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Comparative Efficiency of Two Different Constructed Wetlands for Wastewater Treatment of Small Populations in Mediterranean Continental Climate

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Abstract: The treatment of wastewater from small towns supposes problems of economic efficiency, leading to very high environmental costs in areas with low population density. Constructed wetlands (CW) seems to be the more suitable solution for this kind of situation, but further investigations are needed regarding their efficiency under different climatic conditions. This work presents the results concerning urban wastewater treatment by means of two different constructed wetlands using macrophytes: horizontal subsurface flow (HSSF) and free water surface (FWS). The systems are located in a Mediterranean continental climate area and are fed by a by-pass at the entrance of a wastewater treatment plant. A four-year sampling campaign at the outlet of the CW allowed verifying their relative effectiveness in removing pollutants in the different seasons of the year. BOD_5, COD, and TSS were significantly removed (with average reductions of 55%, 60%, and 57%, respectively) by these natural phytodepuration systems, with HSSF being more efficient during plants' dormancy than FWS, but the concentrations of nutrients indicated that cumulative effects occur in CW with the need of adequate annual maintenance. It was found that the main factors controlling the efficiency of such systems throughout the year are the period of vegetative development, the presence/absence of a solid substrate, and the pollutant load of the wastewater inlet.

Keywords: constructed wetlands; wastewater treatment; small populations; phytodepuration; macrophytes; bulrush

Citation: Acero-Oliete, A.; López-Julián, P.L.; Russo, B.; Ruiz-Lozano, O. Comparative Efficiency of Two Different Constructed Wetlands for Wastewater Treatment of Small Populations in Mediterranean Continental Climate. *Sustainability* **2022**, *14*, 6511. https://doi.org/10.3390/su14116511

Academic Editors: Luis A. Sañudo-Fontaneda, Pablo Rodríguez-Gonzálvez, Cristina Allende-Prieto and Marc A. Rosen

Received: 15 February 2022
Accepted: 25 May 2022
Published: 26 May 2022

1. Introduction

The aim of wastewater treatment is to eliminate elements toxic to humans and ecosystems, accomplishing both hygienist and environmental functions. Wastewater treatment through unconventional systems such as constructed wetlands is an approach widely used with reliable and efficient results [1]. These ecological engineered systems are effective in removing many pollutants, such as organic compounds, suspended solids, pathogens, nutrients and, also, emergent pollutants [2].

Notwithstanding, there are several aspects to be further analyzed in order to optimize the suitability of these techniques for continental climates [3]. The poor knowledge about the efficiency and the maintenance constraints of constructed wetlands in these types of contexts suppose a barrier for their wide implementation.

European law on urban wastewater treatment (Directive 91/271/CEE, modified by 98/15/CE) establishes the obligation to treat these effluents before their return to the natural environment. The implementation of conventional wastewater systems encountered the problem, among others, of population dispersion in different areas of Europe, which increases the costs of construction and operation of treatment plants in areas with low population density. A clear example of this phenomenon is the interior area of Spain where, according to recent statistics (1 January 2020) from the Spanish National Institute of Statistics [4], there are 1400 little towns and urbanized areas with fewer than 100 inhabitants and another 2606 with a population between 100 and 500 inhabitants. Due to high construction and exploitation costs, many of these areas currently still do not have a domestic wastewater treatment system and alternative solutions in respect to conventional treatment plants are being evaluated in order to achieve an effective and economically affordable solution.

The problem of depopulation is especially serious in the Autonomous Community of Aragón, where according to the same statistic data mentioned before, 541 municipalities (out of a total of 731) still do not treat their wastewater. Most of these municipalities have a stable population of fewer than 500 inhabitants. In this framework, the critical need to develop tailored, efficient, and economically affordable treatment systems for these populations and target areas is clear.

Compared with conventional wastewater treatment plants, constructed wetlands offer the main advantages of much lower construction and operating costs and clearly simpler operating conditions [5]. There are three main types of constructed wetland systems [1,6]: horizontal subsurface flow (HSSF), vertical subsurface flow (Vertical Flow, VF), and surface free water sheet (free water surface, FWS). In the literature, there are several works on this subject [2,6–11] and, often, in these works, different aspects influencing the performance of these types of techniques are addressed.

In constructed wetlands, wastewater is treated by means of a set of natural phytodepuration processes. Phytodepuration means the reduction or removal of pollutants from wastewater by using biological and physicochemical processes from aquatic plants [12], that is, macrophyte plants that can live in flooded areas throughout their lives or for prolonged periods of flooding. In addition, phytodepuration uses solar energy through the photosynthesis of macrophyte plants, making this process naturally sustainable.

This paper presents the results obtained during the first four years after the construction of two constructed wetland systems with macrophytes in La Almunia de Doña Godina (Spain). This town is located in the center of the Ebro Basin, within the Aragon region, where there is a conventional urban wastewater treatment plant that also serves the nearby towns of Alpartir, Calatorao, and Ricla. This is a modern activated sludge plant with prolonged aeration, a treatment capacity of 10,500 m^3/day, and a capacity of 28,350 personal equivalent (PE). Thanks to a collaborative research project between the GIHA research group and the Aragon government's Water Institute (Instituto Aragonés del Agua), it was agreed to build a system of horizontal subsurface flow and another of surface free water with floating macrophytes inside the WWTP facilities, with the aim to monitor and verify the efficiency of these techniques during a long period and under real climate and operational conditions.

In this way, it was possible to compare the efficiency of both systems over two complete annual periods, since the incoming sewage quality and quantity (designed to simulate the pollutant loads coming from a small, urbanized nucleus) was the same in both cases. In addition, a part from the differences due to the engineering design itself, the two types of systems differ in the type of macrophytes that are used in their operation: macrophytes fixed to the substrate (rooted) or free-floating macrophytes.

One of the main challenges was to choose the most adaptable plant species to the climatic conditions of the area, classified as temperate continental steppe (BSk according to the Köppen–Geiger classification system), with low annual rainfall and extreme maximum and minimum temperatures with an annual average of 30 days of frost (<0 °C). The location is situated at an altitude of 354 m above sea level.

The difficulties faced during the construction and maintenance of the two types of constructed wetlands, the results obtained, and their distribution throughout the different seasonal periods contributed to a better understanding of the operation of this type of unconventional wastewater treatment systems in this kind of common climatic and social Spanish context (interior areas far from the coast and with sparse and dispersed populations). The seasonal efficiency of both systems and their potential adaptation to adverse climatic conditions were also evaluated.

This paper aims to advance the knowledge about the exploitation and management of these kinds of techniques through experimental research experiences, especially regarding the efficiency of the different CW systems operating under temperate climates, which constitutes the main scientific objective of this work. However, this research also deals with some practical aspects such as those related to both the performance of the different plant species and the adequacy of the plant support devices.

