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Design Methodology of Free Water Surface Constructed Wetlands

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Abstract. Simple criteria, guidelines and models are established for free water surface (FWS) constructed wetland selection and preliminary sizing. The analysis employs models for FWS constructed wetland design, considering simultaneously the removal requirements and the hydraulics of the system. On the basis of these models, a step-by-step methodology is developed outlining the design procedure for new and performance evaluation for existing FWS constructed wetland systems. This methodology is combined with simple equations predicting the maximum wetland capacity in summer, so as to assist designers in sizing installations in tourist areas with increased summer populations. Furthermore, this methodology is further simplified, based on sensitivity analysis of the unit area requirements for wastewaters of various strengths, and various design conditions and performance criteria. In addition, comparison of the unit area requirements of FWS constructed wetland systems, subsurface flow (SF) constructed wetland systems and stabilization pond systems for wastewaters of various strengths and design conditions, provides designers with general guidelines concerning the preliminary selection between alternative natural treatment systems in areas where the use of natural systems is favored because of their low-cost, simple operation and high removal performance.

Key words: design methodology, free water surface constructed wetlands, seasonal performance, sensitivity analysis, stabilization ponds, subsurface flow constructed wetlands, unit area requirement, wastewater treatment

1. Introduction

Natural treatment systems are characterized by low-maintenance, simple and reliable operation and high removal efficiencies. These systems are highly favored in small to medium communities, where the resources and the skilled personnel required for the operation of conventional systems are often limited (USEPA, 1988; Sartoris *et al.*, 2000). Furthermore, they are considered a favorable treatment alternative for the production of effluents that can be reused for irrigation, limiting the fresh water consumption and the possibility for pollution of receiving waters (WHO, 1989). Therefore, emphasis is placed on the development of practical design and analysis procedures that promote the proper evaluation and use of natural systems (e.g., Economopoulou and Tsihrintzis, 2003).

Constructed wetlands have been extensively used in the treatment of wastewaters. A number of constructed wetland projects have been reported to treat various types of wastes (e.g., Hammer, 1989; Schueler, 1992; Moshiri, 1993; Olson, 1993; Etnier and Guterstam, 1997; Mulamoottil *et al.*, 1999; Dialynas *et al.*, 2002; Mander and Jenssen, 2002, 2003; among others). Several natural wetland restoration projects have also been reported (e.g., Mitsch and Gosselink, 1986; Hammer, 1992; Minnesota Board of Water and Soil Resources, 1993; Tsihrintzis *et al.*, 1995a, 1995b, 1996, 1998, among others), and various design procedures have been presented (e.g., USEPA, 1988; Tchobanoglous and Burton, 1991; Reed *et al.*, 1995; Kadlec and Knight, 1996; Tsihrintzis and Madiedo, 2000; Tsihrintzis, 2001; Economopoulou and Tsihrintzis, 2003; among others).

Economopoulou and Tsihrintzis (2003) have presented a step-by-step methodology for designing subsurface flow (SF) constructed wetlands for wastewater treatment. This paper presents a convenient procedure that can be used in the design and sizing of new free water surface (FWS) constructed wetland systems, on the basis of performance criteria, without going through iterations. This procedure can also be used to assess the removal efficiency of existing systems against local design parameters.

2. Pollutant Removal Theory

The present study employs the constructed wetland design theory and typical kinetic rate constants for municipal wastewater in computing pollutant removal efficiencies. The following assumptions have been made:

- The water temperature can be assumed approximately equal to the mean ambient temperature. This is a reasonable assumption for relatively warm climates (Kadlec and Knight, 1996).
- The removal rates for BOD and nitrogen in FWS constructed wetland systems are typically based on first-order kinetics and on the assumptions of plug flow, and are based on the models proposed by the USEPA (1988) and Reed *et al.* (1995), which have been used in the design of most constructed wetland systems in the U.S. and Europe (Chen *et al.*, 1999; Economopoulou and Tsihrintzis, 2003).

BOD and nitrogen removal rates in FWS constructed wetlands are estimated by the following general Equation (1) (Reed *et al.*, 1995), whereas, coliform and phosphorus removals by general Equation (2) (Kadlec and Knight, 1996):

$$\frac{C_\mathrm{e}}{C_\mathrm{i}} = e^{-K_T t} \tag{1}$$

$$\frac{C_\mathrm{e}}{C_\mathrm{i}} = e^{-\frac{K_1}{h_1}} \tag{2}$$

Table I. Pollutant removal equations and rate constants for FWS constructed wetlands

Pollutant	Equation used	Rate constant		Rate constant units
BOD	(1)*	$K_T = 0.678(1.06)^{T\text{-}20}$		[d^{-1}]
Fecal coliforms	(2)**	$K_1 = 0.3$		[m d^{-1}]
Nitrogen				
Nitrification	(1)*	$K_T = 0.0389T$	$0 < T < 1°C$	[d^{-1}]
		$K_T = 0.1367(1.15)^{T-10}$	$1 < T < 10°$ C	[d^{-1}]
		$K_T = 0.2187(1.048)^{T\text{-}20}$	$T > 10$ °C	[d^{-1}]
Denitrification	(1)*	$K_T = 0.023T$	$0 < T < 1°C$	[d^{-1}]
		$K_T = 1.15^{(T-20)}$	$T > 1$ °C	[d^{-1}]
Phosphorus	(2)**	$K_1 = 0.0273$		[m d^{-1}]

*by Reed *et al.* (1995), **by Kadlec and Knight (1996).

In these two general equations: C_e is the pollutant effluent concentration[mg L^{-1} of BOD, nitrogen or phosphorus, or number of fecal coliforms/100mL]; C_i is the pollutant influent concentration [mg L^{-1} of BOD, nitrogen or phosphorus, or number of fecal coliforms/100mL]; K_T is a reaction rate parameter [d^{-1}] dependent on the water temperature T[°C], and the pollutant of interest (Table I); K_1 is a reaction rate constant [m d^{-1}] dependent on the pollutant of interest (Table I); h_l is the hydraulic loading rate[m d^{-1}]; and t is the hydraulic residence time (HRT) in the system [d]. The last two parameters are defined by the following equations:

$$h_l = \frac{Q}{A} \tag{3}$$

$$t = \frac{V}{Q} = \frac{A\,y\,\phi}{Q} = \frac{y\,\phi}{h_l} \tag{4}$$

where Q is the design flow rate [m^3 d^{-1}], assumed constant; A is the mean surface area of the system [m^2]; V is the system volume [m^3]; y is the flow depth [m]; ϕ is the fractional porosity, which expresses the space available for water to flow through the vegetation and litter in the FWS constructed wetland system (Reed *et al.*, 1995).

The estimation of BOD removal in FWS constructed wetlands is simpler compared to SF constructed wetlands (Economopoulou and Tsihrintzis, 2003), since the water temperature T can be assumed equal to the ambient temperature T_α(Kadlec and Knight, 1996), and thus t can be computed directly from Equation (1), setting $T = T_a$ and using the appropriate kinetic rate constant from Table I. Of course, this assumption is valid only for relatively warm climates with no ice cover.

Reed *et al.* (1995), based on the operational experience of several constructed wetland systems in the United States, proposed that the organic loading in FWS constructed wetland systems should not exceed a 10 g m^{-2} d^{-1} limit value, which can be expressed by the following relation (Economopoulou and Tsihrintzis, 2003):

$$C_{\mathrm{i}} \frac{Q}{A} \leq 10 \tag{5}$$

Since the area A [m^2] is not known prior to designing a new FWS constructed wetland system, the estimation of the organic loading requires a trial-and-error procedure.

The removal of coliforms in FWS constructed wetlands is due to physical separation of the particles and die-off (Kadlec and Knight, 1996; Reed *et al.*, 1995), and is estimated from Equation (2) and the appropriate rate constant value listed in Table I. The removal of bacteria, viruses and helminth eggs has also been found to be satisfactory in arid climates (Khatiwada and Polprasert, 1999; Mandi *et al.*, 1998), so effluent wastewaters could be used even for irrigation providing minimum risk to workers and consumers.

