Desalination and Water Treatment
www.deswater.com

19 (2010) 32–41
July

1944-3994 / 1944-3986
doi: 10.5004/dwt.2010.1893

Modeling bacteria concentration in a rice paddy irrigated with reclaimed wastewater

C.H. Seong[a], M.S. Kang[a,b,*], T.I. Jang[c], H.K. Kim[b], E.J. Lee[a], S.W. Park[a,b]

[a]*Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul 151-921, Republic of Korea*
[b]*Research Institute for Agricultural and Life Sciences, Seoul National University, Seoul 151-921, Republic of Korea*
email: mskang@snu.ac.kr
[c]*Department of Biological and Agricultural Engineering, University of Georgia, Tifton, GA 31793, USA*

Received 30 September 2009; Accepted 20 February 2010

ABSTRACT

The objectives of this study were to develop a simulation model of bacteria concentrations in a rice paddy where wastewater is reused, and to assess its applicability with the experimental field data. The data were collected from an experimental plot, the Byeongjeom experiment plot, where some variables are periodically monitored, e.g., rainfall, irrigation discharge, water quality, and coliform concentration. Three irrigation treatments were applied: groundwater (TR#1), wastewater (TR#2), and filtered wastewater with ultra-violet treatment (TR#3). The field scale model for chemicals, runoff, and erosion from agricultural management system for rice paddy fields (CREAMS-PADDY) was used as a hydrologic model in the paddy plot, and a first die-off function was applied for a model of bacteria concentration. Four years of daily hydrologic data were calculated by CREAMS-PADDY and its annual water balance was assessed in comparison of previous studies. Hydrologic result indicated that while the total water inflow of about 1,730 mm was from precipitation (64%), and the remainder from irrigation (36%), total water outflow generally balanced inflow, with about 35% of total outflow to surface drainage, 32% to infiltration, and 39% to evapotranspiration. Developed bacteria model for a rice paddy field was calibrated and validated. The model showed relatively good agreement in TR#2 between the observed and simulated data during the calibration and validation periods. The simulation result of TR#2 indicated that simulated average coliform data in 2003–2006 were 4.3×10^4 MPN/100 ml, 5.6×10^4 MPN/100 ml, 3.8×10^4 MPN/100 ml, and 5.5×10^3 MPN/100 ml, respectively. The simulated result of TR#2 was consistent with the observed data, and demonstrating the applicability of the model for the rice paddy.

Keywords: Bacteria modeling; CREAMS-PADDY; Reuse; Wastewater

1. Introduction

In many countries, water shortage is currently a big problem and will be aggravated in the future because of increasing water demand [1]. Water demand in the Republic of Korea (ROK) increased by 35% during the last decade, and ROK will face a water scarcity by 2011 if no additional water resources are developed [2]. As agricultural irrigation water is upwards of 48% of the total annual water use in the ROK, wastewater reuse for agriculture could be a key alternative irrigation water resource [3].

Meanwhile, the application of wastewater could be limited by potential health problems [4]. Wastewater can contain pathogenic bacteria and can present serious health-related problems for people who have direct or indirect contact with it. Coliform bacilli counts are

*Corresponding author.

commonly used by public health officials as indicators to evaluate the potential presence of pathogens. The effects of the reclaimed wastewater irrigation on bacteria thus need to be addressed and be estimated in order to make wastewater reuse sustainable.

By modeling bacteria from a wastewater reuse field, it can help predicting breakout possibilities of waterborne diseases and take appropriate actions. The fate of coliform bacteria in a waterbody is usually considered in terms of die-off function, and many biotic and abiotic factors influence coliform bacteria death rates, such as the presence of algal toxins, bacteriophages, and the levels of nutrients, pH, predation, temperature, salinity, and irradiance [5]. Generally, irradiance, temperature, and sedimentation are considered the most important factors [6]. Mathematical models for coliform bacteria have been developed from mass balance principles which involve factors such as loading, mass transport, and losses due to death and sedimentation [7–9]. Modeling of coliform mortality in ponds of wastewater treatment plants (WTP) has been conducted under a wide range of physical and operating conditions [10, 11]. Modeling coliform's fate and transport in watersheds has also been conducted using watershed models such as the hydrological simulation program-FORTRAN (HSPF) and the soil and water assessment tool (SWAT) [12, 13]. In a field study, coliform bacteria in an agricultural field plot where the manure applied was evaluated according to the timing of application, the rate of application [14, 15]. Although many studies to simulate coliform bacteria have currently been conducted, the applied model is not good enough for the paddy field blocked by levees to maintain the flooding condition.

The objectives of this study were to develop a model that simulates the coliform concentration in a rice paddy field irrigated with the reclaimed wastewater, and to test its applicability based on the data collected from an experimental plot.

2. Materials and methods

2.1. Study area

The experimental plot, the Byeongjeom paddy field, is located near the Suwon wastewater treatment plant in Gyeonggi-do, South Korea. The average annual rainfall and evaporation of the study area are 1,259 and 1,091 mm, respectively. The annual temperature in this area was 11.6°C, and the mean temperature during the irrigation periods was 16.7°C–25.2°C. The soil of the experimental field is Gangseo series (coarse loamy, mixed, non-acid, mesic family of *Aquic Fluvaquentic Eutrudepts*) [16].

For this experiment with wastewater reuse, three types of irrigation water were applied: groundwater (TR#1), wastewater (TR#2), and filtered wastewater treated with ultra-violet (TR#3). A randomized complete block design with split plot arrangements was applied, with three treatments and four replicates on 5 m × 5 m plots [17]. Basic hydrological data of the paddy plots, irrigation, precipitation, etc., were monitored using gauges. Monitoring of water quality on the experimental

Fig. 1. The study area and experimental plot.

plots was conducted every one or two weeks in the growing seasons in 2003–2006. Analysis of coliforms was performed by the National Instrumentation Center for Environmental Management in Korea (NICEM) and was processed with the P/A test method.

