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French Reed Bed as a Solution to Minimize the Operational and Maintenance Costs of Wastewater Treatment from a Small Settlement: An Italian Example

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Abstract: French Reed Bed (FRB) is a particular constructed wetland (CW) solution which receives raw wastewater. Data from the full-scale FRB wastewater treatment plant of Castelluccio di Norcia (center of Italy) were collected to show the FRB capability to minimize the operational and management (O&M) costs. The system was designed to treat wastewater variable from 200 person equivalent (PE) in off-season up to 1000 PE. Data from 2014 up to 2016 showed high removal efficiency in line with French experiences with FRBs. An interview was conducted with the Water Utility to estimate the operational and maintenance (O&M) costs faced by the WWTP, which allowed us to detail the O&M costs for energy consumption, water quality samples, and personnel for inspection. Other O&M expenditure items were estimated on the basis of parametric costs from the executive design. The FRB O&M costs in euro for 500–1000 PE (6–11 € PE^{-1} $year^{-1}$) resulted from 5 to 13 lower in comparison to those reported for classical activated sludge systems in an Italian context (45–90 € $year^{-1}$). The low O&M costs are mainly due to the limited energy consumed and to the minimized costs of sludge management.

Keywords: activated sludge; constructed wetland; cost; French Reed Bed; small settlement; treatment wetland; wastewater treatment; WWTP

1. Introduction

The so-called French Reed Bed (FRB) is a particular constructed wetland (CW) solution which receives raw wastewater [1–3]. FRB is a two stage system: the first stage involves a vertical subsurface flow (VF) bed receiving raw wastewater and filled with coarse gravel; the second stage is a VF bed filled with coarse sand. Primary treatments are not adopted, since the surface of the first stage VF acts as a filtration stage. Indeed, the solid materials from wastewater will create an organic top layer on the surface area and has to be removed after 10–15 years, i.e., when it is already stabilized and can be used as soil conditioner [4]. FRBs are very efficient in the removal of suspended, dissolved organic matter, and pathogens and have a high nitrification capability, with a relevant contribution due to the first stage [5]. Higher denitrification and total nitrogen removals are achievable with the adoption of a saturation bottom layer [6]. The system does not present odor issues due to the fact that the sludge formed on the surface of the wetland is kept under constant aerobic conditions by the cyclic feeding scheme and the active rhizosphere growing in it. The main advantage of FRB is that it does not require the primary treatment system (septic tank or Imhoff tank), as requested by classical CWs. Consequently, FRB is an attractive solution to minimize the operational and maintenance (O&M) costs of wastewater treatment from small settlement.

FRB is being successfully applied in France, where up to now more than 4000 treatment plants are in operation (<4000 person equivalent—PE), with the oldest having almost 30 years of lifespan [3,7,8]. Moreover, FRB has been also successfully applied for a big city in Moldova, which treats up to 20,000 PE [9], and in tropical climates [10,11].

CWs are well-known to be able to reduce the O&M costs in comparison to classical technological solutions, such as activated-sludge systems [12–14]. However, the particular sludge management of FRB systems allows O&M costs to be lowered even in comparison to classical CWs. Therefore, the aim of this paper is to highlight the following concept: FRB is a suitable solution to provide robust wastewater treatment as well as minimize O&M expenditures of WWTPs for small communities in comparison to activated sludge and classical CW systems. To this aim we discuss one of the first FRB wastewater treatment plants (WWTP) for domestic wastewater in Italy, i.e., the FRB WWTP of the Castelluccio di Norcia town (up to 1000 PE). The discussion is based on data collected from the Water Utility, which include: water quality monitoring; detailed estimations from the executive design; information from an interview to detail the real O&M costs faced by the FRB WWTP.

2. Materials and Methods

2.1. Case Study

Castelluccio di Norcia (42°49′44″ N, 13°12′21″ E) is a touristic village, located into an area of high naturalistic value (the Mount Sibillini National Park) in the center of Italy (Umbria Region). Castelluccio di Norcia represents a typical Italian small settlement below 2000 PE, situated in a hilly area far from big towns or cities (the nearest bigger town, Norcia, is 10 km far from Castelluccio). The population is variable from 100 to 200 PE in off-season up to 500 PE during the touristic season. The system was designed by the Italian firm IRIDRA and considered a potential expansion in the future 10 years of the touristic area up to 1000 PE during peak seasons. Therefore, the FRB treatment was designed to serve up to 1000 PE and to receive up to 150 m^3 day^{-1}.

The layout of the designed CW treatment plant is (Figure 1): (i) preliminary treatment (automatic screw screen); (ii) equalization tank; (iii) siphons; (iv) French Reed Bed (FRB) for raw wastewater at first stage of 1014 m^2; (v) vertical flow constructed wetland (VF) at second stage of 1000 m^2; (vi) Free water system (FWS) at third stage of 920 m^2; (vii) infiltration basin for the disposal of treated wastewater into underground soil (260 m^2).

The only pretreatment is an automatic screw, with a spacing of 3 mm. Classical primary treatment such as septic or Imhoff tanks have been avoided, according to the FRB guidelines and concept. The pretreated wastewater is sent to an equalization tank of 18 m^3. The equalization tank is divided in two sectors: the first sector aims to entrap oil, floating materials and scums; the second sector provides equalization, in order to better distribute the daily and seasonal peaks, especially due to touristic activities. A pumping system is installed in the equalization tank to properly feed the tank with siphons. The FRB beds are fed with siphons to reduce the energy consumption, due to suitable orographic conditions.

