

Assessment of Wastewater Reuse Effects on Nutrient Loads from Paddy Field Using Field-Scale Water Quality Model

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Abstract CREAMS-PADDY, a modified version of the field-scale CREAMS model, simulates the hydrologic, sediment, and nutrient cycles in paddy fields. The CREAMS-PADDY model was applied to estimate the effects of using wastewater for irrigation on nutrient loads from paddy fields in Republic of Korea. The model was calibrated and validated using data from two rice paddy fields. The coefficient of determination between observed and simulated total nitrogen and total phosphorus were 0.92 and 0.57, respectively, for the calibration period and 0.84 and 0.73 for the validation period. Simulations showed that when using wastewater for irrigation, the total nitrogen loads increased by 210% and total phosphorus by 1,270% when compared with conventional water irrigation. The total nitrogen and total phosphorus concentration in the ponded water increased by 254 and 534%, respectively, when compared with conventional water irrigation. The effect of reducing N and P fertilizer application rates by 10, 30, and 50% on nutrient loads exiting a paddy field were also simulated using the validated CREAMS-PADDY model. These simulations indicated that total phosphorus loads from the paddy were reduced only slightly by reducing the fertilizer, while total nitrogen loads were reduced by as much as 8.8, 16.6, and 24.4% when N fertilizer rates were reduced by 10, 30, and 50%, respectively.

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1 Introduction

Demand for fresh water is increasing all over the world. Many countries are facing water shortage at present or will be experiencing scarcity of their water resources in the future [14]. Water use in the Republic of Korea (ROK) is also increasing rapidly, some 37% during the last decade. This increase is attributed to population growth, urbanization, and economic development. In the ROK, if no additional water resources are developed, water scarcity is expected to begin by 2011 [15]. One possible new source of water is reclaimed wastewater.

In the ROK, total wastewater treatment capacity is 7.15 billion cubic meters per year, approximately 21.6% of the annual total water use and 45% of the annual agricultural water use [15, 16]. Unfortunately, a significant volume of treated wastewater from sewage treatment plants is discharged to rivers without planned reuse being considered because no guidelines or regulations for treated wastewater reuse have been established. However, as expected, water scarcity looms, the concern about the wastewater reuse has increased. Several research projects were launched to examine potential gains from reusing wastewater and develop guideline and regulation recommendations for safe water reuse [11].

Wastewater has been reused extensively as a source of irrigation water for centuries [2]. Irrigation does not usually require high-grade water quality compared to drinking water. In addition, reusing wastewater for agriculture has several advantages, such as reducing the amount of effluent discharged into receiving water bodies, nutrient recovery as fertilizers, and increase crop production [3, 14]. As agricultural water use is more than 48% of the total annual

water use in the ROK, wastewater reuse for agriculture could be a key alternative water source.

Irrigation water quality can have potentially detrimental effects on the soil, crops, and downstream water quality [22]. To ensure environmental sustainability, land application of wastewater must be managed in a way that minimizes these adverse effects. While the effects of industrial and municipal wastewater on agricultural soils have been widely documented, mostly with respect to heavy metal concentrations [4, 10, 18] and toxicological studies, the environmental impacts of irrigation with wastewater on water quality have not been widely investigated [8]. Therefore, the impacts of reclaimed wastewater reuse from the wastewater sewage plants on the water quality should be investigated first before potentially making practical use of this alternative water resource.

Through water quality monitoring and modeling, the effects of wastewater reuse on water quality can be estimated quantitatively. Specifically, the effects on plant nutrients such as nitrogen and phosphorus need to be quantified. It is expected that using reclaimed wastewater for irrigation will affect the nutrient loads from agricultural land, and consequently, will affect nutrient loads leaving watersheds. In this study, the field-scale effects of wastewater reuse for agriculture were quantitatively analyzed using a water quality model. The model used is a modified form of the Chemicals, Runoff and Erosion from Agricultural Management System (CREAMS) model—CREAMS-PADDY—that was developed to predict nutrient loads from rice paddy fields by Chin et al. [5].

2 Materials and Methods

2.1 Experimental Paddy Fields

Data for model calibration and validation were obtained from field experiments that were carried out on two irrigated rice paddy fields during the growing seasons 1996 and 2000. The Seoul National University experimental rice paddy field (SNU field), 200 m² in size, is located in Suwon-City, Gyeonggi-Province, Republic of Korea. The Gicheon experimental paddy field (Gicheon field), 2.7 ha in size, is located approximately 10 km southwest of the SNU field.

One-month-old rice seedlings were transplanted in May and harvested in September in both locations. Table 1 summarizes the fertilization rate for the two experimental fields during the 1996 and 2000 growing seasons. In these seasons, all phosphorus (P) fertilizer was applied pre-plant, while the nitrogen (N) fertilizer was applied in three splits pre-plant, tillering, and panicle.