The removal of nitrogen based on nitrification and denitrification is highly dependent on water temperature (USEPA, 1988; Reed *et al.*, 1995; Kadlec and Knight, 1996). This is also in accordance with the works of Bachand and Horne (2000a, 2000b) and Reilly *et al.* (2000), who studied the denitrification of wastewater in FWS constructed wetlands, and concluded that nitrate removal is highly dependent on water temperature and organic carbon availability.

It is assumed that the total Kjeldahl nitrogen entering the system is converted to ammonia, which is partly converted to nitrate by nitrification and subsequently is removed by denitrification (Reed *et al.*, 1995; Economopoulou and Tsihrintzis, 2003). The sum of the unconverted ammonia after nitrification ($C_{\mathrm{e,amm}}$) and unconverted nitrate after denitrification ($C_{\mathrm{e,nitr}}$) represent the total nitrogen (TN) remaining in the system. Nitrification and denitrification are both described by Equation (1), with the appropriate rate constant value from Table I. A minimum design HRT of about 6 to 8 days is advisable, to guarantee oxygen availability for nitrification and maximize ammonia removal efficiency (Reed *et al.*, 1995; Reed and Brown, 1993).

The removal of phosphorus is estimated from Equation (2) and the appropriate rate constant listed in Table I and is believed to range between 30 to 50% in the long term.

3. Hydraulic Design Theory

Kadlec (1990) and Kadlec and Knight (1996) proposed the following general equation for the hydraulic design of FWS constructed wetland systems:

$$Q = a\,W\,y^{b} S^{c} \tag{6}$$

where: Q is the flow rate [m^3 d^{-1}]; W is the wetland width [m]; a, b and c are coefficients assuming the following values: $a = 10^7$ $d^{-1}m^{-1}$ for dense vegetation, $a = 5\times 10^7$ $d^{-1}m^{-1}$ for sparse vegetation, b = 3.0 and c = 1.0; y is the depth of flow [m], which usually ranges from 0.1 to 0.6 m (Reed *et al.*, 1995); and S is the water surface slope [m/m], estimated by the following equation:

$$S = \frac{\gamma\, y}{L} \tag{7}$$

where γ is the fraction of the depth serving as head differential (Reed *et al.*, 1995); and L is the wetland length [m].

Equation (6), with the values of the coefficients a, b and c mentioned above, seems to describe accurate flow through wetland vegetation (Kadlec, 1990). Alternatively, Manning's equation can also be used, if a, b and c in Equation (6) are set equal to $1/n$, 5/3 and 1/2, respectively, with n as the Manning's roughness coefficient. A comprehensive approach on wetland flow resistance, presented by Tsihrintzis and Madiedo (2000) and Tsihrintzis (2001), has shown that the Manning's coefficient values for wetland vegetation are significantly higher than those for turbulent open channel flows controlled by skin friction. Indeed, flow resistance in wetland vegetation is highly dependent on the type, height and density of vegetation, the diameter and flexibility of the vegetation's stem, the depth of flow, the depth of litter layer, etc. (Kadlec, 1990; Kadlec and Knight, 1996; Tsihrintzis and Madiedo, 2000; Tsihrintzis, 2001).

If Manning equation is to be used, then the Manning's roughness coefficient n can be estimated with one of the following three methods:

1. Using the data, procedure and design graphs provided by Tsihrintzis and Madiedo (2000) and Tsihrintzis (2001), where n is presented as a function of parameter VR (product of mean velocity and hydraulic radius), vegetation density and other factors.
2. Using a logarithmic diagram developed by Kadlec and Knight (1996), based on information from existing wetlands, which allows for the preliminary estimation of Manning's roughness coefficient n as a function of flow depth. To simplify the use of this diagram, Economopoulou and Tsihrintzis (2000) have developed two regression lines of the following general equation:

   $$n = \beta_1\, y^{\beta_2} \tag{8}$$

   where: $\beta_1 = 0.1564$ for sparse vegetation and 1.09 for dense vegetation; and $\beta_2 = -1.356$ for sparse vegetation and -1.436 for dense vegetation.

3. Using the general Equation (8), but with the following values for coefficients β_1 and β_2, proposed by Reed *et al.* (1995): $\beta_2 = -0.5$; $\beta_1 = 0.4$ $m^{1/6}$·s for sparse and low-standing vegetation with flow depth $y > 0.4$ m; $\beta_1 = 1.6$ $m^{1/6}$·s for moderately dense vegetation with flow depth y in the range 0.3 to 0.4 m; and

$\beta_1 = 6.4$ m$^{1/6}$·s for very dense vegetation with litter layer and with $y < 0.3$ m. In most FWS constructed wetlands, $\beta_1$ranges from 1 m$^{1/6}$·s (sparse vegetation) to 4 m$^{1/6}$·s (dense vegetation).

It is noticed that in most FWS constructed wetland systems there is water surface control at the outlet. Thus, the depth may not be normal close to the outlet. However, it will tend to normal depth further upstream, particularly if the wetland is designed with a large length to width ratio, something generally recommended. In any case, the downstream control depth can be set close to normal depth. As suggested by Kadlec and Knight (1996), the aspect ratio L:W should be greater than 2:1 to ensure plug flow conditions. However, very high ratios may result in overflow problems due to resistance increase as a result of the gradual accumulation of vegetation litter. Commonly used aspect ratios are between 2:1 and 5:1.

4. Simplified FWS Constructed Wetland Design

As seen in the previous section, the design equation based on total nitrogen, the estimation of FWS system's flow depth and the estimation of the organic loading cannot be solved directly, but require a trial-and-error procedure. Therefore, to avoid this, the theory and equations presented in the previous sections are revisited here. As a result, appropriate nomographs and equations have been prepared and are presented in this section, which simplify the procedure and provide a convenient method for sizing new or for evaluating the performance of existing FWS constructed wetlands.

4.1. NITROGEN

As mentioned in Section 2, effluent total nitrogen is the sum of residual ammonia from nitrification and remaining nitrate from denitrification. Thus, Equation (1) for nitrification and Equation (1) for denitrification were mathematically combined into the following equation for total nitrogen removal efficiency (Economopoulou and Tsihrintzis, 2003)

$$\frac{C_e}{C_i} = e^{-K_{T_N} t} + e^{-K_{T_D} t} - e^{-K_{T_N} t} e^{-K_{T_D} t} \tag{9}$$

where: C_i is the total Kjeldahl nitrogen inflowing concentration (assumed all converted to ammonia) [mg L^{-1}], and C_e is the total nitrogen outflowing concentration [mg L^{-1}]; K_{TN} and K_{TD} are the reaction rate parameters for nitrification and denitrification [d^{-1}], respectively, taken from Table I as a function of the design temperature T. In a new constructed wetland sizing problem, the required t [d] can be obtained from Equation (9), as a function of the total nitrogen removal ratio and T [°C]. However, Equation (9) cannot be solved directly for t, but only by a

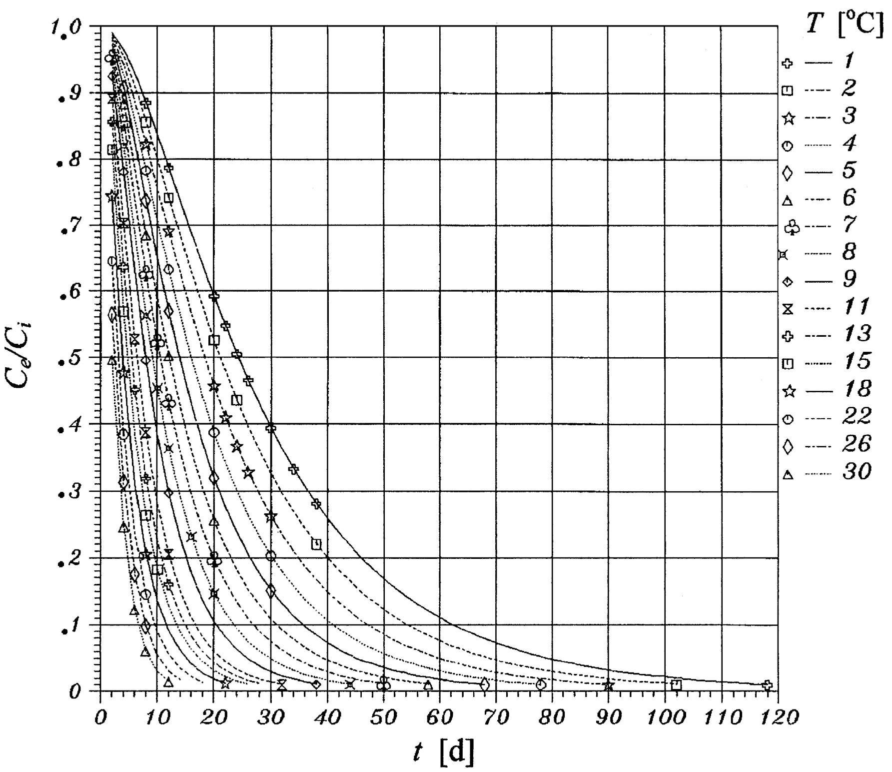

Figure 1. Nitrogen removal efficiency in FWS constructed wetlands.

trial-and-error procedure. To simplify the computation, the nomograph of Figure 1 provides a graphical solution to Equation (9), allowing for direct estimation of t for nitrogen removal as a function of T and C_e/C_i.

