Estimation of the performance of an experimental free water surface wetland in the Venice Lagoon watershed

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Abstract: *We established a pilot wetland to verify the efficiency of free water surface wetlands in improving the inlet surface water quality of Venice Lagoon. Three subsystems were recognized in the wetland: (i) riparian swamp, (ii) riparian-marsh transition zone, and (iii) marsh. We evaluated the abatement efficiency over three experimental years (2002–2005). The effect of detention times of 14 and 7 days was also tested. There was good nitrogen removal (58% of total nitrogen and 85% of N-NO_3 with 14-d detention time), especially in the first subsystem, and variable phosphorus removal (44% of total phosphorus with 14-d detention time), located mostly in the second subsystem. The whole three-subsystem mosaic performed better than each part alone. We calibrated a first-order areal model of nitrogen to estimate local parameters for future planning of treatment wetlands in the Venice Lagoon watershed. To calibrate the model different methods and data sets were used. The calibration of removal rate constants using different approaches led to comparable results; however, the transect data approach provided additional information on wetland performance.*
Keywords: *abatement efficacy, different subsystems, first order area model, free water surface wetland*

1.Introduction

Wetlands have been shown to be effective for the treatment of polluted water sources. In particular, wetlands are considered to be effective nitrogen traps, and nitrification–denitrification processes are probably the main methods of nitrogen removal (e.g., Kadlec and Knight, 1996). Additionally, the use of a mosaic of different subsystems improves wetland performance (Ansola et al., 2003).
The Venice Lagoon is a delicate environment that contains polluted water and is at risk of eutrophication. To address these problems, the region established a master plan for nutrient load abatement that included the use of wetlands, among other nonpoint-source pollution control tools. A pilot plant, in the form of a constructed wetland, was established and monitored to study the effectiveness of free-water surface (FWS) wetlands for the treatment of reclaimed water under local environmental conditions. The aim of the study was to obtain information to facilitate the estimation of local parameters for future planning of reclaimed water treatment wetlands in the Venice Lagoon watershed. In such cases, it is indeed strongly recommended (e.g., Kadlec and Knight, 1996; Rousseau et al., 2004) to use parameters fitted under similar environmental conditions.
We focus on the nutrient removal performance of the wetland to (i) evaluate the system performance and verifying the effects of hydraulic parameters on wetland performance, and (ii) calibrated a first-order model (Kadlec and Knight, 1996) model with different methods and different data sets (input/output data and transect data) to evaluate differences among the obtained parameters.

2. Materials and Methods

In 2002, an experimental FWS wetland (Canale Novissimo) was constructed in the Venice Lagoon watershed near Chioggia (Veneto, Italy). The wetland was created in a reclaimed lowland delta area, currently below sea level, using an abandoned channel (Figure 1).
Water was pumped in and out of the system; in this way, the main hydraulic factors were controlled by means of an integrated remote control system. The water came from an agricultural reclaimed channel, which drained a 135 ha sub basin (80% crops, 20% urban and industrial land use).

