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CONSTRUCTED WETLANDS FOR THE TREATMENT OF WASTEWATER IN SMALL CITIES ON THE PERUVIAN COAST

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Abstract

Peru has the largest amount of the tropical glaciers of the world. Nevertheless, 10% of the population lacks water service and 25.5% lacks drainage (sewerage or sanitation). It's also important to notice that Peru is divided into the coast, mountain, and jungle. Being the coast, the region with the least area but the major population. To wit, Lima, a coast department, has 29.7% of the population of the country. To magnify the problem, 72% of wastewater is treated and discharge to the Pacific Ocean. Thus, it isn't difficult to foresee that this situation is unsustainable. Reuse of treated wastewater could be an excellent alternative to help solve this problem. Accordingly, the current study aims: I) to evaluate the physicochemical and biological quality of UNALM constructed wetland effluent (SDG 6) and II) to know the potentialities of the reuse of this effluent for afforestation irrigation (SDG 11 y SDG 15).

Keywords: Constructed wetlands, wastewater reuse, French system, afforestation.

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INTRODUCTION

In Peru, 10% of the population lacks water service and, 25.5% lacks sewerage service (MVCS, 2017). In addition, more than 70% of the population lives on the coast (Ioris, 2012), where there's a water deficit. The coverage of domestic wastewater in Peru reaches 72% but, if Callao and Lima (capital city) are excluded, the rest of the country only reaches 48% (GWI, 2016). In this framework, is considered to contribute:

SDG_s 6. Target 6.2
"By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations".

Moreover, it is worth mentioning that in Peru, the prime technologies used for the treatment of domestic wastewater consist of the combination of primary and secondary facultative lagoons (ANA, 2016).

As of 2018, the MVCS (Ministerio de Vivienda Construcción y Saneamiento) issued a regulation that considers to constructed wetlands for wastewater treatment. One of them is the so-called constructed wetlands (CW), technology that simulates the natural processes of pollutant removal; and is characterized by low cost, easy operation and maintenance, and potential for application in decentralized situations (Dotro, Langergraber, Molle, Nivala, Puigagut, Stein & Von Sperling, 2017). Furthermore, aquatic plants and chemical, physical, and biological mechanisms are optimal for treating wastewater (Von Sperling & Chernicharo, 2005). On the other hand, investigations carried out in wetlands built in high Andean areas, showed potentialities of using treated water for afforestation (Rosado, Paredes, Joachin, Morató, & Rosario, 2019).

However, constructed wetlands require pre-treatment to remove solids. Against this background, vertical flow wetlands have been successfully tested to treat raw wastewater, known as the "French System", and includes two stages: French cell (1^{st} stage) + vertical flow subsurface wetland (2^{nd} stage). Both provide integrated sludge and wastewater treatment in a single system (Molle, Liénard, Boutin, Merlin & Iwema, 2005).

In 2011, an experience with the French System was carried out in a coastal city of 60 inhabitants (Chinc ha-Peru). The results showed that the pollutant removal in the French cell (1^{st}) is more efficient compared to other treatment technologies: septic tank, ABR, Imhoff tank, UASB (Platzer, Hoffmann & Miglio, 2016).

Also, in 2011, 2 pilot plants were built in the facilities of the Universidad Nacional Agraria La Molina -UNALM (Lima-Peru), to promote research work (Pastor, Miglio, Suero, Arias & Morató, 2016). The system consists of 2 lines, and each of them has been dimensioned for 30 PE, which generates a flow of 6 m^3d^{-1} per line. Two types of pre-treatments have been built, an improved septic tank (Baffled Tank or ABR) and a vertical wetland or "French System".

The research results aimed at optimizing the operation of the French System (León, 2020) are shown in this work and are intended to contribute to SDG 6. Goal 6.3, SDG 11. Goal 11.7 and SDG 15. Goal 15.2.

SDGs 6. Target 6.3
"By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally".

SDGs 11. Target 11.7
"By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities".

SDGs 15. Target 15.2
"By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally".