For this experiment, one-month-old rice seedlings (*Chu-Chung*) were transplanted in May and harvested in October from 2003 to 2006. Fertilizers and insecticides were applied according to the traditional regional cultivation method.

2.2. Water balance in a rice paddy

The field scale model for chemicals, runoff, and erosion from agricultural management system for rice paddy fields (CREAMS-PADDY) [18], which is modified from the CREAMS model, was used for the hydrologic cycle in a rice paddy. The CREAMS-PADDY model was developed to provide field-scale simulation of hydrology, erosion, and nutrient yield of a rice paddy. The hydrology component of the CREAMS-PADDY model simulates paddy field water balance, which is calculated from variations in ponded water depth (WD), expressed as

$$\mathrm{WD}_i = \mathrm{WD}_{i-1} + \mathrm{IR}_i + \mathrm{PR}_t - (\mathrm{DR}_i + \mathrm{ET}_i + \mathrm{IN}_i), \quad (1)$$

where WD is ponded water depth, IR is irrigation, PR is precipitation, DR is surface drainage through a weir, ET is evapotranspiration, and IN is infiltration. The subscript i represents the ith day, and Fig. 2 illustrates the hydrologic cycle in a paddy field.

According to the regional traditional cultivation method, optimal paddy water depth as maintained with irrigation. Table 1 shows optimal depth of paddy water according to rice growth stages. When rainfall exceeds the capacity of paddy fields, surface drainage occurs. Daily evapotranspiration in paddy fields was calculated using the FAO modified Penman equation, with climate data from Suwon weather station. Infiltration data were collected using the double-ring method on the experimental paddy fields.

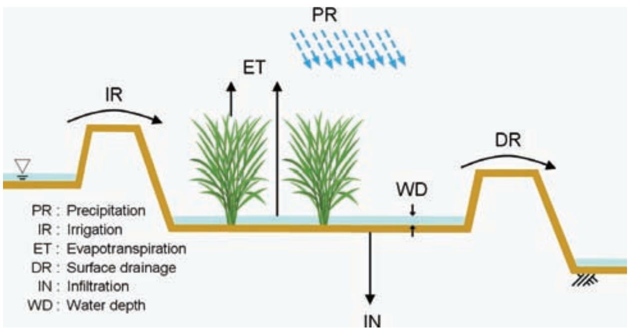

Fig. 2. Hydrologic cycle in a rice paddy.

2.3. Coliform concentration modeling

Although the die-off rates of coliforms in the waterbody were affected by many factors, the multi-factor model was applicable only to pure bacterial strains under laboratory condition [19]. Temperature is the only environmental variable used to modify the die-off coefficient in the widely used watershed-scale-models that can simulate water quality, e.g., HSPF, SWAT, and a numerical one-dimensional model of reservoir water quality (CE-QUAL-R1). For calculating coliform concentration, the coliform module of CE-QUAL-R1 [20], which simulates vertical profiles of water quality in a reservoir, is used and is expressed as

$$\frac{\mathrm{d}}{\mathrm{d}t}(VC) = \frac{\mathrm{d}}{\mathrm{d}z}\left(DA\frac{\mathrm{d}C}{\mathrm{d}z}\right)\Delta Z + \sum Q_{\mathrm{in}}C_{\mathrm{in}} + Q_{\mathrm{p}}C_{\mathrm{p}} - Q_{\mathrm{o}}C - KP^{(T-20)}VC, \quad (2)$$

where C is coliform concentration, V is water volume, Q_{in}, Q_{p} and Q_{o} are inflow, precipitation, and outflow, K is a mortality constant, P is a unitless temperature correction parameter, Z is water depth, T is temperature, and t is time. It is assumed that coliforms move through the waterbody into irrigation water; rainfall does not contain coliforms; concentration of coliforms sink as time goes by in a blocked paddy; and the value of P is relatively constant at 1.07 [21].

3. Results and discussion

3.1. Water balance

Fig. 3 shows daily hydrologic data calculated by CREAMS-PADDY on the experimental plot in 2003–2006. Daily paddy depth well reflected optimal ponded water depth for the growth stage, and two surface drainages over 150 mm occurred by heavy storms in 2006.

Table 1
Optimal ponded water depth in the paddy field according to growth stage.

