French vertical-flow constructed wetland design: adaptations for tropical climates

P. Molle, R. Lombard Latune, C. Riegel, G. Lacombe, D. Esser and L. Mangeot

ABSTRACT

The French Outermost Regions are under tropical climate yet still have to comply with both French and EU regulations. French vertical-flow constructed wetland systems appear well adapted to the technical specifics of these regions but their adaptation to tropical climate requires new design guidelines to be defined (area needed, number of filters, type of plants, material to be used, etc.). A study was started in 2008, with backing from the national water authorities, to implement full-scale experimental sites and assess the impacts of local context on design and performances. This paper reports the monitoring results on three vertical-flow constructed wetlands fed directly with raw wastewater (known as the 'French system') in Mayotte and French Guiana. The plants, now in operation for between 1 and 6 years, range from 160 to 480 population equivalent (p.e.). Monitoring consisted of 28 daily composite flow samples in different seasons (dry season, rainy season) at the inlet and outlet of each filter. Performances are benchmarked against French mainland area standards from Irstea's database. Results show that performances are improved by warmer temperature for chemical oxygen demand (COD), suspended solids (SS) and total Kjeldahl nitrogen (TKN) and satisfy national quality objectives with a single stage of filters. Treatment plant footprint can thus be reduced as only two parallel filters are needed. Indeed, warm temperatures allow faster mineralization of the sludge deposit, making it possible to operate at similar rest and feeding period durations. Systems operated using one twin-filter stage can achieve over 90% COD, SS and TKN removal for a total surface of 0.8 m^2/p.e.

Key words | design criteria, nitrification, raw domestic wastewater, recirculation, tropical climate, vertical-flow constructed wetlands

P. Molle (corresponding author)
R. Lombard Latune
Irstea, Freshwater Systems, Ecology and Pollutions Research Unit,
5 rue de la Doua – CS70077,
69626 Villeurbanne,
France
E-mail: *pascal.molle@irstea.fr*

C. Riegel
SIEAM, BP289,
Mamoudzou 97600,
France

G. Lacombe
ETIAGE,
4 avenue des Plages,
Rémire-Montjoly 97354,
France

D. Esser
SINT,
Chef Lieu, la Chapelle du Mont du Chat 73370,
France

L. Mangeot
ODE Martinique,
7 avenue Condorcet,
BP 32-97201 Fort de France Cedex,
France

INTRODUCTION

The French Outermost Regions (Guadeloupe, Martinique, French Guiana, Mayotte and Reunion Island; FOR) are all under tropical climate and all experience big sanitation problems. Subject to the same regulatory framework as European countries, they are lagging well behind on wastewater treatment plant implementation yet environmental (high biodiversity), health, economic, land-use (very high land pressure) and social (water is at the heart of their business) pressures require rapid development of good sanitation. The FOR also differ from the French mainland in many other ways that could affect the development of sanitation in these territories. In addition to natural factors (insular territories, tropical climate, seismic zone), high population growth has resulted in rapid yet uncontrolled urban development which complicates the technical choices and infrastucturing of sanitation. In parallel, the adaptation of sanitation techniques for both the collecting sewer (H_2S formation, corrosion, clear water intrusion, etc.) and the treatment plant (performances, aging facilities, maintenance, sludge management) is rarely considered, and feedback is not pooled. There is also a serious deficiency in the implementation of self-monitoring facilities.