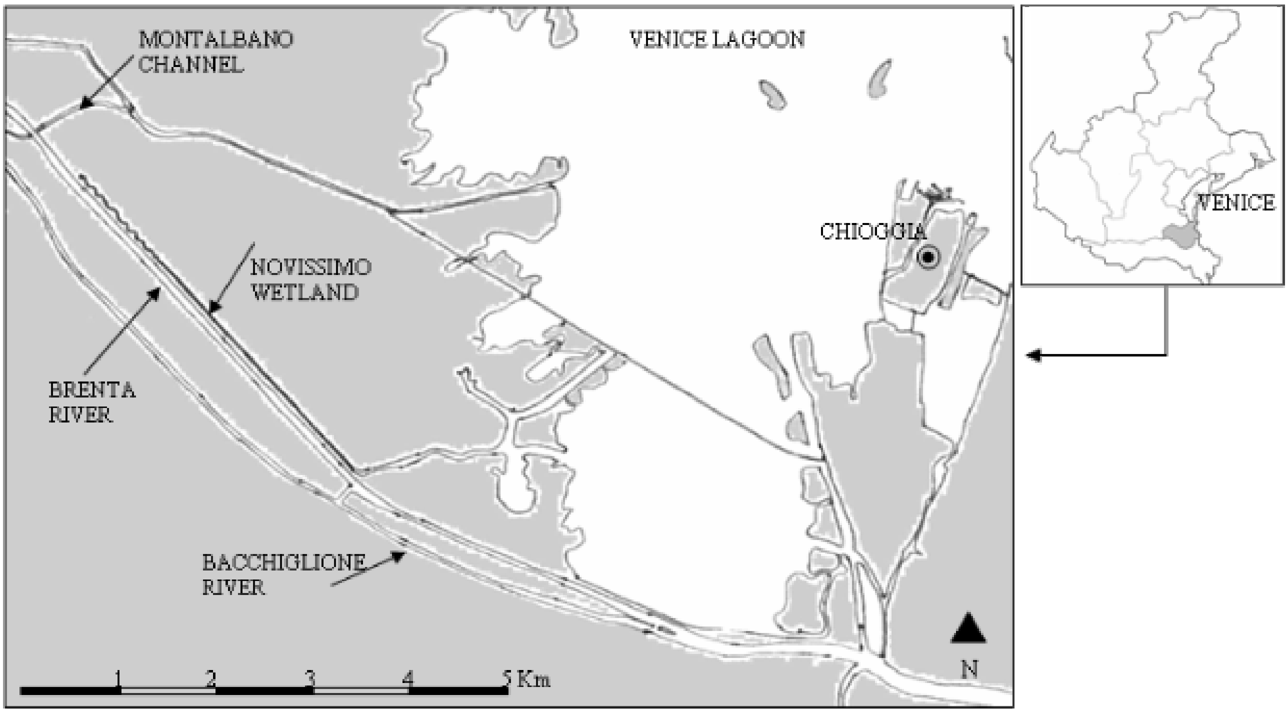

Figure 1: Map of the Canale Novissimo wetland

The wetland was 50 m wide and 4140 m long with a mean depth of 80 cm, and it consisted of three subsystems that differed in morphology and vegetation. The first (1480 m) was a riparian swamp ecosystem, dominated by hydrophytic trees and shrubs, in which meanders were constructed to allow soil flooding and maximize the contact between water and the root zone. The second (1040 m) was a riparian and wet ecosystem, in which trees and shrubs covered one third of the emergent-planted area, whereas the remaining area was covered by marsh vegetation. The third (1620 m) was a marsh ecosystem, with shrubs and trees having an ancillary role (e.g., slope protection, habitat creation). The construction of the first and part of the second subsystems required extensive modifications of the original conditions, which were done by adding agricultural soil to the previous channel banks. The vegetation for restoration of the three subsystems was chosen in accordance with the phytosociological classification of the transitional zone between the mainland and Venice Lagoon. Data loggers at the inlet and outlet pumps gave continuous records of water stage and inflow and outflow. The dataset used here includes two experimental periods: from April 2004 to April 2005 we tested a detention time of 14 days, and from April 2005 to April 2006 we tested a detention time of 7 days.

Free-water samples were collected every 18 days at the entrance point, the exit point, and two intermediate sections. We analyzed pH, total suspended solids (TSS), total phosphorus (TP), soluble phosphorus (Psol), nitrate ($N\text{-}NO_3$), nitrite ($N\text{-}NO_2$; MIPAF, 2000), ammonium ($N\text{-}NH_4$), and organic nitrogen (Norg; CNR-IRSA, 1994) in free water. Total nitrogen (TN) was calculated as the sum of the nitrogen species.

Wetland performance was analyzed as mass removal rate (MRR) and percent mass removal (PMR):

$$MRR\left[kg \cdot d^{-1}\right] = M_{in} - M_{out} \qquad (1)$$

$$PMR = \left(m_{in} - m_{out}\right)/m_{in} \times 100 \qquad (2)$$

where M is the mass input or output rate [kg d^{-1}] and m is the mass load [kg]

The mass removal rate (MRR) is the simplest assessment term and quantifies the nutrient mass removed by the wetland over a given period. It is recommended for its transparency (e.g., Kadlec

and Knight, 1996). The percent mass removal (PMR) describes the nutrient load reduction with respect to the incoming load. PMR and represents the efficiency of a wetland.
To evaluate nitrogen parameters we adopted a first-order areal model. First-order models are the state of the art of mass removal modeling. To date, the model that provides the best performance is the Kadlec and Knight model (Rousseau et al., 2004), if its assumptions are met. A simple mass balance and first order kinetics describe total nitrogen removal (Kadlec and Knight, 1996):