The FRB first stage has been designed according with recommendations gained from French experience [1]; the technical specifications are resumed in Table 1. A freeboard is present on the top of the FRB surface, to accumulate and mineralize the sludge (expected to be withdrawn every 20 years). The FRB first stage has been built with two beds of 507 m^2, each bed is divided in 3 hydraulically separated sectors. The FRB sectors are loaded alternatively to maintain aerobic condition into the FRB beds, and mineralizing the organic layer retained on the surface. To this aim, the 6 FRB sectors are divided in three lines (see Figure 1). Each parallel line is fed for a period of 3.5 days, with a subsequent resting period of 7 days (in which the other lines start to be fed). The feeding of different line and the resting periods are regulated by automatic electro-mechanical valves. The sectors are fed during the feeding period in batch: the volume of flush is sent to the FRB line with different flushes regulated by the pumping station which feeds the siphons; when the flush volume is reached, the FRB line has a resting period to properly infiltrate and treat the wastewater. Effluent of FRB first stage is sent to a pumping system to feed the VF second stage. The FRB beds are planted with *Phragmites australis.*

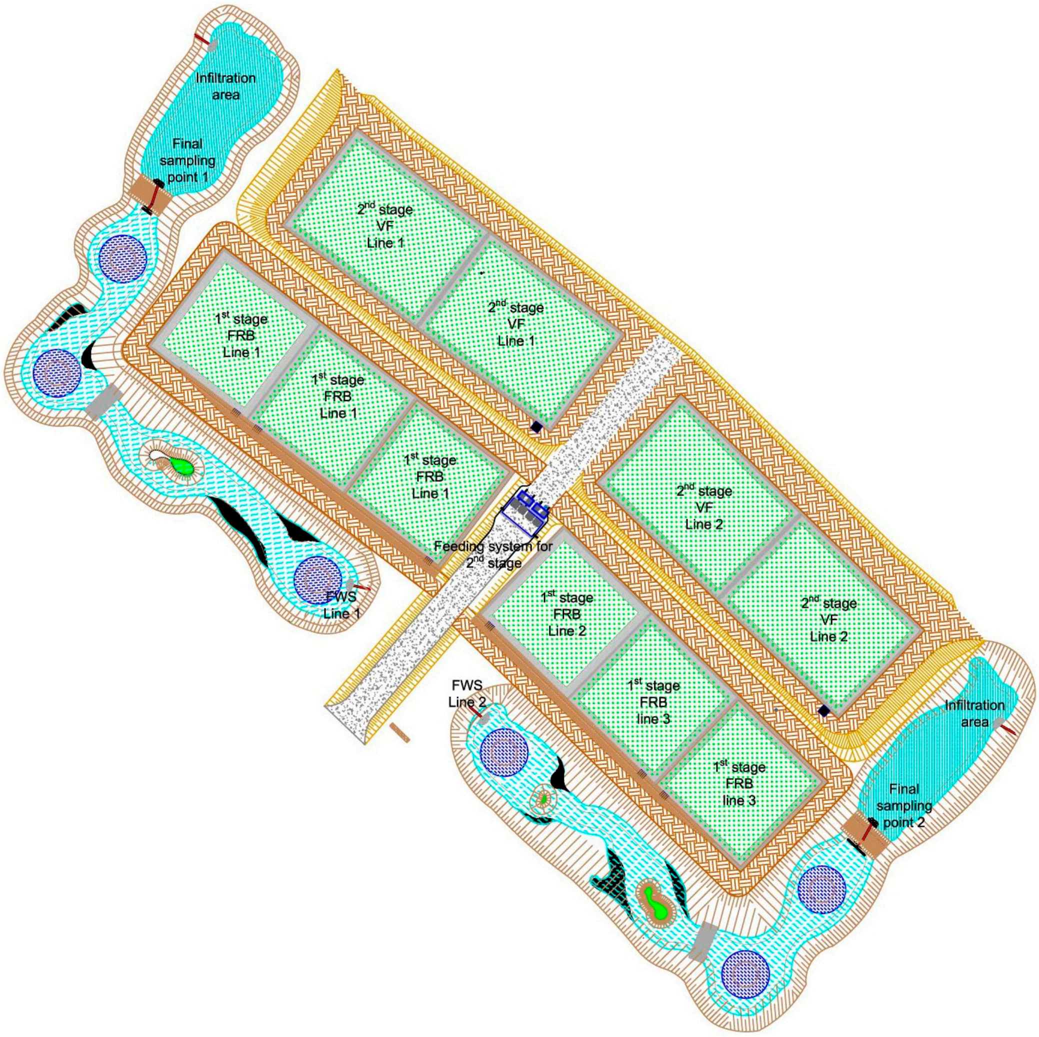

Figure 1. Layout of the French Reed Bed (FRB) wastewater treatment plant (WWTP) of Castelluccio di Norcia (Italy). Note that preliminary treatments, equalization tank, and syphons are not reported in the layout because they are sited farther from the WWTP.

Table 1. Technical specifications of the two stage CW WWTP of Castelluccio di Norcia.