Consequently, the French National water authority (Onema) and the Ministry of Ecology decided to start a research program on the adaptation of French vertical-flow constructed wetlands (VFCWs) to tropical conditions. Two projects are now under way (DOM and ATTENTIVE). The VFCW system was chosen as it looks a good solution for

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small communities in France (Molle *et al.* 2005) and offers a combination of easy sludge management and system robustness to organic and hydraulic overloads (Molle *et al.* 2006, Arias *et al.* 2014), which appear to be valuable assets for tropical-climate settings. Indeed, compact intensive treatment techniques require energy, cost and technical expertise from operators, whereas constructed wetlands look a much more promising option in tropical climates. Nevertheless, there are still issues over how the design should be adapted to local climate, local materials (gravel, sand, plants) and acceptability to local communities (social aspects). More and more tropical countries have been trialling constructed wetlands for wastewater treatment (Kantawanichkul *et al.* 2009; Konnerup *et al.* 2009; Caselles-Osorio *et al.* 2011; Kelvin & Tole 2011; Kurniadie 2011) but the diversity of scales (laboratory, pilot, full scale), influents (domestic, industrial, sludge) and systems (surface-flow, horizontal-flow, vertical-flow, type of materials) makes it difficult to use transposable rules of design adaptation to tropical climates. Feedback from tropical experience with the French system (no primary treatment) is increasingly poor (Esser *et al.* 2006, 2010; Cota *et al.* 2011, Lana *et al.* 2013) and increasingly hampered by disparity in operational parameters – Mélian *et al.* (2010) for example did not use filter alternation on their pilots in the Canary Islands.

To embed the development of VFCWs in the FOR, different real-scale treatment plants have been implemented under specific monitoring schemes. This paper summarizes the monitoring done on VFCWs receiving raw wastewater at three plants located in Mayotte Island and French Guiana. The objective is to discuss the possible design adaptation options for warmer temperature settings. One of the main challenges is to reduce system footprint by using only one filter stage. As warmer temperatures allow a higher mineralization deposit, it was decided to use only two filters in parallel, based on the rationale that it was more appropriate to reduce number of filters rather than surface area of each filter unit in order to maintain good acceptance of hydraulic loads. The other key design parameters are depth of the first filtration layer and whether or not the system features a recirculation loop. Consequently, design is discussed according to load applied, recirculation loop (yes/no), and depth of material in comparison to similar systems in France.

MATERIAL AND METHODS

The main design parameters of the three French VFCW treatment plants (treating raw wastewater) are presented in Table 1. Wastewater for each treatment plant comes from domestic use. Only one filter stage is implemented, and a recirculation loop is possible.

As *Phragmites australis* is unusable in almost all FOR, different kinds of plants were tested. *Typha angustifolia* and *Arundo donax* were initially tested but appeared ill-adapted to the system (difficult to maintain and not growing evenly). Consequently, new species were used in this study (Table 1).

Monitoring

The VFCWs have been monitored for over 6 years for Hachenoua (done by the SIEAM, Mayotte communities water and sanitation federation) and 2 years for Bois d'Opale 1 and 2 (done by Etiage Guyane, a design/engineering office). Monitoring consisted of 24-hour flow composite sampling with refrigerated samplers and flow measurements by time-course measuring of the water level in batch feeding systems. In French Guiana, sampling was split evenly across the rainy season and dry season while in Mayotte Island no difference was noted as the sewer was effectively separative.

Chemical analyses were done in local laboratories using *Standard Methods* (APHA 2012) for chemical oxygen demand (COD; dissolved (COD_d) and total), 5-day biochemical oxygen demand (BOD_5), total suspended solids

Table 1 | Main treatment plant characteristics

Name	Capacity (p.e.)	Starting year	VFCW design	First material layer	Plants
Hachenoua (Mayotte)	160	2006	0.8 m^2/p.e. split across two parallel filters	80 cm of 4/6-mm grain size	*Thysanolaena maxima, Typha angustifolia*
Bois d'Opale 1 (French Guiana)	300	2010	0.8 m^2/p.e. split across two parallel filters	30 cm of 3/8-mm grain size	*Heliconia psittacorum, Phragmites australis*
Bois d'Opale 2 (French Guiana)	480	2012	0.8 m^2/p.e. split across two parallel filters	30 cm of 3/6-mm grain size	*Phragmites australis, Phalaris arundinacea*

p.e.: population equivalent.