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

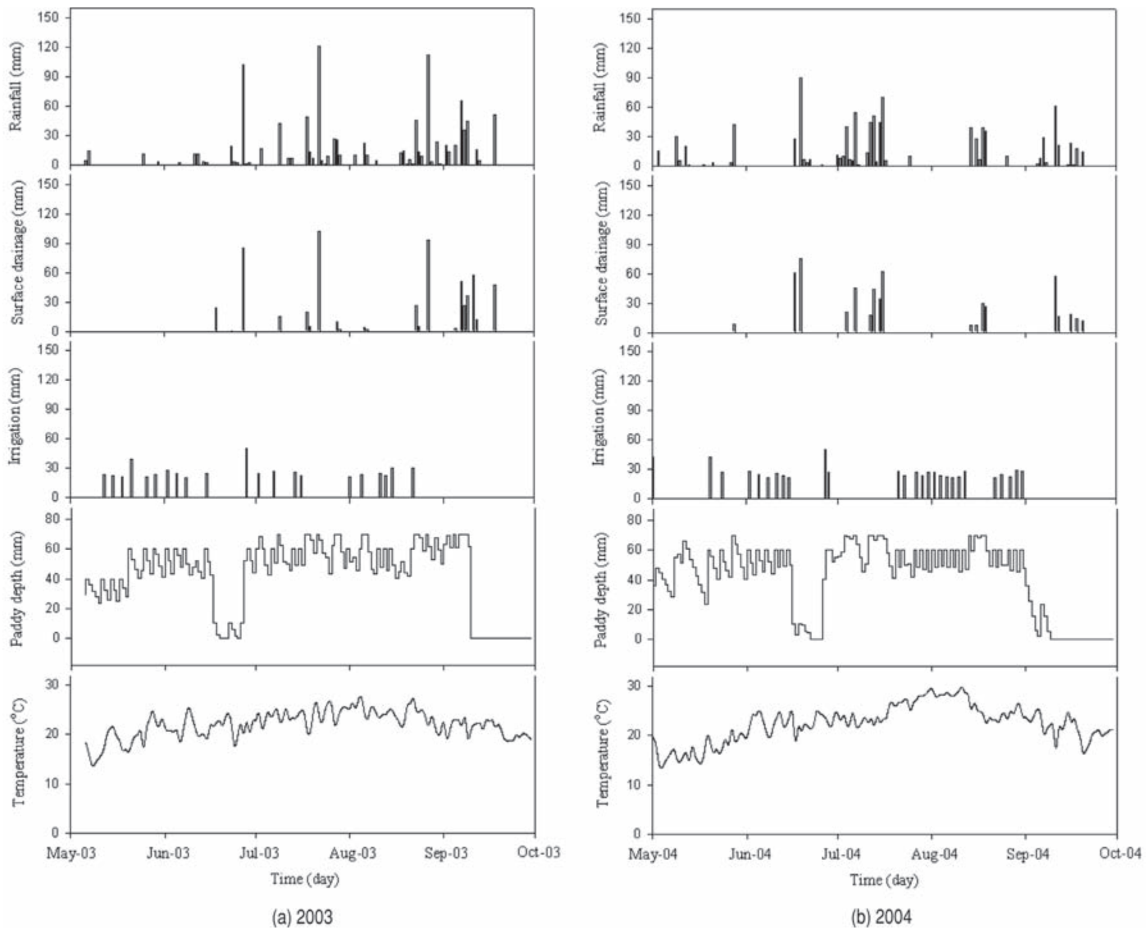

Fig. 3. Daily hydrologic data on the experimental plot in 2003–2006.

Table 2 shows the annual water balance of the experimental paddy fields during the irrigation period. The results show rainfall of 1,174–985 mm (average 1,099 mm), *ET* of 709–627 mm (average 680 mm), and infiltration of 555–538 mm (average 548 mm). Average inflow (precipitation plus irrigation) to the paddy field was 1,730 mm, and about 35% of this was lost to surface drainage. The drainage ranged from 662–557 mm (average 616 mm). Average uncounted amount of inflow water was 116 mm when the water balance was calculated during the study period.

The water input to the paddy during the irrigation period varies from 500–800 mm and reaches more than 3,000 mm [22, 23]. Despite of the similar amount of rainfall in other regions of Korea, the amount of irrigation in the experimental plot was different to other cases e.g., 1,250 mm [24], 1,497 mm [25], and 282 mm [26]. Nevertheless, the average drainage amount from the study field was relatively lower than other regions reported in the previous studies [24–27], due to the high elevation of levees in the study paddy field. In addition, in this study, the amount of irrigation did not surpass consumed water use for the rice paddy (evapotranspiration plus infiltration), and rainfall was used effectively because of the high drainage outlet.

3.2. Coliform monitoring results

Fig. 4 and Table 4 show total coliforms of irrigation water monitored between 2003 and 2006. In irrigation water, total annual average of coliform concentration of TR#1, TR#2, and TR#3 were 1.3×10^2 MPN/100 ml, 1.6×10^5 MPN/100 ml, 2.4×10^3 MPN/100 ml and total standard deviation (SD) of TR#1, TR#2, and TR#3 were 2.3×10^2 MPN/100 ml, 2.9×10^5 MPN/100 ml, and 2.3×10^3 MPN/100 ml, respectively. The monitoring results in the irrigation water show that the coliform concentration of TR#2 was about 10^2–10^3 times greater than the one in TR#1 and TR#3. Except for the coliform concentration of TR#3 in 2003, that of TR#1 and TR#3 were relatively lower than 1.0×10^3 MPN/100 ml, which meets the WHO recommendations for unrestricted irrigation [28].