$$q\frac{dC}{dy} = -k(C - C^*) \qquad (3)$$

where y = x/L is the fractional distance, x is the distance from the inlet [m], L is the wetland length [m], k is the removal rate constant [m d^{-1}], C is the averaged concentration [g m^{-3}], C* is the background concentration (from autochthon production and sediment release) [g m^{-3}], and q is the averaged hydraulic loading rate [m d^{-1}].
We averaged the nutrient concentrations over two sampling data sets, obtaining 15 sets of averaged concentrations. We verified that flow-weighted concentrations were not different from time-averaged concentrations, as suggested by Kadlec & Knight (1996), by means of the nonparametric Wilcoxon's matched pairs test among dependent samples (data not shown).
We used three different methods to calibrate the model removal rate constant.
Input/output data (I/O) about flows and concentrations were used for calibration of a rate constant for each of the 15 averaging periods from equation (3), and the resulting values were averaged over the whole period, obtaining the "averaged k".
The same dataset was used also to estimate the "calibrated k" and the background concentrations using the Generalized Reduced Gradient (Microsoft Excel™ "Solver" routine) with the least-squares minimization criterion (Stone et al., 2004).
Data collected along the length of the treatment wetland produced an alternative parameter set that was used to estimate the "transect data k". The logarithm of relative concentration in each sampling site was regressed with its relative distance from the inlet (y), to estimate the slope (k/q) of the rearranged equation:

$$\ln\left(C_y / C_{in}\right) = -k/q \cdot y \qquad (4)$$

where C_y is the averaged concentration at the y point [g m^{-3}] (first intermediate section y = 0.36; second intermediate section y = 0.61) and C_{in} is the averaged inlet concentration [g m^{-3}]. From the slope of the regression, knowing the hydraulic loading rate q, we calculated the "transect data k".
Normality of the data was tested with a Lilliefors test and a Shapiro–Wilk's test ($p < 0.05$) before applying the regression analysis.

3. Results and Discussion
MRR and PMR are shown in Table 1. We did not include organic nitrogen values because the concentrations were always below the detection limit (1.0 mg L^{-1}). The results suggest that the decrease of the detention time caused the MRRs reduction (Gonzalez et al., 2001), with the exception of total suspended solids, while only total phosphorus and total nitrogen PMR decreased with the reduced detention time. In fact, the PMR of N-NO_3, N-NH_4 increased with reduced detention time (Persson and Wittgren, 2003).

Table 1: Nutrient mass removal rates and percent mass removal, τ: detention time; SS: suspended solids; TP: total phosphorus; TN: total nitrogen.

	Mass Removal Rate [kg d^{-1}]					Percent Mass Removal				
τ	SS	TP	TN	$N\text{-}NH_4$	$N\text{-}NO_3$	SS	TP	TN	$N\text{-}NH_4$	$N\text{-}NO_3$
14	84.04	0.21	4.78	1.17	3.38	56.79	43.65	59.17	71.50	86.22
7	91.18	-0.21	3.37	0.99	2.12	70.29	-	43.75	71.81	98.56

The nutrient removal range reported in the literature is very large (Table 2), but our wetland performance was within that range, despite the low incoming concentrations. The average nutrient concentrations in the outlet water were frequently similar or lower than those found in natural wetlands.

Table 2: Comparison of Canale Novissimo wetland to other surface flow wetlands. τ: detention time; Cin: inlet concentration; Cout: outlet concentration; R: percent mass removal; TP: total phosphorus; TN: total nitrogen.

	TP			TN			$N\text{-}NH_4$			$N\text{-}NO_3$		
	C_{in} [mg L^{-1}]	C_{out}	R %	C_{in} [mg L^{-1}]	C_{out}	R %	C_{in} [mg L^{-1}]	C_{out}	R %	C_{in} [mg L^{-1}]	C_{out}	R %
Canale Novissimo												
τ 14 days	0.14	0.10	44	3.36	1.43	58	0.69	0.22	70	1.67	0.21	85
τ 7 days	0.06	0.11	-	1.92	1.12	44	0.38	0.11	72	0.54	0.01	99
Natural wetlands†		0.04						2.02			0.10	
Surface Flow Wetlands												
Kadlec & Knight, 1996‡	3.78	1.62	34	9.03	4.27	55	4.88	2.23	38	5.56	2.15	51
ITRC, 2003 §	24.40	8.10	55	117.20	36.20	75	86.60	28.70	71			
Frankenbach & Meyer, 1999				11.80	8.63	17	0.72	4.36	-	2.41	0.16	95

†From Kadlec and Knight (1996).
‡Average values for North American surface flow treatment systems.
§Common Constituents and Treatment Efficiencies in Agricultural Wastewaters (pg. 46).

The subsystems MRRs indicated that most part of net removal was located into the first, and partially the second subsystems (Table 3). This could mean that a shorter wetland could be equally efficient.

The performances of the three subsystems could be compared by means of PMRs. The first subsystem was the most efficient at nitrogen removal, whereas the second subsystem was best at phosphorus removal. This could be due to the vegetation of the first subsystem, which was an important source of organic carbon for the denitrification process and a source of oxygen for the nitrification process. The first subsystem was also the more deeply modified because of the reconstruction of meanders with agricultural soils; therefore, it kept a longer time to reach an ecological equilibrium after the flooding (data not shown). This could be the reason of the low or negative phosphorus removal in the first subsystem, with respect to the second one.