4.2. HYDRAULIC DESIGN

On the basis of Equations (6), (7) and (4) the following general equation is derived (Economopoulou and Tsihrintzis, 2000):

$$a^{\frac{2}{c+1}} y^{\frac{2b+3c-1}{c+1}} = \frac{\frac{L}{W} Q \varphi^{1-\frac{2c}{c+1}}}{t^{1-\frac{2c}{c+1}} \gamma^{\frac{2c}{c+1}}} \tag{10}$$

If the Manning's equation is used, then the coefficients a, b and c are equal to 1/n, 5/3 and 1/2, respectively. Their introduction into Equation (10), with n estimated by the general Equation (8) and the values of the constants β_1 and β_2 equal to those proposed by Economopoulou and Tsihrintzis (2000) for sparse and dense vegetation, respectively, yields the following equation for the flow depth y:

$$y = \left(\frac{0.0006}{86400^4} \frac{\left(\frac{L}{W}\right)^3 Q^3 \varphi}{t\,\gamma^2} \right)^{0.0764} \qquad \text{(for sparse vegetation)} \tag{11}$$

$$y = \left(\frac{1.4110}{86400^4} \frac{\left(\frac{L}{W}\right)^3 Q^3 \varphi}{t\,\gamma^2} \right)^{0.0745} \qquad \text{(for dense vegetation)} \tag{12}$$

Similarly, the introduction of the coefficients $a = 1/n$, $b = 5/3$ and $c = 1/2$ in Equation (10), with n estimated by the general Equation (8) and the values of the constants β_1 and β_2 equal to those proposed by Reed *et al.* (1995), results in:

$$y = \left(\frac{\beta_1^4}{86400^4} \frac{\left(\frac{L}{W}\right)^3 Q^3 \varphi}{t\,\gamma^2} \right)^{3/29} \tag{13}$$

Finally, the introduction of the values $b = 3.0$, $c = 1.0$ with $a = 5\times 10^7$ $d^{-1}m^{-1}$ (sparse vegetation) or $a = 10^7$ $d^{-1}m^{-1}$ (dense vegetation) (Kadlec, 1990; Kadlec and Knight, 1996) into Equation (10), yields the following equation for y:

$$y = \left(\frac{1}{a} \frac{\frac{L}{W} Q}{\gamma} \right)^{1/4} \tag{14}$$

4.3. ESTIMATION OF THE ORGANIC LOADING

When designing a new FWS constructed wetland system, the area A of the system is not known in advance, thus it would be preferable to use a more convenient equation to check the organic loading in the wetland, so as to avoid time-consuming iterations. If BOD removal is required, then Equations (1) and (5) are solved for A and the two equations are set equal and solved for K_T, yielding the following formula:

$$K_T \leq -\frac{10 \ln\left(\frac{C_e}{C_i}\right)}{C_i y \phi} \tag{15}$$

Equation (15), which is equivalent to Equation (5), depends on flow depth y rather than the system's area A. As it will be seen later in this paper, the organic loading limit plays an important role, as it usually controls the design of the wetland system for higher temperatures.

5. Method Description and Validation

This section presents a procedure for rapid sizing of a new FWS constructed wetland, based on specified BOD, pathogen, nitrogen and phosphorus removal efficiency, as well as for determining the removal performance of existing constructed wetland systems, using the presented theory and the nomograph of Figure 1. In hydraulic design, Equation (14) is proposed because of its simplicity (it does not require a trial-and-error procedure), and based on the results of the sensitivity analysis presented in the following Section 7.1.

5.1. DESIGN OF NEW FWS CONSTRUCTED WETLANDS

In sizing a new FWS constructed wetland, the following parameters are typically known: the design values of Q, C_e/C_i for one or more pollutants, T, $L\!:\!W$ (preferably between 2:1 to 5:1) and the vegetation porosity ϕ (typically in the range of 0.65 to 0.75) (Reed *et al.*, 1995). To size the system with the above variables specified, the following procedure is used:

1. The value of y is computed from Equation (14), which should be in the range 0.1 m to 0.6 m. If $y > 0.6$ m, two parallel systems are considered or the ratio $L\!:\!W$ is reduced (Reed *et al.*, 1995). For the computed value of y, it is checked if Equation (15) holds. It has to be noted that Equations (11)–(13) can also be used, but a trial-and-error procedure has to be followed, since t enters in these equations.
2. If BOD removal is required, then the hydraulic residence time t_{BOD} [d] is estimated on the basis of Equation (1) and the appropriate reaction rate constant of Table I.
3. If coliform removal is required, then the hydraulic residence time t_{COLI} [d] is estimated on the basis of Equations (2) and (4) and the appropriate reaction rate from Table I.
4. If nitrogen removal is required, then the hydraulic residence time t_{TN} [d] is estimated on the basis of Figure 1, or Equation (9), and the appropriate reaction rate from Table I.
5. If phosphorus removal is required, then the hydraulic residence time t_{PHOS} [d] is estimated on the basis of Equations (2) and (4) and the appropriate reaction rate from Table I.
6. From the above steps up to four hydraulic residence time values are estimated, depending on the removal requirements of the pollutants. The design value of the hydraulic residence time is the maximum of these four values.
7. Steps 1–5 are repeated for winter and summer conditions (i.e., lowest winter and summer season temperatures) resulting in two hydraulic residence time values. On the basis of these two values and the corresponding populations, the design conditions are determined.
8. From the estimated surface area (Steps 1–7) and the chosen aspect ratio $L\!:\!W$, the values of W and L are easily computed.

5.2. PERFORMANCE EVALUATION OF EXISTING FWS CONSTRUCTED WETLANDS

In the removal performance analysis of an existing constructed wetland the design values of Q, T, L, W and ϕ are known. To calculate the system performance with the above variables specified, the following procedure is used:

1. The value of y is computed from Equation (14) or Equations (11)–(13), and it is checked whether $y \leq 0.6$ m. Equation (15) is checked to see if the organic loading is smaller than 10 g m^{-2} d^{-1}, and if not, the influent flowrate Q should be reduced accordingly.
2. The values of t and h_1 are computed from Equations (3) and (4) and, to ensure satisfactory NH_3 removal efficiency, it is checked whether $t > 6$ to 8 d.
3. The removal efficiencies for BOD, coliforms, nitrogen, and phosphorus are obtained from Equations (1), (2) as appropriate, or the nomograph of Figure 1 with the appropriate rate constants found in Table I.

5.3. METHODOLOGY VALIDATION WITH EXISTING DATA

Available data were collected concerning the area and the operating conditions of existing FWS constructed wetland systems in the U.S. from an existing database (Kadlec and Knight, 1996). It has to be emphasized that available data in the literature on such systems are limited, and existing studies usually contain incomplete information which makes validation studies difficult. The data used is summarized in Table II along with the estimated areas from the methodology presented in this paper (Section 5.1). The selected constructed wetland systems that were considered for the validation process had a mean air temperature higher than 5 °C. For the design methodology the water temperature was considered equal to the mean air temperature. Information on the influent and effluent concentrations of at least one pollutant was available. Since other design parameter information was not available, the following assumptions were made in all cases in estimating the system's surface area: $\phi = 0.65$, $\gamma = 0.1$ and use of Equation (14) with $a = 10^7$ d^{-1}m^{-1} (dense vegetation). Computations were made for two aspect ratios, which cover the common range, namely $L{:}W = 2{:}1$ and 5:1.