Rainfall was recorded using a tipping bucket rain gauge located near the site. Irrigation and drainage were measured

Table 1 Fertilization records for the experimental fields during the study period

Experimental field	Fertilization	Nutrient	Growth stage		
			Pre-plant	Tillering	Panicle
SNU	Date		1996/5/24	1996/6/4	1996/7/10
	Fertilization rate (kg ha ⁻¹)	N P	146 80	87 0	59 0
Gicheon	Date		2000/5/20	2000/6/10	2000/7/24
	Fertilization rate (kg ha ⁻¹)	N P	84 63	92 0	59 0

using water level gauges. Irrigation water and ponded water samples were collected manually using the 2-l sampling bottles on a weekly or biweekly basis. Rainfall samples were collected when storms occurred. All water samples were analyzed using Standard Methods [1] for total nitrogen (TN) and total phosphorus (TP).

2.2 CREAMS-PADDY Model

The CREAMS model was developed to provide field-scale simulation of hydrology, erosion, and nutrient and pesticide yield from agricultural areas and to assess nonpoint source pollutant loadings for alternative management systems [12]. Subsequent to the original publication and distribution of CREAMS, a number of modifications have been made to increase the model's applicability and to improve its usability [13]. As the CREAMS model is not designed to simulate conditions in a ponded rice paddy field, the CREAMS-PADDY model was developed [5]. The CREAMS-PADDY model is a modification of a physically based field-scale CREAMS model to more accurately simulate runoff, sediment, nutrient from paddy fields in ponded water conditions [5, 21]. In this study, the CREAMS-PADDY model was applied to estimate nutrient loads from rice paddy fields.

The hydrology component of the CREAMS-PADDY model is based on the water balance in the paddy field. Usually, the paddy field is blocked by a levee to maintain a ponded water condition. Ponded water depth within the paddy field is dependent on the outlet height, which is controlled by the farmer according to the rice growth stage. The water balance in the paddy field is represented in CREAMS-PADDY using the relationship in Eq. 1. The inflow to the paddy field is comprised of irrigation and rainfall, and the outflow includes infiltration, evapotranspiration, and surface runoff.

$$W_t = W_{t-1} + IR_t + RAIN_t - INF_t - ET_t - DR_t \quad (1)$$

where W is ponded water depth (mm), IR is irrigation (mm), $RAIN$ is precipitation (mm), INF is infiltration (mm),

Table 2 Optimal ponded water depth in paddy field according to the growth stages [7]

Growth stage	Root setting	Tiller	Elongation	Heading	Ripening	
Days after transplanting	0–10	11–35	36–40	41–60	61–80	81–110
Ponded water depth (mm)	60	40	10	60	60	40

ET is evapotranspiration (mm), DR is surface runoff (mm), and subscript *t* represents time (days).

Surface runoff does not occur until water depth in the paddy field reaches the height of the outlet. The irrigation amount is determined from the optimal ponded water depth and present ponded water depth assuming that field management is maintaining the optimal ponded water depth. Table 2 shows the optimal ponded water depth in paddy fields according to the growth stages obtained from the field survey.

While the CREAMS model uses Ritchie’s equation to compute the potential evapotranspiration (PET), the CREAMS-PADDY model uses the FAO modified Penman equation [9] to estimate the potential evapotranspiration from paddy fields. Table 3 contains crop coefficients for rice used to estimate evapotranspiration.

As infiltration from paddy fields occurs under saturated conditions, infiltration is governed by the soil type and the ponded water depth. Therefore, the average daily infiltration rate according to soil type was used, 3–6 mm day⁻¹ for sand, 2–3 mm day⁻¹ for sandy loam, and 1–2 mm day⁻¹ for loam [6].

In CREAMS, upland soil erosion is approximated using the Universal Soil Loss Equation (USLE) [19]. To estimate the soil erosion in paddy fields with flat slope and ponded water condition, CREAMS-PADDY adopts USLE with modified USLE C, P factors for paddy fields. USLE C factor is the crop and management factor and P is the conservation support practice factor. Table 4 shows the modified temporal USLE factors for paddy fields [20].

