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Adaptability of wastewater wetland models in estimating nutrient removal in a stormwater wetland on dry days

Heidi B. Guerra, Kisoo Park, Siping Niu, Youngchul Kim*

Department of Environmental Engineering, Hanseo University, Seosan City, Chungnam 356-706, Korea
Tel. +82 41 660 1432; Fax: +82 41 660 1440; email: ykim@hanseo.ac.kr

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ABSTRACT

Several types of nutrient removal models, which were developed for wastewater wetlands, were applied to the data collected from a wetland treating stormwater runoff from extensive cow feeding area. First-order and regression equations were used and calibrated to estimate the removal of total phosphorus (TP), ammonium (NH_4–N), total kjeldahl nitrogen (TKN), and total nitrogen (TN). To evaluate the performance of the models, the coefficient of determination (R^2), relative root mean square error (RRMSE), and model efficiency (ME), were determined. The first-order models developed produced a good prediction of the effluent TP concentration with $R^2 = 0.79$, RRMSE = 0.23, and ME = 0.66. On the other hand, the regression models produced very good predictions of effluent NH_4–N, TKN, and TN concentrations with $R^2 > 0.70$, RRMSE < 0.40, and ME > 0.70. Therefore, the models for wastewater wetlands can be used to estimate the nutrient removal in stormwater wetlands during dry days. The removal of nutrients was greatly affected by hydraulic loading rate which means that the surface area of the wetland is the critical design factor in terms of pollutant removal. Moreover, increasing the surface area of the wetland increases nutrient removal through nitrification/denitrification and sedimentation as well as plant and microbial uptake.

Keywords: Hydraulic loading rate; Nutrient removal; Performance models; Stormwater wetland

1. Introduction

Surface water pollutants especially those coming from nonpoint sources have been reported as one of the leading cause of surface water quality degradation in receiving water bodies [1,2]. In rural areas, nonpoint source pollution includes large concentration of nutrients such as nitrogen and phosphorus, which come from fertilizers, animal manures, sludge, and crop residues. Excess nutrients especially those applied just before rainfall tend to be washed off and brought to aquatic ecosystems where they, in large amounts, may cause eutrophication or algal bloom leading to water quality impairment.

Best management practices such as constructed wetlands are widely used for treating domestic and industrial wastewaters. Recently, they have also been used to treat stormwater runoff from urban and agricultural areas. Runoff from agricultural areas tends to contain great amounts of nitrogen and phosphorus and constructed wetlands are deemed effective to

*Corresponding author.

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reduce these excessive nutrients. In addition, due to their low construction cost and maintenance requirements, they are considered one of the most economical alternatives to conventional wastewater treatment systems. Thus, proper design of constructed wetlands is important in achieving effective removal of nutrients.

One of the preliminary steps in the design of constructed wetlands is performance modeling. During the last several decades, numerous removal models have been proposed by different researchers using a vast amount of operational data. However, these models have been developed specifically for wastewater wetlands. Since the use of wetlands for stormwater runoff treatment had just been done recently, there is a lack of sufficient experience and operational data in this field. In addition, modeling stormwater wetlands have a distinctive challenge because of the variability of the hydraulic and pollutant loadings on stormwater wetlands as compared to wastewater treatment systems. Hence, stormwater wetland models have been rare. However, several researchers have attempted to develop models through adapting previously developed wastewater wetland models to operational data from stormwater wetlands.

Carleton and Montas [3] collected data from 35 studies on 49 wetland systems treating stormwater runoff or runoff-impacted surface waters and attempted to adapt these set of data to the steady-state first-order plug flow models used for wastewater wetlands. He found out that despite the varying nature of hydrologic and pollutant inputs, the model can be adapted for use with stormwater wetlands. Furthermore, the first-order removal rate constants for total phosphorus, ammonia, and nitrate turned out to be similar to values reported in the literature for wastewater wetlands. Similarly, Wong and Geiger [4] suggested the adaption of the $k-C^*$ model to develop design guidelines for stormwater wetlands. However, they pointed out that different removal rate constants should be computed because they were expected to differ from the values derived from wastewater wetlands.