Finally, the PMRs comparison indicates that the whole wetland performed better than the individual subsystems both for TN and SS.

Table 3: Detention time (τ) and nutrient removal rates for the three wetland subsystems. Whole wetland removal rates are shown for comparison purposes. SS: suspended solids; TP: total phosphorus; TN: total nitrogen.

	Mass Removal Rate [kg d^{-1}]			Percent Mass Removal %		
τ [d]	SS	TP	TN	SS	TP	TN
Whole wetland						
14	84.04	0.21	4.78	56.79	43.65	59.17
7	91.18	–0.21	3.37	70.29		43.75
First subsystem						
3	30.31	0.03	2.46	32.43	9.94	42.56
2	59.64	–0.15	2.97	45.97	-	38.55
Second subsystem						
5	23.41	0.22	0.99	25.32	50.37	20.37
3	–10.60	0.07	0.11	-15.30	17.95	2.25
Third subsystem						
6	2.92	–0.06	0.37	4.23	-	9.49
3	42.15	–0.13	0.29	52.24	-	6.35

The Novissimo wetland matched most of the assumptions required by the first-order areal model (Kadlec and Knight, 1996). The period considered in this study corresponded to steady-state conditions (data not shown). The time-averaging period corresponded to at least three hydraulic detention times. The difference between rainfall and ETP was minimal (about 0.02%) and the seepage input was about 0.2% of total inputs; thus the wetland was dominated by surface flow. Flow-weighted concentrations were not significantly different from time-averaged concentrations (data not shown). Atmospheric deposition was not sampled because it was unimportant with regard to watershed input. Indeed, the loads in the wetland via incoming water were 63 kg NO_3-N ha^{-1} yr^{-1} and 28 kg NH_4-N ha^{-1} yr^{-1}, versus 6.43 kg NO_3-N ha^{-1} yr^{-1} and 5.72 NH_4-N ha^{-1} yr^{-1} of atmospheric deposition (Comune di Venezia, 2005). The wetland was a rectangular one, 50 m wide and 4140 m long; therefore, the fractional distance y could be used (Kadlec and Knight, 1996). Flow was assumed to be unidirectional, with no variation in the cross-flow direction and no mixing in the axial direction or back mixing (plug-flow condition). Although the flow in constructed wetlands is generally intermediate between plug-flow and completely mixed conditions, the first-order model provides a conservative design estimate (Stone et al., 2004). However, the hypothesis of a tank-in-series model was also tested for ammonium and nitrates and confirmed that the wetland could be compared to a plug-flow reactor, and thus that the last assumption was matched (data not shown).

The three methods used to estimate the removal rate constant (averaged input/output k, calibrated input/output k, and transect data k) led to similar values (Table 4). The results indicated a null background concentration for ammonium and nitrate, whereas for total nitrogen the model suggested the choice of a background concentration of 1 mg L^{-1}, lower than the 1.5 indicated by Kadlec and Knight (1996).

Table 4 – Removal rate constants [m yr–1] and calibrated parameters for ammonium, nitrate, and total nitrogen

	NH_4	**NO_3**	**N**
Input/output data averaged k	k = 38.51 ± 26.39	k = 76.81 ± 68.40	k = 53.00 ± 36.83
Input/output data calibrated k	k = 30.94 C* = 0.0 mg L^{-1}	k = 69.18 C* = 0.0 mg L^{-1}	k = 50.28 C* = 1.0 mg L^{-1}
Transect data	k = 33.15 $R^2 = 0.25$, $p < 0.0001$	k = 74.29 $R^2 = 0.23$, $p < 0.0001$	k = 51.68 $R^2 = 0.35$, $p < 0.0001$