The CREAMS model simulates soluble and sediment-attached nitrogen (N) in runoff. The nitrogen sub-model calculates plant uptake, denitrification, mineralization of organic nitrogen, and leaching of nitrate. Fertilizer nitrogen can be added to the soil surface or incorporated in single or

Table 3 Crop coefficient for rice paddy [7]

Parameter	JUN			JUL			AUG		
	E	M	L	E	M	L	E	M	L
Crop coefficient (<i>K_c</i>)	0.97	1.03	1.27	1.27	1.34	1.47	1.57	1.43	1.41

E Early, *M* middle, *L* late

Table 4 Temporal variation of modified USLE C, P factors for paddy field

USLE factor	Julian date							
	0	130	140	180	200	220	240	280
C	0.30	0.38	0.38	0.23	0.11	0.07	0.04	0.30
P	0.1	0.5	0.1	0.1	0.1	0.1	0.1	0.1

multiple applications during the year. In CREAMS-PADDY, the reaction zone in the paddy field is distinguished as oxidized and reduced zones. Separate mass balance and transformation equations were used for oxidized and reduced zones. Mass balance of nitrogen in the oxidized zone is calculated with the following equation.

$$\begin{aligned}
 \text{SOXN}_{t,n} = & \text{SOXN}_{t-1,n} + \text{FERN}_{t,n} + \text{RAINN}_{t,n} + \text{IRRIN}_{t,n} \\
 & - \text{INFN}_{t,n} - \text{RUNFN}_{t,n} - \alpha \text{NITN}_{t,n} \\
 & - \beta \text{DNITN}_{t,n} - \chi \text{VOLTN}_{t,n} - \delta \text{SEDN}_{t,n}
 \end{aligned} \tag{2}$$

where SOXN is N in oxidized zone (kg ha⁻¹), FERN is fertilizer N in oxidized zone (kg ha⁻¹), RAINN is N from precipitation (kg ha⁻¹), IRRIN is N from irrigation water (kg ha⁻¹), INFN is infiltrated N into reduced zone (kg ha⁻¹), RUNFN is N in runoff (kg ha⁻¹), NITN is ammonia nitrification amount in oxidized zone (kg ha⁻¹), DNITN is denitrification amount (kg ha⁻¹), VOLTN is ammonia volatilization amount in oxidized zone (kg ha⁻¹), and SEDN is ammonia-N in sediment (kg ha⁻¹). The subscript *t* represents days and *n* represents nitrogen condition, 1 denotes ammonia-N, 2 denotes nitrate-N, and 3 denotes organic-N. Coefficients α , β , χ , and δ are control factors that are dependent on the nitrogen condition. The control values in oxidized zone according to the nitrogen condition are listed in Table 5.

Mass balance of ammonia-N in reduced zone is calculated on the basis of the following equation.

$$\begin{aligned}
 \text{SRDN}_{t,n} = & \text{SRDN}_{t-1,n} + \text{FERDN}_{t,n} + \text{INFN}_{t,n} - \text{UPTN}_{t,n} \\
 & - \text{PERN}_{t,n} - \varepsilon \text{NITDN}_{t,n} + \phi \text{MINN}_{t,n} + \gamma \text{FIXN}_{t,n} \\
 & - \eta \text{DNITN}_{t,n}
 \end{aligned} \tag{3}$$

Table 5 Control factors in the oxidized and reduced zone according to the nitrogen condition

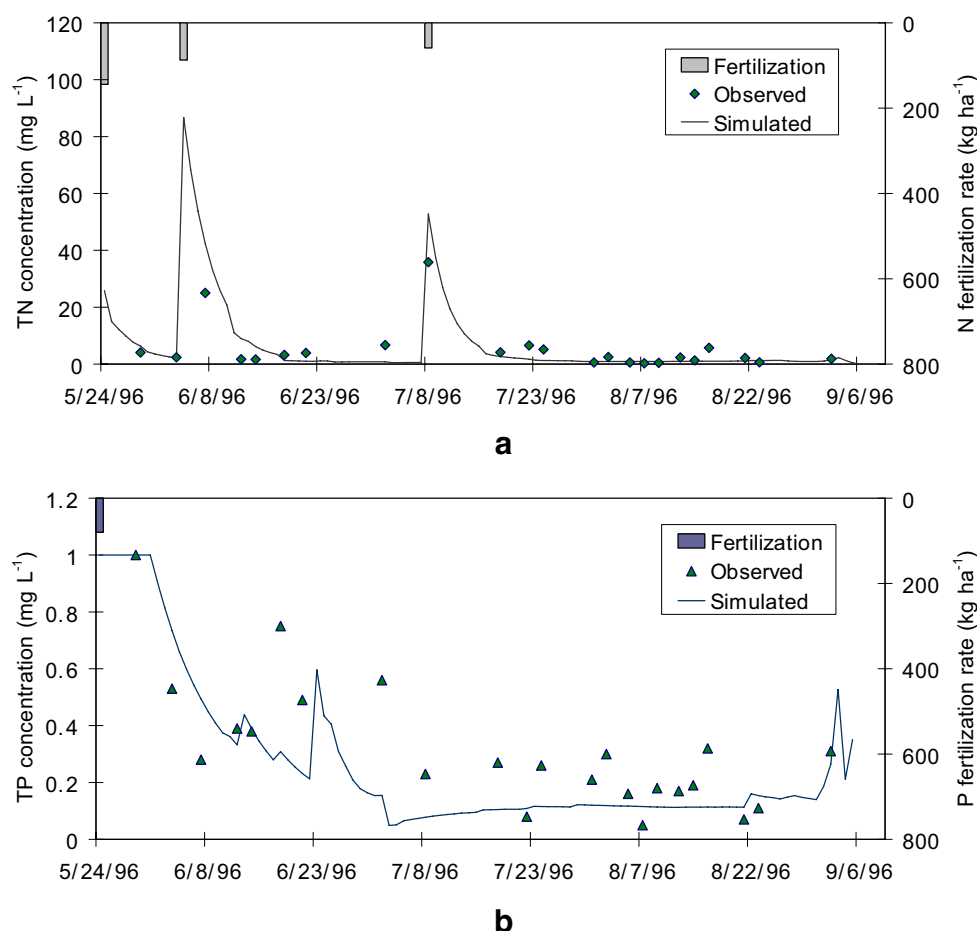
Nitrogen condition (<i>n</i>)	Control factors in oxidized zone				Control factors in reduced zone			
	α	β	χ	δ	ε	ϕ	γ	η
1 (Ammonia-N)	1	1	0	1	1	1	1	0
2 (Nitrate-N)	-1	-1	1	0	-1	0	0	1
3 (Organic-N)	0	0	0	0	-	-	-	-