On the other hand, linear and multiple linear regression models were used [5] to examine the factors affecting nitrogen in small constructed wetlands treating agricultural runoff. The variables included temperature and hydraulic loading. According to his study, sedimentation of organic nitrogen was the primary nitrogen removal mechanism.

Previously developed models used to predict nutrient removal performances of wastewater wetlands are summarized in Table 1. Several other models can also be found in the literatures using the same first-order equations but with different reaction rate constants. On the other hand, more sophisticated models that consider site-specific conditions and different nitrogen removal mechanisms have also been used [6]. This study was aimed at investigating the applicability of wastewater wetland models to the operational data of a wetland receiving stormwater runoff from a rural area with intensive animal feeding operations.

2. Materials and methods

2.1. Study area

The study was done in a stormwater wetland in Jeongeup City, Jeollabuk Province, South Korea. It is one of the best management practices that have been constructed for nonpoint source pollution control. The covered watershed is composed of several land uses, including residential areas, fields, and rice paddies, but majority of the land is used for cow feeding operations. This type of land use tends to contribute high concentrations of nutrients to its nearby water bodies, and the wetland was built to control excess nutrients released from the said areas. The total annual precipitation is about 1,300 mm with about 700 mm during the summer and 120 mm during the winter, while the rest is distributed throughout the year.

The wetland shown in Fig. 1 is composed of a forebay, aeration pond, deep marsh, shallow marsh, and a polishing pond. It covers an area of 3,085 m^2 with a water quality volume of 4,024 m^3. The wetland is partly covered by vegetations such as *Phragmites Autralis* (common reed) in the shallow marsh, *Typha Latifolia* (cattail) in the deep marsh, and *Nelumbo Nucifera* (lotus) in the polishing pond. Oxygen is supplied in the aeration pond through mechanical aeration which is operated intermittently for 3 h with a 3-h interval. The wetland also has an internal recycle wherein the water from the shallow marsh is pumped backed to the aeration pond for further treatment and to improve nitrification. The physical features of the wetland are provided in Table 2.

2.2. Sampling and analysis

Sampling was done randomly during dry days from May to December of the year 2011 as shown in Fig. 2. Sampling days were distributed so that different conditions in terms of antecedent dry days (ADD) and rainfall intensity were achieved. Eight sampling

Table 1
Nutrient removal models in the literatures

Type	Equation/s	Pollutant	Author/s
Regression	$C_e = a \times C_i^b \times q^c$	NH_4–N, TN, TP	[7]
	$C_e = \exp(0.688 \ln C_i + 0.655 \ln(q) - 1.107)$	NH_4–N	[8]
	$C_e = 0.193C_i + 1.55 \ln(q) - 1.75$	TN	
First-order	$C_e/C_i = (1 + k/Nq)^{-N}$ $k = k_{20}\theta^{T-20}$	Phosphorus	[9]
	$C_e/C_i = e^{-kt}$ $k = k_{20}\theta^{T-20}$	Nitrogen	[8]
	$C_e - C^* = (C_i - C^*)e^{(-k/q)}$	All pollutants	[7]

C_e = effluent concentration, mg/L; C_i = influent concentration, mg/L; C^* = background concentration; k = reaction rate constant, /day; q = HLR, m/day; N = hydraulic efficiency parameter; T = temperature; θ = temperature coefficient; a, b, c = constants.

