and Mikkelsen, 1985). However, long- terms application of reduced fertilization can occurs nutrient deficiency, so plant uptake will sensitively respond to amount of fertilizer. The T-N inflow was mainly supplied by the three applications of fertilizer (71-92%). In addition, significant amounts were supplied by precipitation and from the upper paddy field, comprising 7-32 % of the total inflow. Groundwater irrigation did not contribute much to the nutrient loading because of its relatively clean water quality. Although most of the nutrient outflow was attributed to plant uptake (70-94%), nutrient loss by surface drainage was substantial showing about 15-29 % for T-N, 6-13 % for T-P. However, we could not find remarkable responses of yield and drainage outflow to fertilization.

Table 3. Nutrient balance summary in the treatment plots during the study

		Inflow (kg ha^{-1})					***Outflow (kg ha^{-1})***				Difference
		I_{Fer}	I_{R1}	I_{R2}	I_{PR}	Total	O_{DR}	O_{INF}	O_{HRV}	Total	
T-N	EF	165.0	1.33	4.47	9.05	179.85	21.83	2.12	126.27	150.22	-29.63
2001	SF	110.0	0.76	8.47	9.05	128.28	32.75	5.20	115.95	153.90	25.62
	RF	77.0	1.05	12.03	9.05	99.13	32.46	5.32	105.63	143.41	44.28
2002	EF	165.0	1.37	41.94	15.32	223.63	51.61	2.29	122.66	176.56	-47.07
	SF	110.0	1.36	37.70	5.32	154.38	33.21	2.21	125.95	161.37	6.99
T-P	EF	29.46	0.10	0.43	0.20	30.19	1.13	0.00	18.49	19.62	-10.57
2001	SF	19.64	0.06	0.67	0.20	20.57	2.00	0.00	17.56	19.56	-1.01
	RF	13.75	0.08	0.78	0.20	14.81	1.27	0.00	16.81	18.08	3.27
2002	EF	29.64	0.11	1.74	0.35	21.84	2.51	0.00	17.03	19.54	-12.30
	SF	19.64	0.11	1.57	0.35	21.66	1.25	0.00	16.94	18.19	-3.47

Model calibration and validation

The comparisons between observed and predicted ponded depth, runoff, nutrient concentration are shown as Fig. 3. The mean error (AE) of ponded depth, TN and TP concentration were 0.81 mm, -0.11 mg/L and -0.06 mg/L, and the model efficiencies (EF) were 0.93, 0.98 and 0.95, respectively. In the calibration parameter, runoff coefficient was 0.81 and it indicated the runoff lag-time is very short (Table 4). If paddy field area is lager than this study area, this coefficient will be small because of longer runoff lag-time. The parameters of TN loading by fertilization (m_1, m_2, m_3) were 47kg/ha, 34kg/ha and 19kg/ha, respectively, and these values are similar with actual TN fertilization, which is 55kg/ha, 33kg/ha and 22kg/ha, respectively. However TP was smaller than actual fertilization. The TN decay rates of fertilization was little differ $\lambda_1$and λ_2 with λ_3 as 0.04, 0.03 and 0.17, respectively. It indicates that the TN decay during July more fast than during May-June, because high temperature stimulate ammonium volatization and more efficient plant uptake. In the æ parameters, the background concentrations of TN and TP in paddy field were 4.01 mg/L and 0.15 mg/L respectively.

As shown the Fig.3, the nutrient concentration appeared high during early cultural periods, and was low when mainly outflow occurred by forced drainage and heavy rainfall. Some studies reported ammonia nitrogen concentrations in surface water of paddy field were as high as 25-100 mg/L during the initial periods of irrigation and fertilization (Takamura et al., 1977). Although fertilizer inputs in paddy field, high amount of nitrogen is loss by adsorption, volatilization and denitrification. A percolation rate less than 30mm/day may sufficiently eliminate fertilizer nutrients from water by percolation and ammonia volatilization losses as high as 60% of applied nitrogen (Ghosh and Bhat, 1998; Ishikawa et al., 2002). The initial phosphorus flush is followed subsequently by a decrease from sorption or precipitation of Fe ( )-P compounds (Kirk et al., 1990). This result show the reducing surface drainage during fertilization period can abate non-point source loading effectively from paddy field, and explain the reason why we could not find the response of nutrient drainage outflow to fertilization (Table 3).