A way to assess the validation is through the use of scattergrams where predicted quantities are plotted against observed ones. In the scattergram, a regression straight line of the following form is fitted through the data: $A_p = r\,A$, where A_p is the predicted wetland surface area [ha] and A is the real (as constructed) wetland surface area [ha]. The slope r of this regression line is compared with the 1:1 slope line (perfect match). The value of the slope r is a measure of the over ($r > 1.0$) or underestimation ($r < 1.0$) of the predicted values compared to the real data. In addition, the square of the correlation coefficient R^2 of the regression line is computed. The lower the value of R^2 falls below 1.0, the worse the data correlation is (i.e., the greatest the scatter). Therefore, best calibration requires that values for both slope r and correlation coefficient R^2 be as close to 1.0 as possible.

Table II. Summary of data from existing constructed FWS wetlands (Kadlec and Knight, 1996) and listing of the predicted area based on these data

			Concentrations		Wetland surface area		
						Predicted* A_p [ha]	
System name	T [°C]	Q [m^3 d^{-1}]	Influent[mg L^{-1}]	Effluent [mg L^{-1}]	Real A [ha]	$L{:}W = 2{:}1$	$L{:}W = 5{:}1$
Bear Bay, SC, USA	6.0	876.63	$C_{i,BOD} = 13.50$	$C_{e,BOD} = 1.90$	28.3	18.2	14.5
			$C_{i,TN} = 17.58$	$C_{e,TN} = 2.35$			
			$C_{i,PHOS} = 3.88$	$C_{e,PHOS} = 0.40$			
Boggy Gut, SC, USA	6.0	5826.78	$C_{i,BOD} = 6.30$	$C_{e,BOD} = 3.00$	20.2	48.0	38.2
			$C_{i,TN} = 11.22$	$C_{e,TN} = 3.53$			
			$C_{i,PHOS} = 4.26$	$C_{e,PHOS} = 3.35$			
Fort Deposit, AL, USA	9.0	673.73	$C_{i,BOD} = 32.90$	$C_{e,BOD} = 6.90$	6.0	2.4	1.9
Gustine, CA, USA	9.0	128.71	$C_{i,BOD} = 173.30$	$C_{e,BOD} = 36.70$	0.4	0.7	0.5
Johnson City, TX, USA	10.0	114.00	$C_{i,BOD} = 20.0$	$C_{e,BOD} = 8.00$	0.1	0.3	0.3
			$C_{i,PHOS} = 7.00$	$C_{e,PHOS} = 5.50$			
Mt View CA, USA	5.0	2820.98	$C_{i,BOD} = 33.40$	$C_{e,BOD} = 23.10$	4.3	2.1	1.6
W. Jackson County, USA	5.0	6268.00	$C_{i,BOD} = 25.93$	$C_{e,BOD} = 7.40$	22.7	12.8	10.2

**Note*: In area estimate A_p, it was assumed: $\varphi = 0.65$, $\gamma = 0.1$ and use of Equation (14) with $a = 10^7$ d^{-1}m^{-1} (dense vegetation). Two computations were made with aspect ratios $L{:}W = 2{:}1$ and 5:1.

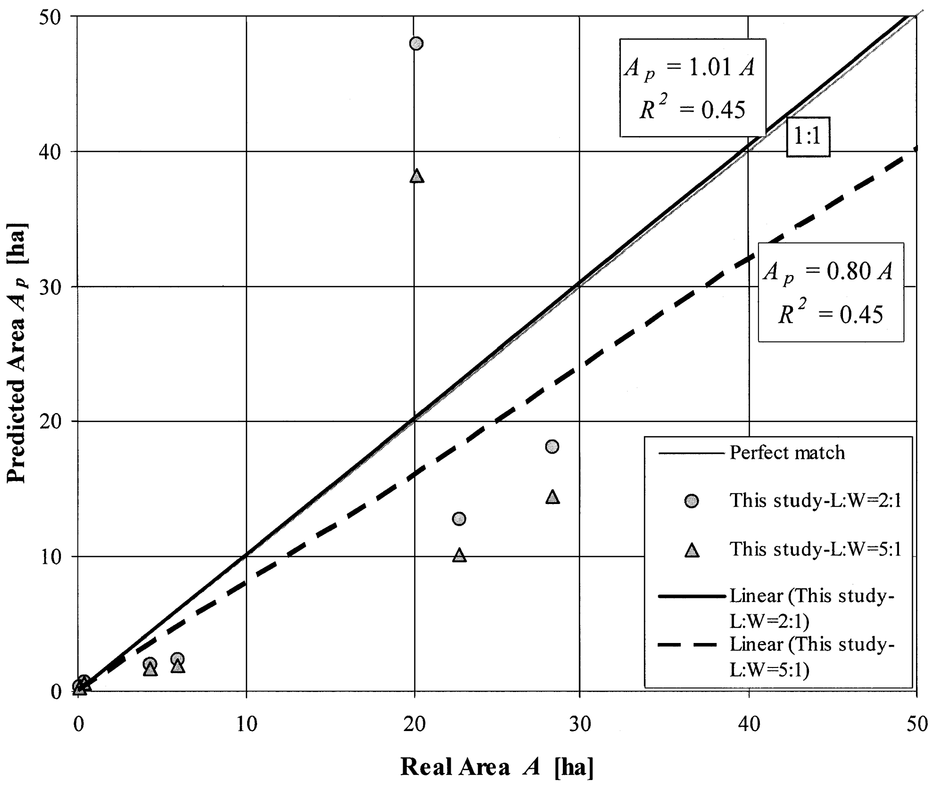

Figure 2. Linear correlation between real (as constructed) and predicted wetland area values for existing FWS constructed wetland systems.

Results for the selected wetland sites are presented in Figure 2. The slope r of the regression line, based on the methodology presented in this paper, has the value of 1.01 for $L{:}W$ = 2:1 and 0.80 for $L{:}W$ = 5:1. Since this range of $L{:}W$ values is the common one, the predictions of the estimated values are considered good. The R^2 value is the same for both values of the aspect ratio (0.45); it is not very high, showing scattering of the data around the line. However, the agreement is considered overall satisfactory, taking into account that, as mentioned earlier, the exact values of the design parameters T, ϕ, $L{:}W$, γ and a for each system were not available and assumptions were made.

6. Season-Dependent System Capacities

The increased capacity of a constructed wetland system during the hot summer months makes possible wastewater treatment from larger summer populations, while still providing the required removal efficiency in the winter. This can be a significant advantage over conventional systems in areas where the summer temperatures are high and tourism can increase the permanent (winter) population. FWS constructed wetland systems can accept higher loads during summer, when the design is controlled by BOD or nitrogen removal, since in both cases the removal efficiency depends on temperature.

In relation to BOD, if Equation (15) is not fulfilled under winter or summer conditions, then $P_S/P_W = 1$, where P_W and P_S are the winter and summer populations, respectively. If Equation (15) is fulfilled under winter but not under summer conditions, then Equation (5) can be expressed as:

$$A_S = \frac{C_i\, Q_S}{10} \tag{16}$$

Similarly, Equation (1) for BOD removal under winter conditions can be expressed as:

$$A_W = -\frac{\ln(C_e/C_i)\ Q_W}{K_{TW}\, y_W\, \varphi} \tag{17}$$

where: T_W is the winter design water temperature [°C]; y_W is the winter flow depth [m]; and K_{TW} is the reaction rate parameter [d^{-1}] for BOD removal (Table I) under winter conditions. Since $A_S = A_W$, Equations (16) and (17) are set equal and the resulting equation is solved for P_S/P_W:

$$\frac{P_S}{P_W} = -\frac{10\ \ln(C_e/C_i)}{C_i K_{TW}\ y_W\ \phi} \tag{18}$$

If relation (15) is fulfilled under summer but not under winter conditions, then similarly to the procedure used for the estimation of Equation (18) the ratio P_S/P_W can be estimated from the following equation:

$$\frac{P_S}{P_W} = -\frac{C_i\, K_{TS}\, y_S\, \phi}{10 \ln(C_e/C_i)} \tag{19}$$

where: T_S is the summer design water temperature [°C]; y_S is the summer flow depth [m]; and K_{TS} is the reaction rate parameter [d^{-1}] for BOD removal (Table I) under summer conditions.

