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Vertical flow constructed wetlands subject to load variations: an improved design methodology connected to outlet quality objectives.

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Abstract This study set out to assess how vertical flow constructed wetlands (vfCW) adapt to different types of tourism-driven variations in influent load, i.e. (i) campsites, closed for six months of the year and featuring a two-month-only window of high-season activity, and (ii) tourist-interest villages either hosting tourists over at least the six months of summer while the permanent population is resident or summer festivals that create intense pollution loads in a short burst of just a few days.

The study surveyed 4 campsites and 4 tourist-interest villages that were monitored for several years, generating over 70 performance balances for vfCW that were intentionally scaled down in relation to the conventional French design for experimental trials.

The influent wastewater effectively qualifies as domestic sewage, although relatively concentrated, with the campsites presenting particularly high nitrogen concentrations (122 gTKN.L^{-1}).

The applied daily loads were also particularly high, with some combinations of load parameters (hydraulic load, organic matter, TKN) leading to 400% overloading.

Even under these drastic conditions, quality of effluent remained excellent on the characteristic organic matter parameters, with removal performances always over 85%. However, nitrification performances were poor to good. Analysis of the dataset points to two major design thresholds:

For campsites, in order to keep a 73% nitrification rate even at the height of the summer season, the load applied to the 1st stage filter in operation has to be capped at less than $600 \text{ gCOD.m}^{-2}.\text{d}^{-1}$.

For tourist-interest villages, in order to keep an 85% nitrification rate in the summer season, the load applied to the 2nd stage filter in operation has to be capped at less than $22 \text{ gTKN.m}^{-2}.\text{d}^{-1}$.

Here, vfCW were demonstrated to robustly handle a massive increase in loads applied, providing the wetland construction and operation stringently follow best design standards and practices.

Key words: applied loads, design, fluctuations, nitrogen, vertical flow Constructed Wetlands

INTRODUCTION

Tourism is a major driver of the French economy, with tourism consumption—up 3% between 2011 and 2012—put at an estimated €149 billion in 2012 (Ministère en charge du tourisme, 2013). France pulls tourists in across the whole country, even if the distribution is uneven, with tourists gravitating towards the zones lining the Mediterranean and Atlantic coastline zones and the mountain–upland regions. The net result is that rural-sector tourism is outstandingly-well catered for, with 2,713.7 thousand beds on campsites (reflecting the rural-zone-specific accommodation offer) accounting for almost half (47.2%) of global accommodation offer across France.

Friendly weather thus brings the additional influx of a seasonal population that needs to be provided with appropriately-scaled infrastructure amenities (potable water, wastewater treatment, transport links, and so on)—whether by publicly-authority organizations (including tourist-interest villages) or private-sector host facilities such as campsites and holiday parks.

Campsites stand out by their extreme seasonality. The general pattern is two-month-only window of high-season activity, with amenities closed to the public in winter. For tourist-interest villages, the situation is less clear-cut—the tourist season is longer, and there is a permanent population resident all year round. Simple economics dictates that (to avoid scaling up infrastructure based exclusively on peak affluence activity) amenities should ideally be optimally scaled while continuing to meet both variable needs and any regulatory targets set.

To address the issue, experimental trials in France have installed several vertical flow Constructed Wetlands (vfCW) scaled at a variety of sizes. The vfCW treatment solution offers a number of advantages: the technology is accessible, robust and reliable, and the signs suggest it can appropriately adapt to tourism-driven variations in influent load (Kadlec *et al.*, 2008). In an equivalent approach, trials have been led in Italy in several types of CW—including one vfCW—preceded by a primary settlement (Masi *et al.*, 2007). The 8 vfCW studied here were designed to conventional French construction basis and are fed with raw wastewater that has simply been screened. The filters are batch-fed in doses to ensure optimal water and TSS distribution and improve oxygen supply. This configuration is known to enable good degradation of organics, good capture of TSS, and practically full nitrification (Boutin *et al.*, 1997; Molle *et al.*, 2005).

After a brief description of the influent wastewater tackled, this paper reports our in-depth analysis of running conditions for these 8 experimental vfCW. The analysis emerges a definition of the acceptable influent load thresholds on each stage according to the effluent quality objectives targeted. We conclude by proposing a specific design scale adapted the various situations of summer-season pollutant load variation.