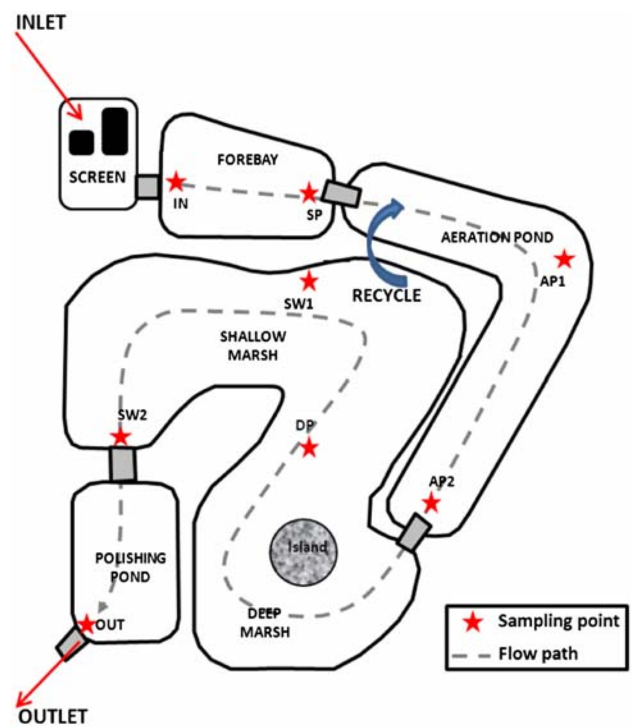

Fig. 1. Sketch of the stormwater wetland.

Table 2
Physical features of the stormwater wetland

Section	Surface area (m^2)	Volume (m^3)	Water depth* (m)
Forebay	288	351 (8.7)	1.2
Aeration Pond	660	708 (17.6)	1.1
Marsh Wetland	1892	2,592 (64.4)	1.4
Polishing Pond	243	373 (9.3)	1.5
Total	3,085	4,024	1.3*

*Mean; () Percentage.

points as shown in Fig. 1 were established within the wetland. Temperature, DO, and pH were measured *in situ* after which the samples were taken to the laboratory for testing. Concentrations of NH_4–N, NO_3–N, NO_2–N,TN, TP, and total suspended solids (TSS) were determined using the Standard Methods for the Examination of Water and Wastewater, 19th edition [10]. In total, 15 sampling trips were made and 120 samples were collected on the duration of the sampling period.

Table 3 summarizes the characteristics of the influent to the stormwater wetland. The concentration of TN and TP are apparently higher as compared to the concentrations typical in other types of land use. In addition, the concentration of ammonia is comparably higher than those that are usually observed in stormwater wetlands.

2.3. Investigated wastewater models

The models pursued in this study are shown in Table 4. In the equations, C_i and C_e are the influent and effluent concentrations, HLR is the hydraulic loading rate, k is the reaction rate constant and a, b, and c are constants. The model for phosphorus removal was developed with the assumption that sediment deposition is the major removal pathway for phosphorus removal; hence, it is in terms of the surface area of the wetland. In addition, the suggested reaction rate constant, k, is 2.73 cm/day based on the analysis of the North American Data Base (NADB) [8]. However, in this study, k was assumed to be temperature-dependent, that is, $k = aT^b$ wherein a and b are constants [3,9]. On the other hand, regression models for nitrogen removal proposed by the US Water Environment Federation (WEF) were used as base equations for estimating NH_4–N, TKN, and TN

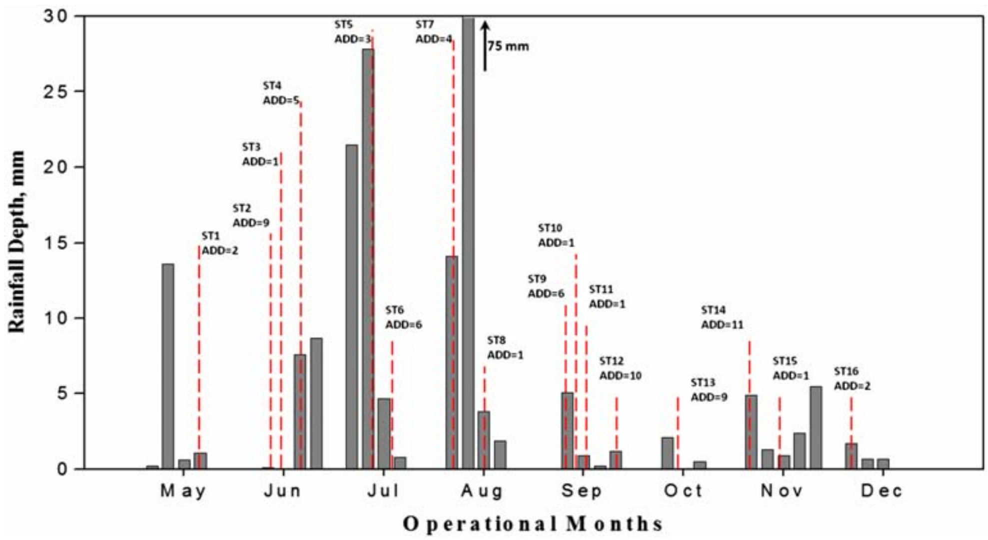

Fig. 2. Sampling trips and rainfall events during the sampling period.