where SRDN is N in reduced zone (kg ha^{-1}), FERDN is fertilizer N in reduced zone (kg ha^{-1}), INFN is infiltrated N amount from oxidized zone (kg ha^{-1}), UPTN is crop uptake (kg ha^{-1}), PERN is percolated amount below root zone (kg ha^{-1}), NITDN is nitrification amount (kg ha^{-1}), MINN is mineralized N (kg ha^{-1}), FIXN is nitrogen fixation from atmosphere (kg ha^{-1}), and DNITN is denitrification amount from oxidized zone (kg ha^{-1}). The subscript t represents days and n represents nitrogen condition, 1 denotes ammonia-N and 2 denotes nitrate-N. Coefficients ε , ϕ , γ , and η are control factors dependent on the nitrogen condition. The control values in reduced zone according to the nitrogen condition are listed in Table 5.

The CREAMS model simulates soluble and sediment-attached phosphorus (P) in runoff. Fertilizer phosphorus can be added to the soil surface or incorporated in the profile in single or multiple applications during the year. Mass balance of phosphorous (P) in oxidized zone is calculated using the following equation.

$$\text{SOXP}_t = \text{SOXP}_{t-1} + \text{FERP}_t + \text{RAINP}_t + \text{IRRIP}_t - \text{INFP}_t - \text{RUNFP}_t - \text{SEDP}_t \quad (4)$$

Fig. 1 Simulated and observed ponded water TN (a) and TP (b) concentrations for calibration period in SNU field (1996)



where SOXP is P in oxidized zone (kg ha^{-1}), FERP is fertilizer P (kg ha^{-1}), RAINP is P from precipitation (kg ha^{-1}), IRRIP is P from irrigation (kg ha^{-1}), INFP is infiltrated P into reduced zone (kg ha^{-1}), RUNFP is P in runoff (kg ha^{-1}), SEDP is P in sediment (kg ha^{-1}), and subscript t represents days.

Mass balance of phosphorous (P) in reduced zone is calculated using the following equation.

$$\text{SRDP}_t = \text{SRDP}_{t-1} + \text{FERDP}_t + \text{INFP}_t - \text{UPTP}_t - \text{PERP}_t \quad (5)$$

where SRDP is P in reduced zone (kg ha^{-1}), FERDP is fertilizer P in reduced zone (kg ha^{-1}), INFP is infiltrated P from oxidized zone (kg ha^{-1}), UPTP is crop uptake (kg ha^{-1}), PERP is percolated P amount below root zone (kg ha^{-1}), and the subscript t represents days.

3 Results and Discussion

3.1 Experimental Paddy Field Monitoring

Rainfall, irrigation, and drainage amounts were measured for the experimental rice paddy fields. Total rainfall for the growing season was 607 and 1,243 mm in 1996 and 2000,

Table 6 Summary of calibration and validation result for ponded water nutrient concentration

Experimental field	Constituent	Mean concentration (mg l ⁻¹)		R ²	RMSE ^a (mg l ⁻¹)
		Observed	Simulated		
SNU field	TN	5.15	6.68	0.92	2.68
1996 (Calibration)	TP	0.32	0.27	0.57	0.08
Gicheon field	TN	2.36	6.42	0.84	0.73
2000 (Validation)	TP	0.04	0.08	0.73	0.03

^aRoot mean square error

respectively. Considering that the annual mean rainfall in the ROK is 1,283 mm, the rainfall in 1996 was below the average [15]. In 1996, irrigation supplied 863 mm to the SNU field from groundwater at the site and 918 mm to the Gicheon field from a neighboring agricultural reservoir. The drainage from the SNU field and Gicheon field was 543 and 917 mm, respectively.