MATERIAL & METHODS

The dataset comes from 8 vfCW receiving wastewater of 4 campsites and 4 tourist-interest villages.

The campsites have a several-hectare area and are rated ‘deluxe/luxury’ according to the classification scheme proposed under the opposite French legislation dated 11 January 1993.

The tourist zones studied are in rural-area settings where peak populations remain modest, at up to 1500 inhabitants for the two tourist-interest villages. Population can double or quadruple in summer depending on local setting. A very high coefficient of high-season/off-season swing is explained by a village that counts 290 permanent residents but hosts a summer festival, whereas a modestly-sized public campsite connected to the sewerage network will bring a much lower population swing (*see* Table 1).

The area of all 8 vfCW is reported in Table 1. Seven sites were intentionally down-scaled in relation to classic values—with six sites down-scaled by over half. All other key implementation factors (material, ventilation pipes, batch-fed dosing, etc.) remain unchanged. The measurement campaigns spanned several years, starting as soon as the amenities were opened to the public in 2007 and running through to 2013 for the campsites. The vast majority of measurements were naturally taken in high tourist season, but a fraction (10%–20% of the performance balances depending on measurement point) were taken off-season, i.e. in mid-June and late-August for the campsites and in winter for the tourist-interest villages. The bulk of the measurements came from site 1, site 2 and site A. To integrate the uneven split in number of performance balances available per site, the values cited are, where appropriate, weighted averages corrected for site-count.

All data processed are measured from 24-hr performance balances, generally reconstructed samples proportional to flow rate. The final dataset ultimately features 25 performance balances co-characterizing raw wastewater influent, output from the 1st stage of the vfCW, and effluent, 33 performance balances co-characterizing influent raw wastewater and effluent, and 17 performance balances characterizing effluent only.

Special focus was paid to the raw wastewater samples, which posed real challenges to sample collection at the campsites where there was no pre-treatment of pollutant load transiting

through a short-loop network. To resolve this issue, we opted to re-position the sampling strainer and to synchronize samplings at each batch-feed.

Each treatment stage was assessed against the parameters COD, BOD₅, TSS, TKN, N-NH₄⁺, N-NO₃⁻, TP and P-PO₄³⁻ in line with standardized methods (AFNOR, 2008).

Table 1 Descriptive data on the 8 tourist facility activities and their corresponding 8 vfCW

Campsites			Site 1	Site 2	Site 3	Site 4	
Classification / grade		stars	4	4	3	4	
Pitch allocation	mobile homes		40	160	40	94	
	tents		160	0	60	157	
Total area		hectares	7	10	8	4	
Host capacity		campers	900	800	400	1000	
vCW	total area	m ²	744	651	755	1044	
		m ² /camper	0.83	0.81	2.02	1.04	
	1 st stage	number of filters	3	3	3	3	
		total area	m ²	474	456	453	612
			m ² /camper	0.53	0.57	1.21	0.61
		2 nd stage	number of filters	3	3	2	3
	total area		m ²	270	195	302	432
			m ² /camper	0.30	0.24	0.81	0.43
	Tourist-interest villages			Site A	Site B	Site D	Site E
	Tourist activity category			heritage village		festival once/year, lasting 1 week	village with campsite
Population	over wintertime	inhabitants	555	420	290	350	
	summer peak	inhabitants	1552	1500	5000	500	
Coefficient of high-season/off-season swing			2.8	3.6	17.2	1.4	
vCW	total area	m ²	1550	738	1830	720	
		m ² /inhab. max	1.00	0.49	0.37	1.44	
	1 st stage	number of filters	3	3	4	3	
		total area	m ²	1050	432	1200	432
			m ² /inhab. max	0.68	0.29	0.24	0.86
		2 nd stage	number of filters	2	2	2	2
	total area		m ²	500	306	630	288
			m ² /inhab. max	0.32	0.20	0.13	0.58

RESULTS & DISCUSSION

Quality of domestic wastewater

Wastewater pollutant concentrations were relatively homogeneous depending on campsite (*see* Table 2). The drinking water-saving recycling systems at certain sites led to higher pollutant concentrations on all parameters across the board. The mean values of the characteristic organic matter parameters remained consistent with earlier results (Boutin *et al.*, 2010) and depict a typically-concentrated effluent transiting through a short-loop network. However, the wastewater was nevertheless nitrogen-packed (mean of 122 mgTKN.L⁻¹) at almost double normal concentrations. People camping tend to make basic meals that thus generate less domestic wastewater—therefore leading to a lower organic matter fraction in relation to nitrogen that is mainly vectored in via urine.