2. Materials and Methods

2.1. Description of Constructed Wetlands

The wastewater treatment systems were built in an available area into the WWTP of La Almunia de Doña Godina, a town in the Valdejalón region in the province of Zaragoza (Spain). Thus, on one side of the facilities, two constructed wetlands were located, each of them divided into three ponds connected in a row. Each individual pond is 10.50 m long, 2.30 m wide, and 0.60 m deep, with a trapezoidal section. The systems' sizing was based on the main reference technical manuals [13,14], with the aim of treating a pollutant load of 50 PE (typical value for small towns in Aragon), setting the input flow for a hydraulic retention time of 3 days at a constant hydraulic loading rate of 41 mm/day. Each system was divided into three ponds in order to check, separately, the behavior of the different types of plants used during the monitoring phase of the project. In addition, the ponds were connected, ensuring the possible variation of the order of filling and treatment of the three units.

The wastewater inlet was taken from the WWTP entrance chamber of the biological treatment system, just after the pretreatment that removes coarse objects, sands, and fats, and samples were recovered at the end of each linear circuit. The horizontal subsurface flow (HSSF) constructed wetlands consist of channels or ditches with impermeable bottoms, in which water flows through a gravel bed that supports the root structure of the emergent vegetation (Figure 1). The water level always remains below the top level of the water, thus avoiding both the proliferation of insects and bad odors. To limit the reactivity between wastewater and the solid bed and to facilitate a high pore space, coarse and well-sorted siliceous gravel was selected to fill the ponds. This gravel substrate was made from cobble-sized fragments with grain size Φ = 80–100 mm, with a coefficient of uniformity C_U = 4.6, in order to ensure a high pore space able to facilitate the purification process during the subsurficial transit of sewage. This granular material was characterized by sieving at the aggregate production plant.

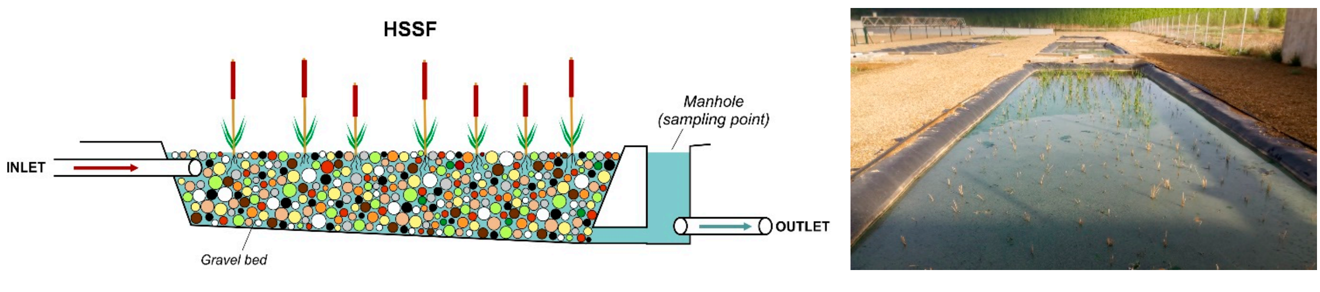


Figure 1. Conceptual scheme of a horizontal subsurface flow constructed wetland (**left**). Picture of the HSSF built for this work (**right**).

On the other hand, the free water surface (FWS) constructed wetlands consist of narrow channels in which the water circulates freely through the surface of the substrate around the stems and leaves of the plants (Figure 2). Although there are systems designed for plants rooted in a submerged layer of sand or gravel, in this case it was decided to hold the plants by means of artificial floating elements. In this way, the treatment occurs during the circulation of water through the stems and roots of the emergent vegetation, thus allowing to achieve a state in which the root system and submerged organs are intertwined, forming a filtering mat permanently bathed by the wastewater during the treatment.

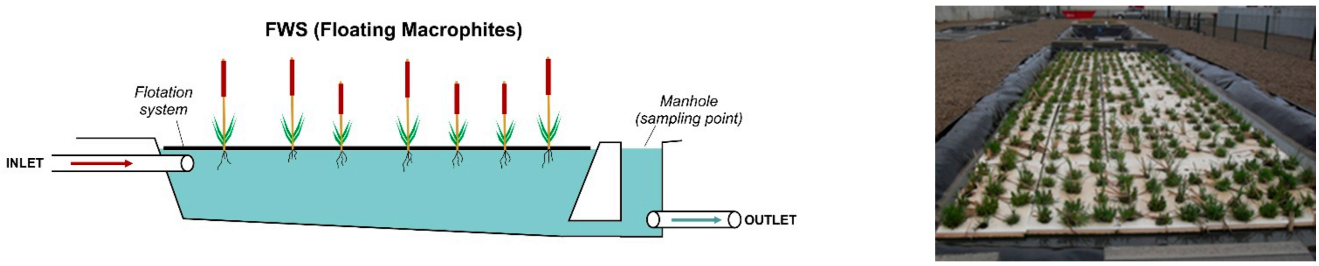


Figure 2. Conceptual scheme of a free water surface constructed wetland with floating macrophyte (**left**). Picture of the FWS built for this work, with floating plants held by polystyrene plates (**right**).

The unsatisfactory results obtained during the first year of the project indicated the need for an extra supply of oxygen to the FWS constructed wetland. For this purpose, a submerged system of PVC pipes was installed in this line of ponds in July 2019, which periodically supplied oxygen powered by an alternating blower with around 6 h of daily operation.

Finally, it is necessary to indicate that the construction project did not include a solids removal tank, since it was intended to run the system with wastewater only altered by the pretreatment of the WWTP. However, daily practice showed that sludge accumulated in the ponds and conductions, making the treatment difficult, so a settling system was installed. It was located before the distribution box towards the constructed wetlands. Figure 3 shows a conceptual scheme of the facilities described above, as well as the location of the sample collection points along the flow line of water.

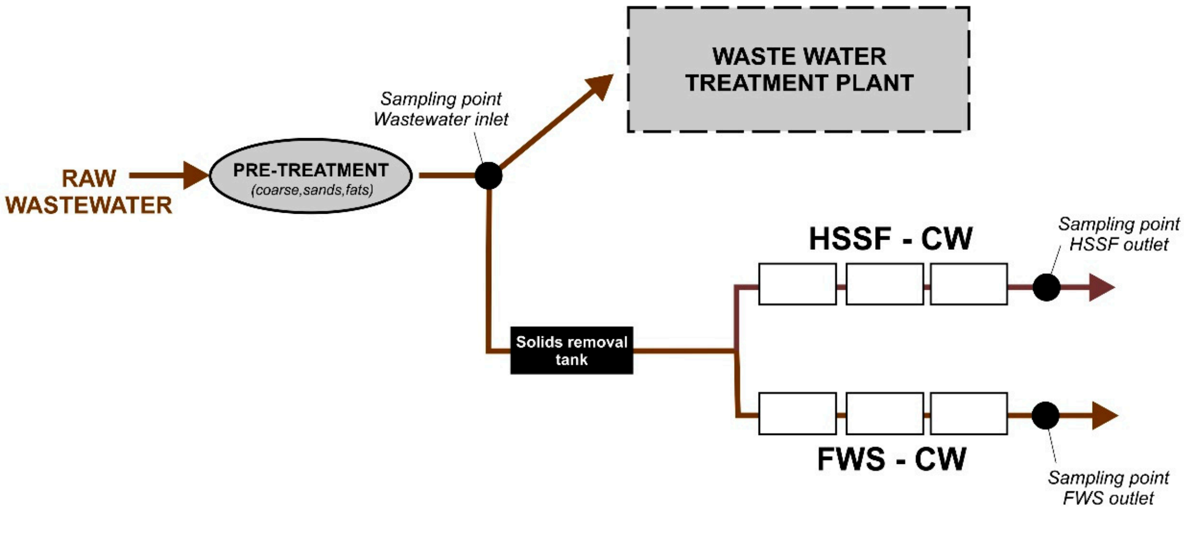
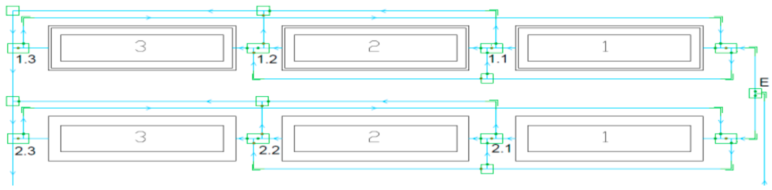