(TSS), total Kjeldahl nitrogen (TKN), NH_4-N, N-NO_3 and total phosphorus (TP). As analytical quality can prove problematic in tropical climates due to the warm temperatures and a lack of local skills, the data validation procedure led us to rule out 30% of the monitoring campaign data for Mayotte Island. The validation procedure consisted of verifying analytical coherency with the scheme TKN > NH4-N; $1 < COD/BOD_5 < 4$; $0.5 < (COD-COD_d)/TSS < 1.9$. A total of 28 monitoring campaigns were ultimately used for the discussion that follows.

Statistical analysis

Statistical comparisons were done by first checking the data distribution and variance comparison (Fisher's *F*-test). When data were normally distributed and variance not significantly different, the Student test was used. The Wilcoxon test was used if data were not normally distributed or the variance was significantly different. As sample sizes were not large enough and include some uncertainties, the *p*-value threshold (the least significant difference) was set to 0.001.

Since COD and TSS removal efficiencies remain stable with increasing applied loads, design and climatic effect on performances were analyzed on mean removal rate. For TKN, removal efficiencies usually decrease with the TKN load applied. Therefore, we chose a different approach. First we compared measured yield values to those corresponding to the fitted curve presented in Molle *et al.* (2008) with data from a tropical climate (this study) and mainland France (Molle *et al.* 2005). Then we tested if the mean of the residue distribution significantly differs between both datasets.

RESULTS AND DISCUSSION

Inlet wastewater characteristics

While inlet concentrations generally fit the range found in France for small communities (Mercoiret 2010), there was potentially broad variation depending on type of location (risk or not of clear water intrusion). In Guiana, the Bois d'Opale treatment plants, although equipped with new sanitary sewers, are located in a plain with near-surface groundwater and consequently experience infiltration of clear water during the rainy season. In this context, there is substantial dilution (Table 2) and hydraulic overload throughout the wet season. Hydraulic load on Guiana-based filters in the rainy season is about 250% of dry-season levels.

In contrast, the Hachenoua case shows concentrations consistent with those measured in small communities in Europe. Note that the subdivision connected to the study

Table 2 | Average pollutant concentrations (standard deviation) of inlet raw wastewaters

	Possible intrusion of groundwater (Bois d'Opale 1 and 2)		
	Dry season	Rainy season	Strictly separated sewer (Hachenoua)
BOD_5 (mg/L)	230 (114)	74 (29)	410 (113)
TSS (mg/L)	230 (143)	102 (35)	414 (145)
COD (mg/L)	531 (228)	217 (70)	793 (245)
COD_d (mg/L)	179 (50)	102 (67)	335 (133)
TKN (mg/L)	59.7 (17.3)	21.6 (10.6)	89.3 (14.9)
NH_4-N (mg/L)	43.3 (13.6)	16.4 (9.0)	68.2 (15.3)
TP (mg/L)	12.9 (5.0)	4.1 (1.6)	12.8 (3.9)
COD/BOD_5	2.47 (0.56)	3.14 (0.75)	2.00 (0.23)
Hydraulic load on the filter in operation (m/d)	0.31 (0.05)	0.88 (0.35)	0.24 (0.05)
Number of valid monitoring campaigns	9	9	10
Climatic conditions			
Mean monthly temperature (°C)	25.8 to 27.5		23.3 to 26.9
Mean monthly precipitation (mm)	51 (September) to 508 (June)		13 (August) to 298 (January)

