Title: Assessing the economic suitability of aeration and the influence of bed heating on constructed wetlands treatment efficiency and life-span

Article Type: Research Paper

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Abstract: Constructed wetlands including aeration and heating were studied to improve treatment efficiency and prevent clogging. The experiments were carried out in a pilot plant (0.4 m²) treating urban wastewater with an organic loading rate of 40-60 gCOD/m²·d. Continuous and intermittent aeration was performed from the bottom on 8% of the wetland surface, leading to different dissolved oxygen concentrations within the wetlands (from 0.2 to 5 mgO₂/L). Continuous aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in wastewater treatment caused by aeration can result in reduction of the surface area requirement of future systems. This work demonstrated that for the studied configuration the cost of the power consumption of the continuous aeration was largely covered by the reduction of the wetlands surface. Even if the heating of 8% of the wetland surface at 21°C had no effects on treatment performance, positive results showed that solids accumulation rate within the granular medium, which is closely related to the development of clogging. It has been demonstrated that heating for 10 days per year during 20-year period would delay the equivalent of 1 year of solids accumulation.
The effect of aeration and heating was tested in a pilot constructed wetland. Continuous aeration increased organic matter and ammonium removal by 56% and 69%. Continuous aeration can result into reduction of the surface area. Electricity costs of continuous aeration was covered by the reduction of the surface. Heating had a positive effect on solids accumulation rate delaying clogging.
Assessing the economic suitability of aeration and the influence of bed heating on constructed wetlands treatment efficiency and life-span

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Abstract

Constructed wetlands including aeration and heating were studied to improve treatment efficiency and prevent clogging. The experiments were carried out in a pilot plant (0.4 m$^2$) treating urban wastewater with an organic loading rate of 40-60 gCOD/m$^2$·d. Continuous and intermittent aeration was performed from the bottom on 8% of the wetland surface, leading to different dissolved oxygen concentrations within the wetlands (from 0.2 to 5 mgO$_2$/L). Continuous aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in wastewater treatment caused by aeration can result in reduction of the surface area requirement of future systems. This work demonstrated that for the studied configuration the cost of the power consumption of the continuous aeration was largely covered by the reduction of the wetlands surface. Even if the heating of 8% of the wetland surface at 21°C had no effects on treatment performance, positive results showed that solids accumulation rate within the granular medium, which is closely related to the development of clogging. It has been demonstrated that heating for 10 days per year during 20 year period would delay the equivalent of 1 year of solids accumulation.

Keywords: Artificial aeration, Heating, Wastewater treatment, Clogging, Constructed Wetlands.
Introduction

Constructed wetlands (CW) are widely used for the treatment of wastewater including urban wastewater, mine water, landfill leachate, industrial effluents, air-striprunoff and road runoff (Kadlec and Wallace, 2009).

In horizontal subsurface flow constructed wetlands (HSSF CW) the water, maintained at a constant depth, flows horizontally below the surface of a granular medium planted with emergent rooted wetland vegetation. In such systems contaminants are removed thought a number physical, chemical, and biological processes taking place simultaneously (García et al., 2010). Note that vertical flow constructed wetlands, are not a topic covered in this manuscript.

In recent years research on HSSF CW has focused on the improvement of treatment performance, as well as on the prevention of clogging phenomenon and on the understanding of fundamental processes occurring in wetlands (García et al., 2010).

Since HSSF CWs are generally considered to be anaerobic, organic matter oxidation and nitrification may be enhanced by promoting more oxidized conditions (Caselles-Osorio and García 2007). Among the strategies to increase CW performance, forced (or active) aeration patented by Wallace (2001) has been recently suggested as an efficient way to improve removal of organic matter and reduced nitrogen species (Nivala et al., 2007; Wu et al. 2014; Fan et al., 2013a).