Figure 3. Schematic diagram showing the water flow and the sampling points.

One of the most important issues in both the design and operation of constructed wetlands is the selection of the most suitable types of plants adapted to the local climate. In general, the most used plant species are bulrush and reed. There are also species placed in wetlands that are more specific, depending on the climate of the area in which they are located. Regarding the type of wetland used, the most studied systems are subsurface flow wetlands [15,16]. This is because the water surface remains under the gravel and odors and mosquito-related problems disappear. In this case, bulrush, reed, and rush were selected for the HSSF ponds. On the other hand, for the FWS system, bulrush, reed, and bur reed were chosen. The main characteristic in this case is that nonfloating vegetation was forced to stay on the water surface with a floating system, while other studies used self-floating vegetation instead [17,18].

Table 1 summarizes the main descriptive features of the two constructed wetlands built for this investigation project and shows the floor plan of both CWs, each arranged as a succession of three ponds in a row, with manholes at the outlet of each one to be able to modify the flow sewage circulation.

Table 1. Main features of the two constructed wetlands developed in this work.

TREATMENT SYSTEM	FWS	HSSF
VEGETATION	Bulrush *(Typha latifolia)* Reed *(Phragmites australis)* Bur reed *(Spargamium erectum)*	Bulrush *(Typha latifolia)* Reed *(Phragmites australis)* Rush *(Scirpus lacustre)*
ARRANGEMENT	 The system has pipes to change the incoming order of the influent to the channels.	
INITIAL INSTALLED FLOTATION SYSTEM	Burlap mantle Burlap sacks HD-Polystyrene	
DIMENSIONS	3 channels Trapezoidal section 10.50 m length 2.30 m wide 0.60 m depth +0.20 m guard	3 channels Trapezoidal section 10.50 m length 2.30 m wide 0.60 m depth +0.20 m guard

2.2. Sampling and Analytical Routine

The assessment of the performance of two types of constructed wetlands in real conditions being the main objective of this work, it was decided to collect samples weekly for the following key points (see Figure 3):

- Wastewater inlet to characterize the wastewater flow at the entrance of the system.
- Two points at the outlet of each constructed wetland to characterize treated sewage.

In order to maximize their representativeness, liquid compound samples were collected over a period of 24 h using periodically operating peristaltic pumps and stored in 10 l plastic bottles. Samples were stored at low temperature (around 4 °C) until performance analyses in laboratory within 24 h.

The sampling period spanned from February 2018 to December 2021, although it should be noted that the results of the first year are not representative of the actual performance of constructed wetlands, as it was the beginning of plant development and vegetation did not fully cover the surface area. Throughout the entire study period (February 2018–December 2021), a total of 156 sample collections were carried out both at the wastewater inlet point and at the outlet of each constructed wetland. The sampling campaign was designed to achieve a weekly record, but the mobility restrictions due to the COVID-19 pandemic prevented access to the facilities and collection of samples between March and June 2020, although the constructed wetlands remained active.

The analytical routine was designed according to both the typology of the samples and the control parameters for wastewater treatment. Simultaneously to sample recovery, pH, electrical conductivity, and dissolved oxygen were determined in situ using the portable multiparametric probe Hanna Instruments (HI 98194).

In addition, samples were analyzed to determine biological oxygen demand (BOD_5), chemical oxygen demand (COD), turbidity, suspended solids, and content in phosphorous, nitrate, and ammonium. COD was analyzed using a multiparameter photometer Hanna (HI 83314-02) with COD after reaction with a strong oxidizer agent at 150 °C. BOD_5 analyses were carried out by the respirometric method using a BOD sensor (F102B0134 VELP Scientifica), which provides a direct measurement of the oxygen consumed by the microorganisms present in samples in a closed environment at constant temperature and under constant agitation. The measurements of turbidity were taken with a turbidity meter (TN-100 Thermo Scientific Eutech Instruments). For the determination of total suspended solids (TSS), 1 L of sample was filtered using Whatman cellulose filters with pore size of 0.45 µm, then dried at 105 °C, and finally weighed on a precision balance. Phosphorous determination was carried out using a digital photometer (Hanna HI 706) for high-range (HR) levels. Nitrate was analyzed by means of a photometer (Hanna HI 96728). Finally, for ammonium estimate, a digital colorimeter (Hanna HI 733) was used for HR concentration levels, and total N was analyzed by means of chromotropic acid method using a spectrophotometer (Hanna HI 801).

The periodicity of sampling and the collection of samples at the inlet (wastewater) and outlets of both constructed wetlands allowed to assess the temporal variation of the characteristics of wastewater, as well as to compare the seasonal efficiency of both treatment systems by calculating sewage load and removal load rates for the main pollutant parameters.

With the aim of carrying out a comparative evaluation of the degree of development of the different species used, a monitoring campaign was carried out to verify the height reached in each case and, in addition, at the end of the third annual harvest, the entire plant mass contained in an area of 1 m^2 in each of the ponds was removed, which allowed to obtain the productivity value expressed in dry plant mass.

3. Results

Using all the data obtained from sample analyses, an overall descriptive statistical treatment, whose main results are shown in Table 2, was carried out. Regarding inlet wastewater samples, the statistical summary allowed to verify that there is a high irregularity in its chemical characteristics as shown by standard deviation values and their comparison with the average ones.

Table 2. Statistical summary of analytical results, with indication of average value, standard deviation, and percentage of reduction (in terms of removal rate) calculated at the outlet of constructed wetlands. The legal European limits for discharge are also shown.