In tourist-interest villages, in high summer season, mean effluent quality tends to be more pollutant-packed than a typical average domestic wastewater—at around 20%–40% more depending on parameter. In the winter season, the mean concentrations confirm that the influent is regular domestic wastewater. The range of variability is particularly high in winter: wastewater concentrations directly reflect responsible water use and type of network: combined/separate sewer system.

Table 2. Quality of domestic wastewater discharges from in-season campsite activity and in rural tourist-interest villages

			Concentrations (mg.L ⁻¹)					Ratios		
			BOD ₅	COD	TSS	TKN	N-NH ₄ ⁺	TKN/ COD	N-NH ₄ ⁺ /TKN	
Campsites	weighted mean 4 sites		367	915	432	122	99	0.14	0.80	
	Max.	33 - 34	680	1400	740	170	150	0.19	0.94	
	Min.	data	220	529	160	79	51	0.09	0.62	
Tourist-interest villages	summer	weighted mean 3 sites	378	792	311	90	71	0.13	0.86	
		Max.	12 - 19	704	1298	571	113	85	0.20	1.97
		Min.	data	190	476	160	25	38	0.07	0.67
	winter	weighted mean 3 sites	320	647	302	60	43	0.10	0.76	
		Max.	6 - 7	1102	1677	1072	119	68	0.12	0.89
		Min.	data	45	105	35	13	11	0.07	0.57
Values for rural-area settings		mean	265	646	288	67	55	0.12	0.74	
(Mercoiret, L., 2010)		Max.	570	1341	696	123	98	0.18	0.97	
		Min.	39	122	53	14	12	0.063	0.50	

All-round efficiency of the 8 vfCW

Quality of effluents

Quality of effluents (*see* Table 3) appears globally better from tourist-interest villages than from campsites, even if the weighted means across sites in both settings qualify as excellent when benchmarked in terms of the regulatory thresholds (Council Directive 91/271/EEC of 21 May 1991).

Looking at total nitrogen, the results on indicators of nitrification are fairly scattered (*see* Figure 2a).

Table 3. Quality of effluents (mg.L⁻¹) and removal performances (%) of the 8 vfCW surveyed

			Concentrations (mg.L ⁻¹)				Removals (%)					
			BOD ₅	TKN	N-NH ₄ ⁺	N-NO ₃ ⁻				BOD ₅	TKN	N-NH ₄ ⁺
Campsites	weighted mean	4 sites	17	29	28	57	4 sites	95	75	69		
	Max.	34 - 36	53	95	85	110	31- 33	99	98	98		
	Min.	data	3	2	1	0.2	data	86	37	20		
Tourist-inter villages	summer	weighted mean	4 sites	5	7.2	6.5	52.4	3 sites	98	88	87	
		Max.	15 - 26	18	20	37.3	230	12- 19	100	99	100	
		Min.	data	1	1	00.4	15.5	data	94	80	75	
	winter	weighted mean	4 sites	7	4.2	1.2	47.5	3 sites	95	93	97	
		Max.	13 -18	25	13	5.1	151	6-7	100	98	100	
		Min.	data	1	1	0.1	20.7	data	93	85	92	

For campsites, the site sample size-weighted mean effluent remains TKN-heavy (29 mg.L⁻¹) consistently with the high initial concentration of the raw wastewater. All organic nitrogen content gets fully oxidized. Nitrates production is variable (averaging 57 mg N-NO₃⁻.L⁻¹ but peaking at over 110 mg N-NO₃⁻.L⁻¹). Certain concentrations are near-zero, flagging a limit that typically signals impending anoxia and that can be used to define the threshold for particular operating conditions imposed on intentionally down-scaled vfCW.