Rainfall, irrigation, and ponded water samples were collected and analyzed for the TN and TP. In 1996 (SNU field), the mean of TN and TP for nine rainfall samples was

2.48 and 0.10 mg l⁻¹, respectively. Eleven rainfall samples from 2000 (Gicheon field) produced means of 0.952 and 0.036 mg l⁻¹ for TN and TP, respectively. The TN concentration in ponded water ranged between 0.28 and 35.84 mg l⁻¹ (mean 5.17 mg l⁻¹) for SNU and ranged 0.51 and 13.00 mg l⁻¹ (mean 2.29 mg l⁻¹) for Gicheon. The TP concentration in ponded water ranged between 0.05 and 1.00 mg l⁻¹ (mean 0.317 mg l⁻¹) for SNU and ranged 0.012 and 0.16 mg l⁻¹ (mean 0.041 mg l⁻¹) for Gicheon.

3.2 Calibration and Validation of CREAMS-PADDY Model

The CREAMS-PADDY model was calibrated for the ponded water concentration of TN and TP using the observed data from the SNU field. Most of the parameters were determined on the basis of the physical characteristics of the paddy field and agricultural practices. Parameter values recommended in the CREAMS user’s guide [12] were also selected if no measured data was available.

Simulated and observed ponded water concentrations for TN and TP in SNU field are shown in Fig. 1. Simulated results showed that the concentrations of TN and TP increased after fertilization. The root mean square error

Fig. 2 Simulated and observed ponded water TN (a) and TP (b) concentrations for validation period in Gicheon field (2000)