Table 3
Water quality of the influent to the wetland during dry days

Parameters	Units	Range	Mean	Standard deviation
Temperature	℃	11.7–34.8	23.1	5.9
pH		5.91–8.62	7.24	0.59
ALK as $CaCO_3$	mg/L	30.38–177.6	75.52	26.63
DO	mg/L	4.23–9.50	6.79	1.33
Total COD_{Cr}	mg/L	12.1–68.0	36.4	14.9
Soluble COD_{Cr}	mg/L	11.6–48.0	25.5	11.2
NH_4–N	mg/L	0.04–6.16	2.08	1.97
NO_3^-–N	mg/L	0.08–2.14	1.13	0.74
NO_2^-–N	mg/L	0–1.57	0.52	0.48
TN	mg/L	3.41–21.08	7.90	4.16
TP	mg/L	0.27–2.23	0.96	0.65
TSS	mg/L	4−166	32	43

removal. These are areal loading models and do not consider water depth as a design factor. In the literatures, areal loading models are more preferable than volumetric models because many pollutant removal mechanisms are mainly affected by the surface area of the wetland. Moreover, water depth is difficult to specifically determine in large systems and is likely to change during the long term [11]. The models were calibrated through regression analysis using the operational data in this study and Excel™ Solver, a spreadsheet routine inside MS Excel.

To evaluate the performance of the models, three statistical parameters namely the coefficient of determination (R^2), relative root mean square error (RRMSE), and model efficiency (ME) were determined. R^2 and RRMSE measure the extent of linear correlation and the difference between the observed and predicted models, respectively. On the other hand, ME is a measure of the extent of variability of the model in relation to the mean of the observed values. These three statistical parameters have been used in determining the performance of mathematical models such as those used in this study [12]. Specifically, a perfectly fit model has $R^2 = 1$, RRMSE = 0, and ME = 1.

Table 4
Wastewater wetland models used in this study

Pollutant	Proposed model	References	Remarks
TP	$\frac{C_e}{C_i} = e^{(-k/\mathrm{HLR})}$	[8,13]	Based on the operational data from the North American Data Base
NH_4–N and TKN	$C_e = e^{[a\ln C_i + b\ln(\mathrm{HLR}) - c]}$	[11]	Appeared in the WEF manual of practice FD-16 and recommended by reed
TN	$C_e = aC_i + b\ln(\mathrm{HLR}) - c$		

3. Results and discussion

3.1. Stormwater runoff characteristics

The variation of temperature, TSS, pH, and DO during the sampling period is shown in Fig. 3. Temperature slightly increased as the stormwater went through the wetland and is exposed to solar radiation. TSS greatly increased in the aeration pond due to the resuspension of settled particles during aeration and is generally increased in the wetland due to algal growth. DO and pH also increased due to the photosynthetic activity in the wetland except in the polishing pond where the water was covered from sunlight by the lotus plants.

Fig. 4(a), on the other hand, gives the variation of the average nutrient concentrations through the wetland. TP was continuously removed from the inlet to the outlet. This signifies the effective removal of phosphorus in the system. Similarly, NH_4–N and TKN were also removed as they went through the wetland that shows the existing nitrification in the system. However, it does not mean that there is great removal of nitrogen. The slight decrease of NO_3–N implies that denitrification occurs at a much slower pace than nitrification. With the great amount of DO, there is no suitable condition for denitrification. This is also evident in the distribution of nitrogen species in the wetland. As shown in Fig. 4(b), TKN was significantly decreased in the wetland. However, a considerable amount of nitrate that can still be removed was observed in the effluent. This implies that the denitrification capacity should be improved for complete nitrogen removal.