Table 3 | Concentrations and percent removal of the two filtration layer depths

		Filters with 30 cm of filtration layer (Bois d'Opale 1&2)												Filter with 80 cm of filtration layer (Hachenoua)											
		Without recirculation (clogged by laterite)				Recirculation < 125 %				Recirculation > 125 %				Without recirculation				Recirculation < 125 %				Recirculation > 125 %			
		min	**mean**	max	SD	min	**mean**	max	SD	min	**mean**	max	SD	min	**mean**	max	SD	min	**mean**	max	SD	min	**mean**	max	SD
	Hydraulic load (m/d)	0.28	**0.3**	0.33	0.04	0.27	**0.29**	0.31	0.02	0.15	**0.16**	0.18	0.02	0.2	**0.43**	1.06	0.32	0.39	**0.49**	0.69	0.14	0.5	**0.58**	0.63	0.05
	Number of data		**2**				**4**				**3**				**3**				**4**				**3**		
COD	Outlet (mg/L)	93	**100**	107	9.9	75	**92**	126	23.13	70	**82**	91	10.8	36	**71**	163	53	42	**61**	71	13	23	**44**	59	16
	Removal efficiency (%)	65%	**71%**	77%	8.2%	63%	**82%**	91.9%	12.6%	78.5%	**80.7%**	84.9%	3.6%	77%	**91%**	96%	8%	92%	**93%**	94%	1%	90%	**91%**	93%	1%
BOD5	Outlet (mg/L)	22	**27**	33	8	7	**12**	16	3.7	18	**23**	29	5.6	8	**33**	90	33	23	**23**	23	-	8.6	**8.6**	8.6	-
	Removal efficiency (%)	73.3%	**74.3%**	75%	1%	91.2%	**95.2%**	97.5%	2.8%	85.1%	**87.2%**	89.7%	2.3%	79%	**91%**	98%	9%	94%	**94%**	94%	-	-	**-**	-	-
TSS	Outlet (mg/L)	74	**77**	81	5	17	**20**	25	4	15	**27**	36	11	9	**26**	63	22	10	**38**	80	32	9	**16**	30	12
	Removal efficiency (%)	34.7%	**55.1%**	75.5%	28.8%	86.4%	**90.9%**	95.7%	3.8%	67.4%	**78.4%**	89.9%	11.2%	77%	**91%**	98%	9%	88%	**93%**	95%	4%	94%	**95%**	97%	2%
TKN	Outlet (mg/L)	29.3	**34.3**	39.3	7.1	18.3	**21.8**	23.7	2.5	6	**11.8**	17.5	5.7	2	**10**	27	12	3	**4.9**	6	1.3	3	**4**	5	1
	Removal efficiency (%)	-19.1%	**2.8%**	24.9%	31%	61.8%	**70.3%**	73.9%	5.77%	65.1%	**77%**	88.5%	11.7%	70%	**90%**	98%	13%	89%	**93%**	96%	4%	94%	**95%**	96%	1%
	Hydraulic load (m/d)	0.87	**0.99**	1.2	0.19	0.23	**0.44**	0.58	0.16	0.56	**0.63**	0.69	0.09												
	Number of data		**3**				**4**				**2**														
COD	Outlet (mg/L)	47	**50**	55	4.2	43	**62**	84	16.8	48	**66**	85	26												
	Removal efficiency (%)	49.5%	**64.1%**	73.3%	12.7%	78.4%	**82.5%**	87.3%	4.7%	61.2%	**68.3%**	75.4%	10%												
BOD5	Outlet (mg/L)	5	**5.3**	6	0.58	8	**12**	18	4.9	7	**9**	11	2.8												
	Removal efficiency (%)	83.3%	**86.6%**	88.9%	2.9%	80.3%	**89.7%**	94.6%	6.42%	89.2%	**90.8%**	92.3%	2.2%												
TSS	Outlet (mg/L)	25	**32**	35	4.36	8	**20.8**	26	8.54	6	**7**	8	1.4												
	Removal efficiency (%)	67.5%	**69.3%**	72.9%	3.1%	82%	**86.4%**	90.5%	4.27%	87.8%	**88.6%**	89.5%	1.2%												
TKN	Outlet (mg/L)	5.8	**9.5**	13.4	3.8	11.9	**15.3**	20.9	4	5.8	**7**	8.2	1.7												
	Removal efficiency (%)	11.8%	**22.9%**	36.3%	12.4%	59.1%	**61.2%**	66.7%	3.67%	59.8%	**60.8%**	61.8%	1.4%												

Dry season

Rainy season

Phosphorus (not a treatment target) and $N\text{-}NH_4$ (can be estimated by TKN minus 6% of TSS concentration) are not presented.

station is predominantly occupied by expatriates whose uses do not necessarily reflect those of Mayotte's local communities.