Parameter (Units)	Wastewater (Inlet)		FWS (Outlet)			HSSF (Outlet)			Limits EC
	Range	Standard Deviation	Range	Standard Deviation	Removal Rate (Mean)	Range	Standard Deviation	Removal Rate (Mean)	
pH	6.49–8.38	0.16	6.75–8.43	0.13	-	6.90–8.37	0.16	-	
CE (mS/cm)	2.09	0.50	2.02	0.37	-	2.13	0.51	-	
BOD_5 (mg/L)	181.49	138.60	77.03	58.51	54%	57.32	23.10	57%	25
COD (mg/L)	394.88	301.56	152.59	124.59	59%	113.82	50.99	61%	125
Turbidity (NTU)	132.85	104.77	112.83	107.58	16%	104.99	119.21	22%	
TSS (mg/L)	179.72	198.02	72.42	78.15	54%	64.63	64.03	59%	35
P (mg/L)	2.0	1.7	3.1	1.7	−52%	3.3	2.0	−57%	2
$(NO)_3^-$ (mg/L)	5.38	6.28	5.45	14.45	−4%	9.79	24.51	−70%	
$(NH)_4^+$ (mg/L)	28.76	16.44	34.23	16.04	−33%	34.23	17.12	−32%	
N_T (mg/L)	21.26	19.85	17.82	16.13	9%	17.17	14.98	8%	15

The average values of the analyzed parameters at the inlet are characteristic of this type of domestic wastewater in rural areas. In a seasonal assessment, it is found that the concentrations of wastewater pollutants are clearly higher in winter than during other periods of the year. The entry of irrigation water into the sewer and sanitation systems, mainly in the spring and summer periods, tend to dilute the inlet concentration and significantly increase the total volume of wastewater to be treated. The rainy episodes, more frequent in autumn and spring, also give rise to episodic events of decreases in the concentration of pollutants in the inlet due to dilution effect, again together with an increase in total wastewater volume to be treated.

In the present case, the water flow in each constructed wetland was initially set at 3 m^3/day and was kept constant throughout the study period, giving rise to a hydraulic loading rate (41 mm/day) in a range of usual values for CW that deal with domestic sewage [9,10,19]. Therefore, the variations referred to above and caused by the entry of irrigation and stormwater into the sewer and sanitation systems generated specific changes in the concentration of pollutants that reach the constructed wetlands, which simulates the existing conditions in any real system. These variations allow differentiating periods with pollutant concentrations significantly different in the wastewater inlet that occur over time (normal and shock loading periods [20]), which expose the treatment systems to demanding changing conditions. Additionally, occasional discharges caused by industrial livestock activities also constitute shock loading events, although in this case without a defined seasonal pattern.

Periodic control allowed to verify the behavior of these constructed wetlands in relation to their buffering capacity against these specific variations under realistic conditions. The main aspects regarding the variables analyzed and their temporal relationship with the vegetative activity and dormant periods of plants are described below.

3.1. pH

The pH of the wastewater inlet and the outlets of both constructed wetlands has usually shown neutral or slightly basic values, with averages of 7.88 at the inlet, 8.06 at the HSSF outlet, and 7.90 at the outlet of the FWS system. During the dormant vegetative period (winter), the pH resulting from the FWS treatment was significantly higher than in the HSSF system, while during the vegetative activity period no significant variations were observed between both treatments.

3.2. Electric Conductivity

This parameter has been very stable over time for each of the sets of values analyzed. It should only be noted that electric conductivity shows an upward trend at the outlet of HSSF treatment with respect to both the wastewater inlet and the outlet of the FWS system. This behavior is manifested in all the considered periods, both in active and in dormant vegetative ones.

3.3. Dissolved Oxygen

In situ measurement indicated that dissolved oxygen was not present in any sample in both the wastewater inlet and the HSSF outlet. On the other hand, most of the samples collected at the FWS outlet did not indicate the presence of dissolved oxygen either, although some of them showed low concentration values. However, the intermittent supply of air pumped into the FWS system since June 2019 must have undoubtedly intervened in the presence of dissolved oxygen in some of the collected samples, so it is not possible to carry out an interpretation about the natural evolution of this parameter in the present work.

3.4. BOD_5

A strong oscillation is verified regarding the measured BOD_5 values of wastewater inlet with seasonal independence, which causes the existence of an evolutionary pattern with abundant peak values (Figure 4). The water treatment along the constructed wetlands gives rise to lower analytical values than those corresponding to wastewater inlet but with equally irregular and sharply evolutionary patterns. However, it is important to note here that the HSSF system shows a smoother pattern than that corresponding to the FWS constructed wetland.

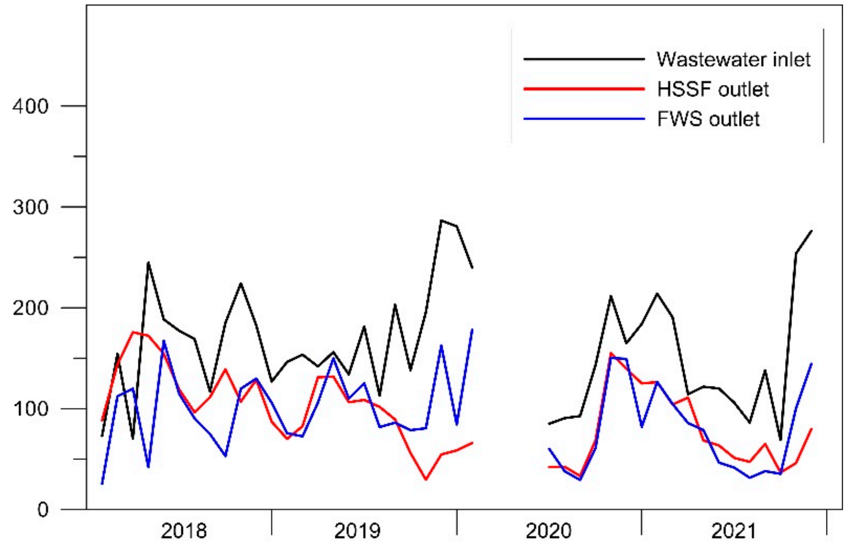


Figure 4. BOD_5 evolutionary pattern along the 2018–2021 period, expressed as monthly average values.

In relation to the remotion of the contaminant load, current European discharge regulations establish a maximum limit of 25 mg/L for BOD_5 in treated effluents. This premise is only fulfilled on samples 14 and 15 for HSSF and FWS, respectively, which globally constitutes about 20% of the total samples analyzed.

Additionally, current regulations include the requirement of a minimum percentage of reduction of 90% with respect to BOD_5 concentration at the wastewater inlet. Taking into account all the samples analyzed in this work, overall average reductions of 54% and 57% were calculated for the FWS and the HSSF constructed wetlands, respectively. In terms of individualized values, the rule of 90% reduction is only fulfilled in cases 3 and 5 for FWS and HSSF systems, respectively.

3.5. COD

The graphical representation of the mean monthly COD values offers similar features to those of BOD_5, that is a pattern with high contents and highly variable values for the inlet wastewater; also, for waters treated in both constructed wetlands, the graph shows smoother evolutionary lines at clearly lower concentration levels (Figure 5). The highest COD values of the wastewater inlet are recorded in winter periods, since during the rest of the seasons the contaminant load is diluted due to the effect of both the irrigation effluents and the rainy events.