3.2. TP removal

The equation for TP removal resulted in a good relationship between the observed and predicted normalized TP concentrations with R^2 value equal to 0.79 as shown in Fig. 5. Moreover, the prediction of increase and decrease in values between the sampling days is comparable with the observed variations. Therefore, it is safe to assume that a first-order model can be used to estimate the phosphorus concentration in the wetland. This is consistent with the initial assumption that the removal of phosphorus is greatly affected by the surface area of the wetland. The adaptability of the pursued model in the data in this study implies that phosphorus in the wetland is primarily removed through adsorption to suspended particles and available surface area and by sedimentation.

The behavior of P in terms of temperature in the wetland is different from those reported in the literatures. Kadlec [9] stated that temperature has little or no apparent effect for P removal in treatment wetlands by recommending a temperature coefficient, θ, of 1.00 in the Arrhenius temperature relation. However, it is clear in this study that phosphorus removal was

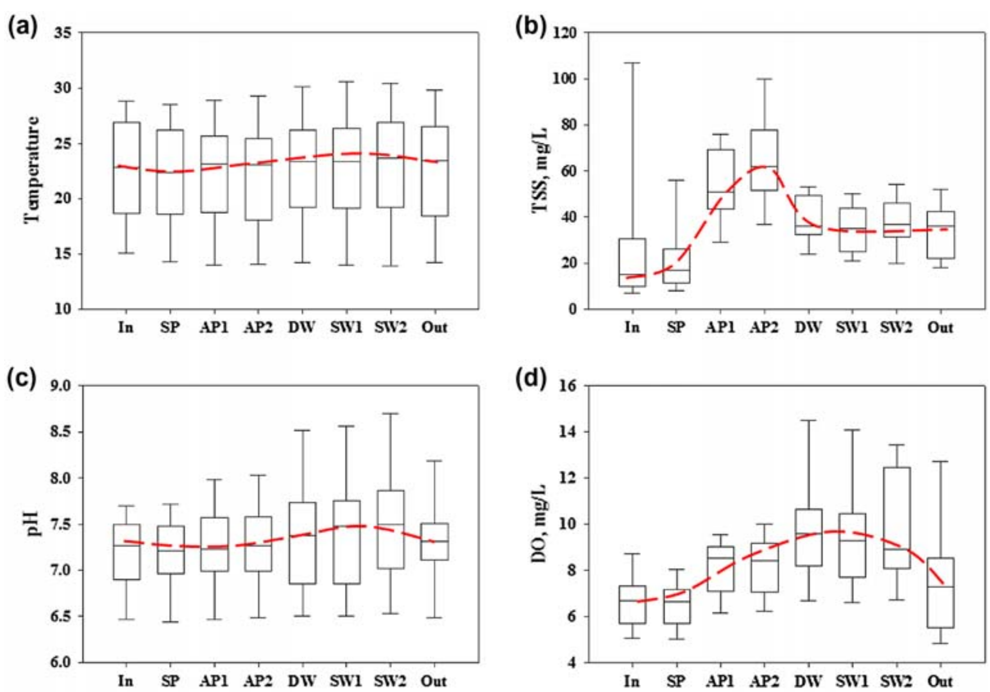

Fig. 3. Variation of temperature, TSS, pH, and DO though the wetland.

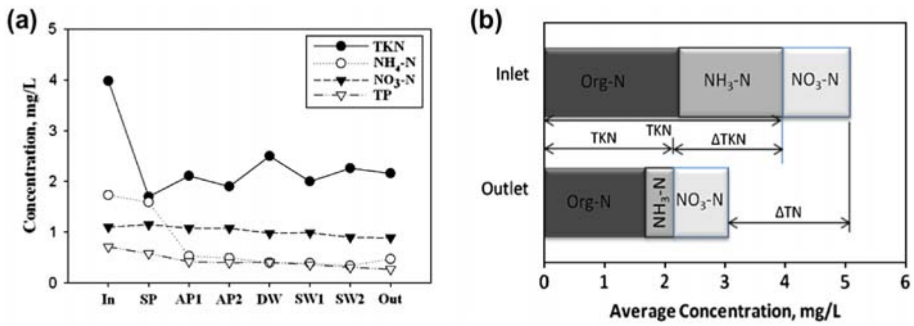

Fig. 4. Variation of the nutrient concentrations and distribution of nitrogen species through the wetland.