METHODS

Location

The research was carried out in the pilot plant for the treatment of domestic wastewater (PTAR) located at the Universidad Nacional Agraria La Molina (UNALM), Lima - Peru.

This pilot plant has three lines. Line one is made up of the French System - FS (French cell + 02 vertical flow subsurface wetlands).

Work was done on the SF line (Figure 1), that is, on the French cell (1^{st} stage) and the 02 vertical flow subsurface wetlands (2^{nd} stage).

Figure 1. *French System of UNALM. Left: 1st stage (French cell); Right: 2^{nd} stage (vertical flow subsurface wetlands)*

The FS is made up of a French cell (1st stage) and two vertical flow subsurface wetlands (2nd stage) (Figure 2). The domestic wastewater that enters the French System (raw water) comes from a domestic sewerage network and passes through a 24.5 mm opening grate that is manually cleaned. The wastewater is diverted to a pumping chamber (CB1) and is pumped from there to the French cell using two submerged pumps (B1 and B2). The French cell has a surface area of 36 m^2 and is subdivided into two subunits or lines of 18 m^2 of surface each. The two lines operate alternately to guarantee the rest period in each of the lines after a time of use of 72 h (3 d). Each line is fed by one of the pumps; the wastewater enters through two vertical PVC pipes with a diameter of 76.2 mm per line (from 1.1 to 2.2). To ensure an equitable distribution of the wastewater on the surface of each line, the outlet pipes are surrounded by circular concrete plates.

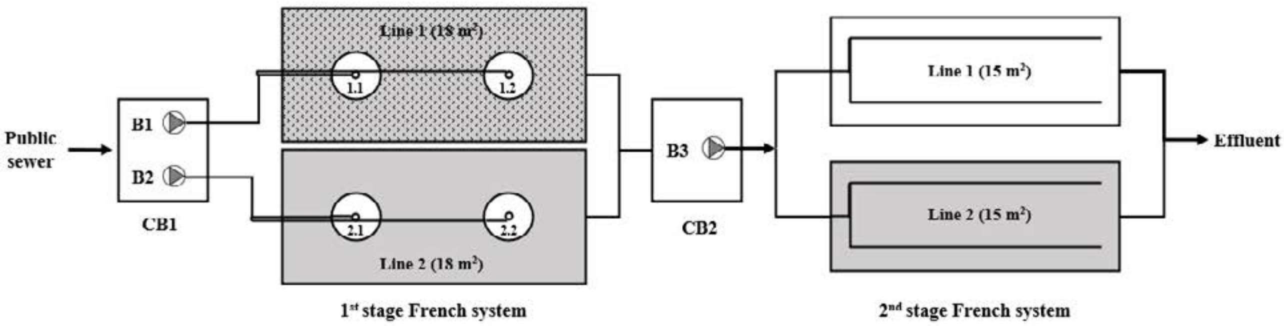

Figure 2. *French System Scheme*

After passing through the filtering material of the 1st stage, the wastewater is collected through perforated drainage tubes located in the lower part of the filter (diameter of 110 mm), which discharge by gravity to the pumping chamber CB2, from where they are pumped with a submerged pump (B3) to the 2nd stage of the French System. The B3 pump, unlike the other pumps, is controlled by a float to maintain a constant level of water in the pumping chamber. The 2nd stage of the FS has a surface area of 30 m^2, subdivided into two units or lines of 15 m^2 of surface each. The treated water enters and is distributed uniformly over the entire surface through pipes, with a diameter of 50.8mm; which are diametrically opposite perforated. After passing through the filter medium, the residual water is captured by drainage tubes (diameter of 101.6 mm) located at the bottom of the cell and finally, the treated water is discharged.

The 1st stage of the French System and one of the subsurface vertical flow wetlands of the 2nd stage have been considered. In Figure 1 the systems studied are shaded in lead colour. The 1st and 2nd stages of the French System are planted with umbrellas (*Cyperus alternifolius*) and vetiver grass (*Chrysopogon zizanioides*), respectively.

The B1 and B2 pumps are controlled by an automated SCADA (Supervisory Control and Data Acquisition) system to ensure a pumping and resting sequence.