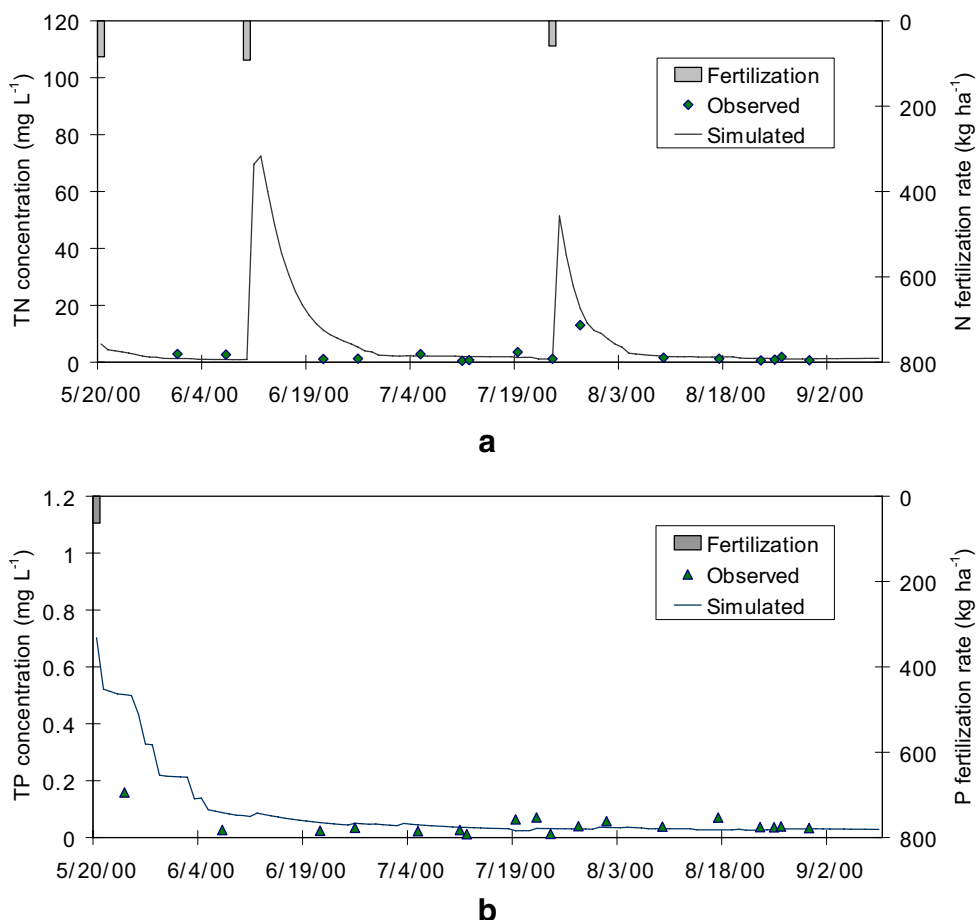
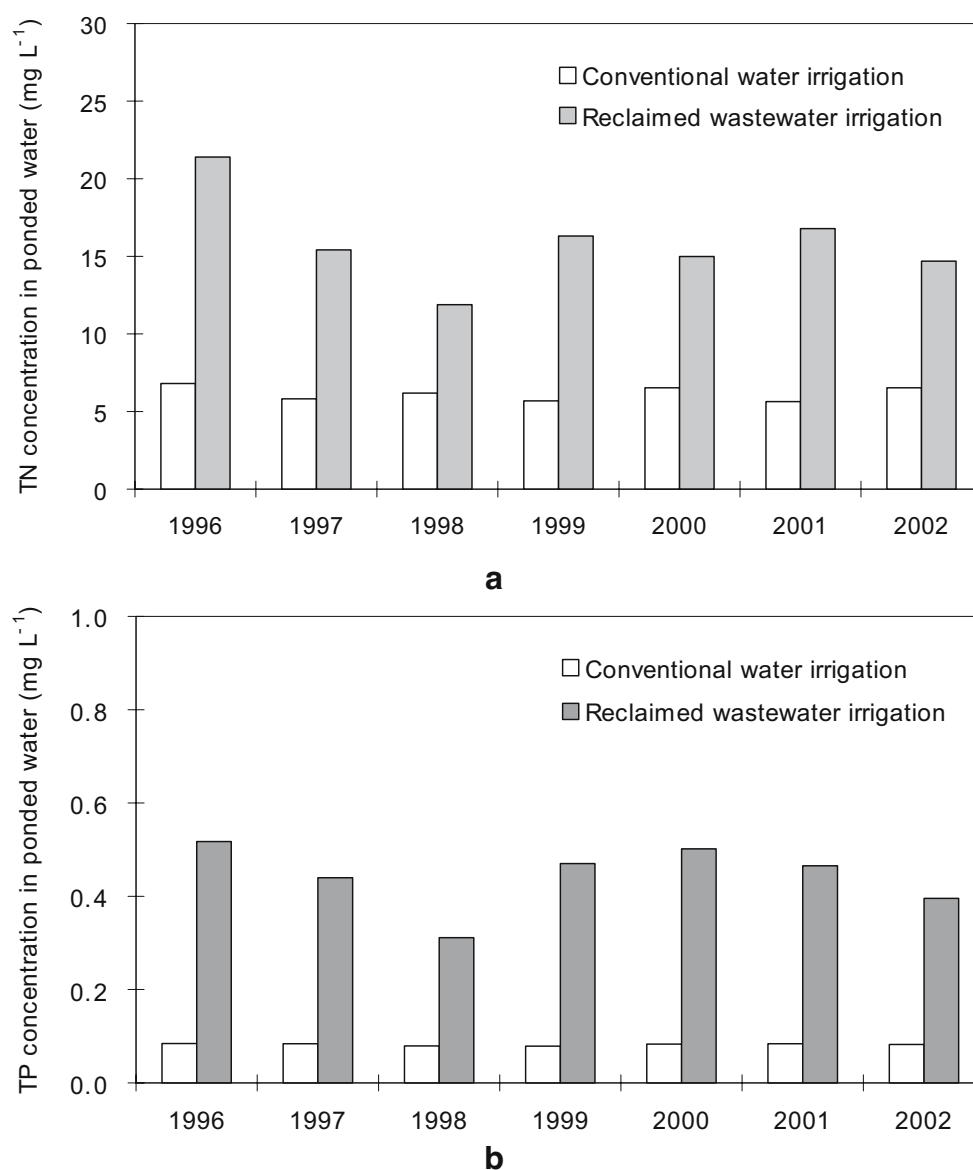


Fig. 3 Comparison of simulated annual mean TN (a) and TP (b) concentrations in ponded water between conventional water and reclaimed wastewater irrigation, Gicheon field (1996–2002)



(RMSE) between the observed and simulated TN and TP concentrations were 2.68 and 0.08 mg l⁻¹, respectively, for the calibration period. The coefficient of determination (R^2) for the daily TN concentration was 0.92, while R^2 between the simulated and observed daily TP concentration in 1996 was 0.57 (Table 6).

The validation of CREAMS-PADDY model was conducted with the observed data collected at Gicheon in 2000. Simulated and observed ponded water concentrations for TN and TP at Gicheon for the validation period are presented in Fig. 2. The R^2 and RMSE values were 0.84 and 0.726 mg l⁻¹, respectively, for the TN concentration. The R^2 and RMSE between the observed and simulated TP concentration water were 0.73 and 0.032 mg l⁻¹, respectively, for the validation period. The mean of observed TN concentration was 2.36 mg l⁻¹ for the validation period, while the mean TN

concentration of model prediction was 6.42 mg l⁻¹. The mean values of the observed and simulated TP concentrations were 0.04 mg l⁻¹ and 0.08 mg l⁻¹, respectively (Table 6).