The tourist-interest villages post excellent effluent concentrations that never go over 20 mgTKN.L⁻¹.

Removal performances

Treatment efficiency in terms of characteristic organic matter parameters is demonstrated by the fact that removal performances were systematically over 86% for BOD5 (see Table 3).

Looking at the total nitrogen parameters, for tourist-interest villages, the systematically 80%-plus removal performances fit with expectations (Molle et al., 2005). For campsites, the mean removal performances of 75% for total Kjeldahl nitrogen and 69% for ammoniacal nitrogen very nearly fit with expectations, although the range of variability on both these parameters underscores how nitrogen is the critical factor shaping vfCW performances.

This survey highlights (i) good, solid, stable results on ability to degrade organic matter, and (ii) that degree of nitrification is the critical factor shaping vfCW performances.

In order to propose productive ways to improve nitrification, we led a finer-grained stage-by-stage analysis. We cross-compared the various situations studied were (see Table 1) based on comparing real-world daily surface-dose loads applied against the conventional scaling rules (see Table 4) for a total vfCW surface of 2 m².inhab⁻¹ in two stages.

Table 4. Conventional criteria for French vfCW

conventional criteria	surface area		load applied on the filter in operation			expected removal performances	
	total	unitized	hydraulic	organic			
	m ² .inhab ⁻¹		cm.d ⁻¹	g.m ⁻² .d ⁻¹		%	
				COD	TKN	COD	TKN
1 st stage	1.2	0.4	37.5	300	≈ 30	79	56
2 nd stage	0.8	0.4	37.5	75	13.5	56	70
total	2					90	86

This design (Molle *et al.*, 2005) is based on the pollutive once-daily effluent of one rural-area inhabitant, as evaluated by statistical analysis of 10,000 datapoints: 120 gCOD, 11.9 gTKN, 46 gBOD₅ and 150 L (Mercoiret L., 2010).

Efficiency of the 1st treatment stage of the 8 vfCW

Hydraulic load

In high season, wastewater treatment plants tend to run at slight hydraulic underload: mean flush (35.6 cm.d⁻¹ for campsites and 27.3 cm.d⁻¹ for tourist-interest sites) onto the 1st stage filter in operation is close to conventional-design hydraulic loads (37.5 cm.d⁻¹). Note however that we did record a handful of extreme overload events that reached up to 175%.

Surface loads applied and removal performances

The COD loads applied at tourist-interest villages and campsites were 2-fold-higher and 1.5-fold-higher, respectively, than the design loads set under conventional conditions. Despite reaching 460–600 gCOD.m⁻².d⁻¹, the organic matter content was treated reliably and relatively effectively given the regression coefficient (0.98) of the curve plotting daily surface-area loads applied vs treated. The mean COD removal performances of this 1st stage filter were 77% for campsites and 82% for tourist-interest villages.

TKN loads applied reached 75 gTKN.m⁻².d⁻¹ for campsites and 37 gTKN.m⁻².d⁻¹ for tourist-interest villages, which equates to substantial overloads ranging from 250% to 125% over the conventional value of 30 gTKN.m⁻².d⁻¹.

Once over the 35–40 gTKN.m⁻².d⁻¹ threshold, removal performances at campsites clearly start to drop away (see Figure 1a). Outside of these overload conditions, operational mistakes on certain sites—including over-slow dosing rates—explain certain mediocre results.