Global performances

Overall treatment plant performances and outlet levels are reported in Table 3 according to depth of the first filtration layer and recirculation rate tested. As Bois d'Opale 1 and 2 share the same design, we have made no distinction in terms of pollutant removal. And only season (dry vs. rainy season) is separated for these plants as the inlet concentrations were different. Different recirculation rates were tested for periods over 1 year, and so are also reported separately in the table. As inlet and outlet flows were similar, it is easy to recalculate average inlet concentration for each dataset.

Globally, these treatment levels enable the systems to comfortably meet the minimal levels set under French regulations (60% for COD and BOD_5 and 50% for TSS). This finding is not surprising given feedback from trials in France on the first VFCW stage with (Prost-Boucle & Molle 2012) or without (Molle *et al.* 2005, 2008) recirculation.

A closer look at this table suggests that a filter with 30 cm of filter material (2–6 mm) and without effluent recirculation may perform less well and show low nitrification. Indeed, while the treatment of carbon pollution (COD, BOD_5 and TSS) is satisfactory, recirculation and the thickness of the first gravel layer seem to impact nitrification performances, as it is more sensitive to oxygenation conditions and hydraulic retention time. Nevertheless, this observation hides two factors impacting yields: (i) level of inlet wastewater dilution during the rainy season and (ii) clogging issues encountered on this filter (Bois d'Opale 1 – all the data of Table 3 corresponding to 30 cm without recirculation). The clogging was due to misuse of the sewers through repeat inputs of laterite. People on the private housing estate did some earth-moving work without any forethought as to the what problems laterite could cause if it got into the sewers. Consequently, huge amounts of laterite get filtered by the top surface of the filters, thus inducing chronic clogging that could only be solved by removing this clogging layer. This point highlights the necessity to educate both workers and inhabitants on responsible use of sensitive wastewater treatment systems.

Treatment performances

To better highlight the impact of climate on filter behavior, it is useful to analyze removal rates of the filter itself, i.e. the loads applied and removed by the filter (Figure 1). The load applied comes from the wastewater treatment plant inlet as well as from any recirculation loop present. Comparison was made on the basis of performances observed in France (Molle *et al.* (2005) for COD and TSS and Molle *et al.* (2008) for nitrification. Molle *et al.* (2008) worked on a filter with a first filtration layer higher than 60 cm. Filters from Guiana and Mayotte are presented according to filter depth, which is the main different parameter impacting performances in our case study.

The analysis enabled us to learn several lessons on filter behavior patterns in tropical climates. First, we observed similar removal efficiencies to mainland France for COD and TSS (p-values >0.001; Table 4). Increasingly stable removal rates, for first-layer filter depths of 80 cm, are observed for COD (p-value for COD removal comparison between 30 and 80 cm <0.001). Performances on TSS are similar regardless of the thickness of the first filter layer.

However, for nitrification, filters with only 30 cm of gravel (3–6 mm) demonstrated similar removal rates to 60–80-cm deep filters on the French mainland (p-value >0.001). In Mayotte, with a layer of 80 cm, nitrification performances are higher and more stable than similar designs in France (p-value <0.001): 90% of TKN removal is achieved on just one filter stage. This observation may be related to two factors: (i) higher and regular temperatures throughout the year that may promote the maintenance of an active and abundant autotrophic flora; and (ii) more frequent alternation (only two parallel filters) that may maintain higher water content in rest periods, which aids bacterial survival.