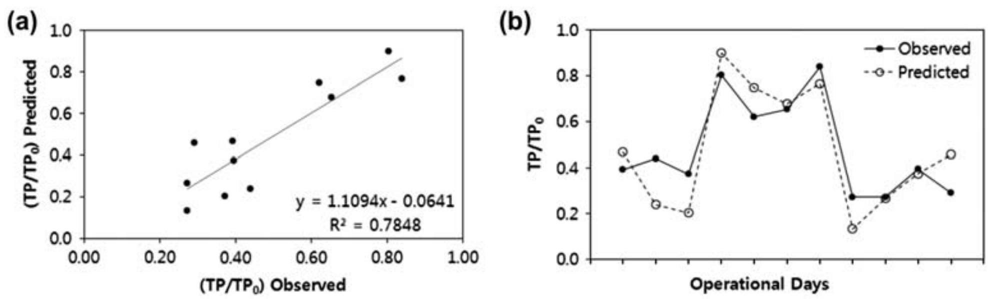

Fig. 5. Application of the developed equation for TP removal.

affected by temperature. Therefore, it should be considered that pollutant removal in different treatment wetlands may have different temperature dependence.

3.3. Nitrogen removal

The calibrated models proposed by WEF appeared to have a good forecast on the nitrogen species. Fig. 6 shows the relation between the observed and predicted nitrogen effluent concentrations with R^2 values of not less than 0.70. For NH_4–N, underestimations were observed for influent concentrations greater than 0.5 mg/L. This may be because majority of the influent NH_4–N are less than 0.5 mg/L so the model was inclined in favor of these conditions when the calibration was made. A larger set of data with a wide variation of concentration may be required to lessen these underestimations and to improve the model calibration. Generally, the model may be applied for effluent prediction of NH_4–N.

The WEF-based model for TKN showed a better forecast performance. As shown in Fig. 6(b), the model produced a good relationship between the observed and predicted effluent TKN concentrations. It also gave a very good prediction of the increase and decrease in concentrations between sampling days as shown in Fig. 7(b). The model produced less error as compared to the NH_4–N model with several overlapping points. TKN models are usually made with the assumption that all the organic nitrogen which enters the wetland will be converted to ammonia and the remaining TKN at the effluent represents the remaining ammonia in the wetland. However, in this study, this cannot be assumed since the concentration of NH_4–N is too small as compared to the TKN in the effluent of the shallow marsh which means organic nitrogen still represents a big portion of TKN.

Since ammonia volatilization is not significant in the FWS wetland in this study, the decrease in ammonia does not necessarily mean the removal of nitrogen. The increase in NO_3–N that is observed in the wetland is an evidence of nitrification that exists in the wetland. Therefore, the removal of total nitrogen may be represented by denitrification.

The WEF model for TN removal produced a very good relationship between the predicted and observed TN effluent concentrations as shown in Fig. 6(c). Also, in Fig. 7(c), the prediction of concentration increase or decrease between sampling days is very good with a majority of overlapping points. Moreover, among the nitrogen models, the model for TN produced the least errors in the prediction of effluent concentration. Therefore, overestimates and underestimates are tolerable as they are very near the observed values.