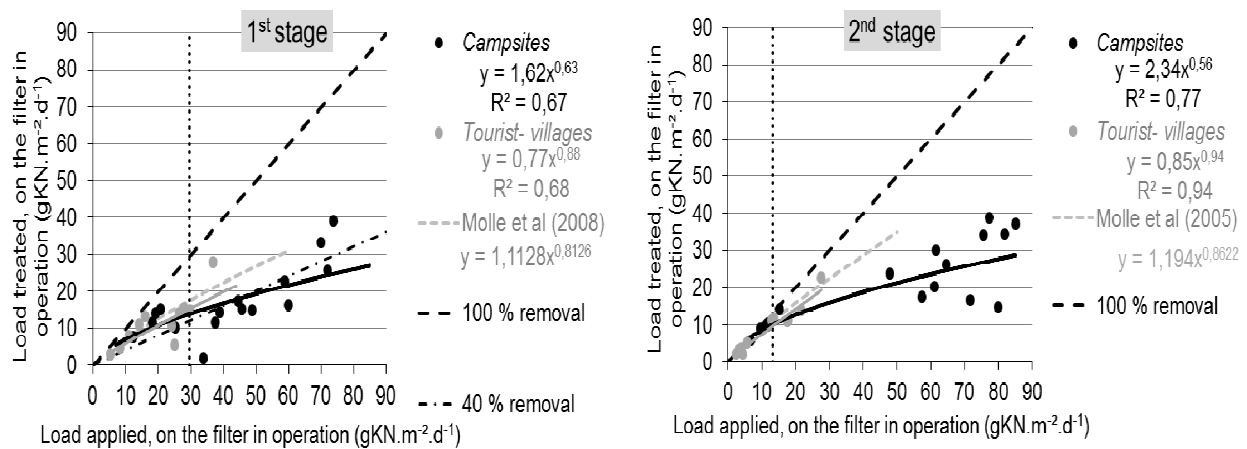


Figure 1 Efficiencies of the 1st treatment stage (a) and the 2nd treatment stage (b) on TKN

Even in these big load ranges, at least 75% of organic matter still gets removed. However, the lack of oxygen strangles the nitrification figure, which reaches 40% instead of a conventional 55% removal performance. These results are achievable inside the 1st treatment stage provided the vfCW is designed, employed and maintained as per code of practice.

Efficiency of the 2nd treatment stage of the 8 vfCW

Hydraulic load

In tourist-interest villages, even in high season, the diurnal hydraulic overloads remain modest (at around just 110%). The design of the 2nd stage at many campsite-based vfCW (see Table 1) that are equipped with 3 independent filters (rather than 2) explains the heavy hydraulic overloading (260%) applied on the filter in feed-mode. A standard design would have led to mean overloads of around the 175% mark.

Surface loads applied and removal performances

The peak measured COD loads applied at tourist-interest villages and campsites were comfortably over the conventional design loads, i.e. 2.25-fold-higher at tourist-interest villages and 4-fold-higher at campsites. Nevertheless, treatment performances on organic matter were systematically at very respectable levels. Mean COD removal performance (58%) was not just excellent but even matched the expectations set for conventional normal situations (Molle *et al.*, 2005).

The TKN loads applied at tourist-interest villages and campsites were way over the conventional design loads (2.25-fold-higher at tourist-interest villages and 6.4-fold-higher at campsites, i.e. corresponding to peak values of 28–85 gTKN.m⁻².d⁻¹ for the filter in feed mode; see Figure 1). For tourist-interest villages, the removal performances still fit with expectations, in contrast with campsites, where nitrification first stalls at an applied load of 58 g TKN.m⁻².d⁻¹.

Figure 2 also highlights how hydraulic loads applied on the in-feed-mode filter at the 2nd stage impact negatively on nitrification performances. This negative impact is particularly visible at the many campsites working with a triple-filter design rather than the two-filter design. This is because excessive water input affects the ability of the matrix to reoxygenate and the oxygen content needed for nitrification.

For implementation in line with standard-practice technical guidelines, by keeping hydraulic overload under 175%, the regression line plotting flush input against nitrification performance ($y = -65.96x + 100$) would put the predicted minimum nitrification threshold at 55%.