If Equation (15) is fulfilled under winter and summer conditions, then, similarly to the procedure used for the estimation of Equation (18), the ratio P_S/P_W can be estimated from the following equation:

$$\frac{P_S}{P_W} = \frac{K_{TS}\, y_S}{K_{TW}\, y_W} \tag{20}$$

If the ratio of the actual summer to winter population exceeds the computed ratio P_S/P_W for the given summer and winter design water temperatures, on the basis of Equations (18) or (19) or (20), then summer conditions control the design. Otherwise, winter conditions control the design and the constructed wetland can serve a summer population up to P_S.

The ratio of summer to winter population based on nitrogen removal for FWS constructed wetland systems is not a simple expression. One way, however, to compute this ratio is the following. On the basis of Equation (4), and assuming that A, y and ϕ do not change, one gets:

$$\frac{P_S}{P_W} = \frac{t_{TN,W}}{t_{TN,S}} \tag{21}$$

where $t_{TN,W}$ and $t_{TN,S}$ are winter and summer hydraulic residence times required for nitrogen removal. Values for $t_{TN,W}$ and $t_{TN,S}$ can be computed from Figure 1, as a function of winter and summer temperatures T_W and T_S, and the ratio P_S/P_W can be computed from Equation (21).

For FWS systems, y is a function of Q (Equation (14)), and therefore, population. In other words, the summer flow will be deeper if $P_S > P_W$. Since the summer depth y_S is larger than the winter depth y_W, the summer value γ_S of parameter γ is lower than the winter value γ_W of γ, because for the same bed slope (assuming normal flow) it is:

$$\gamma_S y_S = \gamma_W \, y_W \tag{22}$$

7. Sensitivity Analysis

7.1. FLOW DEPTH

The sensitivity of Equations (11)–(14) used for flow depth estimation is analyzed as a function of the population served (Figure 3) and the ratio $L{:}W$ (Figure 4). Figure 3a presents the flow depth y [m] as a function of the population P [capita], assuming $L{:}W = 2{:}1$, the unit daily BOD production $\beta = 50$ g capita^{-1} d^{-1}, the unit flow rate $q = 0.15$ m^{3}capita^{-1}d^{-1} and $t = 5$ d. Figure 3b presents the flow depth y [m] as a function of the population P [capita], assuming $L{:}W = 5{:}1$, the unit daily BOD production $\beta = 50$ g capita^{-1}d^{-1}, the unit flow rate $q = 0.15$ m^3 capita^{-1}d^{-1} and $t = 5$ d. The two graphs cover the common range of aspect ratio $L{:}W$ (between 2:1 and 5:1).

Graphs 4a, 4b and 4c in Figure 4 present the flow depth y [m] as a function of the ratio $L{:}W$, assuming three populations served, namely $P = 1000$, 5000 and 10000 capita, respectively. For all three, $\beta = 50$ g capita^{-1}d^{-1}, $q = 0.15$ m^3/capita^{-1} d^{-1} and $t = 5$ d. As mentioned, in Equation (13), for sparse vegetation $\beta_1 = 1$ m$^{1/6}\cdot$ s and for dense vegetation $\beta_1 = 4$ m$^{1/6}\cdot$s, and in Equation (14) for sparse vegetation $a = 5\times 10^7$ d^{-1}m^{-1} and for dense vegetation $a = 10^7$ d^{-1}m^{-1}.

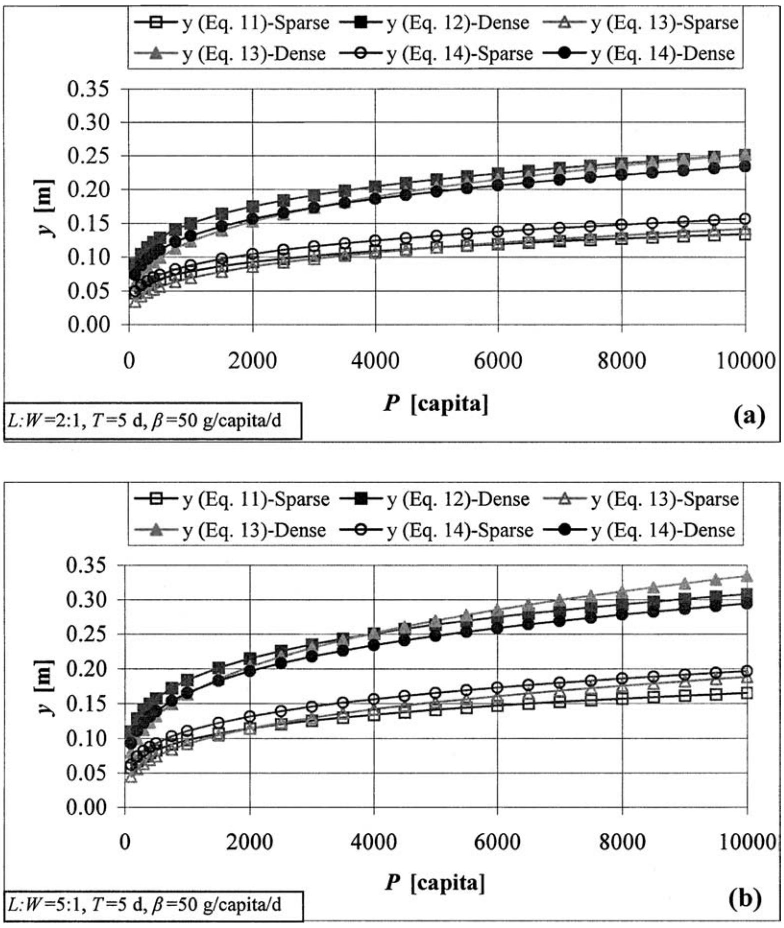

Figure 3. Flow depth of the FWS constructed wetland system, as function of population P [capita] for two aspect ratios L:W: (a) L:W = 2:1; and (b) L:W = 5:1.

From Figure 3 one can conclude the following:

1. The flow depth increases as population increases and as L:W increases.
2. For sparse vegetation [Equations (11), (13) with $\beta_1 = 1m^{1/6}\cdot$s and (14) with $a = 5 \times 10^7$ $d^{-1}m^{-1}$] and for dense vegetation [Equations (12), (13) with $\beta_1 = 4$ $m^{1/6}\cdot$s and (14) with $a = 10^7$ $d^{-1}\cdot m^{-1}$], it is evident that the flow depth y increases by approximately 50 to 70% when the vegetation changes from sparse to dense. This conclusion is independent of the aspect ratio L:W, and it is valid for a wide range of hydraulic residence time and population values. Therefore, in designing the FWS constructed wetland system, the use of equations for sparse vegetation would, based on this conclusion and Equation (4), yield a larger (more conservative) area requirement for a given hydraulic residence time instead of