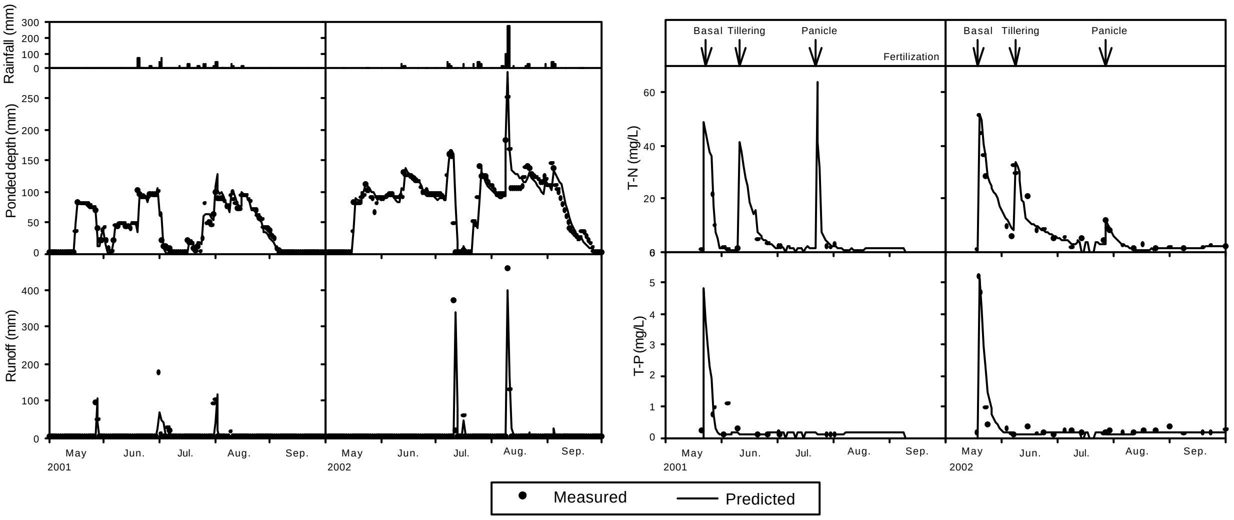


Fig. 3. Observed and simulated surface runoff and nutrient concentration in paddy field.

Table 4. The input parameter.

Description	***Symbol***	Unit	Value
Water balance			
Infiltration coefficient	a_1	-	0.008
Runoff coefficient	a_2	-	0.80
Nitrogen			
Loading by fertilization (basal, tillering, panicle)	m_1, m_2, m_3	kg/ha	47, 34, 19
Decay rate of fertilization	λ_1, λ_2, λ_3	-	0.04, 0.03, 0.17
Concentration by sediment	æ	mg/L	4.01
Sediment loading coefficient	λ_s	-	0.01
PHOSPHORUS			
Loading by fertilization	m	kg/ha	5.4
Decay of fertilization	λ	-	0.2
Concentration by sediment	æ	mg/L	0.15
Sediment loading coefficient	λ_s	-	0.13

CONCLUSION

From this study, about half of the total water inflow was contributed by precipitation and the remainder by irrigation. Water outflow generally balanced the inflow with about half of total outflow to surface drainage and about 500mm to evapotranspiration for plant growth. The nutrient balance for phosphorus and nitrogen shows that most (71–98 %) of the inflow was supplied by fertilization and most (69–94 %) of the outflow occurred through plant harvest. However, significant amounts (6–29 %) of nutrients were lost through surface drainage. Fertilization rate itself affected less on the rice yield and nutrient loss by surface drainage. Reducing nutrient loss by lowering fertilization rate may not work well in the range of normal paddy rice farming practices. The effects of fertilization and release from sediment were used by *Dirac delta function* and continuous source function, respectively, and the calibrated and validated model demonstrates good agreement with observed data and high modeling efficiency. Nutrient concentration is strongly influenced by fertilization, and surface drainage runoff during early cultural periods may impact receiving water seriously because of fertilizer effect. Reducing nutrient loss through surface drainage could be achieved effectively by reducing surface drainage. Water-saving irrigation by reducing ponded water depth, raising weir heights in diked rice fields, and minimizing forced surface drainage are suggested to reduce surface drainage outflow. These practices can save water and protect water quality, however, deviation from conventional standard practices might affect the rice yield and further investigations are recommended.

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