The 1st stage has a total filter bed depth of 1m and is divided into three layers of different filter material. From top to bottom, these layers are: 0.6 m gravel Ø 4.75 - 19.0 mm; 0.25 m transition layer Ø 12.7 mm crushed stone; 0.15 m drainage layer Ø 25.4 mm crushed stone. The 2nd stage of the French System has a total filter bed depth of 0.9 m and is divided into 3 layers of different material filters. From top to bottom, these layers are: 0.1 m gravel Ø 4.75 - 12.5 mm; 0.6 m transition layer sand Ø 9.53 mm; 0.2 m drainage layer Ø 4.75 - 12.5 mm (Rotaria del Perú, 2012).

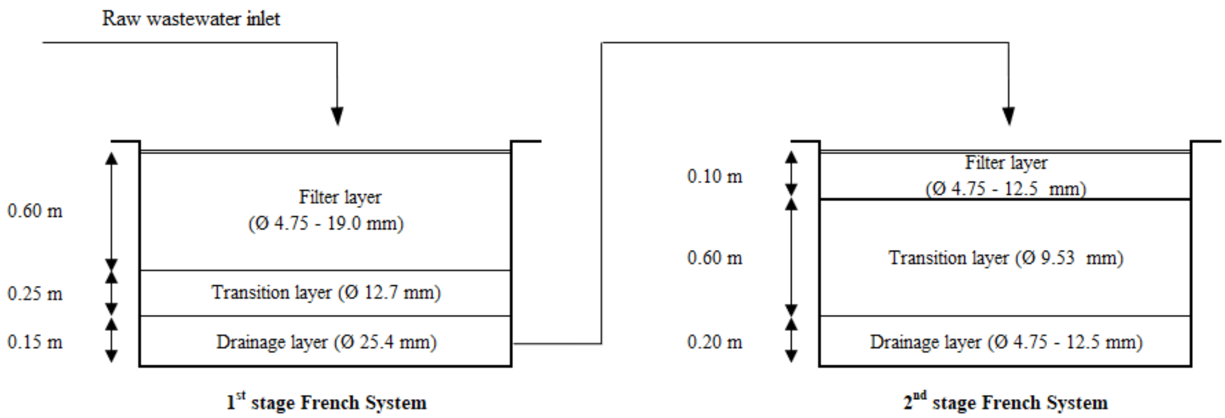

Figure 3. *Cross-sectional view of the French System installed at UNALM by Rotaria del Perú (2012)*

Operating loads

Four hydraulic load increments were applied to the 1st stage of the SF, with a duration between 6 - 12 weeks each. Table 1 shows the 4 applied load campaigns. In each campaign, B1 and B2 ran alternately for three days each, so that line 1 and line 2 were fed for three days and then rested for the same time.

Throughout the investigation, the system was fed with raw domestic wastewater in hydraulic batches of 6 minutes each. The hydraulic load increased by increasing the number of batches per day, starting 3 batches d-1, and increasing to 6, 8, and 12 batches d^{-1}.

Table 1. *Research period for 4 campaigns*

Campaign	Station	Date	Research period (week)	Batch duration (min)	Batch number (d^{-1})	Pumping time (min d^{-1})
I	Spring	Oct - Nov 2017	6	6	3	18
II	Summer	Dic - Jan 2017	8	6	6	36
III	Summer	Feb - May 2017	12	6	8	48
IV	Winter	Jul- Aug 2018	8	6	12	72

Parameters analysed

The temperature (T) and pH parameters were measured in the field. Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), Total Suspended Solids (SST), Turbidity, Total Nitrogen (N_{Total}), Ammonia Nitrogen (NH_4-N), Nitrate (NO_3- N), and total phosphorus (PO_4-P) were analysed in the Sanitation and Environment laboratory of UNALM. NO_3-N was not analysed in the influent samples, since the raw wastewater was assumed to be anaerobic. Thermotolerant coliforms (CT) and helminth eggs (HH) were analysed in an accredited external laboratory.