Since the years 2000, active aerated systems have shown interesting results increasing significantly the removal rates compared to passive systems (Ouellet-Plamondon et al. 2006; Maltais-Landry et al. 2009). A laboratory-scale study has indicated that aeration has a certain effect on the solids degradation rates, increasing the amount of accumulated total organic suspended solids against the mineral fraction (Chazarenc et al., 2009; Zhang et al., 2010).
In spite of the advantages of aeration, the costs increase should be taken into account as CW ordinarily have a low operating cost. Most of the studies on active aeration referred to “continuous aeration mode” (i.e. 24 h per day) which has a significant energy consumption. Nonetheless, energy requirements of aerated CW (0.16-0.49 kWh/m$^3$ of water treated) are still largely lower than conventional wastewater treatments such as activated sludge (0.76-0.88 kWh/m$^3$ treated) (Kadlec and Wallace, 2009; Austin and Nivala, 2009).

Moreover, this option can lead to a contradiction between the removal of ammonium and total nitrogen because of the lack of favourable anoxic conditions for denitrification (Wu et al., 2014). Important improvements could be achieved with intermittent aeration where the level of aeration could be adjusting and controlled (i.e. adjusting the dissolved oxygen within the wetland) and excessive aeration could be avoided (Fan et al., 2013b). In this case intermittent aeration has been shown to achieve high total nitrogen removal by providing alternate aerobic/anoxic conditions for the simultaneously occurring nitrification and denitrification (Boog et al., 2014; Li et al., 2014).

The higher contaminant removal rates achieved in forced aerated CW might lead to a significant surface requirement reduction for future systems. Therefore, the aeration is only justified when its costs are counterbalanced by the reduction in the capital cost derived by the decrease of the wetland size (Kadlec and Wallace, 2009).

Apart from the efficiency in pollutant removal, the clogging of the porous medium is among the main operational problems of HSSF CW. Clogging may result in hydraulic malfunction associated with reduced treatment performance due to preferential water flows, dead zones and short circuits. Clogging affects the longevity of the systems, indeed the original life span predictions were in the order of 50–100 years (Conley et
al., 1991) whereas experimental evidence has shown lifetimes of 8 years (Griffin et al., 2008).

Clogging has been widely studied during recent years (Knowles et al., 2011; Nivala et al., 2012; Maloszewski et al., 2006; Murphy et al., 2010; Ragusa et al., 2004; Tietz et al., 2007). It is well known that clogging is caused by the accumulation of materials associated with treatment. The quantity and composition of the clog matter may vary but typically consists of highly hydrated gels and sludge with inorganic (e.g. solids from chemical erosion of gravel) and organic solids (e.g. biomass growth, plant roots, biofilm and plant detritus) (Knowles et al., 2011; Pedescoll et al., 2011a).

It is generally accepted that soluble COD in spring or beginning of summer increases at the outlet of a wetland, thus decreasing treatment efficiency after winter time (Pedescoll et al., 2011b). This is mainly due to the organics accumulation during winter. When temperature raises (spring time) hydrolysis of organics retained in the wetlands increases. The increase of the temperature within the CW may enhance the organic matter oxidation (Garfi et al., 2012; Kirschbaum et al., 2004). In this context, warming up the wetland might be of use not only on the increase of treatment efficiency but also on the mobilization of organics accumulated within the treatment bed. Furthermore, nitrification is limited in winter time (even in warm regions such as Spain). Warming the water up few degrees at the beginning of spring-time could help to decrease the soluble background COD generally found in this period. Increased background COD at the beginning of spring is a consequence of organics hydrolysis accumulated during winter time.