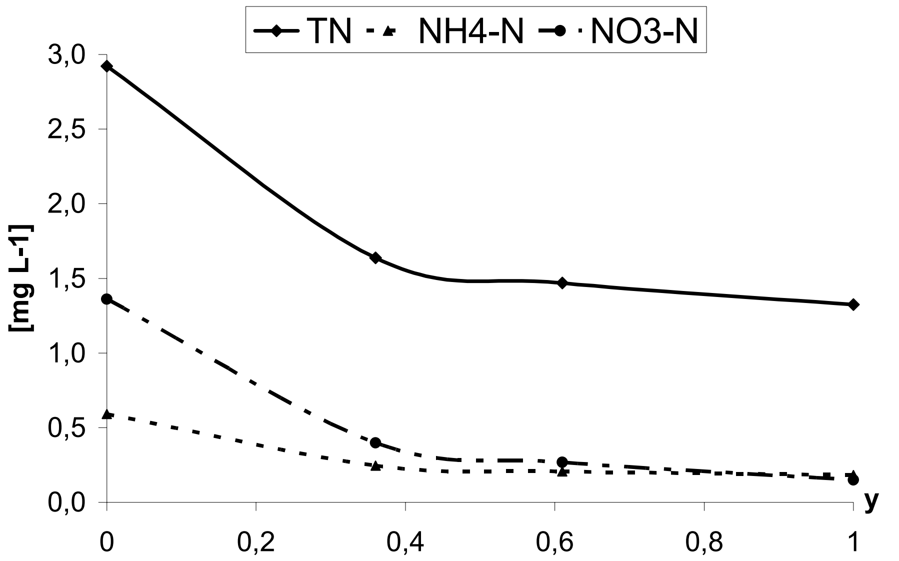

Figure 2 – Concentration profiles through the wetland. TN: total nitrogen; NH4-N: ammonium nitrogen; NO3-N: nitrate nitrogen; y: fractional distance from the inlet.

The regression equations used to calibrate the model with transect data (equation 4) explained a small fraction of the original variability. Indeed, the concentration profiles were not exactly exponential (Figure 2) because of a steep concentration reduction in the first section. This behavior could be caused by the low incoming concentrations; in the first section, they were reduced to concentrations similar to background values, limiting removal in subsequent sections.
Table 5 presents some removal rate constants estimated for free-water surface wetlands. Our wetland had the lowest nutrient loading rates, but the removal rate constants were comparable with the highest values reported in the literature, particularly for ammonium and total nitrogen.

Table 5 – Comparison among hydraulic loading rates (HLR), mass loading rates, and removal rate constants from literature data and the Canale Novissimo wetland

References	HLR [cm d^{-1}]	TN	NH_4	NO_3	kN	kNH_4	kNO_3
		[kg h^{a-1} d^{-1}]				[m yr^{-1}]	
Arheimer and Wittgren, 2002		102			40.3* ± 54.1		
Kallner and	2.1	4.9	3.6			8.4*	237.3*
Wittgren, 2001	4.8	10.1	3.4	6.7		36.5*	29.2*
Dortch, 1996	5.1	0.8			16.8		
Kadlec and Knight, 1996					22*	18*	35*
This study	8.0	0.4	0.1	0.2	53.0 ± 36.8	38.5 ± 26.4	76.8 ± 68.4

* The removal rate constant was referred to 20°C.

4. Conclusions

This research showed that wetlands could be effective also with low inlet concentrations, typical of reclaimed drainage water, reaching removal rates comparable with those described in literature (Kadlec and Knight, 1996). The wetland efficiently supported the nitrogen cycle; ammonium, nitrate, and total nitrogen removal were closely interconnected. In contrast, total phosphorus

removal was more variable. This was primarily because of the limited input, which was close to the detection limit and to the natural background levels in marsh subsystems.
The results indicated that the whole wetland was more efficient with a 14-day detention time than with a shorter one, as has been observed in other wetlands (e.g., Gonzalez et al., 2001). Our results agree with the observation that a succession of different subsystems performs better than a simpler network, and in particular, that the introduction of a terrestrial subsystem increases nutrient removal (Gonzalez et al., 2001).
The calibration of ammonium, nitrate, and total nitrogen removal rate constants for the Canale Novissimo wetland using different approaches led to comparable results, indicating that several ways can be used to estimate reliable model parameters. The choice depends on what the researcher wants to estimate; the calibration with the least-squares minimization criterion allowed estimation of both the removal rate and the background concentration, whereas the estimation of k for each averaging period could allow the study of the dependence of this parameter on temperature, hydraulic loading rate, and mass loading rates. The regression used to calibrate the model with transect data explained only a small fraction of the original variability because of spatial variability in wetland performance. While this result indicated a peculiar concentration profile, it also highlighted the opportunity to use transect data instead of an input/output data approach because it provided additional information on wetland performance.
The values obtained for nitrogen removal rate constants were comparable to literature data, despite the low mass loadings rates; therefore, the wetland was demonstrated to be effective in the treatment of reclaimed water in the Venice Lagoon watershed. An extended experimental project is ongoing to deepen the study, in particular to determine the relationships among removal rate constants and hydraulic and mass loading rates.

5. Acknowledgements
Research founded by the Ministry of Infrastructures – Venice Water Authority through its concessionary Consorzio Venezia Nuova.

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