RESULTS AND DISCUSSION

Characterization of untreated wastewater

Table 2 shows the characteristics of the concentrations of raw wastewater during the 4 research campaigns (October 2017 to August 2018).

The average pH value of the influent wastewater was 7.5, which is slightly alkaline, and the average temperature was 24.9 °C. The average concentration of the N_{Total} was 55.9 mg L-1, and the NH_4-N represents 70.3% of the N_{Total}, which is 29.7% of the nitrogen that enters the 1st stage was in organic form. The average PO_4-P concentration was 10.1 mg L^{-1}. The average concentrations of COD and BOD_5 (biological oxygen demand) were 699.9 mg L^{-1} and 344.3 mg L^{-1} respectively, which turn in a BOD_5 / COD ratio of 0.49 that indicates that any biological treatment can be applied to wastewater (Von Sperling & Chernicharo, 2005). The COD, BOD_5, SST, and Turbidity present high standard deviation, which means the data is dispersed concerning the average, and therefore there is a higher standard error.

Table 2. *Characteristics of the concentrations of raw wastewater during the 4 research campaigns.*

	Unit	Concentration
COD	mg L^{-1}	699.9 ± 276.6
BOD_5	mg L^{-1}	344.3 ± 149.7
SST	mg L^{-1}	584.9 ± 471.9
N_{Total}	mg L^{-1}	55.9 ± 14.0
NH_4-N	mg L^{-1}	39.3 ± 8.3
PO_4-P	mg L^{-1}	10.1 ± 2.8
Turbidity	NTU	476.6 ± 239.5
pH	-	7.5 ± 0.5
T	(°C)	24.9 ± 2.4

Hydraulic loads

The hydraulic load results applied to the 1st and 2nd stage of the French System are shown in Table 3. For practical purposes, the hydraulic load applied in the 1st stage was the average of the two lines; instead, the hydraulic load applied in the 2nd stage was only the one calculated in line 2 (see Figure 2).

The hydraulic loads applied in campaign 3 for the 1st and 2nd stages were 0.329 m d^{-1} and 0.395 m d^{-1} respectively. These values are similar to those proposed by Dotro, Langergraber, Molle, Nivala, Puigagut, Stein, and Von Sperling (2017) (maximum design hydraulic loads) related to one of the active lines in the 1st and 2nd stage under temperate conditions (0.37 m d^{-1}).

The small variations in hydraulic load applied in the 1st stage are because the power of the pumps was not controllable. The pumps were operating at maximum capacity during the operation periods. Although the pumps manufactured are similar, they do not generate the same volumetric flow generating different hydraulic loads for each of the lines. Other factors were the pipe connections and valves of the installed system.

Table 3. Hydraulic loads applied to the 1st stage (French cell) and line 2 of the 2nd stage (vertical flow subsurface wetland) of the French System.

Campaign	*Unit*	**1st stage**			**2nd stage**
		Line 1	**Line 2**	**Average**	**Line 2**
I	m d^{-1}	0.125	0.113	0.119	0.143
II	m d^{-1}	0.254	0.247	0.251	0.301
III	m d^{-1}	0.338	0.319	0.329	0.395
IV	m d^{-1}	0.449	0.483	0.466	0.589

Treatment efficiencies

Table 4 show the pollutant removal efficiencies of the 1st and 2nd stages, and the whole system (1st + 2nd stage) during the 4 research campaigns. The removal efficiencies in the 1st stage were > 79.9%, > 83.3%, > 96.0%, > 58.2%, > 53.0%, and > 39.3% for COD, BOD_5, SST, N_{Total}, NH_4-N, and PO_4-P respectively. The results obtained are higher than those registered by Molle, Liénard, Boutin, Merlin, and Iwema (2005) for moderate climates and similar to those registered by Lombard and Molle (2017) for temperate climates regardless of the operating hydraulic load.

The removal efficiencies in the 2nd stage were > 84.5%, > 76.7%, > 79.2%, > 38.1%, > 81.6%, and > 22.5% for COD, BOD_5, SST, N_{Total}, NH_4-N, and PO_4-P, respectively. The results obtained are higher than those recorded by Molle, Liénard, Boutin, Merlin, and Iwema (2005) for moderate climates and lower than those recorded by Gomez (2017) for temperate climates, regardless of the operating hydraulic load.