Carrying out an assessment in the same terms as for BOD_5, to quantify in this case the degree of COD reduction, it must be taken into account that current European discharge regulations establish a maximum limit of 125 mg/L for treated effluents. During the campaign, this premise was fulfilled in samples 56 and 70 for FWS and HFFS constructed wetlands, respectively, which globally constitutes about 45% of the total samples analyzed.

It was observed that in autumn–winter periods, the HSSF system adjusted better to the legal discharge limit of 125 mg/L than the FWS system, also showing better behavior in relation to the removal rate established by the regulations in a minimum of 75%. On the other hand, in spring–summer seasons (especially in the last two years) both constructed wetlands adjusted to the discharge concentration limit, showing the FWS system's greater stability and removal rate.

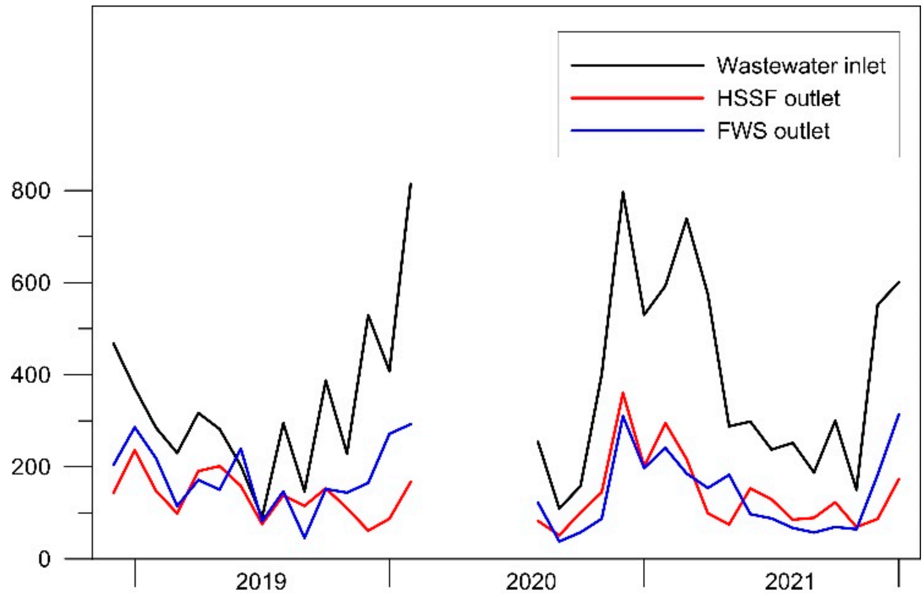


Figure 5. COD evolutionary pattern during the 2019–2021 period, expressed as monthly average values.

3.6. TSS

The total amount of suspended solids (TSS) is the third parameter established by the regulations as a control variable for effluents of wastewater treatment systems, setting it at a maximum value of 35 mg/L and with a minimum reduction percentage of 90%.

Figure 6 indicates that this parameter has clearly reduced its value in both treatment systems, after an initial period (year 2018) in which its efficiency was quite poor. Since the summer of 2019, once the vegetation cover was fully developed in both constructed wetlands, it was found that nearly 45% of the total HSSF outlet samples were below the maximum legal value, while this percentage being around 35% for those treated in the FWS system. Regarding the percentage of reduction achieved, it was generally between 50% and 60% in both constructed wetlands with respect to the wastewater inlet. Focusing on seasonal analyses, better relative behavior in the FWS system in active vegetative periods was observed in relation to TSS reduction, while conversely, the HSSF system showed a better relative efficiency in dormant periods.

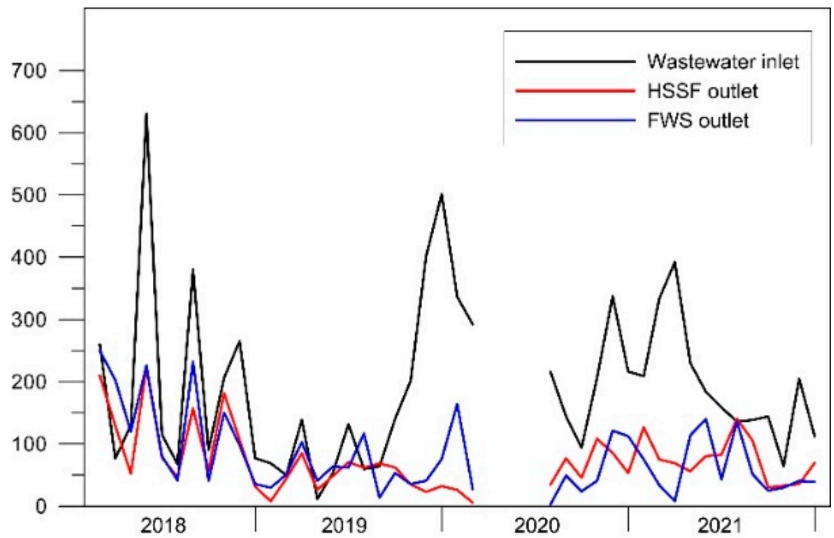


Figure 6. TSS evolutionary pattern during the 2018–2021 period, expressed as monthly average values.

3.7. Nitrogen Compounds

Nitrogen is present in urban wastewater mainly as reduced ammoniacal form. The different mechanisms involved in purification treatments (both conventional and unconventional) tend to transform them into nitrites and later into nitrates through a set of processes called nitrification.

In this work, the contents of ammonium, nitrate, and total nitrogen were analyzed both in the inlet and outlet waters, with the aim of evaluating the efficiency of these unconventional treatments in relation to the nitrification process. As can be seen in Table 2, the outlet flow of constructed wetlands presented a higher ammonium content than the input wastewater, with an average increase of about 30% in both cases.

The same behavior is observed for the nitrate content, although in this case the increase is much more pronounced in the HSSF constructed wetland, with an average of 70%, than in the FWS system, where the average increase is only 5%.

On the other hand, the results allow verifying that the waters treated in the constructed wetlands present slightly lower total nitrogen contents (with averages close to 10% in both cases) than those of the incoming wastewaters, which indicates a certain removal of nitrogen in the studied systems.

3.8. Phosphorous

Phosphorous content in the outlet-treated wastewaters of both constructed wetlands was constantly higher than that of the wastewater inlet, with an average increase of around 60%. The analytical method used here determines the content of phosphorous present in the form of orthophosphate, taking as a reference the maximum value of 2 mg/L (the limit for sensitive eutrophic areas but not applicable here). Approximately 35% of the total outlet samples met this regulatory requirement.

3.9. Vegetation Cover Behavior and Development

The initial project contemplated the use of different support systems for floating macrophytes in the FWS constructed wetland, with the aim of verifying their suitability: burlap mantle, burlap sacks, and polystyrene plates. However, the poor behavior of the burlap sacks made them inadequate as support systems in the flotation ponds (even with the sinking of several burlap sacks already in the first weeks of operation), so it was decided to adopt the polystyrene plates instead. The thickness of these supporting plates depends on the maximum height that the different plants can reach and, in this case, it was found that the optimal support system for reed and bur reed consisted of 5 cm thick polystyrene plates, with holes 7–8 cm in diameter. On the other hand, for bulrush, the most suitable system was based on 15 cm thick polystyrene plates and holes, also with a diameter of 7–8 cm. The greater polystyrene thickness in the case of bulrush is due to the greater height that this plant species can reach (up to a maximum of 2.30 m high in this case).