First Stage French Reed Beds			Second Stage VF CWs		
n° of FRB parallel line	3		n° of parallel line	2	
n° of FRB sector per line	2		n° of VF sector per line	4	
Total surface area FRB	1014	m^2	Total surface area VF	1000	m^2
Surface area of each FRB line	338	m^2	Surface area of each VF line	500	m^2
Surface area of each FRB sector	169	m^2	Surface area of each VF sector	250	m^2
feeding period per each sector	3.5	days	Minimum resting period between flushes for each sector (1000 PE)	2.4	h
resting period per each sector	7	days	Total height of the filter media	80	cm
Total height of the filter media	100	cm	VF filter media layers (from the bottom)		
FRB filter media layers (from the bottom)			coarse gravel—Ø 30–70 mm	15	cm
coarse gravel—Ø 30–70 mm	20	cm	gravel—Ø 10 mm	15	cm
gravel—Ø 5–10 mm	20	cm	sand—Ø 0.2–5 mm	40	cm
fine gravel—Ø 2–6mm	60	cm	gravel—Ø 10 mm	10	cm
freeboard height	40	cm			
Minimum organic loading rate (250 PE)	32	g_{COD} m^{-2} day^{-1}			
Peak organic loading rate (1000 PE)	130	g_{COD} m^{-2} day^{-1}			
Minimum Hydraulic loading rate (250 PE)	40	L m^{-2} day^{-1}			
Peak Hydraulic loading rate (1000 PE)	150	L m^{-2} day^{-1}			

The VF second stage has been designed with an oxygen transfer rate of 50 g_{O2} m^{-2} day^{-1} [15], and following the German Guidelines for domestic wastewater [16]. The technical specifications of VF second stage are resumed in Table 1. The VF second stage has been built with two beds of 500 m^2, each bed is divided in 2 hydraulically separated sectors. In order to guarantee sufficient oxygen transfer for BOD_5 reduction and nitrification, the VF beds are fed in batch with an approach similar to FRB first stage, i.e., flush volume, feeding time, feeding stop and resting period set "a priori" and regulated by a timer. The VF beds are planted with *Phragmites australis.*

Two free water surface (FWS) beds have been designed. Each bed has a first waterproofed area for tertiary treatment and a subsequent not waterproofed area for infiltration of treated wastewater into the soil. The waterproofed areas have different water depth (from 0.2 to 0.8) to place different autochthonous plant species (helophytes and hydrophytes). The infiltration areas are also equipped with overflow infiltration trench drains.

The WWTP was designed to respect the following water quality targets: COD 160 mg L^{-1}; BOD_5 40 mg L^{-1}; N-NH_4^+ 25 mg L^{-1}; TSS 80 mg L^{-1}. The construction costs for the WWTP was about 395,000 €.

2.2. Water Quality Dataset and Statistical Analyses

The water quality dataset comes from the Water Utility of the WWTP of Castelluccio di Norcia. The data are from influent, and effluent from the two FWS beds (see Figure 1) called hereinafter OUT 1 and OUT 2. Only influent and effluent concentration values are available, since the influent and effluent wastewater hydraulic loads were not monitored.

The data were sampled from the 18 February 2014 up to 18 October 2016, and a total of 43 samples among IN, OUT 1, and OUT 2 are available. Point grab samples were collected by the Water Utility without a specific frequency, as visible in Supplementary online material. More samples were taken after the start-up phase in 2014, covering 8 months per year, and fewer in 2015 and 2016 (4 and 3 months per year, respectively). More recent data are not available, since the WWTP stopped to be in operation after the big earthquake happened in the center of Italy the 30 October 2016. The WWTP of Castelluccio di Norcia is planned to come back in operation in the summer 2018. Analyzed water quality data regards total suspended solid (TSS), chemical oxygen demand (COD), biochemical oxygen demand after five days (BOD_5), total nitrogen (TN), ammonium nitrogen (N-NH_4^+), and total phosphorous (TP); the samples were analyzed by external certified laboratory, according to standard methods [17].

The dataset was used to calculate mean, standard deviation, minimum and maximum values for each pollutant parameter at IN, OUT 1, and OUT 2. Each sample has more than 10 data, therefore *t*-tests were used to test the significance of differences of mean values. Unpaired *t*-test with one-tail distribution was used to check if the effluent concentrations are significantly lower than influent concentrations; this test was separately performed for both OUT 1 and OUT 2. Moreover, unpaired *t*-test with two-tail distribution was used to test if the effluent OUT 1 and OUT 2 concentrations are significantly different. The statistical analyses are done with Microsoft Excel.

2.3. Interview Regarding Water Utility and Parametric Costs

An interview was undertaken with the Water Utility, asking them to fill in a data sheet to detail the real O&M costs afforded for the FRB WWTP of Castelluccio di Norcia. The interview regarded:

1. Energetic consumption and costs per year
2. Reed maintenance
3. Green maintenance
4. Annual costs for grit disposal
5. Occurrence of ordinary and/or extraordinary maintenance of electro-mechanical components
6. Occurrence of ordinary and/or extraordinary maintenance of treatment plant in general
7. Number of workers used during the inspection of the treatment plant

8. Average time of each inspection
9. Frequency of inspection (1 per week, 1 per month, etc.)
10. Number of water quality samples collected to monitor the treatment plant
11. Height of the sludge layer on the first FRB beds

However, the Water Utility was not able to fulfill all the requests, and some expenditure items were estimated on the basis of parametric values set in the executive design. The parametric values used for O&M cost estimation are resumed in Table 2.