The removal efficiencies of the whole system (1st + 2nd stage) were > 97.7% in all Research Campaigns for COD, BOD_5, and SST, and NH_4-N > 91.5%, these results are even higher than those registered by Molle, Liénard, Boutin, Merlin, and Iwema (2005) for moderate climates and similar to those established by Platzer, Hoffmann, and Miglio (2016) for temperate climates regardless of the operating hydraulic load. Likewise, for the N_{Total} and PO_4-P they present significant efficiencies in all campaigns > 76.2%, without considering the result of PO_4-P in campaign 4.

However, during field observations, it was noted that in campaign 4 of research, there were signs of clogging and slower passage of residual water over the filter in the 2 stages of the French System. These indications must be confirmed by working with a longer operating time under the operating loads indicated in each investigation campaign.

Table 4. *Efficiency of removal of pollutants from the whole system (1st + 2nd stage) during the 4 research campaigns.*

	Campaign	Affluent	Effluent 1st stage	Effluent 2nd stage	Efficiency 1st + 2nd stage
		mg L^{-1}	mg L^{-1}	mg L^{-1}	%
COD	I	497.6	100.0	10.3	**97.9**
	II	827.6	92.1	11.2	**98.6**
	III	856.3	81.2	12.6	**98.5**
	IV	465.1	73.1	10.6	**97.7**
BOD_5	I	254.1	42.5	5.0	**98.1**
	II	546.0	38.2	7.9	**98.6**
	III	372.0	29.5	6.9	**98.2**
	IV	220.1	28.4	3.1	**98.6**
SST	I	378.2	15.2	1.8	**99.5**
	II	540.3	15.9	3.3	**99.4**
	III	1019.2	19.0	1.5	**99.9**
	IV	207.3	8.3	1.6	**99.2**
N_{Total}[3]	I	55.0	23.0	10.0	**81.8**
	II	65.5	23.7	10.2	**84.5**
	III	64.2	19.0	9.8	**84.8**
	IV	47.0	18.1	11.2	**76.2**
NH_4-N	I	42.8	20.1	3.0	**92.9**
	II	42.6	19.6	3.6	**91.5**
	III	37.0	16.2	1.8	**95.2**
	IV	36.7	16.7	2.6	**92.8**

[3] N_{Total}: 10 mg N.L^{-1}, maximum allowable value (VMA) for recharge of aquifers by localized percolation through the ground or by direct injection. RD 1620/2007 Legal regime for the reuse of treated wastewater in Spain.

PO_4-P	I	7.2	4.3	1.6	**77.8**
	II	10.2	4.5	1.2	**87.9**
	III	12.6	6.2	2.9	**76.6**
	IV	8.2	5.4	4.2	**49.1**

Wastewater reuse in forestry

The Urban forest can be considered a goods solution (Randrup et al., 2020) which has several benefits: regulating urban microclimates, filtering air pollution, providing shade, capturing CO_2, and regulating temperature. Within the framework of SDGs 11, they can help citizens have access to safe, inclusive, and accessible green areas and public spaces for the development of social, cultural, and sports activities. However, as can be seen in Figure 4, in Lima, since 2005, more than 200ha have been reforested each year but from 2015 to 2018 this number has decreased considerably.