Regarding the behavior and the development degree of the plants in the constructed wetlands, the species that offered the best results was the bulrush, both in the HSSF and in the FWS systems: the one placed in the flotation ponds overturned when it reached a height greater than 1 m (in the absence of adequate support), while in the subsurface flow system it reached a height of around 2.70 m (Table 3). Floating rushes were not suitable under these conditions and were replaced at an early stage during the first year by bur reed. This species developed correctly once the support system was changed from the one initially projected. Finally, and in relation to the performance of the vegetation under different pollutant amounts, bulrush can be considered as the plant species with the best behavior in respect to the highest loads, obtaining the highest values of plant productivity in terms of dry mass per m^2 in view of the results offered in Table 3.

Table 3. Plant development obtained in each pond, expressed in both maximum height attained and dry mass per m^2 at the end of season 3.

	Pond Number	Vegetation	Dry Mass (kg/m^2)	Max. Height (m)
FWS	1	Bulrush	6.24	2.30
	2	Reed	4.56	1.70
	3	Reed + Bur reed	0.75	0.40
HSSF	1	Bulrush	7.10	2.70
	2	Reed	5.62	2.45
	3	Reed	1.84	1.70

Figure 7 below includes two images showing the appearance of the constructed wetlands in the period of vegetative activity (summertime 2021).

Figure 7. Images of constructed wetlands in summertime. On the (**left**), FWS pond with reed and bur reed (the installation for air pumping is observed along the right side). On the (**right**), HSSF pond with reed, with the sample collection device in the foreground.

4. Discussion

Phytodepuration, understood as the reduction or elimination of pollutants from wastewater through biological and physicochemical processes with the active participation of plants from the aquatic ecosystem itself [9], led here to a relatively significant reduction in terms of BOD_5 and COD in treated wastewater for both constructed wetlands. However, the global level of efficiency achieved during the project does not allow to confirm the initial hypothesis of fully achieving the wastewater treatment related to 50 PE according to the current legislation. This was probably due to an undersizing of the system's surface with respect to the fixed applied contaminant load.

Phytodepuration in constructed wetlands involves a set of processes [21] and is based on the following basic principles: the biochemical activity of microorganisms; the supply of oxygen through vegetables during the day; and the physical support of an inert bed that serves as a support for the roots of the plants (in HSSF system), in addition to serving as filtering material. It is possible to differentiate some mainly physical processes (settling and filtration/retention of solid particles) from those of a chemical nature. In the latter, the availability of dissolved oxygen is essential to allow the chemical reactions.

Concerning the physical processes, the analytical results of TSS indicate that both types of constructed wetlands have yielded a very significant removal in suspended particles present in the wastewater inlet, which was verified especially after the installation of the solids removal tank. Figure 8 shows the boxplot diagrams made from the data series, which show that for both treatment systems the median value decreases by more than 50% and, in addition, the variability of set data is significantly reduced. The dimensions and morphology of the boxplots obtained for the samples treated in both purification systems indicate a very similar behavior in relation to TSS removal.

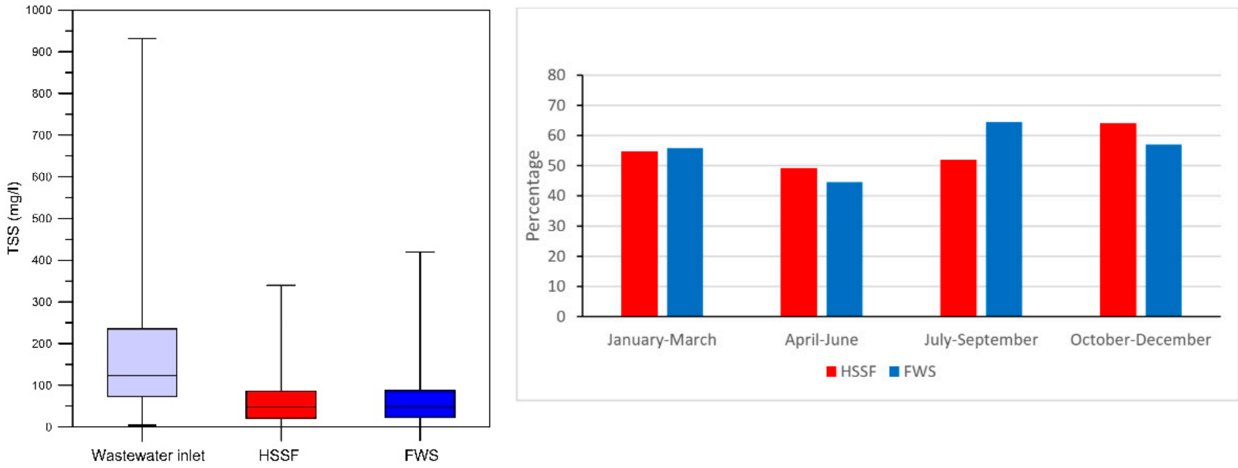
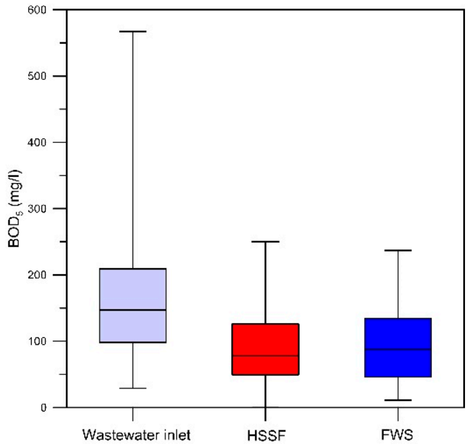


Figure 8. Boxplot diagrams of TSS content (mg/L) at the three sampling points (**left**) and seasonal removal rate registered in both constructed wetlands (**right**).

The results also indicate that, despite the undersizing of these systems, treated wastewater accomplished the strict European legal limits for TSS in practically half of the samples for HSSF constructed wetland and in a third for FWS treatment. In the first case, retention is produced mainly by the effect of the solid substrate, which is constantly present throughout the year; therefore, the efficiency of the subsurface system shows a more stable and seasonally independent temporal behavior. Regarding the flotation constructed wetland, the effect of retention of suspended solids appears more linked to the vegetative activity periods, so it was concluded that the FWS system behaves slightly more efficiently in the months of intense plant growing (summertime) than in the less productive autumn–winter periods (Figure 8 Right).