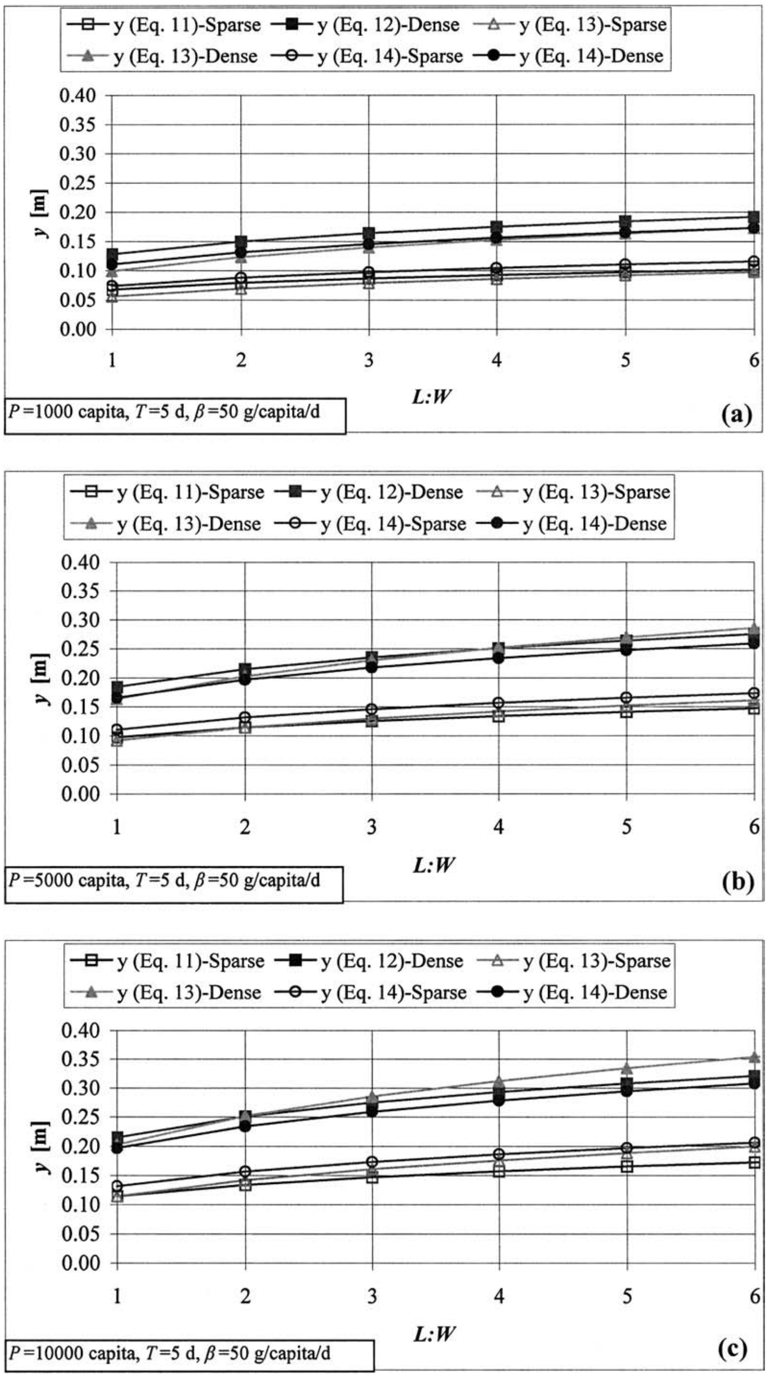

Figure 4. Flow depth of the FWS constructed wetland system, as function of aspect ratio $L:W$ for three population P values: (a) $P = 1000$ capita; (b) $P = 5000$ capita; and (c) $P = 10000$ capita.

those for dense vegetation. Or, in reverse, a certain system's performance would increase as the vegetation becomes denser.

3. For the commonly used range of L:W and for sparse vegetation the highest flow depths are estimated on the basis of Equation (14) ($a = 5 \times 10^7$ d^{-1}m^{-1}); the lowest flow depths are estimated on the basis of Equation (11) for population more than about 2000 capita (L:W = 5:1) to 4000 capita (L:W = 2:1), otherwise by Equation (13) ($\beta_1 = 1$ m$^{1/6}\cdot$s). For dense vegetation and L:W = 2:1, the highest depth is predicted on the basis of Equation (12); for L:W = 5:1, the highest depth is predicted on the basis of Equation (12) up to a population of about 4000 capita and Equation (13) ($\beta_1 = 4$ m$^{1/6}\cdot$s) for higher populations. The lower flow depth is estimated on the basis of Equation (14) ($a = 10^7$ d^{-1}m^{-1}) for a population greater than about 3500 capita (L:W = 2:1) or 1250 capita (L:W = 5:1), otherwise by Equation (13) ($\beta_1 = 4$ m$^{1/6}\cdot$s).

From Figure 4 one can conclude the following:

1. For sparse vegetation, the highest flow depth is estimated on the basis of Equation (14) ($a = 5\times 10^7$ d^{-1}m^{-1}) for the entire population range; for dense vegetation, the highest flow depth is estimated on the basis of Equation (12) for $P = 1000$ capita, and on the basis of Equation (13) for large populations and aspect ratios.
2. The flow depth increases as the ratio L:W increases. Therefore, increased values of L:W result in increased values of y, which, based on Equation (4), would yield a smaller area requirement (more economic design) for a given hydraulic residence time. Nevertheless, as mentioned, it is not recommended to use L:W > 5:1, and increased depths can be achieved with water surface control at the outlet of the system.
3. A system serving a larger population would be more economic, in terms of unit area (m^2/capita) requirements, because of the increased depth (see also the following Section 7.2).

From this sensitivity analysis of the alternative equations used for the estimation of the flow depth it is evident that differences in flow depth result in differences in the required area, depending on the selected equation. Thus, one can conclude that the research on flow resistance in free water surface constructed wetland systems is not yet complete and probably the more conservative design should be employed. In this study, Equation (14) was selected for use in the following sections, as this equation estimates, for dense vegetation, relatively reduced values of flow depth and consequently relatively increased values of the required area, which leads to a conservative design. Another advantage of this equation is that it can be used for the estimation of the wetland's flow depth without time-consuming iterations.

7.2. WETLAND UNIT AREA

For a FWS constructed wetland system four typical performance criteria can be recognized, which correspond to different disposal options:

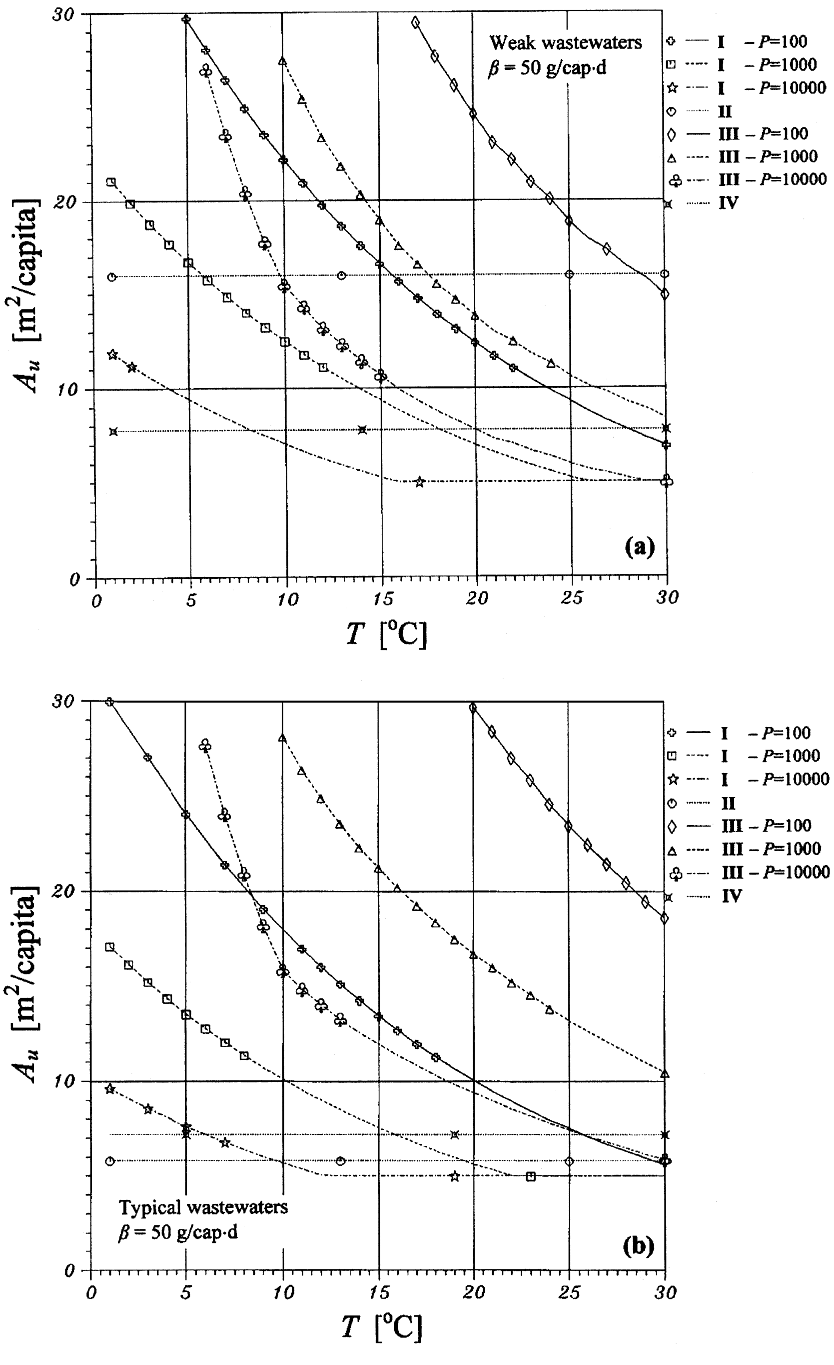

Figure 5. Unit area requirements of FWS constructed wetlands, depending on performance criteria I, II, III and IV, assuming $\beta = 50$ g capita^{-1} d^{-1}, and treating: (a) weak; (b) typical; and (c) strong domestic wastewater.

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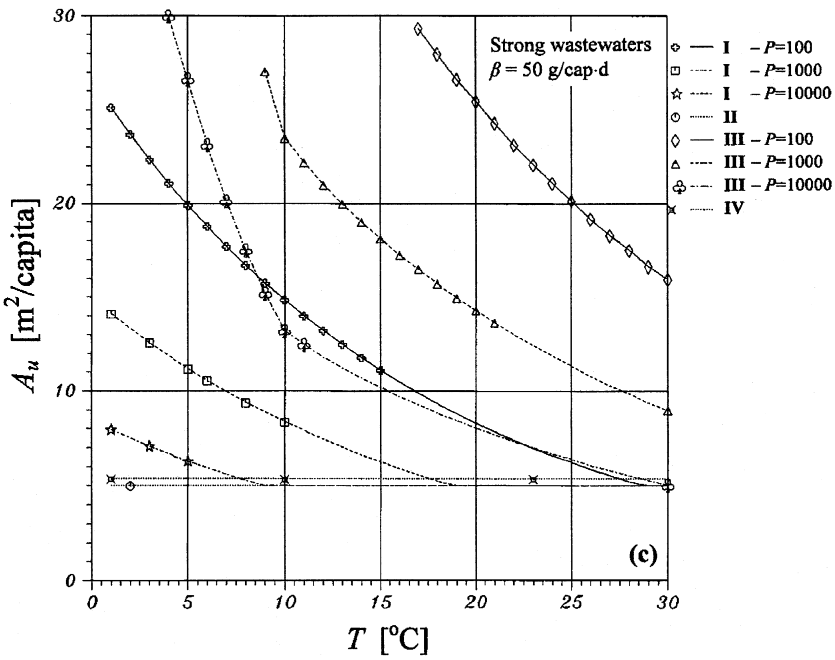

Figure 5. (*Continued*)

- Performance criterion I corresponds to a BOD effluent concentration of 30 mg L^{-1} (e.g., for effluents discharged into rivers);
- Performance criterion II corresponds to a fecal coliform effluent concentration of 1000/100 mL (e.g., for effluents used for irrigation or discharged near the coastline);
- Performance criterion III corresponds to a total nitrogen effluent concentrations of 5 mg L^{-1} (e.g., for effluents discharged into lakes); and
- Performance criterion IV corresponds to a phosphorus effluent concentration of 3 mg L^{-1} (e.g., for effluents discharged into lakes).

The graphs 5a, 5b and 5c in Figure 5, yield the unit area requirements [m^2 $capita^{-1}$] of FWS constructed wetland systems designed to meet the above defined performance criteria I, II, III and IV, as a function of the water temperature T, based on treatment of weak, typical and strong municipal wastewater, respectively. Weak wastewaters have the following characteristics: influent BOD, total nitrogen and phosphorus concentrations of 120 mg L^{-1}, 12 mg L^{-1} and 5 mg L^{-1}, respectively. For typical wastewaters, the influent BOD, total nitrogen and phosphorus concentrations are 330 mg L^{-1}, 50 mg L^{-1} and 11 mg L^{-1}, respectively. Finally, for strong wastewaters, the influent BOD, total nitrogen and phosphorus concentrations are 550 mg L^{-1}, 90 mg L^{-1} and 15 mg L^{-1}, respectively. In all cases the total coliform number is 10^8/100mL, the daily BOD contribution is $\beta = 50$ g capita^{-1} d^{-1} and the vegetation porosity $\phi = 0.65$. For the computation of the unit area requirements, and for all performance criteria, the maximum organic loading limit was set equal to 10 g m^{-2} d^{-1}.

Figure 5 can help designers in analyzing the design as a function of the *wastewater* type treated, the design temperature and the performance criteria I, II, III and IV. From this figure, one can draw the following conclusions:

1. For BOD and nitrogen removal (performance criteria I and III), the required unit area increases as population increases.
2. For BOD removal (performance criterion I), the required unit area tends to become independent of temperature for high-design temperatures and large populations served, as the design of the wetland is controlled by the maximum organic limit of 10 g m^{-2} d^{-1} (Equation 15).
3. For BOD and coliform removal (performance criteria I and II) of strong wastewaters, the design of the FWS constructed wetland system is controlled by performance criterion I, as performance criterion II is fulfilled for any *T*.
4. For coliform and phosphorus removal (performance criteria II and IV) of typical to strong wastewaters, the design of the FWS constructed wetland system is controlled by performance criterion IV, as performance criterion II is fulfilled for any T.
5. For coliform and phosphorus removal (performance criteria II and IV) of weak wastewaters, the design of the FWS constructed wetland system is controlled by performance criterion II, as performance criterion IV is fulfilled for any *T*.
6. For BOD, coliform, phosphorus and nitrogen removal (performance criteria I, II, III and IV) of typical to strong wastewaters, the design of the FWS constructed wetland system is controlled by performance criterion III, as performance criteria I, II and IV are fulfilled for $T < 25$ °C.

Figure 5 can help designers in formulating an overview of the system's behavior relative to the wastewater type treated, the design temperature and the performance criteria I, II, III and IV. From Figure 5 one can make the following simplifications in the design procedure presented above:

1. For BOD and coliform removal (performance criteria I and II) of strong *wastewaters*, Steps 3, 6 and 7 can be omitted since the design of the FWS is based on BOD removal. When the area requirements are constant, independent of temperature, then the conditions controlling the design of the wetland are determined on the basis of maximum population between summer and winter. If the area requirements for BOD removal is function of the design temperature, then the conditions controlling the design of the wetlands are determined on the basis of Equations (18) or (19) or (20) or (21).
2. For coliform and phosphorus removal (performance criteria II and IV) of typical to strong wastewaters, steps 3, 6 and 7 can be omitted, since the design of the FWS