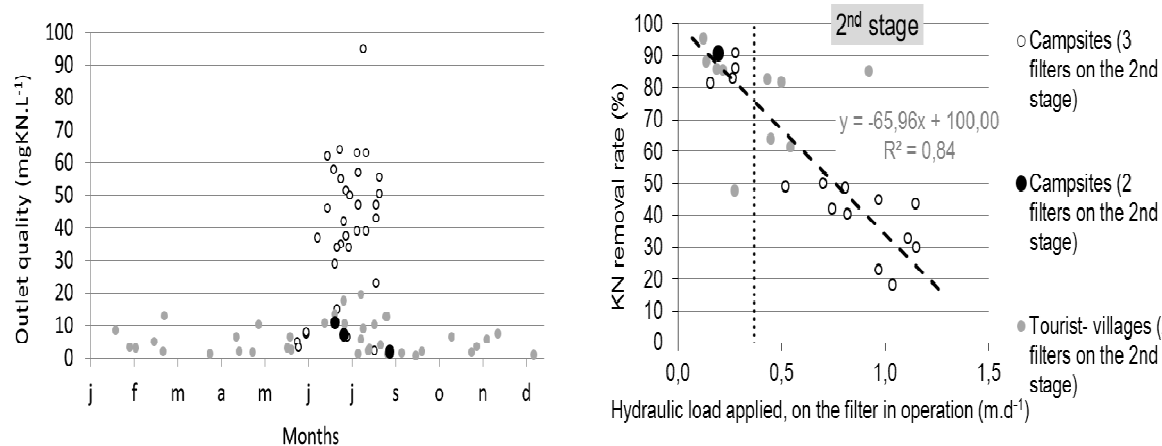


Figure 2: Season-stratified TKN concentrations of 74 effluents (a) and impact of hydraulic loads at the 2nd treatment stage on nitrification (b)

CONCLUSION

Tourism is a major driver of the French economy. Simple economics dictates that amenities should ideally be optimally scaled while continuing to meet both variable needs and any regulatory targets set.

The study on 8 vfCW at 4 campsites and 4 tourist spots tracked over several years confirms the promise of this pollutant treatment solution as an appropriate technology in terms of robustness and ability to adapt to tourism-driven variations in influent load. However, appropriate and experienced design is absolutely fundamental to the success of these down-scaled vfCW, making it vital to stick to the prescribed split in number of same-surface-area filters at each stage, i.e. 3 at the first stage and 2 at the second. Furthermore, vfCW will only deliver the expected performance results if they are run strictly in line with code of operational practice (including the filter dosing and resting intervals).

There are three situation profiles differentiated according to season and length of the peak pollution period.

(i) Campsites

Heavy overloads can be handled thanks to the absence of in-feed over the long winter season and subsequent virtually complete mineralization of vfCW surface deposits. While managing to maintain acceptable nitrification levels, at around 73% in peak periods, the limiting factor identified here is organic load applied on the in-feed-mode filter at the 1st stage, which must not be allowed to go 200% over the basic conventional design level, i.e. 600 gCOD g.m⁻².d⁻¹. These conclusions can be extrapolated up to any short-term pollutant discharges lasting less than three months if the system is allowed to stay completely pollution-free over the winter season. An analysis of the raw wastewater discharged by campers (Boutin *et al.*, 2010) prompted the proposed design of 0.75m²/camper—a scale we can now confirm here.

(ii) Tourist-interest villages

Overloads can be handled thanks to the better conditions for summer-season organic matter degradation and mineralization. In relation to campsites, the viable handleable overloads are modulated by two key factors: (i) the fact that the tourist season is likely to be longer (spanning 5–6 months) and (ii) the fact that the vfCW receives pollution even during the off-season winter period. While managing to maintain nitrification performances at around 85%,

the limiting factor identified here is nitrogen load applied on 2nd stage, which must not be allowed to go 160% over the basic conventional design level, i.e. 22 gTKN g.m⁻².d⁻¹.

To translate these findings into concrete real-world application, vfCW designers should evaluate the coefficient of high-season/off-season swing of the user population. If this coefficient is under 1.6, then the extra summer-season pollution can be absorbed without having to up-scale the wetland facility designed for winter-season treatment of pollution by a permanent resident population. If this coefficient is over 1.6, then vfCW design needs to be scaled against peak summer-season pollution load, but while allowing a 160% overload.

(iii) Festivals

The vfCW prove particularly robust if subjected to short-burst demand spanning very short periods (a few days up to a whole week). In this particular sub-setting, our proposal is to base vfCW design scale exclusively on the hydraulic load parameter and to assess operational performance based on the stage-by-stage organic and total nitrogen loads applied. These design parameters—provided the system is deployed to best design standards and practice—guarantee effective and dependable organic matter removal performances (88%).

The level of the hydraulic and nitrogen loads applied has a direct impact on nitrification performances. Consequently, if local configuration requires stronger nitrification, it will be necessary to fall back on conventional scaling benchmarks. This point is by far the most critical design parameter when faced with heavily nitrogen-packed raw wastewater.

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