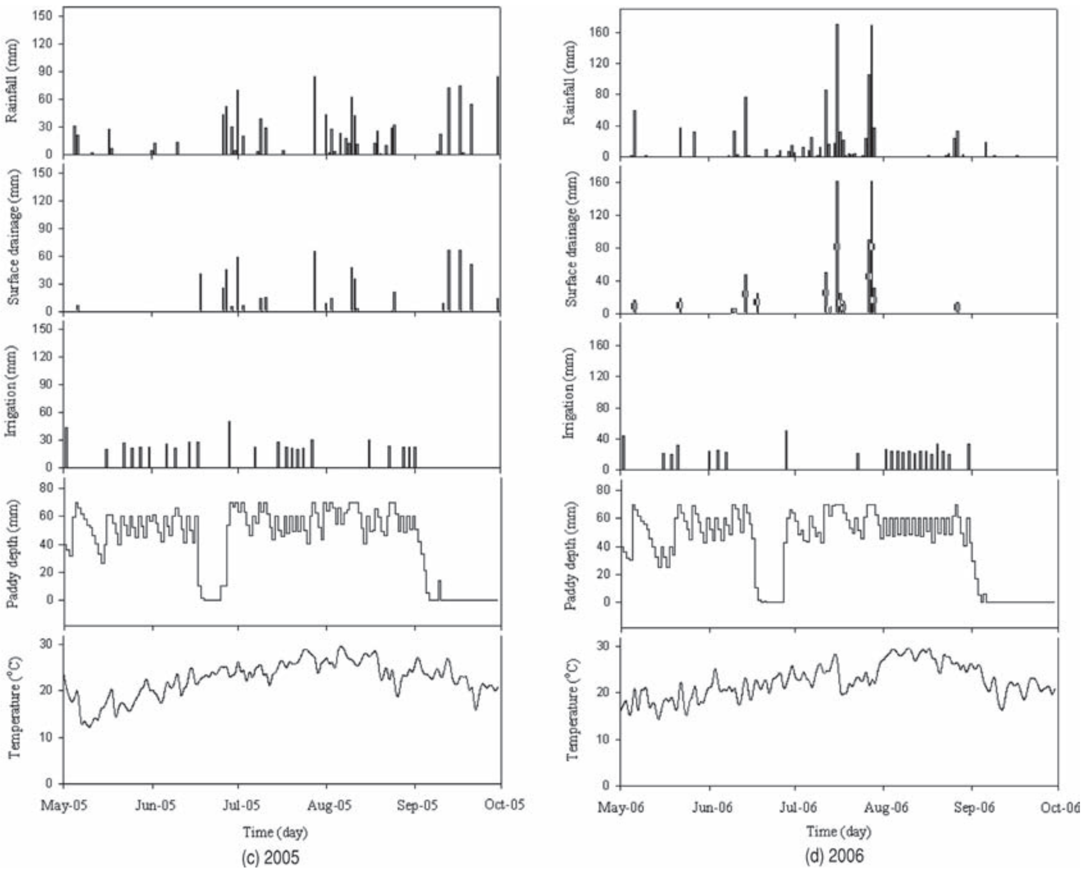

Fig. 3. *(continued)*

Table 2
Water balance of the treatment plots during the irrigation period.

Year	Inflow (mm)		Outflow (mm)			Uncounted (mm)
	PR	IR	DR	ET	IN	
2003	1,101	595	628	627	555	114
2004	985	739	557	706	551	89
2005	1,174	601	618	680	549	72
2006	1,134	588	662	709	538	188
Average	1,099	631	616	680	548	116

PR, precipitation; IR, irrigation; DR, surface drainage; ET, evapotranspiration; IN, infiltration.

Table 3
Comparison of water balance of paddy fields in Korea.

Reference	Water balance (mm)			
	PR	IR	DR	ET
[24]	1,289	1,250	1,329	532
[27]	1,231	816	1,027	451
[25]	1,183	1,497	1,618	594
[26]	1,030	282	886	330

PR, precipitation; IR, irrigation; DR, surface drainage; ET, evapotranspiration.

Table 5 shows the total coliforms in ponded paddy water in 2003–2006. The average coliform concentration in the ponded paddy water were 2.0×10^4 MPN/100 ml in TR#1, 8.2×10^4 MPN/100 ml in TR#2, and 2.2×10^4 MPN/100 ml in TR#3, and the total annual SD of that were 2.3×10^4 MPN/100 ml in TR#1, 1.1×10^5 MPN/100 ml in TR#2, and 2.9×10^4 MPN/100 ml in TR#3. Although there were great differences in coliform concentration of irrigation water between TR#2 and other treatments, the average coliform concentration of TR#2 in the ponded