This study had two main objectives, to assess the economic suitability of active aeration in HSSF constructed wetlands and to study the effect of heating on the longevity of HSSF constructed wetlands.
Materials and Methods

Pilot plant

The experimental plant was located in Barcelona (Spain) at the Department of Hydraulic, Maritime and Environmental Engineering of the Universitat Politècnica de Catalunya-BarcelonaTech. The plant was set in operation in March 2011. Wastewater was pumped from a municipal sewer where it was then screened and subsequently stored for approximately 5 h in a continuously stirred plastic tank (1.2 m$^3$ volume). The primary treatment consisted of a hydrolytic upflow sludge bed reactor (HUSB) with 3 h of hydraulic retention time (HRT). The primary treatment was followed by two HSSF CW in parallel acting as secondary treatment. Each CW was made of a PVC container with a surface of 0.4 m$^2$ (0.75 m long, 0.55 m wide, 0.39 m high). A uniform gravel layer (40% initial porosity) was used which provided a wetland depth of 0.35 m. The water level was kept at 0.05 m below the gravel surface to give a water depth of 0.30 m, as suggested by García et al. (2004). CW were planted with common reed ($Phragmites australis$) at an initial density of 16 plants/m$^2$.

Both CW were fed under continuous flow regime and operated at 0.8 days HRT, hydraulic loading rate (HLR) of about 160 L/m$^2$·d and an organic loading rate (OLR) ranging from 40 to 60 gCOD/m$^2$·d. Such conditions were set in order to “force” the systems to detect the effect of aeration and heating.

In order to measure the evapotranspiration, the water flow was measured at the inlet and at the outlet of each wetland by means of peristaltic pumps (at the inlet) and a flow meter device located at the outlet. However, values recorded from the flow meter device indicated that evapotranspiration effect was negligible during the experimental period.

Physical and Chemical analysis
Water quality was monitored from influent and effluents samples twice a week from November 2013 to May 2014. The surveyed water quality parameters were the total chemical oxygen demand (COD), ammonia nitrogen, nitrite and nitrate nitrogen. Such parameters have been selected as reliable indicators for water quality monitoring. Analyses were carried out according to Standard Methods (APHA-AWWA-WEF, 2005). Nitrite and nitrate nitrogen was analyzed with ion chromatograph (ICS1000, Dionex, USA).

Aeration experiment

In order to assess the effect of aeration on wetlands performance, from November 2013 to February 2014 one of the CW (named “experimental CW” henceforth) was equipped with an aeration system whereas the other wetland (control) operated under normal saturated passive conditions. The aeration system consisted of a pierced resin pipe of about 50 cm long, rolled at the bottom of the wetland at its central zone (Figure 1). The aeration roll occupied a surface of 0.03 m$^2$, which corresponded to 8% of the total bed surface. The air was injected by means of an air pump working at a flow rate of 720 L/h.

Dissolved oxygen at the bottom of both of the CW was continuously monitored by means of a dissolved oxygen probe placed above the aeration device (CS512 Oxyguard Type III, Campbell Scientific Inc., USA) connected to a data logger (CR1000, Campbell Scientific Inc., USA).

At the beginning of the experiment air was continuously injected (24h/d), reaching an oxygen concentration within the bulk liquid of 5 mg/L. Afterwards, in order to have an intermittent aeration, the oxygen concentration within the bed was controlled by means of a control program of the data logger (control Deadbond version 2.5). This program worked according to oxygen concentration set points. The valve controlling air injection
was opened when the oxygen concentration was higher than the set point and airflow stopped when the set point concentration was reached. Thus, after 9 days of continuous aeration the oxygen concentration within the bed was set at 3 mg/L and successively reduced to 1.5, 0.5 and 0.2 mg/L in order to test the treatment performance at different aeration rates. Each condition was maintained during 2 weeks. The aeration configuration and the control system were able to constantly provide the pre-established oxygen concentrations within the bed.

For each configuration, the removal efficiencies of the experimental wetlands with respect to the control wetland were calculated for NH$_4^+$-N and COD according to Eq. 1.

\[
\text{Removal efficiency(\%)} = (1 - \frac{C_e}{C_i}) \times 100 \quad \text{Eq. 1}
\]

Where \(C_e\) was the effluent concentration (in mg/L) and \(C_i\) was the effluent concentration. The statistical significance of the experimental results was evaluated by the repeated measures ANOVA test using R statistics software.