In general, the oxidizable contaminant load in the wastewater inlet is reduced in the constructed wetlands through a combination of physical (settling and retention of particulate organic material) and chemical processes. The control of the efficiency of this reduction is carried out by analyzing BOD_5 and COD. In this work, it was verified that the two types of constructed wetlands have achieved a significant reduction in both variables, with removal rate around 40–60%. These abatement values are similar, although slightly lower, to those obtained in case studies carried out under relatively similar climatic conditions (see compilation in [22]). Figure 9 allows to interpret that both constructed wetlands reduce the median value practically by half, further reducing the variability significantly, although not as markedly as in the case of the TSS. Comparatively, the HSSF system shows a slightly more efficient performance, since it exhibits a lower median with a lower data dispersion than the FWS system. The bar chart in Figure 9 (Right) indicates that the FWS system performs clearly better than HSSF in vegetative periods (spring and summer) in removing BOD_5.

The behavior of both systems against COD removal is shown graphically in Figure 10. Again, the highly irregular distribution of this parameter in the inlet sewage was clearly reduced in both constructed wetlands, whose outlet values encompass a much lower variability, and median values were approximately reduced by half. As in the case of BOD_5, HSSF performs better than FWS in comparative terms of variability reduction in the data set, but FWS is more efficient in relation to COD removal rate in seasons of vegetative activity (spring and summer).



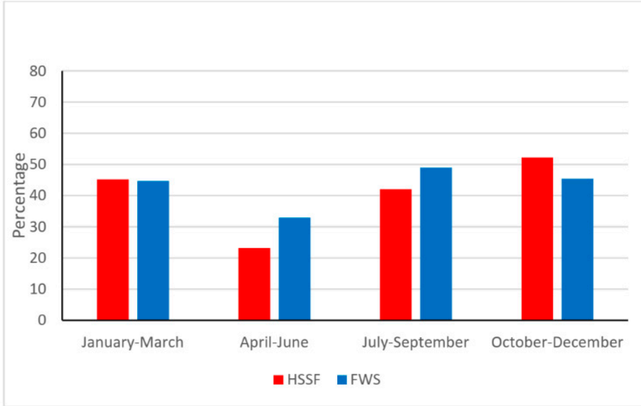
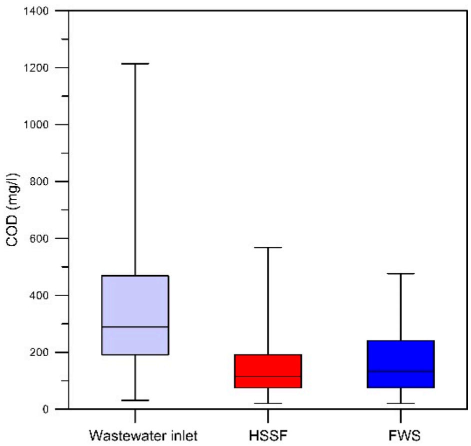


Figure 9. Boxplot diagrams of BOD_5 content (mg/L) at the three sampling points (**left**) and seasonal removal rate registered in both constructed wetlands (**right**).



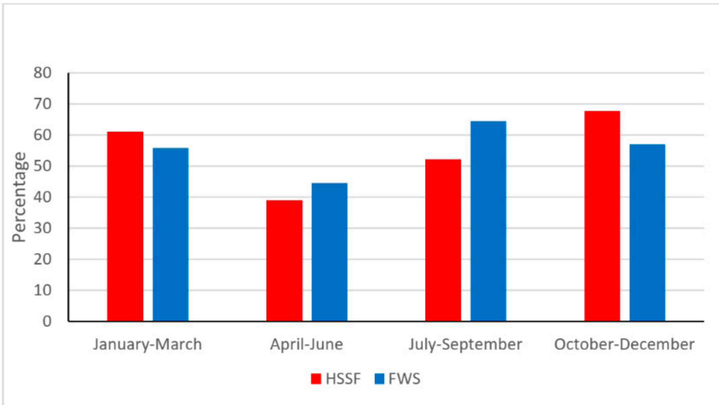


Figure 10. Boxplot diagrams of COD content (mg/L) at the three sampling points (**left**) and seasonal removal rate registered in both constructed wetlands (**right**).

The BOD_5/COD ratio is related to the biodegradability of the organic matter present in the water. In this project, the BOD_5/COD ratio for the wastewater inlet had an average of about 0.45 (after pretreatment), which is a characteristic value for water of high biodegradability [23]. In the literature, it is usually considered that after conventional wastewater primary and secondary treatments, the BOD_5/COD ratio decreases to 0.1–0.3 [24]. The results obtained in this work for wastewaters at the outlet indicate that this ratio showed a barely perceptible reduction after treatment through the constructed wetlands, which in turn indicates that the biochemical processes here were not as highly efficient as might be expected. In terms of comparison analysis, the nutrient content in the wastewater inlet and in treated wastewaters at the outlets of constructed wetlands, it was observed that plant growth and the microbial activity associated with their root structures did not lead to a substantial reduction in the ammonium concentrations. In general, in these types of unconventional systems, phytodepuration acts by means of three main reactions: nitrification (oxidation of ammonium to nitrate with oxygen consumption); denitrification (reduction in nitrate to nitrogen gas, N_2, under anoxic conditions); and assimilation by vegetation [25]. Nitrification and denitrification depend on temperature, and they need carbon as an energy source for the bacteria to carry out the chemical conversion of nitrogen species [26]. The degree of progress of these chain reactions to produce the removal of nitrogen depends on the oxidation state and the availability of dissolved oxygen. The reduction in BOD_5, COD, and nitrogen requires a stabilized system, and this stabilization period is usually one year, until the vegetation and microorganisms reach their optimal development [27].

In situ measurements of dissolved oxygen systematically indicated here zero values for both wastewater inlet samples and treated wastewater at the outlet of HSSF constructed wetland. For the case of the FWS system, only a very small number of samples showed a low content of dissolved oxygen, despite that a submerged device was installed in this constructed wetland that periodically pumped air into the aquatic environment after a first year of very low performance. In any case, analyses indicate that significant nitrification took place in both constructed wetlands, which, together with the uptake of nitrogen by the plants in their growing development, yielded a reduction of almost 10% in the total nitrogen of the samples at the outlet compared with the wastewater inlet. However, the outlet wastewaters showed, in most cases, an increase in ammonium of around 30% with respect to wastewater inlet, which indicates that in the ponds of constructed wetlands the nitrification processes are very limited due to the low availability of dissolved oxygen. Furthermore, fermentation processes must have taken place mainly in vegetative dormant periods with decomposition of plant tissues, thus involving the return of nitrogenous nutrients to the aquatic environment [28].

Phosphorus is the other nutrient with a relevant presence in sewage waters, appearing as phosphate under dissolved or particulate forms. Regarding chemical speciation, phosphorus appears in this type of aquatic environment mainly as polyphosphates, orthophosphates, and as organic phosphorus, the last being much less abundant. The mechanism for the elimination of the phosphorus is based on its accumulation in sediments and biomass [12]. Polyphosphates are present in household detergents, and in the aquatic environment they tend to be converted into ortophosphates through hydrolysis reactions, thus remaining biologically available. This reaction is a very slow process, and that is why wastewater treatment by means of constructed wetlands do not normally lead to significant reductions in phosphorous content in waters [28]. In this study, orthophosphate soluble content in samples was analyzed, registering an increase in the concentration in treated waters compared with the wastewater inlet. This confirms that in constructed wetlands there is a removal of phosphorus through hydrolysis of polyphosphates and subsequent absorption by plants, but that it is not quantitatively significant.