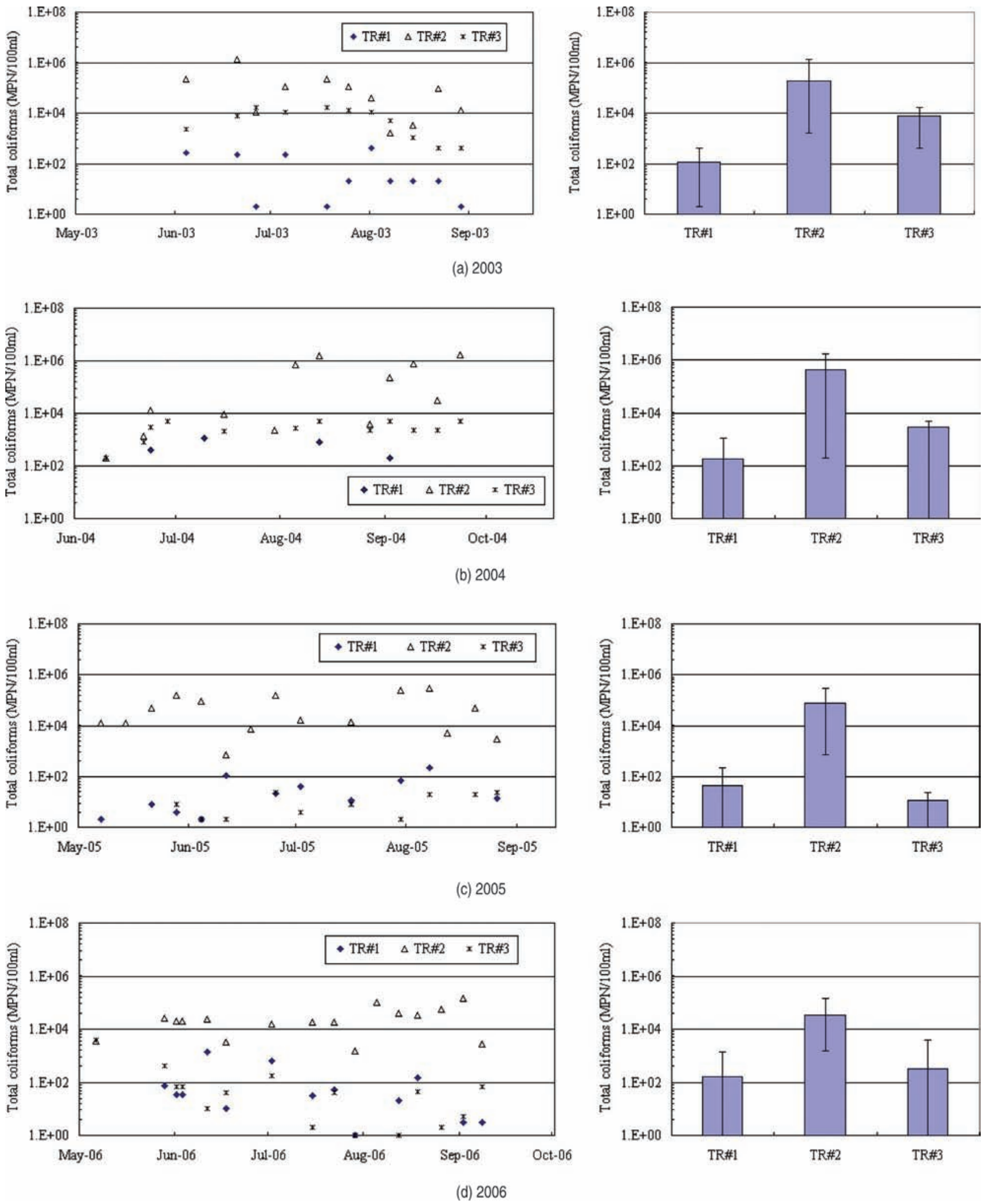

Fig. 4. Total coliforms in irrigation water in 2003–2006. TR#1, groundwater; TR#2, wastewater; TR#3, filtered wastewater treated with ultra-violet.

Table 4
Monitoring results of total coliform counts in irrigation water.

Year	Total moliforms (MPN/100ml)	Treatment		
		TR#1	TR#2	TR#3
2003	Mean	111	192,636	7,836
	min	>2	1,700	400
	Max	400	1,300,000	17,000
	SD	143	375,873	6,398
	samples	11	11	11
2004	Mean	179	424,150	2,754
	min	>2	200	>2
	Max	1,100	1,700,000	5,000
	SD	351	637,840	1,808
	samples	14	12	13
2005	Mean	45	74,847	11
	min	>2	700	>2
	max	210	300,000	23
	SD	58	95,908	9
	samples	15	15	15
2006	Mean	162	33,117	321
	min	>2	1,450	>2
	max	1,396	141,360	3,873
	SD	376	38,528	989
	samples	16	16	15
Total	Mean	125	164,099	2,352
	min	>2	200	>2
	max	1,396	1,700,000	17,000
	SD	232	289,037	2,301
	samples	56	54	54

TR#1, groundwater; TR#2, wastewater; TR#3, filtered wastewater treated with ultra-violet; SD, standard deviation

Table 5
Monitoring results of total coliform counts in paddy ponds.

Year	Total coliforms (MPN/100 ml)	Treatment		
		TR#1	TR#2	TR#3
2003	Mean	15,763	63,638	37,213
	Min	1,700	200	700
	Max	40,000	220,000	170,000
	SD	13,574	74,323	55,754
	Samples	8	8	8
2004	Mean	8,300	120,842	21,755
	Min	>2	400	400
	Max	50,000	900,000	90,000
	SD	15,403	256,977	27,836
	Samples	11	12	11
2005	Mean	7,858	25,004	2,533
	Min	70	40	17
	Max	30,000	80,000	13,000
	SD	12,643	28,291	4,250
	Samples	9	9	9
2006	Mean	43,023	100,374	26,399
	Min	100	7,330	300
	Max	173,290	241,960	98,040
	SD	49,972	81,188	27,219
	Samples	11	11	11
Total	Mean	19,522	82,209	21,800
	Min	70	40	17
	Max	173,290	900,000	170,000
	SD	22,898	110,195	28,765
	Samples	39	40	39

TR#1, groundwater; TR#2, wastewater; TR#3, filtered wastewater treated with ultra-violet; SD, standard deviation

water was only 0.4×10 times higher than that of other treatments.

3.3. Coliform simulation results

Model calibration was conducted by adjusting the decay die-off parameter, K, with coliform concentration data for 2003 and 2004. According to a review by Ref. [21], the K value ranges from 0.1 to 2 d^{-1}. The calibration was carried out manually by changing K by 0.1, evaluating the model results with visual comparison of the coliform-concentration-graph and scatter plot with simulated and observed data. The final calibrated K was 0.3, and Fig. 5 and Table 6 show calibration results. Daily simulated data and observed data is shown in Fig. 5a. Fig. 5b shows ranges of simulated data of TR#2, including two days before and after the observation. In Fig. 5c, scatter plot is shown with observed and simulated data.

The results of calibration showed that the root mean square error (RMSE) of TR#2 were 3.8×10^4 MPN/100 ml in 2003 and 6.5×10^4 MPN/100 ml in 2004, which was about half of the level of observed average coliforms. As shown in Fig. 5, calibrated result of TR#2 was relatively consistent with the observed data. A visual comparison of the simulated and observed coliform concentration graph indicated that the model was simulating the paddy of TR#2 satisfactorily.

On the other hand, the simulation result of TR#1 and TR#3 did not reflect the observed data and were relatively small, from one 20th to one 500th to the values in the observed data. This can be caused by the contri bution of naturally present bacteria in soil that increased the total number of coliforms of the observed data. Additional research is needed to identify and define bacteria phases of TR#1 and TR#3 by considering other factors in the future.