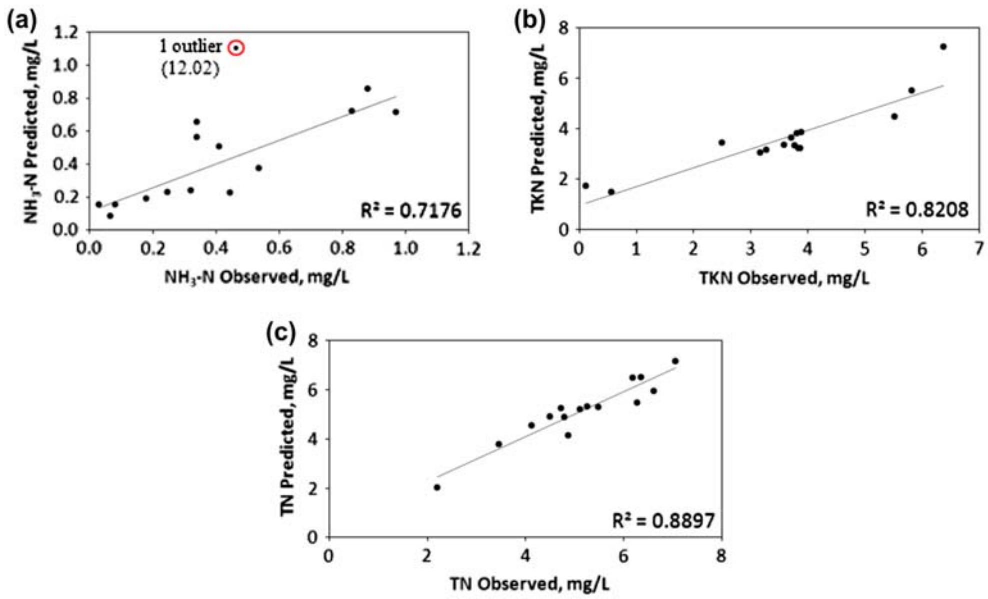

Fig. 6. Observed and predicted effluent nitrogen concentrations.

The results showed that the model proposed by WEF can be used as a basis for the prediction of nitrogen removal in the wetland. This is in agreement to several reports in previous studies that nitrogen transformation and removal is greatly affected by nitrogen concentrations and HLR [14,15].

Influent concentrations are often included in regression analysis to determine whether there is a significant relationship between the inlet and outlet concentrations in the wetland [16]. On the other hand, HLR is widely used as a design variable in constructed wetland systems and has been employed in various design models [8–11]. Different design manuals in the USA suggest that wetland performance is enhanced when the wetland has a high surface area to volume ratio because of several reasons [17–19]. First, larger surface area provides more space for microbial growth and activity and therefore enhances biological

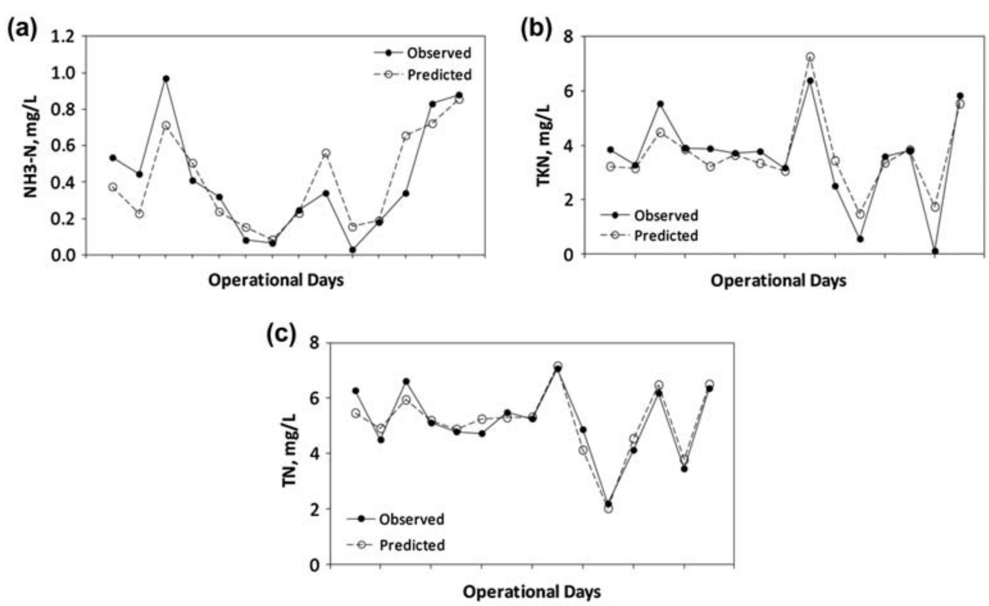

Fig. 7. Variation of the effluent nitrogen concentrations during the sampling period.