Table 2. Parametric values from executive design used to estimate expenditure items for which Water Utility did not provide information.

Parametric Values	Value	Unit
Cost of sludge transport and disposal	20	€ m^{-3}
Frequency of sludge removal from first FRB beds	20	years
Reed harvested	5	kg m^{-2}
Parametric cost for reed and green harvest	0.1	€ m^{-2}
Parametric cost for transport, load and unload of harvested reed and green	18	€ ton^{-1}
Parametric cost for waste in landfill of harvested reed and green	50	€ ton^{-1}
Green area	500	m^2
Green material harvested for maintenance	2	kg m^{-2}
Manhole cleaning, grit removal	200	€ $year^{-1}$
Ordinary and extra-ordinary maintenance of electromechanical components	400	€ $year^{-1}$
Ordinary and extra-ordinary maintenance of concrete structures, sewer, embankments, etc.	600	€ $year^{-1}$
Cost of not-specialized personnel	18	€ h^{-1}
Cost of water quality sample	50	€ per sample

The data from the interview and the parametric costs are used to estimate the yearly O&M costs for the FRB of Castelluccio di Norcia, which are divided in the following 9 expenditure items:

1. Sludge removal (allocation of resources to remove the sludge layer after 20 years of operation)
2. Energy consumption
3. Reed harvesting
4. Green maintenance
5. Manhole cleaning, grit removal
6. Ordinary and extra-ordinary maintenance of electromechanical components
7. Ordinary and extra-ordinary maintenance of concrete structures, sewer, embankments, etc.
8. Personnel
9. Water quality samples for the monitoring of the WWTP

3. Results

3.1. Water Quality Dataset Analysis

High variability is observed in influent concentrations due to the use of grab point samples (Table 3). On the other hands, effluent concentrations from the FRB WWTP of Castelluccio di Norcia are quite stable and low, highlighting very robust performances during the whole period of functioning. Indeed, the effluent from the WWTP always respected the water quality target set in the design phase (Figure 2). The *t*-tests confirm that outlet concentrations are significantly lower than influent concentrations for both OUT 1 and OUT 2, with a significance lower than 0.05 for COD, BOD_5, TN, N-NH_4^+, and TSS, and lower than 0.1 for TP (see Table S1 in Supplementary online material).

The mean value and standard deviation reported in Table 3 as well as the *t*-test (Table S2 in Supplementary online material) show that the water quality effluent from the two FWS beds (OUT 1 and OUT 2) are not significantly different.