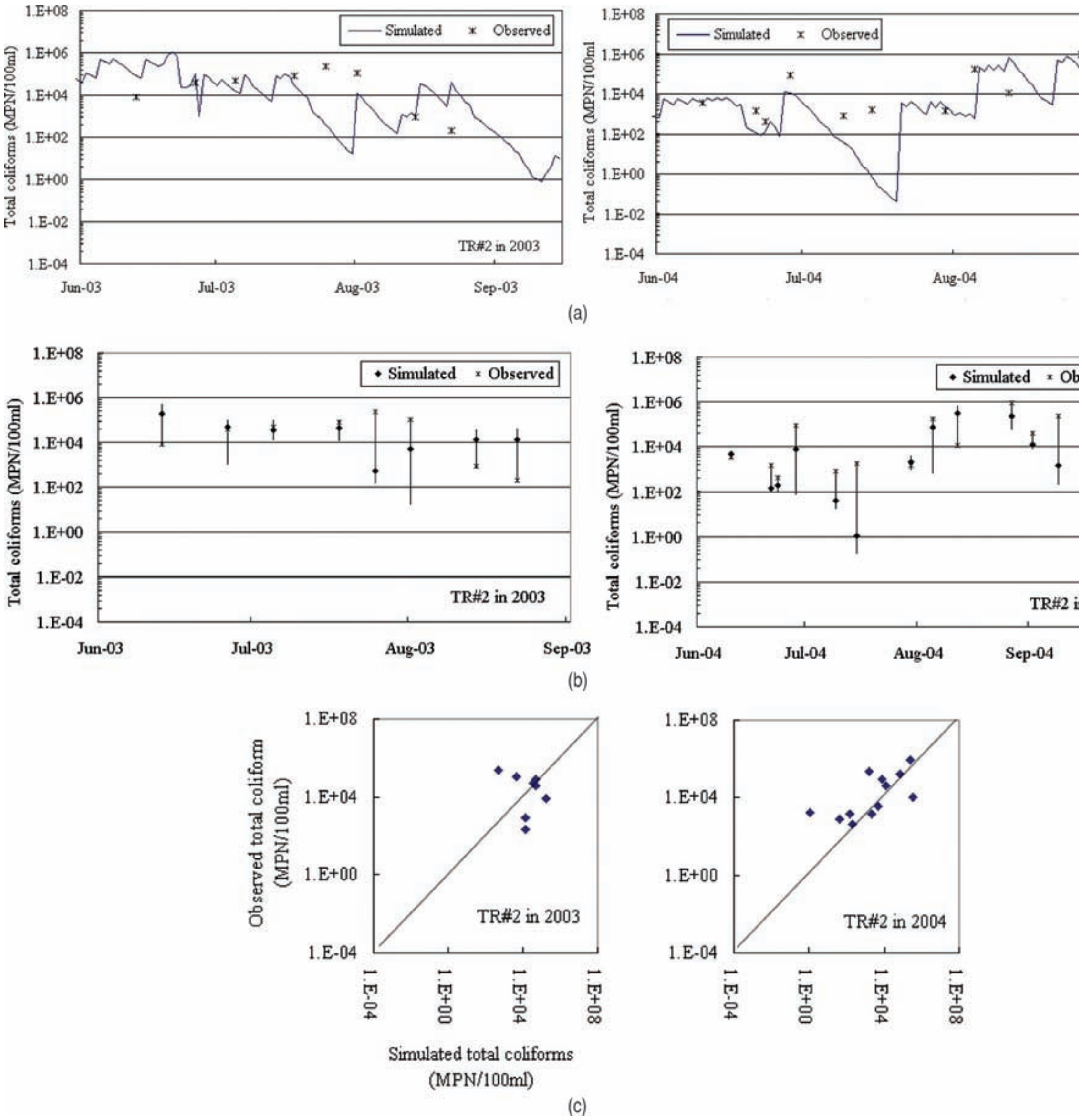

Fig. 5. Result of model calibration for coliform concentration in TR#2 in 2003 and 2004. TR#2, wastewater.

Table 6
Model calibration results of coliform concentration in 2003 and 2004.

Year	Treatment	Average (MPN/100 ml)		RMSE (MPN/100 ml)
		Simulated	Observed	
2003	TR#1	30	15,763	5,138
	TR#2	43,267	63,638	37,976
	TR#3	1,773	37,213	22,244
2004	TR#1	97	8,300	5,079
	TR#2	55,562	120,842	64,974
	TR#3	863	21,755	10,009

TR#1, groundwater; TR#2, wastewater; TR#3, filtered wastewater treated with ultra-violet.

Using the calibrated parameters, coliform bacteria simulation was validated for two years with the collected data. Figure 6 presents simulation results of the total coliform concentration in ponded paddy water of TR#2 in 2005 and 2006. As shown in table 7, RMSE of TR#2 was 1.7×10^4 MPN/100 ml in 2005 and 1.5×10^4 MPN/100 ml in 2006. The simulation result of TR#2 was more consistent with observed data in 2005 than that in 2006, while observed data of TR#2 in 2006 were, on average, about 25 times higher than the simulated data. The values of simulation of TR#1 and TR#3 in 2005 and 2006 on average were one 10,000th values of the observed data.