Data was used to compare the cost of the aeration in each configuration in order to assess the viability of the active aeration (Table 1). Three wetlands sizes were considered for this study, corresponding to 100, 500 and 1,000 (PE). These sizes were selected as a range of small-medium communities. This study was carried out considering a wetland located in Spain and a wetland located in the United Kingdom. For each CW, the annual cost was calculated including construction and maintenance considering a 20 year amortization period. The costs of the Spanish CW were calculated using information provided by Ortega et al. (2010), while data for the CW costs in United Kingdom were provided by ARM Ltd (Rugeley, UK). Both cases were calculated considering the price in euro for the year 2010. The electric consumption (Table 2) was calculated according to data gathered from the experiments carried out in the pilot plant.
**Heating experiment**

Even if in Mediterranean countries water temperature in winter might not be a big problem when compared to other countries, nitrification can be highly affected in winter time even in warm regions such as Spain (Pedescoll et al., 2011b). For this reason this experiment was carried out to assess whether warming up the water few degrees at the beginning of spring-time would be of use not only to rise the nitrification but also to reduce background COD coming from winter accumulation of organics. In order to test the effect of temperature on CW, from March to May 2014, a heating system (Wave 300W) was introduced into the center of the experimental wetland, with a temperature set to 21°C. As for aeration, the removal efficiency of the experimental wetlands was calculated with respect to the control wetland for COD (Eq. 1).

Concerning clogging, a calculation was made to estimate the delay of solids accumulation rate heating 8% of the wetland surface during 10 days. Reduction of solids accumulation was estimated starting from the difference of COD concentrations in the experimental and control wetlands and considering the correlation between volatile suspended solids (VSS) and COD (VSS/COD = 0.84) (Caselles-Osorio and Garcia, 2007)). From this, the amount of VSS removed from the experimental wetland was calculated. Subsequently, considering different VSS/TSS ratio summarized in Table 3, a calculation of the released total suspended solids (TSS) retained within the gravel was made. From these values it was possible to estimate the delay on the annual solids accumulation rate. All calculations were based on data from different full-scale constructed wetlands found in literature. In accordance with our experimental set-up in all cases we considered the heating of 8% of the bed surface during 10 days per year.
Results and discussion

Aeration as a strategy to increase treatment efficiency

The aeration at different set points entailed significant increment of dissolved oxygen within the wetland, and a consequent increase in COD and $\text{NH}_4^+-\text{N}$ removal ($p<0.05$). This means that, even if the aeration was not uniformly distributed along the surface area, the aeration was efficient. As shown in Figure 2, for a COD concentration of 311±80 mgO$_2$/L in the inlet a decrease to 134±14 mgO$_2$/L at the outlet was observed in the control bed, whereas lower values (about 70mgO$_2$/L) were reached in the effluent of the beds with oxygen concentration set at 5, 3, 1.5 and 0.5 mg/L. No significant differences ($p>0.05$) were found between the effluents concentrations of the experimental beds. Conversely, the COD concentrations in the effluent of the control and the experimental beds were similar when the aeration set point was 0.2 mg/L. The differences between the COD concentration in the effluents of the two beds decreased from 80 to 40 mg/L when the aeration set point was 0.5 mg/L, while almost no differences between the systems was observed when the set point was 0.2 mg/L as the aeration set point. On the whole, aeration increased COD removal by 56%, 46%, 40%, 35% and 3% for 5, 3, 1.5, 0.5 and 0.2 set points, respectively.

Concerning ammonium nitrogen ($\text{NH}_4^+-\text{N}$) (Figure 3), differences between systems with and without aeration were even more evident. Ammonia nitrogen concentrations in the influent ranged between 14 and 32 mgNH$_4^+$/N/L due to variations in the wastewater quality. The concentration of ammonia nitrogen in the effluent was generally higher in the control (18-29 mgNH$_4^+$/N/L) than in the experimental beds (9-24 mgNH$_4^+$/N/L). Note that in some cases the effluents concentrations was higher that the influent, this could be partially due to ammonification and to the fact that the influent values do not correspond to the effluent of the same day (due to the HRT).
The aeration increased ammonium removal between the control and the experimental wetland by 69%, 45%, 28%, 18% and 2% for 5, 3, 1.5, 0.5 and 0.2 set points, respectively. As for COD, the difference between the aerated and the non-aerated bed was evident up to and including 0.5 ppm, while no significant differences (2%) were observed at 0.2 ppm (p>0.05).