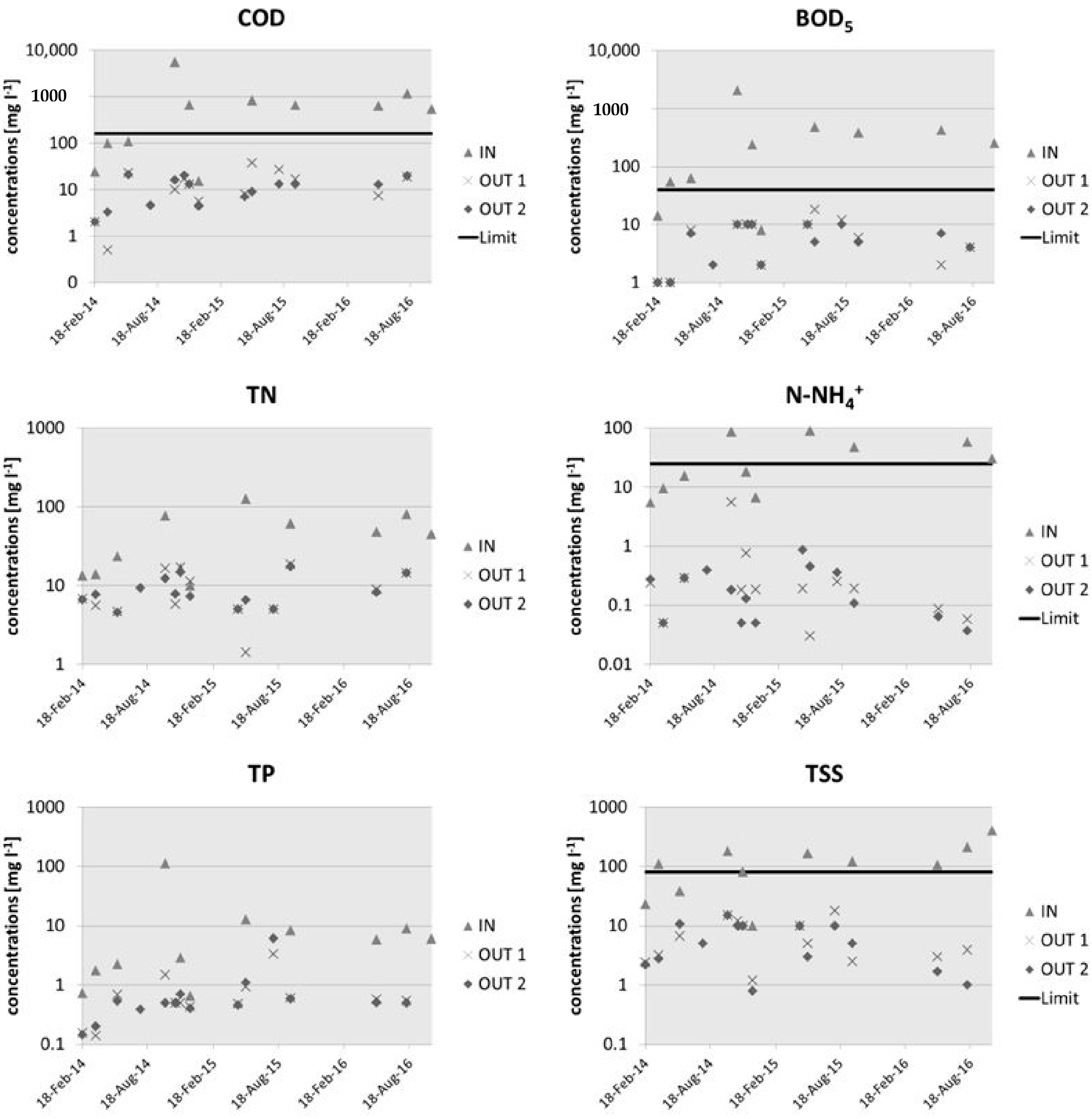

Figure 2. COD, BOD_5, TN, $N\text{-}NH_4^+$, TP, and TSS concentrations of treated wastewater effluent from the FRB WWTP of Castelluccio di Norcia from the 18 February 2014 to the 18 October 2016, compared with the set targets for effluent water quality. IN: influent to first FRB beds. OUT 1 and OUT 2: effluent from the two FWS beds.

Table 3. Analysis of pollutant concentrations of wastewater treated by the FRB WWTP of Castelluccio di Norcia municipality. OUT 1 and OUT 2 refer to the effluent from the two FWS beds. Data from the 18 February 2014 to the 18 October 2016.

	COD (mg L^{-1})			**BOD_5 (mg L^{-1})**		
	IN	**OUT 1**	**OUT 2**	**IN**	**OUT 1**	**OUT 2**
Mean	928.8	14.3	11.3	394.8	7.2	6.0
Std. dev.	1566.6	10.5	6.4	603.8	5.1	3.6
Min	15.1	0.5	2.0	8.0	1.0	1.0
Max	5520.0	37.4	20.7	2040.0	18.0	10.0
80° perc.	825.0	21.2	17.4	432.0	10.0	10.0
No. of s.	11	13	14	10	13	14

Table 3. *Cont.*

	COD (mg L^{-1})			BOD_5 (mg L^{-1})		
	IN	**OUT 1**	**OUT 2**	**IN**	**OUT 1**	**OUT 2**
	TN (mg L^{-1})			**N-NH_4^+ (mg L^{-1})**		
	IN	**OUT 1**	**OUT 2**	**IN**	**OUT 1**	**OUT 2**
Mean	46.4	9.3	9.1	36.4	0.6	0.2
Std. dev.	36.6	5.6	4.1	31.8	1.5	0.2
Min	9.9	1.4	4.5	5.5	0.0	0.0
Max	126.0	18.5	17.5	89.4	5.6	0.9
80° perc.	75.9	15.6	13.1	63.1	0.3	0.4
No. of s.	11	13	14	10	13	14
	TP (mg L^{-1})			**TSS (mg L^{-1})**		
	IN	**OUT 1**	**OUT 2**	**IN**	**OUT 1**	**OUT 2**
Mean	14.6	0.8	0.9	131.9	7.1	6.2
Std. dev.	32.2	0.8	1.5	111.8	5.4	4.6
Min	0.7	0.1	0.1	10.0	1.2	0.8
Max	111.0	3.4	6.1	407.0	18.0	15.0
80° perc.	8.9	0.8	0.6	180.0	11.2	10.0
No. of s.	11	13	14	11	13	14

3.2. Results of the Tnterview and O&M Costs

The information of the interview with the Water Utility allowed estimating in detail: (i) energy consumption and costs; (ii) number of inspection to the WWTP; (iii) number of water quality samples collected for the monitoring of the WWTP. These results are summarized in Table 4, while daily and monthly details of the information provided by the Water Utility are reported in Supplementary online materials.

Table 4. Summarization of detailed information gained from the interview.

	2014	2015	2016	Yearly Mean
N° of water quality samples	24	10	9	**15**
N° of inspections	16	14	8	**13**
Energy				
Cost of energy per kwh (€)		169	148	**159**
Other costs (€)		850	846	**849**
Total energetic costs (€)		1020	994	**1007**

The average O&M costs for the FRB WWTP of Castelluccio di Norcia are summarized in Table 5. The total average yearly O&M cost was equal to 5531 € per year. The most important expenditure items are cost for energy, personnel used for the WWTP inspections, reed harvesting, and water quality samples for WWTP monitoring, while the cost of sludge removal is relatively low (Figure 3). As visible from Table 4, the majority of energy cost is due to other costs (84%—i.e., the costs for the energy network and fees), while the cost of consumed energy per kWh is significantly lower (16%).

Table 5. Expenditure items considered for the O&M cost estimation and source of information used for the evaluation.