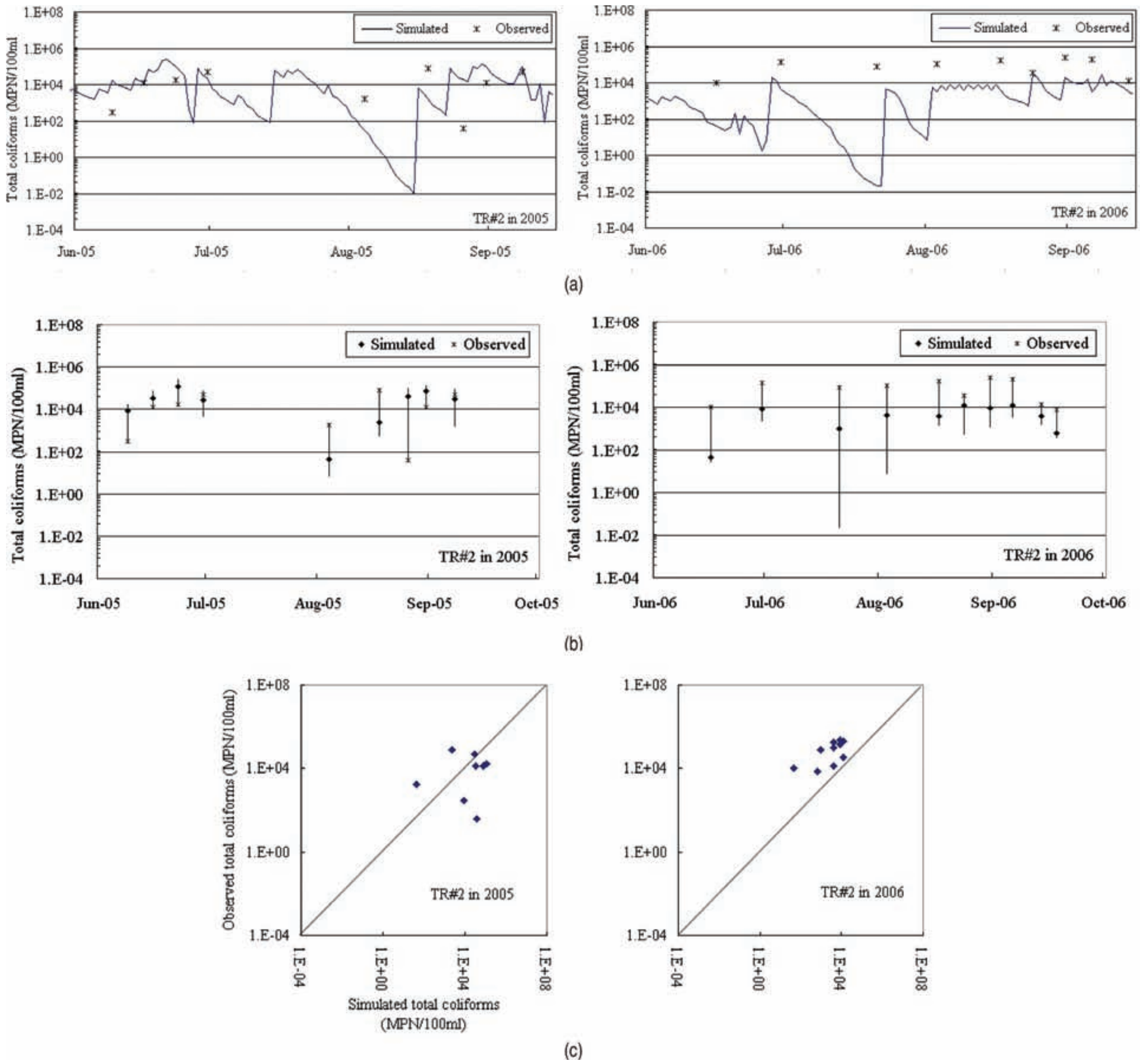

Fig. 6. Result of model calibration for coliform concentration in TR#2 in 2005 and 2006. TR#2, wastewater.

Table 7
Model verification results of coliform concentrations in 2005 and 2006.

Year	Treatment	Average (MPN/100 ml)		RMSE (MPN/100 ml)
		Simulated	Observed	
2005	TR#1	18	7,858	4,753
	TR#2	37,365	25,004	16,927
	TR#3	3	2,533	1,580
2006	TR#1	18	44,328	4,278
	TR#2	5,499	100,607	15,234
	TR#3	12	26,804	1,422

TR#1, groundwater; TR#2, wastewater; TR#3, filtered wastewater treated with ultra-violet.

4. Conclusions

This study developed a simulation model of bacteria concentration for wastewater reuse in a rice paddy and assessed its applicability with four years of data collected from an experiment plot.

CREAMS-PADDY model was used for daily hydrologic data of the experimental paddy plot. More than half of the total water inflow of about 1,730 mm was from precipitation, and the remainder from irrigation. Water outflow generally balanced inflow, with about 35% of total outflow to surface drainage, 32% to infiltration, and 39% to evapotranspiration.

Monitored annual averages of coliform data in irrigation water were 1.3×10^2 MPN/100 ml in TR#1,

1.6×10^5 MPN/100 ml in TR#2, and 2.4×10^3 MPN/100 ml in TR#3. In the ponded paddy water, annual average of coliforms concentration of TR#1, TR#2, and TR#3 were 2.0×10^4 MPN/100 ml, 8.2×10^4 MPN/100 ml, and 2.2×10^4 MPN/100 ml, respectively. Even though the total coliforms in the irrigation water between TR#2 and other treatments had a significant difference, the total coliforms of the ponded water of paddy were shown in similar level for all treatments.

Developed bacteria model for a rice paddy field was calibrated and validated. Model calibration results showed that simulated average coliform data of TR#2 were 4.3×10^4 MPN/100 ml in 2003 and 5.6×10^4 MPN/100 ml in 2004. In the validation, simulated average coliform in 2005 and 2006 were 3.8×10^4 MPN/100 ml and 5.5×10^3 MPN/100 ml, respctively. The simulated results of TR#2 reflected relatively well the observed data, and a first-order die-off function was found to be applicable to the fates of coliforms in paddy fields.

Acknowledgments

This research was supported by a grant (code# 4-5-3) from the Sustainable Water Resources Center of the 21st Century Frontier Research Program.