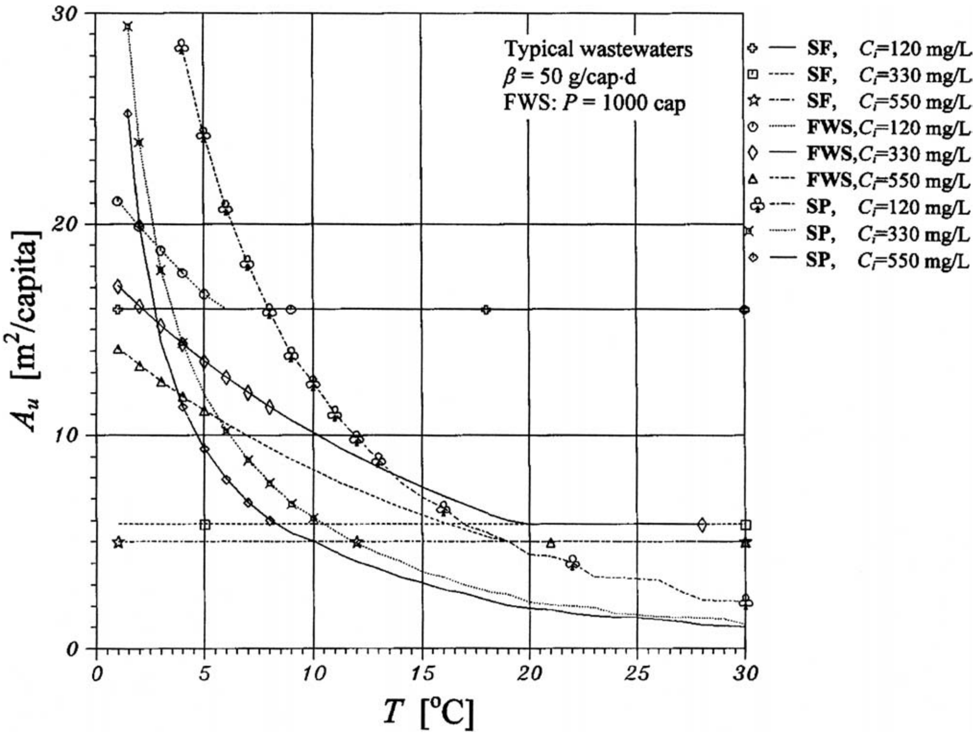

Figure 6. Unit area requirements (performance criteria I and II) of FWS and SF constructed wetland systems, and stabilization pond systems, assuming $\beta = 50$ g capita^{-1} d^{-1} and BOD influent concentrations of 120 mg L^{-1}, 330 mg L^{-1}, and 550 mg L^{-1}.

constructed wetland system is based on phosphorus removal. The conditions controlling the design of the wetland are determined on the basis of maximum population between winter and summer.

3. For coliform and phosphorus removal (performance criteria II and IV) of weak wastewaters, steps 5, 6 and 7 can be omitted, since the design of the FWS constructed wetland system is based on coliform removal. The conditions controlling the design of the wetland are determined on the basis of maximum population between winter and summer.
4. For BOD, coliform, phosphorus and nitrogen removal (performance criteria I, II, III and IV) of typical to strong wastewaters and for $T < 25$ °C, steps 2, 3, 5 and 6 can be omitted, since the design of the FWS constructed wetland system is based on nitrogen removal. The conditions controlling the design of the system are determined on the basis of maximum hydraulic residence time value for nitrogen removal, and population served between winter and summer (Equation 21).

8. Comparison of FWS Constructed Wetlands with Other Aquatic Natural Systems

To guide planners in a preliminary selection between SF and FWS constructed wetland systems and stabilization pond systems that provide secondary treatment (BOD concentrations and number of fecal coliform effluent less than 30 mg L^{-1} and 1000/100 mL, respectively, i.e., performance criteria I and II) the unit area requirements are compared for various influent BOD concentrations. Figure 6 presents the unit area requirements for these three aquatic natural systems for BOD influent concentrations C_i ranging from 120 mg L^{-1} to 550 mg L^{-1}, coliform influent concentration equal to 10^8/100 mL and daily BOD contribution equal to $\beta = 50$ g capita^{-1} d^{-1}.

The design of the FWS system is based on the procedure presented above assuming $P = 1000$ capita and $\phi = 0.65$. The design of the SF system is based on the design procedure presented by Economopoulou and Tsihrintzis (2003), assuming $y = 0.6$ m and $\phi = 0.38$. The design of the stabilization pond system, which comprises one anaerobic, one facultative and several maturation ponds, is based on the design procedure presented by Economopoulou and Tsihrintzis (2004), which estimates the optimum area of the system designed to meet the desired performance criteria. For the estimation of the optimum stabilization pond area the anaerobic, facultative and maturation pond depths are assumed equal to 3 m, 1.5 m and 1.5 m, respectively.

From Figure 6 it is evident that constructed wetland systems are favored over stabilization ponds for high BOD influent concentrations, small differences between summer and winter populations and low design temperatures. Thus, in developing countries where C_i is high, and in regions with temperate or cold climate and nearly constant population throughout the year, constructed wetland systems should always be considered as an alternative control system.

9. Application Example

The following illustrative design example is based on the steps described in Section 5.1: A coastal city in the Mediterranean has a winter population P_W of 2000 capita. The unit wastewater flow q is 0.15 m^3 capita^{-1} d^{-1} (therefore, Q is 300 m^3 d^{-1}), the design winter air temperature $T_{\mathrm{a,W}}$ is 6 °C. The BOD concentration of the untreated influent is 330 mg L^{-1} (about 50 g capita^{-1}d^{-1}) and after preliminary treatment the BOD concentration is reduced to 220 mg L^{-1}. The fecal coliform number is 10^8/100 mL. Total nitrogen and phosphorus influent concentrations are 30 and 7 mg L^{-1}, respectively. The performance criteria only consider BOD and coliforms. The required BOD effluent concentration is 30 mg L^{-1}, whereas the effluent number of fecal coliforms should not exceed 1000/100 mL. The design summer air temperature $T_{\mathrm{a,S}}$ is 18 °C and the summer population rises to 2500 capita. Under these design conditions size the FWS constructed wetland system that provides the required removal efficiency throughout the year.

The solution is according to the following steps:

1. From Equation (14), $y = 0.173$ m given $Q = 300$ m^3 d^{-1} and assuming $L{:}W = 3{:}1$, $\gamma = 0.1$ and $a = 10^7$ m^{-1}d^{-1}. Relation (15) is fulfilled under winter conditions, assuming $\phi = 0.65$.
2. Since $P_S > P_W$ then from Equations (14) and (22) $\gamma_S = 0.09$ and $y_S = 0.183$ m. Relation (15) is fulfilled under summer conditions, assuming $\phi = 0.65$. The actual ratio P_S/P_W is smaller than the ratio estimated from Equation (20), thus winter conditions control the design of the wetland for BOD removal. Given $C_e/C_i = 0.14$ and $T_a = 6$ °C, Equation (1) yields $t_{BOD} = 6.64$ d, which from Equation (4), results in $A_{BOD} = 17, 704$ m^2.
3. Since $P_S > P_W$, then summer conditions control the design of the wetland for coliform removal. Hence, on the basis of Equation (2) and the appropriate values of the reaction rate constant listed in Table I, one estimates $(h_1)^{-1} = 38.46$ d m^{-1}, and Equation (4), under summer conditions, yields $A_{COLI} = 14, 391$ m^2.
4. The value of A_{BOD}, for BOD removal in winter, is higher than the value of A_{COLI}, for coliform removal in summer, therefore, BOD removal controls the design under winter conditions.
5. For $L{:}W = 3{:}1$, the length $L = 230.5$ m whereas the width $W = 76.8$ m.
6. The effluent concentrations for nitrogen and phosphorus estimated from Figure 1 and Equation (1) under winter conditions are: 22.6 mg L^{-1} and 1.3 mg L^{-1}, respectively. Similarly, the effluent concentrations for nitrogen and phosphorus under summer conditions are: 9.5 mg L^{-1} and 1.9 mg L^{-1}, respectively.

10. Summary and Conclusions

A simplified step-by-step approach was presented allowing for the design of new and performance evaluation of existing FWS constructed wetland systems. The area requirements are based on the removal of BOD, coliforms, nitrogen and phosphorus. Alternative equations are presented for hydraulic computations. The methodology was validated through the comparison of estimated surface areas with areas of existing systems.

An overview of the FWS system's behavior over a wide range of conditions was offered by sensitivity analysis of the unit area requirements for different types of wastewaters and performance criteria. The results of this analysis simplify considerably the design methodology. In addition, for tourist areas with increased summer populations, simple equations were derived for the estimation of the maximum seasonal population that can be served considering the system's performance and capacity dependency on the seasonal climatic conditions. In addition, the sensitivity of the unit area requirements of SF and FWS constructed wetlands, and stabilization ponds was presented. This analysis can facilitate enforcement agencies in the preliminary screening of existing or perspective constructed wetland systems based on their performance, or help environmental planners in properly evaluating alternative wastewater control and disposal options.

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