	Yearly O&M Costs	Source of the Information for the Evaluation	Average Yearly Costs	
1	Sludge removal	Parametric values	400	€ $year^{-1}$
2	Energy consumption	Interview	1007 *	€ $year^{-1}$
3	Reed harvesting	Parametric values	924	€ $year^{-1}$
4	Green maintenance	Parametric values + Interview	236 **	€ $year^{-1}$
5	Manhole cleaning, grit removal	Parametric values	200	€ $year^{-1}$
6	Ordinary and extra-ordinary maintenance of electromechanical components	Parametric values	400	€ $year^{-1}$
7	Ordinary and extra-ordinary maintenance of concrete structures, sewer, embankments, etc.	Parametric values	600	€ $year^{-1}$
8	Personnel	Interview	702 *	€ $year^{-1}$
9	Water quality sampling	Interview	750 *	€ $year^{-1}$
	Total O&M costs		**5531**	**€ $year^{-1}$**

Notes: * Mean value among the values for 2015 and 2016; ** Frequency of green maintenance per year equal to 2 on the basis of information given by the Water Utility during the interview.

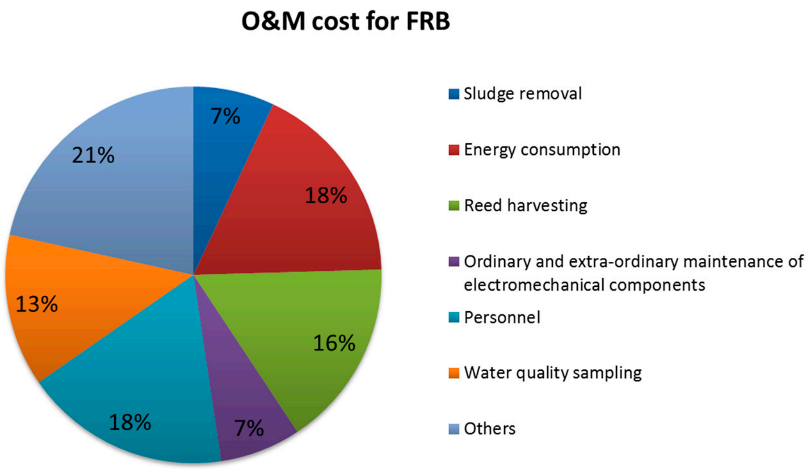

Figure 3. Relative contribution of expenditure items to yearly O&M costs of the FRB WWTP of Castelluccio di Norcia.

4. Discussion

The FRB WWTP of Castelluccio di Norcia was designed to face touristic fluctuation of produced wastewater. To this aim, the system is designed according to guidelines from French experience [1,3,7,8] (1.2 m^2 PE^{-1} for the first FRB stage; 0.8 m^2 PE^{-1} for the second stage) for the future peak of tourism, i.e., 1000 PE, with a slight undersize of the first stage to consider the seasonal fluctuation: 1 m^2 PE^{-1} for the first stage FRB; 1 m^2 PE^{-1} for the second stage VF. However, the system can be considered highly conservative for the touristic peaks faced during the monitoring period 2014–2016, assumable equal to 500 PE (2 m^2 PE^{-1} for the first stage FRB; 2 m^2 PE^{-1} for the second stage VF), and oversized for the off-season population of 200 PE (5 m^2 PE^{-1} for the first stage FRB; 5 m^2 PE^{-1} for the second stage VF). Although the size of the system should be considered in the interpretation of the water quality results, the average removal efficiencies of the FRB WWTP of Castelluccio di Norcia can be considered to be generally in line with the value reported from the ample dataset of French WWTPs (Table 6). Even if the overall performance from Castelluccio reported in Table 6 are from a three stage system (FRB + VF + FWS), the results are comparable with the data from the two stage systems analyzed by Paing et al. [7] and Morvannou et al. [8]. Higher nutrient removal resulted in comparison with French values (Table 6). The higher TN removal can be attributed to denitrification in the third stage FWS, which is not considered (and usually not adopted) in French WWTPs. The FRB WWTP of Castelluccio di Norcia is a quite young WWTP in comparison to the systems analyzed by Paing et al. [7] and Morvannou et al. [8] (only 2 years old); therefore, the higher TP removal can be attributed to still not saturated adsorption sites for phosphorous. However, a part of the higher TP removal could be due to the effect of the third stage FWS.

Table 6. Comparison of average removal efficiencies of the FRB WWTP of Castelluccio di Norcia with the data from the ample French dataset analyses.

	FRB + VF + FWS Castelluccio di Norcia		**FRB + VF Paing et al. 2015 151 WWTP < 2000 PE * [7]**	**FRB + VF Morvannou et al. 2015 380 WWTP < 2000 PE ** [8]**
	OUT 1	**OUT2**		
TSS	94.6%	95.3%	96 ± 9%	93 ± 9%
COD	98.5%	98.8%	93 ± 4%	87 ± 14%
BOD_5	98.2%	98.5%	98 ± 1%	
TN	80.0%	80.5%	39 ± 30%	
$N\text{-}NH_4^+$	98.3%	99.4%	93 ± 7% ***	84 ± 17% ***
TP	94.5%	93.8%	30 ± 28%	

Notes: * Up to 12 years old; ** 55% of the WWTP are between 7 and 11 years old; *** As TKN.