Another key factor is the abundant arrival of laterites (Bois d'Opale 1) clogging the filter surface and to a lesser extent its depth, which may have hindered oxygenation as nitrification was highly impacted. Likewise, higher TSS contents were measured at the outlet, with a particulate COD/TSS ratio of 0.5. This unusual mineral aspect of solids at the outlet (a 'normal' ratio would be 1.2) seems to indicate that fine laterite particles passed through the filter, thus degrading filtration performance.

Maintenance and operation

Maintenance of the CW can prove problematic as small treatment plants are often considered able to work with little if any hands-on effort. Consequently, some actions or the absence of action can lead to serious problems for filter functioning.

One of the first aspects is linked to the minimal operation an owner has to do, i.e. ensure proper plant development filter rotations. Against a background of social tension in Mayotte,

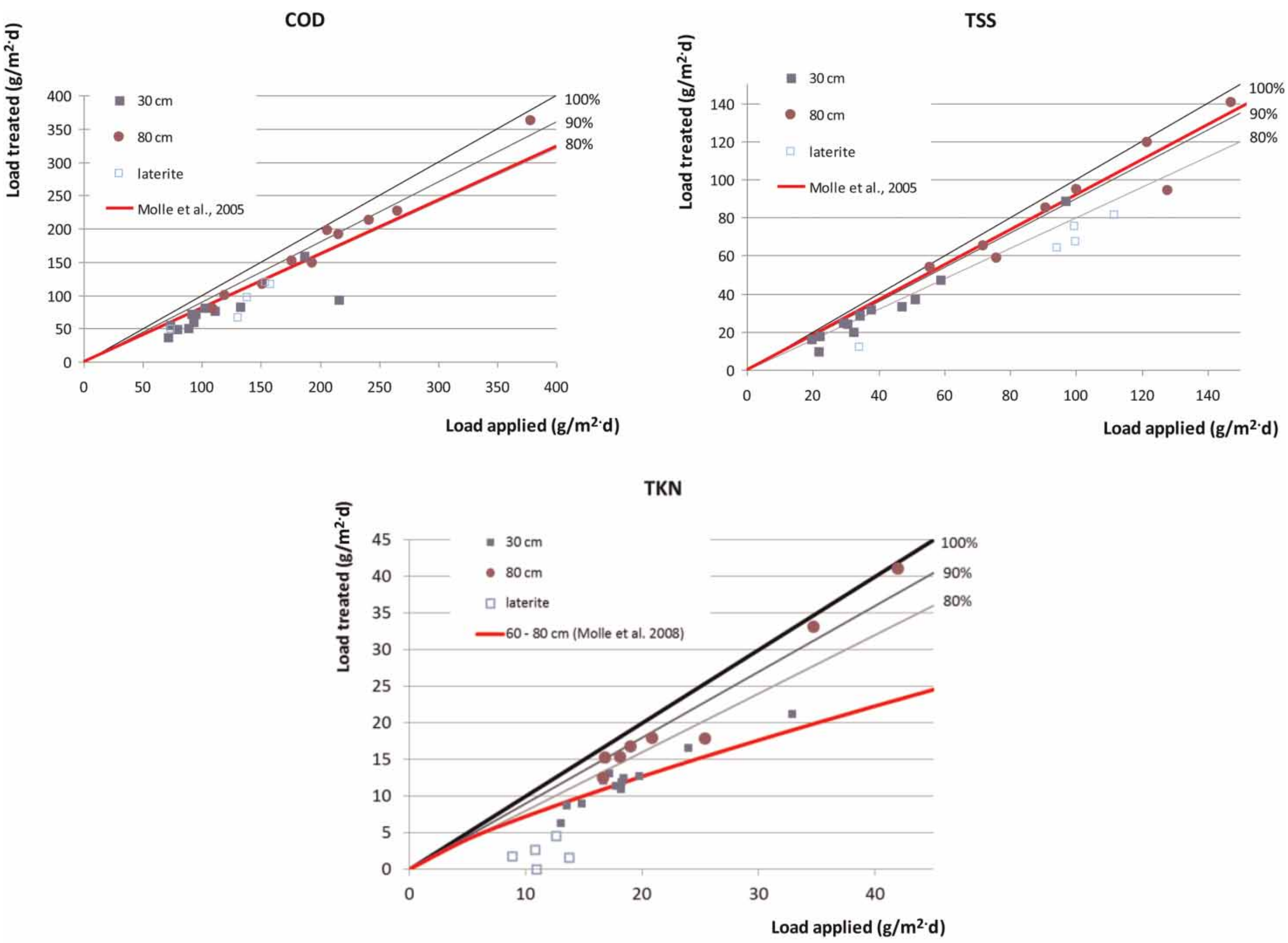

Figure 1 | Removal rates of the filter in operation (30 cm: Bois d'Opale 1 and 2; 80 cm: Hachenoua).

Table 4 | *p*-values of statistical comparisons

France mainland/tropical condition comparison	COD	TSS	TKN
VFCW 30 cm	0.021	0.016	0.60
VFCW 80 cm	0.232	0.636	0.000001
30/80 cm comparison in tropical condition	0.001	0.014	0.00025

the treatment plant has not been operated for around a year, which means no rotation/alternation and no plant control. Due to the very long absence of rotation, the filter in operation clogged. The deposit has since been removed and the filters restarted. Despite these failures, the filters nevertheless show an amazing resilience through the ability to quickly recover complete nitrification in tropical climates. Indeed, nitrification dropped back to normal rates in the space of a few days.

Plants

The right plant to use in each tropical region has not yet been determined. While the mechanical role of plants is the major expectation, plants in tropical climates also need to meet other expectations. Note that the plant must not allow rainwater to sit and stagnate in the leaves (as was observed with *Dieffenbachia*) to prevent the risk of mosquito larvae developing. Furthermore, plant choice has to factor in easy operability (harvesting, plant competition). The first plants tested in Mayotte (*Typha angustifolia*) and French Guiana (*Arundo donax*) do not appear suitable as they are difficult to harvest, and grow in clumps.