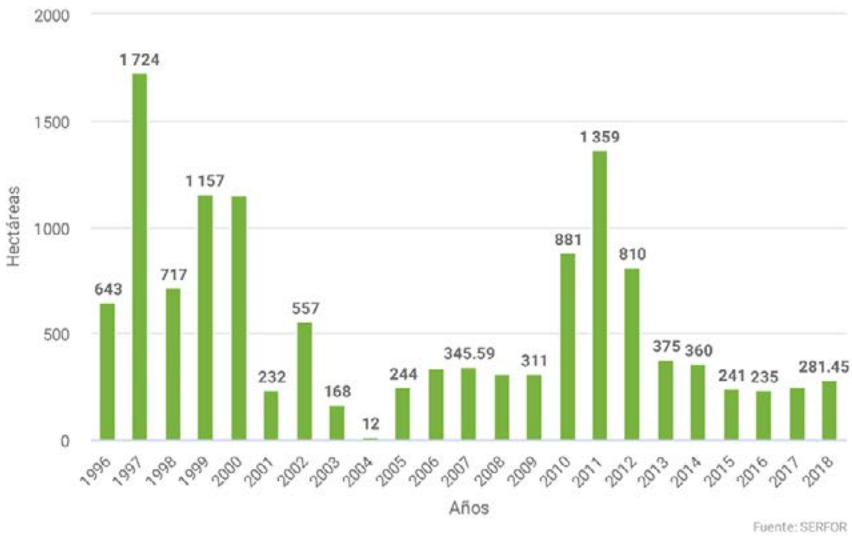

Figure 4. *Area reforested annually in the city of Lima-Peru. Source: MINAM, 2021.*

On the other hand, the urban forest requires "a planned development and maintenance approach" (Schwab, 2009), where water is the key element for its proper functioning. Although reforestation is undoubtedly beneficial, each tree consumes water and in this coastal city water is not an abundant resource. That is why it would be optimal to use treated wastewater for irrigation of afforestation in the city of Lima.

Evaluation of microbiological quality for the reuse of wastewater in forestry

Table 5 shows the microbiological quality parameters for irrigation reuse purposes. The results in the tributary fluctuate between $2x10^8$ - $4x10^8$ NMP mg L^{-1} for the CT, and at the same time, these are similar to those found by Platzer, Hoffmann, and Miglio (2016) for a similar design of the French system under the same climatic conditions. Likewise, the HH fluctuates between 205 - 2200 N ° L^{-1}.

The high removal of CT in the 1st and 2nd stages of the French System is due to sedimentation and filtration in the first 20 cm of the filter medium (Sleytr, Tietz, Langergraber & Haberl, 2007) and the elimination of HH, possibly due to the porosity of filters (Jimenez, 2007).

Table 5. *Characteristics of the concentrations of thermotolerant coliforms (CT) and helminth eggs (HH) in wastewater treated in the SF during 4 campaigns.*

Campaign			effluent	Effluent 1st stage SF	Effluent 2nd stage SF	WHO regulations Restricted irrigation	WHO regulations Unrestricted irrigation
CT	I	NMP ml^{-1}	$2x10^8$	$4.5x10^5$	$2.5x10^3$	≤ 1	≤10^3
	II	NMP ml^{-1}	$4x10^8$	$6.7x10^6$	$3.4x10^3$		
	III	NMP ml^{-1}	$3.4x10^7$	$3.9x10^6$	$1.6x10^4$		
	IV	NMP ml^{-1}	$2.8x10^6$	$1.6x10^6$	$4.7x10^3$		
HH	I	N° L^{-1}	2200	0	0	-	≤ 1
	II	N° L^{-1}	485	0	0		
	III	N° L^{-1}	205	0	0		
	IV	N° L^{-1}	113	0	0		

CONCLUSIONS

The characterization of the physical, chemical, and microbiological properties of the effluent from the "French System" as a whole (1st + 2nd stage), indicates an efficiency superior to 90% of elimination of COD, BOD_5, N_{Total}, P_{Total}.

Regarding the N_{Total}, the values (9.8 ± 2.9 - 11.2 ± 2.1 mg N / L) indicate that the effluent can have an environmental use both for recharging aquifers by localized percolation through the ground and by direct injection (RD 1620/2007 - Catalunya). This indicates that a post-treatment would not be necessary for its use in forest irrigation and that it would not affect the quality of the aquifers.

The microbiological evaluation carried out during 4 campaigns showed values of Thermotolerant Coliforms (1.6 $x10^4$ - $7x10^3$ NMP ml^{-1}) and of Helminth Eggs equal to 0 N ° egg L^{-1}, showing that French System produce AR with optimum quality for use in afforestation irrigation.

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