Table 5
Nutrient removal models for Jeongeup wetland

Pollutant	Equation	Constants			R^2	RRMSE	ME
		a	b	c			
TP	$\frac{C_e}{C_i} = e^{(-k/\mathrm{HLR})}$	30.462	−1.924	–	0.79	0.23	0.66
NH_4–N	$C_e = e^{[a\ln C_i + b\ln(\mathrm{HLR}) - c]}$	0.766	0.192	0.228	0.72	0.38	0.72
TKN		0.258	0.066	−0.321	0.82	0.20	0.81
TN	$C_e = aC_i + b\ln(\mathrm{HLR}) - c$	1.003	0.225	0.000	0.89	0.08	0.90

removal of nutrients. Second, HLR, which is similar to overflow rate from the concept of particle settling, indicates that organic nitrogen and ammonia may have also been removed through sedimentation. This implies that a fraction of nitrogen species in the wetland such as ammonia and organic nitrogen were in particle associated form. Increasing the surface area of the wetland also increases the chance of pollutant uptake by plants and microorganism in soil. Lastly, it increases the oxygen transfer from the atmosphere.

3.4. Stormwater wetland models for nutrient removal

Table 5 summarizes the constants obtained from the regression analysis for TP and Excel™ Solver routine for NH_4–N, TKN, and TN as well as the statistical parameters for each model. The constants obtained for the k equation for TP ($k = aT^b$) resulted in a reaction rate constant equal to 0.0745 m/day. This is slightly far from Kadlec and Knight's proposed reaction rate constant value of 0.0273 m/day. This may be caused by the wide variety of constructed wetlands in the NADB as compared to the single system used in our study and the difference in the wetland conditions. In spite of these, the model gave a very close relationship between the observed and predicted normalized TP concentrations with $R^2 = 0.79$, RRMSE = 0.23, and ME = 0.66.

On the other hand, the constants for the equations based on the WEF models are different from those that are given in the original equations for the removal of NH_4–N, TKN, and TN. However, the resulting equations also gave a good prediction of the effluent concentrations with $R^2 > 0.70$, RRMSE < 0.40, and ME > 0.70.

Therefore, it can be resolved that the nutrient removal models developed for wastewater wetlands can be used as base equations to estimate the removal in stormwater wetlands. It should be noted nonetheless that these models are empirical and should be used with appropriate caution for future applications.

4. Conclusions and recommendations

The nutrient removal capability of the stormwater wetland treating stormwater runoff from rural areas can be estimated by first-order and regression models developed for wastewater wetlands. All the previously proposed models investigated in this study gave a good prediction of the nutrient removal in the system.

For phosphorus, the first-order model provided good prediction of the TP removal. The results implied that adsorption by plants and algae as well as sedimentation are the removal mechanism of phosphorus in the wetland. Furthermore, the effect of temperature in reaction rate indicates that biological removal of phosphorus may have also contributed to the removal. The effect of these mechanisms may be substantiated by the analysis of phosphorus content in the wetland plants and sediments. This can be done for further studies in the future.

As for nitrogen, the models based on the WEF equations gave very good predictions of the effluent nitrogen concentrations in the wetland. The significance of HLR that was apparently shown in the model denotes that the removal of nitrogen is mainly affected by the available surface area in the wetland which is beneficial to different removal mechanisms such as nitrification-denitrification, sedimentation, and plant and microbial uptake. This means that in design, the size of the wetland surface area will be based on the desired pollutant removal efficiency.

All in all, it can be concluded that the removal of nutrients in the wetland is independent of the water depth and is affected only by the surface area of the wetland. This implies that pollutant removal capacity can be increased by increasing the surface area and not the volume of the wetland. Finally, it is surprisingly evident that the models that are initially developed for wastewater wetlands can also be used to model nitrogen removal in stormwater wetlands. This may be because the stormwater wetland acted as a wastewater wetland during dry days. It should be emphasized, however, that some wetlands may behave differently in terms of treatment performance, wetland conditions, and characteristics of the stormwater runoff. Therefore, these models should be employed cautiously.

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