Energy consumption is one of the expenditure items known for reducing the O&M costs of CWs in comparison to technological solutions. The FRB WWTP of Castelluccio di Norcia confirms this statement, with energy consumption in line with literature values reported for CWs. Assuming 200 PE for 5 months of off-season and 600 PE for peak touristic season to estimate the treated volume of wastewater (no measured data are available) and 150 L day^{-1} PE^{-1}, the energy consumption results 0.15 kWh m^{-3}. This value is in line with the 0.1 kWh m^{-3} for subsurface flow CW reported in literature, and one order of magnitude lower than energy needed from the most common technological solutions [18]. The energy consumed by the WWTP of Castelluccio di Norcia is low, with low O&M cost. However, it must be noted that the majority of the energy costs are not due to consumed energy but to other costs, linked to energy network and fees. The other energy costs are probably so high, in comparison with the cost of energy, due to remote area in which the WWTP is sited and the low possibility, for the Energy Utility, to have income from the few activities connected to the electricity network. Therefore, the possibility to use renewable energy for WWTP functioning should be always considered in conditions similar to those of Castelluccio di Norcia, to reduce O&M costs not only in terms of cost of energy itself but principally for the linked cost to the service provider.

Another expenditure item in which classical CWs are known to be more advantageous in comparison to classical WWTP regards the sludge management. Essentially, activated sludge systems remove both particulate and dissolved organic load through sludge. Additional sludge is produced from activated sludge treatment plant if nitrification is required. Contrarily, CWs remove only the settable particulate organic matter as sludge within primary septic tanks. Indeed, the dissolved organic load in CWs is removed by biofilm attached to the porous media in subsurface systems, or by further settling of fine particle and biofilm attached to plant stems in FWS systems [18], i.e., not contributing to sludge formation. Therefore, the amount of sludge to be disposed from classical CW systems is very low in comparison to that produced by classical activated sludge WWTPs, and consequently also the correlated costs. For instance, Masotti and Verlicchi [13] reports for a small settlement of 300 PE in the Italian context a cost of 40 € PE^{-1} $year^{-1}$ for sludge transport and disposal from classical activated sludge system, which is one order of magnitude higher in comparison to the value estimated by the same authors from the same settlement treated with classical CWs, i.e., 3.5 € PE^{-1} $year^{-1}$. Regarding the issue of O&M cost reduction due to sludge management, the FRB solution represents a further improvement for CWs. Indeed, FRB system avoids septic tanks of classical CW schemes and accumulates the sludge on the top of the first FRB stage through the formation of a sludge deposit layer. The cracks produced by the movement of the plants with wind and the aeration pipes maintain the aerobic conditions within the deposit layer [4], i.e., similarly to what happens within sludge drying reed beds [3]. The oxic conditions are more favorable for the sludge mineralization than the anaerobic one developed in septic tanks, and the amount of sludge to be disposed at the end of a filling cycle of the first stage FRB freeboard is lower in comparison to that produced by classical CW schemes.

Therefore, the FRB scheme adds two further advantages to classical CWs: (i) no need of yearly removal, transport, and disposal of sludge; (ii) lower volume of sludge to be removed, transported, and disposed during the overall lifecycle of the WWTP. These advantages contribute to a further decrease in O&M costs of FRB solution in comparison to classical CWs. The freeboard on the top of the first FRB stage at Castelluccio di Norcia was designed with a height of 0.4 m. The assumed growth rate of the deposit layer for FRB of Castelluccio di Norcia is 2 cm per year, slightly lower than the 2.5 cm per year suggested for FRB system [4] to consider the fluctuation of the population due to touristic activities. Therefore, the freeboard is expected to be filled in 20 years. The transport and disposal of the accumulated sludge after 20 years is estimated to be equal to 8000 €, i.e., 400 € per year if distributed during the lifespan of the WWTP. Translated in terms of PE, the O&M sludge cost for the FRB WWTP of Castelluccio di Norcia results equal to 0.4–0.8 € PE^{-1} $year^{-1}$ (1000 PE and 500 PE, respectively), i.e., one and two orders of magnitude lower than the costs for classical CWs and activated sludge reported by Masotti and Verlicchi [13], respectively.

The FRB WWTP of Castelluccio di Norcia can be used to highlight the advantages of FRB scheme on the activated sludge system through the analysis of construction and O&M overall costs, which are reported in Table 7. In terms of construction costs, it is proper to compare the cost of the FRB WWTP of Castelluccio di Norcia as dimensioned for 1000 PE (i.e., maximum treatment capacity of the WWTP); Table 7 shows how the construction costs of the FRB WWTP (394 € per PE) were slightly higher but comparable with the construction costs of activated sludge systems in Italian context (263–360 € per PE). If the system would be realized strictly following the French scheme with only two stages (FRB + VF), the construction costs of FRB WWTP could be even lower. In this case, FWS was included due to restrictive water quality target requested to discharge on soil. If the FRB WWTP would be realized in area with less restrictive water quality limits (e.g., discharge in water body), the FWS could be avoided (about 30,000 €), leading to construction cost for the FRB scheme fully in line with higher range of activated sludge WWTP (364 € per PE). The FRB construction costs are in accordance with the value reported by Gikas and Tsihrintzis [19] for a real WWTP in Greece, also designed with the FRB approach; the system discussed by Gikas and Tsihrintzis [19] is designed for 600 PE, includes an additional third horizontal subsurface flow CW for denitrification and costs 477 € PE^{-1}. The FRB construction costs for the Castelluccio di Norcia WWTP are also in line with the value reported by Geenens and Thoeye [20] for 1000 PE in Belgian context, both for CWs (430 € PE^{-1}) and activated sludge systems (380 € PE^{-1}). The ratio between construction costs of activated sludge systems and CWs is also in line with the analysis proposed by Batchelor and Loots [12], which is based on a pilot CW study and is aimed for WWTP serving below 5000 PE in South Africa context; this study reports construction costs of CWs only 24% higher than those of activated sludge systems.