With regard to nitrites and nitrates, very low concentrations were found in the effluents along the experiment (Table 4). Nitrate concentrations in the experimental wetland clearly showed the effect of the aeration, which was the likely cause for enhanced nitrification. Moreover, the higher the oxygen supply to the wetland reduced the anoxic environment for denitrification to take place.

Indeed, 6.8±0.1 mg NO$_3^-$-N were found in the effluent of the wetland when continuously aerated. Concentrations decreased to values lower than 0.1 mg NO$_3^-$-N in accordance with the reduction of the dissolved oxygen in the wetland (from 5 to 0.2 mg/L). These results underline that the intermittent aeration of solely a part of the wetland can favor the presence of anoxic conditions enhancing denitrification.

The results presented in this study show that aeration significantly improved the treatment performance. Considering European legislation (91/271/CEE) effluent concentrations of the control (119-149 mg/L) were near to the threshold (125 mg/L). Therefore we can assume that the control fulfilled the legislation threshold. In this case, aeration could be seen as a strategy to reduce the surface of the future beds without affecting the performance (Kadlec and Wallace, 2009).

Based on the efficiency of aerated beds in comparison with the control the potential reduction of the surface of the beds could be calculated, as shown in Table 5 which indicates the percentage of surface reduction according to the COD and the NH$_4^+$-N removal efficiency.
According to the surface reduction for CW of different sizes and locations, summarized in Table 5, the cost (€/year) of different wetlands size (100, 500 and 1,000 PE) was calculated for two locations (Spain and United Kingdom) (Figure 4). An average soil cost was used for each country.

In general CW costs are higher in United Kingdom. The results showed that every aeration configuration entailed an economic advantage with respect to the control. In the case of a set point at 0.2 mg/L no difference was found between an aerated bed and the control. However, already from an aeration set-point of 0.5 mg/L the electric consumption was largely covered by the surface reduction, reducing the costs by 27-31% considering COD removal and by 10-14% considering the ammonium removal. In general up to 50% of the costs could be reduced with the continuous aeration of the beds.

It should be noted that the calculations were performed considering the configuration of this experiment (i.e. aeration of 8% of the total surface). Hydraulic aspects have not been considered in this study, in fact it should be verified if the decrease of HRT due to the reduction of surface area could affect the treatment efficiency.

The results highlight that the land and excavation cost has a significant weighting on the total CW cost, thus the reduction of the surface justifies the aeration of the beds in spite of the increase in the power consumption. It is important to take into account that results are based on theoretical calculations and more data at different size are required to confirm these findings.

In this study the effect of continuous and intermittent aeration were tested in terms of oxygen supply. Further experimental testing should examine the influence of the proportion of surface aerated and the position of the aeration within a CW.
Heating as a strategy for clogging prevention and remediation

It is well known that the organic matter accumulated within the granular medium is among the main responsible factors for CW clogging. According to Wang et al. (2014), heating of CW can be a suitable strategy to release the retained organic matter.

During the heating experiment (from March to May), the control water temperature was 13±5 °C, while the water temperature of the experimental wetland was 26±8°C. As shown in Figure 5, heating the experimental bed at 21°C did not enhance the COD removal. The mean value of COD concentration in the effluent of the experimental and control CW were 126±37 mg/L and 135±27 mg/L, respectively. The differences between beds were not statistically significant (p >0.05) during the two months of experimentation.

During the first 10 days of experimentation, the COD concentration in the effluent of the experimental wetland was 176±14 mg COD/L, which was 15% higher than the control concentration (153±18 mg COD/L). The authors consider that this could be attributed to the hydrolysis and subsequently release of part of the organic matter retained in the granular medium (Conant et al., 2011), meaning that the heating enhanced by 15% COD mobilization in the experimental wetland.