Regarding nutrients removal in wastewater depuration, it is important to note that oxygen is necessary for nitrogen, phosphorus, and organic matter removal reactions. The absence or insufficiency of this element slows down the natural purification processes and, therefore, the efficiency of constructed wetlands is relatively limited compared with conventional treatments. For this reason, in FWS-type, the installation of submerged air pumping systems is common, which supplies additional oxygen to the aquatic media and thus enhances the nitrification and denitrification reactions, improving the removal efficiency of nutrients [29]. This effect was verified in this work by observing that the two types of constructed wetlands yielded a similar reduction in BOD_5 and COD, to which the artificial aeration device installed in the FWS system undoubtedly contributed. The overall depuration capacity per surface unit (removal load) is shown in Table 4, which includes the very similar average values calculated for both CW systems.

Table 4. Average values calculated for sewage load relative to the main parameters and for removal load achieved in both CW.

Parameter	Sewage Load (Mean) ($g{\cdot}m^{-2}{\cdot}d^{-1}$)	Removal Load (Mean)	
		FWS ($g{\cdot}m^{-2}{\cdot}d^{-1}$)	HSSF ($g{\cdot}m^{-2}{\cdot}d^{-1}$)
BOD_5	6.76	2.93	2.95
COD	14.62	8.17	8.80
TSS	7.46	4.46	4.79

Finally, it is necessary to point out that in constructed wetlands there is a cumulative effect with respect to organic matter that determines the temporary durability of its purifying efficiency. In general, vegetation itself acts as a temporary storage of nutrients, so that especially at the beginning of the active vegetative period (springtime) large amounts of nutrients are taken up by the root system. If the vegetation is not harvested, most of these nutrients end up in the pond compartment and, during the dormant periods (autumn–winter), a large part of these nutrients are gradually released again through leaching and organic matter mineralization [21], giving rise to an increase in the nitrogen compounds mobilized in solution and exported by outlet waters. This aspect determines the need for maintenance that includes both annual pruning and cleaning of the ponds (removing all the material accumulated at their bottom). In this project, pruning was carried out at the end of each season of vegetative activity, but the bottom of the FWS system ponds was not regularly cleaned, and this circumstance has undoubtedly conditioned the analytical results of nutrient content in the treated waters.

5. Conclusions

The results obtained and described previously allow to state that the constructed wetlands built for this project are capable to achieve a phytodepuration that significantly reduces the pollutant load of urban wastewater from small towns. In this way, it is concluded that constructed wetlands can be used as urban wastewater treatment systems to serve small population centers in temperate climatic conditions, as long as a series of key aspects derived from the results of case studies, such as the ones analyzed in this work, are taken into account.

The first conclusion derived from the global analysis of the results is that the sizing the bibliography recommends for the design of constructed wetlands for small-sized populations are clearly underestimated. This requires further investigations in order to specify the minimum dimensions necessary based on the population served for small-sized population centers.

The issue of undersizing marked significant fluctuations in the concentration of the wastewater inlet, which subjected the constructed wetlands to alternating periods of normal load and shock load in terms of received contamination. The reduction in the main pollution control parameters (BOD_5, COD, and TSS) in the treated waters in both constructed wetlands was significant in all seasons, and a high number of samples at the outlet of the constructed wetland systems met the strict legal thresholds, despite their undersizing to treat the design flow. The purification treatments carried out here not only reduced the individual values of contaminants entering waters, but also, when analyzed as a whole, led to a significant reduction in the variability of data sets, which illustrates the ability of these systems to deal with sewage with a highly irregular distribution in its parameters without the need for specific instrumental control. In relation to the main pollutant parameters, both systems behaved in a similar way when analyzing the values globally, although in a seasonal analysis, FWS showed a better performance with respect to HSSF in the removal of oxidizable contaminant load (BOD_5 and COD).

In order to achieve an optimal performance of constructed wetlands over time, it is essential that the wastewater undergoes a pretreatment (solids, coarse, and fats removal) and a decantation prior to entering the depuration system, thus avoiding both the clogging of solid substrate matrix in the subsurface systems and the overaccumulation of organic matter in the bottom of the flotation ponds. Annual maintenance consisting of pruning the vegetation and, in the flotation systems, removing settled material from the bottom of ponds are also essential. These operations avoid the cumulative effect of nutrients in these unconventional treatment systems, allowing the effective removal of nitrogen and phosphorus compounds.

Finally, it is necessary to emphasize that the choice of species and plant support elements are crucial aspects in relation to the performance of constructed wetlands. For the case of this project, the species that offered the best results is bulrush, both in the subsurface and in the flotation systems, adequately resisting the highest contaminant loads and reaching a productivity of about 7 kg dry mass per m^2 in both systems, much higher than that obtained by the other species used here. The support elements must be capable of keeping the vegetation upright, allowing its development until its maximum height without overturning but also avoiding suffocating its growth. The flotation constructed wetland has design features that allow easier maintenance than the subsurface one, and a relatively higher treatment capacity in vegetative periods. Conversely, the subsurface system showed a relatively better behavior in dormant vegetative periods

6. Patents

The research carried out in this Project included the development, registration, and exploitation of two utility models: "Support for floating vegetation substrate", with publication number ES1239469 and approval date 17 June 2020, and "Automated sampler device", with publication number ES1243954 and approval date 19 August 2020.

Author Contributions: Conceptualization, A.A.-O. and O.R.-L.; methodology, A.A.-O.; validation, P.L.L.-J.; formal analysis, P.L.L.-J. and B.R.; investigation, A.A.-O. and P.L.L.-J.; resources, A.A.-O., O.R.-L. and B.R.; data curation, A.A.-O. and P.L.L.-J.; writing—review and editing, B.R.; visualization, P.L.L.-J.; supervision, B.R.; project administration, A.A.-O.; funding acquisition, A.A.-O. and O.R.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Gobierno de Aragón through the Instituto Aragónes del Agua (IAA), thanks to the collaboration agreement "Macrophyte filter design for the La Almunia (Zaragoza, Spain) treatment plant" (2017–2021). The budget included the necessary funds for the construction and also for the maintenance of the constructed wetlands throughout the entire research period, as well as all the costs associated with sampling and chemical analyses.

Data Availability Statement: Not applicable.

Acknowledgments: The results presented in this article come from the research activity of the Group of Hydraulic and Environmental Engineering (GIHA) of the EUPLA (group recognized by the Government of Aragón, Spain). The authors also acknowledge the staff of Acciona Agua that manage the Wastewater Treatment Plant of La Almunia for their kindness and all the help provided to carry out this research work within its facilities.

Conflicts of Interest: The authors declare no conflict of interest.

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