3.3 Wastewater Reuse Effects

The validated CREAMS-PADDY model was applied to estimate the wastewater reuse effects on the paddy fields in terms of ponded water nutrient concentration and nutrient loads. The wastewater reuse effects on paddy fields were estimated by comparing the nutrient loads between the reclaimed wastewater irrigation and conventional water irrigation that meets the agricultural water criteria in the Republic of Korea. Irrigation water from Gicheon agriculture reservoir, which supplies water to Gicheon, was selected for the conventional irrigation treatment. Effluents from Suwon

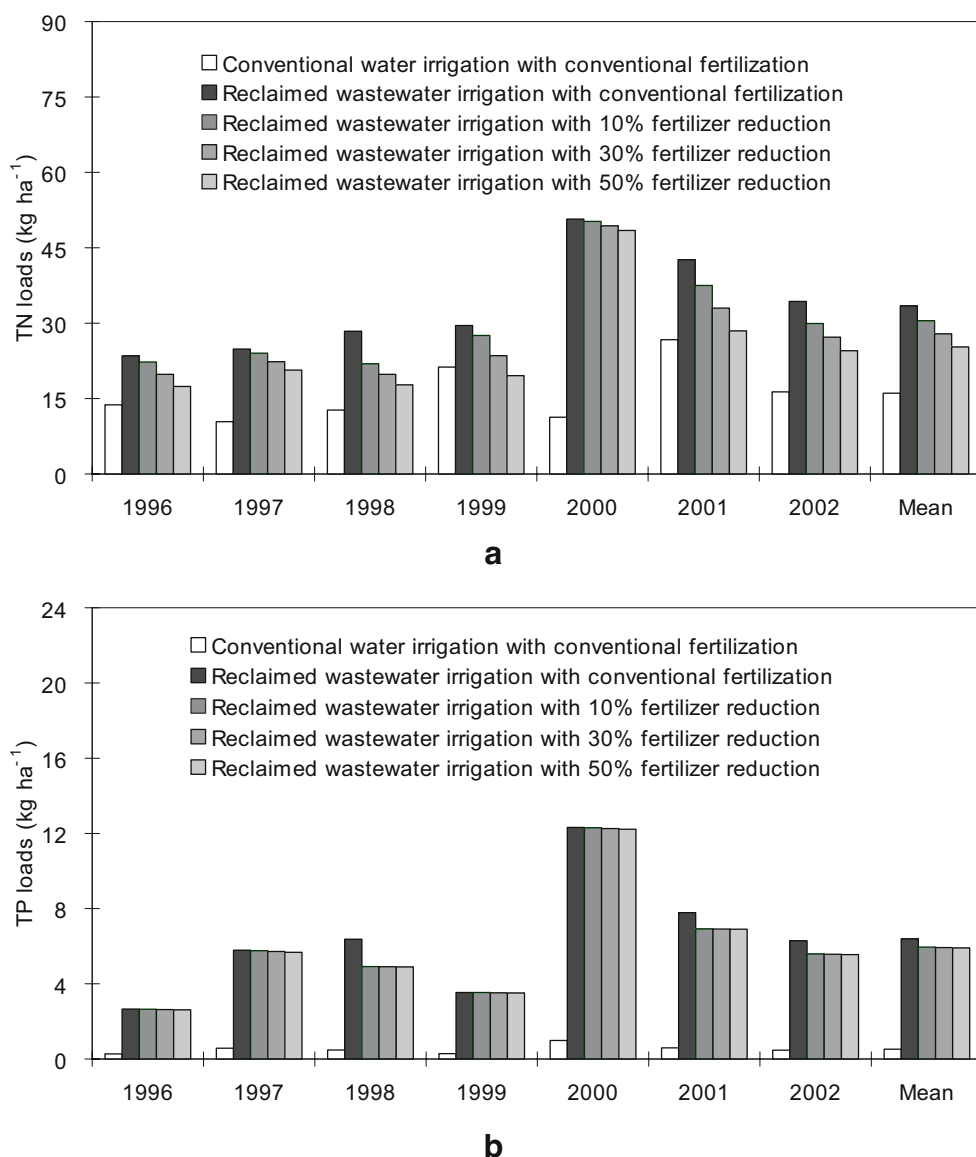
Table 7 Comparison of nutrient loads from Gicheon field between conventional water and wastewater irrigation

Year	Rainfall (mm)	Runoff (mm)	Conventional water irrigation		Wastewater irrigation	
			TN (kg ha ⁻¹)	TP (kg ha ⁻¹)	TN (kg ha ⁻¹)	TP (kg ha ⁻¹)
1996	885	252	13.75	0.27	25.13	2.90
1997	1,205	629	10.39	0.58	24.86	5.79
1998	1,617	683	12.70	0.48	28.40	6.37
1999	1,193	593	21.27	0.29	29.54	3.54
2000	1,330	948	11.27	0.98	50.71	12.32
2001	1,312	864	26.71	0.60	42.64	7.78
2002	1,236	586	16.34	0.47	34.32	6.29
Mean	1,254	651	16.06	0.52	33.66	6.43

Sewage Disposal Plant, which is located approximately 11 km east of Gicheon, was selected as the irrigation source for the reuse treatment. Water quality of the conventional irrigation water and reclaimed wastewater was monitored on a monthly basis. The annual mean total nitrogen concentration of the reclaimed wastewater (19.10 mg l⁻¹) was 17.5 times greater than that of the conventional water (1.09 mg l⁻¹), and total phosphorus concentration was 152 times greater with the value of 1.52 mg l⁻¹ for reclaimed wastewater and 0.01 mg l⁻¹ for conventional water.