References

[1] International Water Management Institute, Urban wastewater: A valuable resource for agriculture. A case study from Haroonabad, Pakistan, Research Report 63, Colombo, Sri Lanka, 2002, p. 21.
[2] MLTM, Water vision 2020, ministry of land, transport and marine affairs: Gwacheon city, Gyeonggi-do, Republic of Korea, 2001, p. 136 (in Korean).
[3] S.M. Kim, S.W. Park, J.J. Lee, B.L. Benham and H.K. Kim, Modeling and assessing the impact of reclaimed wastewater irrigation on the nutrient loads from an agricultural watershed containing rice paddy fields, Journal of Environmental Science and Health Part A, 42 (2007) 305–315.
[4] M.Y. Abdulraheem, Health considerations in using treated industrial and municipal effluents for irrigation, Desalination, 72 (1989) 81–113.
[5] G.L. Bowie, W.B. Mills, D.B. Porcella, C.L. Campbell, J.R. Pagenkopf, G.L. Rupp, K.M. Johnson, P.W.H. Chan, S.A. Gherini and C. Chamberlain, Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling, 2nd edn., US Environmental Protection Agency, Athens, GA, 1985, EPA/600/3-85/040.
[6] M.T. Auer and S.L. Niehaus, Modeling fecal coliform bacteria: I. Field and laboratory determination of loss kinetics, Water Research, 27 (1993) 693–701.
[7] P.L. Freedman, R.P. Canale and J.F. Pendergast, Modeling storm runoff impacts on a eutrophic urban lake, Journal of the Environmental Engineering Division, American Society of Civil Engineers (ASCE) 106 (1980) 335–349.
[8] M.D. Palmer and R.J. Dewey, Beach fecal coliforms, Canadian Journal of Civil Engineering, 11 (1984) 217–224.
[9] R.P. Canale, M.T. Auer, E.M. Owens, T.M. Heidtke and S.W. Effler, Modeling fecal coliform bacteria: II. Model develop ment and application, Water Research, 27 (1993) 703–714.
[10] V.S. Marcos, Modeling of coliform removal in 186 facultative and maturation ponds around the world, Water Research, 39 (2005) 5261–5273.
[11] R.M. Sanchez-Roman, A.A. Soares, A.T. DeMatos, G.C. Sediyama, O. DeSouza and A.H. Mounteer, Domestic wastewater disinfection using solar radiation for agricultural reuse, Transactions of the ASABE, 50(1) (2007) 65–71.
[12] B.L. Benham, C. Baffaut, R.W. Zeckoski, K.R. Mankin, Y.A. Pachepsky, A.M. Sadeghi, K.M. Brannan, M.L. Soupir and M.J. Habersack, Modeling bacteria fate and transport in watersheds to support TMDLs, Transactions of the ASABE, 49(4) (2006) 987–1002.
[13] S.M. Kim, B.L. Benham, K.M. Brannan, R.W. Zeckoski and G.R. Yagow, Water quality calibration criteria for bacteria TMDL development, Applied Engineering in Agriculture, 23(2) (2007) 171–176.
[14] J.L.B. Culley and P.A. Phillips, Bacteriological quality of surface and subsurface runoff from manured sandy clay loam soil, Journal of Environmental Quality, 11 (1982) 155–158.
[15] E.A. Warnemuende, R.S. Kanwar, J.L. Baker, J.C. Lorimor, S. Mickelson and S.W. Melvin, Indicator bacteria in subsurface drain water following swine manure application, An ASAE Meeting Presentation. Paper No. 012197, 2001.
[16] NIAST, Taxonomical classification of Korean soils, National Institute of Agricultural Science and Technology (NIAST), Suwon, Korea, 2000.
[17] T.I. Jang, S.W. Park and H.K. Kim, Environmental effects analysis of a wastewater reuse system for agriculture in Korea, Water Science and Technology: Water Supply, 8(1) (2008) 37–42.
[18] Y.M. Chin, S.W. Park, S.M. Kim, M.S. Kang and M.G. Kang, Nutrient loads estimation at paddy field using CREAMS-PADDY model, Journal of the Korean Society of Rural Planning, 8(1) (2002) 60–68 (in Korean).
[19] M. Wegelin, S. Canonica, K. Mechsner, T. Fleischmann, F. Pesaro and A. Metzler, Solar water disinfection: Scope of the process and analysis of radiation experiments. Journal of Water Supply: Research and Technology – AQUA, 43(3) (1994) 154–169.
[20] USACE, CE-QUAL-R1: A Numerical One-Dimensional Model of Reservoir Water Quality: User's Manual, US Army Corps of Engineers, Washington, DC, 1995.
[21] S.R. Crane and J.A. Moore, Modeling enteric bacterial die-off: A review, Water, Air and Soil Pollution, 27(3–4) (1986) 411–439.
[22] S.K. DeDatta, W.P. Abilay and G.N. Kalwar, Water stress effects in flooded tropical rice. In: Water management in Philippine irrigation systems: Research and Operations. International Rice Research Institute, Los Banos, Philippines, 1973.
[23] S.B. Hukkeri and A.K. Sharma, Water-use efficiency of transplanted and direct-sown rice under different water management practices, Indian Journal of Agricultural Science, 50 (1980) 240–243.
[24] J.Y. Cho and J.K. Choi, Nitrogen and phosphorus losses from a broad paddy field in central Korea, Communications in Soil Science and Plant Analysis, 32(15–16) (2001) 2395–2410.
[25] K.S. Yoon, J.Y. Cho, J.K. Choi and J.G. Son, Water management and N, P losses from paddy fields in Southern Korea, Journal of the American Water Resources Association (JAWRA), 42(5) (2006) 1205–1216.
[26] J.Y. Cho, J.K. Son, C.H. Song, S.A. Hwang, Y.M. Lee, S.Y. Jeong and B.Y. Chung, Integrated nutrient management for environmental-friendly rice production in salt-affected rice paddy fields of Saemangeum reclaimed of South Korea, Paddy and Water Environment, 48(3) (2008) 301–306.
[27] J.Y. Cho and K.W. Han, Nutrient losses from a paddy field in central Korea, Water Air Soil Pollution, 134 (2002) 215–228.
[28] WHO, Health guidelines for the use of wastewater in agriculture and aquaculture, Report of a WHO Scientific Group, WHO Technical Report Series, No. 778, World Health Organization, Geneva, Switzerland, 1989.