The O&M costs of the FRB WWTP of Castelluccio di Norcia must be considered for population faced during the monitoring period, i.e., assumable equal to 500 PE. Under this assumption, the O&M costs of the analyzed FRB WWTP results very low (11 € per PE) due to the advantages in terms of energy consumption and sludge management previously discussed. Comparing with classical WWTPs from Italian context, the O&M cost of the FRB WWTP of Castelluccio di Norcia results among 5 to 8 lower than classical activated sludge systems (Table 7). It must be noted that the estimated O&M costs would not change significantly even if WWTP would face the maximum designed population of 1000 PE; among the considered 9 expenditure costs, the only one that is expected to change is the energy consumption for consumed kWh, while all the other activities and costs could be assumed to be done and spent in the same way for both 500 and 1000 PE (e.g., water quality samples, WWTP inspections, fees for energy network). Therefore, the O&M costs for 1000 PE reported in Table 7 is estimated assuming all the expenditure item costs equal to those afforded for 500 PE, only doubling the energy costs per consumed kWh (additional 159 € $year^{-1}$–318 € $year^{-1}$ in total for 1000 PE). The result is reported in Table 7 and shows an O&M cost per 1000 PE of 6 € PE^{-1} $year^{-1}$, i.e., 8 to 13 lower than those of classical activated sludge systems. It must be noted that the O&M costs for the FRB WWTP of Castelluccio di Norcia are in line with the value reported by the Greece FRB real case study for 600 PE proposed by Gikas and Tsihrintzis [19], who estimate an O&M cost equal to 12 € per PE. The calculated ratio between O&M of activated sludge system and FRB for Castelluccio di Norcia seems to confirm the capability of FRB system to minimize O&M in comparison to classical CWs. Batchelor and Loots [12] reports O&M cost of CWs 4.6 lower than those of activated sludge solution (target 5000 PE). Masotti and Verlicchi [13] estimated the O&M costs of activated sludge (prolonged aeration) 1.7 times those of CWs for a WWTP serving 300 PE. Therefore, the previous ranges report a saving of O&M costs due to the use of classical CWs instead of activated sludge all lower than the reduction of O&M costs calculated for the FRB WWTP of Castelluccio di Norcia; however, more comparison studies on both classical and FRB CWs with activated sludge system O&M costs are needed to confirm this trend.

The previously discussed O&M costs does not include any estimation of benefits due to additional ecosystem services provided by green instead of gray infrastructures [21]. For instance, Ghermandi and Fichtman [22] estimated a mean and median monetary flow due to recreational activities linked with FWS systems of 8397 and 530 € ha^{-1} $year^{-1}$, respectively. Therefore, the O&M of FRB system could be even lower including also the natural capital revenues in the cost estimations.

Table 7. Comparison of construction and O&M costs of the FRB WWTP of Castelluccio di Norcia with typical costs for activated sludge systems in Italian context.

	FRB WWTP of Castelluccio di Norcia		Activated Sludge Systems *			
	500 PE	1000 PE	500 PE		1000 PE	
			min	max	min	max
Construction costs (€ PE^{-1})		364 **–394 ***			263	360
O&M average yearly costs (€ PE^{-1} $year^{-1}$)	11	6 ****	54	90	45	75

Notes: * Data from Italian context with scheme: activated sludge with classical scheme + tertiary filtration + UV disinfection [23]; ** Without FWS: FRB + VF; *** With FWS: FRB + VF + FWS; **** Assuming the same O&M costs except the energy costs for consumed kWh, which are doubled.

5. Conclusions

Through the investigation of the real FRB WWTP of Castelluccio di Norcia, this study confirms that FRB applied to small settlement can provide robust wastewater treatment as well as minimize O&M costs in comparison to activated sludge systems and even classical CWs:

- The effluent concentrations of the FRB WWTP of Castelluccio di Norcia were stable below the water quality targets, with high mean removal efficiencies in line with French experiences for COD, BOD_5, TN, N-NH_4^+, TP and TSS
- The FRB construction costs (364–394 € PE^{-1}) were slightly higher but in line with higher range of activated sludge systems in Italian context
- An interview with the Water Utility allowed us to detail the FRB O&M in terms of energy consumption, water quality monitoring, and personnel used for inspections
- The FRB O&M costs (6–11 € PE^{-1} $year^{-1}$) resulted 5 to 13 lower in comparison to those of activated sludge systems in Italian context, due to lower energy consumption and sludge management
- The FRB sludge management also allows to reduce the O&M costs in comparison to classical CWs

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/2/156/s1: Table S1: Detailed energy consumption and costs at monthly basis for the two year of functioning of the FRB WWTP of Castelluccio di Norcia; Table S2: Calendar of inspections done by Water Utility personnel to the FRB WWTP of Castelluccio di Norcia; Table S3: Calendar of water quality sample done by Water Utility personnel to monitor the FRB WWTP of Castelluccio di Norcia.

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Technical Director of the WWTP, and revised the manuscript from the point of view of both Scientific validity (robustness of references and discussion) and English readability.

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