In order to quantify the benefit of heating the delay on the annual solids accumulation corresponding to the COD mobilization was calculated. Taking into account the correlation factor of 0.84 between VSS and COD (Caselles-Osorio and Garcia, 2007), 0.02 g/L VSS were removed in 1 day of heating.

Considering the VSS/TSS and the solids accumulation rate found in literature the TSS mobilization and the delay on the annual solids accumulation were calculated for the hypothetical heating during 10 days per year on 8% of the surface of the wetland as summarized in Table 3. The TSS removal was calculated for 11 real HSSF CW (Tanner...
et al 1998; Caselles-Osorio et al. 2007; Martin et al. 2010). The results highlighted that heating CW would delay the annual solids accumulation by 8 to 28 days, depending on the VSS/TSS considered. In order to delay the annual solids accumulation for 1 year of operation, it would be necessary to heat 8% of the surface during 200 days (on average). This means that heating 10 days per year during 20 years would delay 1 year of the annual solids accumulation. Considering the electric consumption of heating (7.2 KWh/d), the annual cost for the application of this strategy would be 20€/m²-year. According to Nivala et al. (2012), the cost of the gravel excavation and landfill or gravel excavation, washing and reuse is approximately 5€/m².

It should be taken into account that the experiments have been carried out in the Mediterranean region in spring, where the temperatures were rising, with the average water temperature of the control being 18°C). It is therefore possible that the hydrolysation of the organic matter could be enhanced by heating wetlands during the cold season, but this would require further work.

**Conclusions**

In this study aeration and heating were investigated in a pilot plant that constituted of two horizontal flow subsuperficial constructed wetlands treating urban wastewater. Continuous aeration increased organic matter (COD) and ammonium nitrogen removal by 56% and 69%, respectively. Improvements in the wastewater treatment were satisfactory for intermittent aeration until oxygen concentrations within the wetlands were maintained at 5mg/L.

Aeration can result into reduction of the surface area requirement for future systems, leading to significant cost reduction. This study highlighted that the land and excavation cost had a significant weight on the total constructed wetlands cost. Thus, in spite of the
increase of the electric consumption, the reduction of the surface could justify the continuous aeration of the beds.

Even if the heating of 8% of the wetland surface at 21°C had no effects on treatment performance, positive effect were noticed on the solids accumulation rate within the granular medium, which is closely related to clogging development. Results demonstrated that the annual solids accumulation could be delayed of 1 year by heating for 10 days per year during 20 years. Thus, heating of a small area of CW could be an efficient solution to reduce the annual solids accumulation rate, delaying the clogging of the bed.

This study provided encouraging outcomes for intensified constructed wetlands. Nevertheless, further research is needed in order to reproduce the results using full scale systems over a longer time scale.
Acknowledgements

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Table 1. Investment and operation costs of artificially aerated constructed wetlands in Spain and United Kingdom over a 20 year period for 100, 500 and 1,000 PE.

<table>
<thead>
<tr>
<th></th>
<th>Costs (€/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 PE</td>
</tr>
<tr>
<td><strong>Spain</strong> (according to Ortega et al., 2010)</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>2.6</td>
</tr>
<tr>
<td>Construction of the aeration system</td>
<td>2.1</td>
</tr>
<tr>
<td>Operation and maintenance</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>United Kingdom</strong> (according to ARM Ltd. data)</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>4.5</td>
</tr>
<tr>
<td>Construction of the aeration system</td>
<td>15.9</td>
</tr>
<tr>
<td>Operation and maintenance</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Table 2. Power consumption and cost calculated experimentally for each aeration set point.