CREAMS-PADDY was used to simulate pond water quality in Gicheon field during the period from 1996 to 2002. Figure 3 shows the simulated annual mean concentration of ponded water comparing reclaimed wastewater and conventional water irrigation. The simulated concentration of the TN in the ponded water averaged 6.17 mg l⁻¹ for conventional water irrigation, and 15.70 mg l⁻¹ for waste-

Fig. 4 Simulated fertilizer reduction effects on annual mean TN (a) and TP (b) load losses in drainage water from Gicheon paddy field (1996-2002)



water irrigation. The simulated concentration of the TP in the ponded water averaged 0.082 mg l^{-1} for the conventional water irrigation, and 0.438 mg l^{-1} for wastewater irrigation.

For the period from 1996 to 2002, the simulated mean annual TN load that exited the paddy in drainage water was 16.06 kg ha^{-1} , and the TP load was 0.52 kg ha^{-1} for the conventional irrigation water. The mean annual wastewater irrigation loads exiting via drainage water were 33.66 kg ha^{-1} and 6.43 kg ha^{-1} for TN and TP, respectively (Table 7). When wastewater was used for irrigation, the nutrient loads increased to 2.1 times for TN and 12.7 times for TP compared with the conventional irrigation water. The increase of nutrient loads resulted mainly from the high concentration of nutrient in the wastewater used for irrigation.

3.4 Fertilizer Reduction Effects

High concentrations of nutrients in reclaimed wastewater may cause rice lodging and excessive nutrient loads exiting paddy fields in drained water. As a result, fertilizer application rates may need to be reduced to prevent these expected adverse effects when using reclaimed wastewater for irrigation. Research indicates that conventionally applied fertilizer rates could be reduced significantly without reducing rice yields or affecting leaf nutrient levels when using reclaimed wastewater [17]. In this research reported here, the effects of reducing fertilizer rates on nutrient loads exiting rice paddy fields via drainage water were simulated using the validated CREAMS-PADDY model.

The effects of reducing fertilizer rates by 10, 30, and 50% on drainage water quality were simulated. These fertilizer reductions are thought to be in the range of possible reductions where reclaimed wastewater (and nutrients therein) is used for irrigation. Figure 4 shows the effects of reducing fertilizer applications on nutrient loads in drainage water exiting the rice paddy. The TN load in the drainage water decreased an average of 8.8, 16.6, and 24.4% when 10, 30, and 50% of the N fertilizer was reduced, respectively. The TP load reductions were not as significant.

4 Conclusions

CREAMS-PADDY, a modified CREAMS model, which was developed to simulate ponded rice paddy field conditions, was used to estimate the wastewater reuse effects on the nutrient load losses in water drained from a rice paddy. Nutrient concentrations in ponded water in two experimental paddy fields were monitored in 1996 and 2000. The CREAMS-PADDY model was calibrated and validated using observed data. During the calibration period, the R^2 and RMSE for the ponded water TN concentration were 0.92, 2.68 mg l^{-1} , respectively, and

$0.57, 0.08 \text{ mg l}^{-1}$ for the TP concentration. For the validation period, the R^2 and RMSE statistics were 0.84, 0.726 mg l^{-1} , respectively, for the TN concentration and $0.73, 0.032 \text{ mg l}^{-1}$ for TP concentration.

There is an increase in nutrient concentration in the ponded water when reclaimed wastewater was irrigated using the validated model. A 7-year simulation for the Gicheon experimental field illustrated that the nutrient loads increased to 2.1 times for TN and 12.7 times for TP when comparing using wastewater instead of conventional irrigation water. The reduction in the nutrient loads in the drainage water exiting the rice paddy that resulted from a 10, 30, and 50% reduction in fertilizer rate application combined with reclaimed wastewater for irrigation was simulated. These simulations indicated that TP loads from the paddy were reduced only slightly by reducing the fertilization rates, while TN loads were reduced by as much as 8.8, 16.6, and 24.4% when N fertilization rates were reduced by 10, 30, and 50%, respectively.

The study presented here investigated wastewater reuse effects at the field-scale. Additional monitoring and modeling research is needed to investigate wastewater reuse effects/benefits at the watershed-scale.

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