Sludge deposit

Sludge deposit and consequently sludge management is a key factor in tropical climates. Although we were unable to put a figure on accumulation rates due to operational problems in Mayotte and lack of mature plants in French Guiana plants, sludge deposits appeared to accumulate at visibly lower rates than on the French mainland. As only two filters are implemented in parallel, this confirms the design choice to not implement three filters in parallel. Considering the lack of viable means to properly manage this by-product and the limited agricultural land available for sludge disposal, very low sludge accumulation becomes a key selling point that should prompt local authorities to implement CW where geography and demographics permit.

CONCLUSION

This study monitored three VFCW located in tropical-climate sites and implementing two different material depths (30 and 80 cm), and validated 28 24 hour flow-proportional campaigns. The plants, in operation for 1 and 6 years, showed that warmer climate improves performances, especially for nitrification, compared to locations on the French mainland, making it possible to meet national quality objectives with just a single filter stage. The evidence suggests that a specific design (80 cm of material and intermediate aeration) is able to achieve very high nitrification efficiency (90%) on just one treatment stage.

This in turn makes it possible to reduce the footprint of the treatment plant by reducing the number of filters working in parallel to just two. The low accumulation of deposit observed on the filters and the good nitrification efficiencies further support this design choice. This choice helps maintain additional hydraulic acceptance of rain events or clear water intrusion during the wet season, as seen in the Bois d'Opale treatment plant in French Guiana.

A number of issues relating to tropical climates still need to be resolved or better engineered in the future:

- Working with only one treatment stage can sometimes lead to TSS outlet levels of over 25 mg/L, which means TSS outlet levels need to be made more reliable by adding a treatment step or modifying the first stage.
- As organic load limits have not been reached, it would be valuable to test higher loads to see the feasibility of further reducing the footprint.
- On-filter deposit accumulation rates need to be more accurately investigated.

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