<table>
<thead>
<tr>
<th>Aeration set point (mg/L)</th>
<th>Working time of the air pump (min/d)</th>
<th>Consumption (kWh/m² year)</th>
<th>Cost (€/m² year)</th>
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<tbody>
<tr>
<td>5</td>
<td>1440</td>
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<td>14.5</td>
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<tr>
<td>3</td>
<td>626</td>
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<tr>
<td>1.5</td>
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<tr>
<td>0.5</td>
<td>55</td>
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<tr>
<td>0.2</td>
<td>23</td>
<td>0.001</td>
<td>0.6</td>
</tr>
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</table>
Table 3. Total solids released and delay of the annual solids accumulation assuming heating 8% of the surface during 10 days/year.

<table>
<thead>
<tr>
<th>VSS/TSS Solids accumulation rate (Kg/DM m².year)</th>
<th>Solids released (kg TSS/m²·year)*</th>
<th>Delay of the annual solids accumulation (d)**</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 1.3</td>
<td>0.04</td>
<td>9</td>
<td>Tanner et al. (1998)</td>
</tr>
<tr>
<td>80 1.5</td>
<td>0.04</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>80 1.9</td>
<td>0.04</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>80 3.0</td>
<td>0.04</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>24 2.0</td>
<td>0.12</td>
<td>21</td>
<td></td>
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<tr>
<td>50 1.7</td>
<td>0.06</td>
<td>11</td>
<td>Caselles-Osorio et al.(2007)</td>
</tr>
<tr>
<td>10 4.7</td>
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<td>11 7.9</td>
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<td>16 3.9</td>
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<td>15</td>
<td></td>
</tr>
<tr>
<td>24 5.1</td>
<td>0.13</td>
<td>8</td>
<td>Martin et al. (2010)</td>
</tr>
</tbody>
</table>

* Calculated using VSS/TSS solids accumulation rate.
** Calculated using VSS/TSS.
Table 4. Nitrites and nitrates concentration detected in the effluents of the control as well as the aerated and heated wetlands.

<table>
<thead>
<tr>
<th>Oxygen concentration set point (mgO₂/L)</th>
<th>Control Nitrites</th>
<th>Control Nitrates</th>
<th>Heated Nitrites</th>
<th>Heated Nitrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>5</td>
<td>1.0 ± 0.5</td>
<td>6.8 ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>&lt;0.1</td>
<td>2.0 ± 0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>&lt;0.1</td>
<td>0.4 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Percentage of surface reduction according to the COD and the NH$_4^+$-N removal efficiency for different aeration set points.

<table>
<thead>
<tr>
<th>Aeration set points (mgO$_2$/L)</th>
<th>% of surface reduction according to the COD removal</th>
<th>% of surface reduction according to the NH$_4^+$-N removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>56%</td>
<td>69%</td>
</tr>
<tr>
<td>3</td>
<td>46%</td>
<td>45%</td>
</tr>
<tr>
<td>1.5</td>
<td>40%</td>
<td>31%</td>
</tr>
<tr>
<td>0.5</td>
<td>35%</td>
<td>18%</td>
</tr>
<tr>
<td>0.2</td>
<td>3%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Figure 1. Scheme of the pilot wetland with the aeration systems. During the construction of the system, a cylindrical part of the central zone of the bed was kept without gravel in order to allow experiments.
Figure 2. Influent and effluents concentrations of Chemical Oxygen Demand (COD) of control and experimental bed under different operating conditions.
Aeration set point (mgO₂/L)

NH₄⁺-N concentration (mg/L)

Figure 3. Influent and effluents concentrations of ammonium nitrogen (NH₄⁺-N) under different operating conditions.
Figure 4. Cost(€/year) of different wetlands size (100, 500 and 1,000 PE) located in Spain (a1, a2) and in United Kingdom (b1, b2) considering different aeration strategies (set points at 5, 3, 1.5, 0.5, 0.2 mgO₂/L). Data were calculated according to the percentage of surface reduction shown in Table 5. Figures a1 and b1 refers to the surface reduction calculated corresponding to COD removal, while figures a2 and b2 were refers to the surface reduction corresponding to ammonium removal.
Figure 5. Influent and effluents concentrations of Chemical Oxygen Demand (COD) of control and experimental bed under heating.