Combined Sewer Overflow (CSO) Treatment With Constructed Wetlands

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Summary

Whenever the affluent flow exceeds the treatment capacity of a WWTP, untreated effluent is directly discharged into the waterlines, endangering the environment and public health. In this context it is relevant to study natural and sustainable solutions of combined sewer overflow (CSO) treatment. The aim of this thesis is to analyse the treatment capacity of constructed wetlands (CW) with subsurface flow (planted and unplanted) when treating CSO, through an experimental facility located in Frielas WWTP, which had its start-up in 2011. As the facility was located inside the WWTP it was possible to analyse the treatment response when subjected to local conditions (environmental conditions as well as organic loading, since the CW were always fed with screened effluent). Regarding the experimental stage, two campaigns were carried out at different times, the first one was executed from April to June 2012 and a second one from December 2012 to January 2013. The analysed parameters were COD, pH, redox, dissolved oxygen, and also (only during the first experimental phase) TSS and Enterococci. It was further evaluated, in a qualitative way, the beds evapotranspiration and their porosity. Aiming to achieve a better knowledge on how a CW treats COD, the k-C* model for the hydraulic retention time was calculated. In summary, the COD removal efficiency was higher in planted beds, for the first experimental phase, while in the second phase greater efficiencies were obtained for the beds supplied with a lower organic load. In terms of residual concentrations (C*), in a adjustment of experimental results to a k-C* kinetic model, the second experimental phase registered higher values than the first phase, with C* up to 150 mg/L of COD.

Keywords: constructed wetlands, subsurface flow, combined sewer overflow; natural solutions; sustainability.

1 INTRODUCTION

In recent years, there has been an increased attention given to the treatment of rainwater and combined sewer overflow, since in many cases these waters do not receive any treatment, becoming a major source of global pollution. This situation is aggravated with the undue stormwater inflows to separative domestic systems and the existence of numerous combined systems in Portugal and in many regions of the world, since in case of a rainfall event polluted water can be directly discharged into the waterlines, often with significant impacts on the environment (Amaral, 2011). To add to these negative aspects of the current urban wastewater systems, there is deposition of mineral and organic matter inside the sewage pipes, as well as on paved surfaces, during the dry period preceding the first rainfall event (Singh and Malaviya, 2012). These pollutants are then transported by rainwater, which can affect the quality of the receiving waters when CSO is discharged.

Since constructed wetlands treatment is characterized as "green", "environmentally friendly" and "sustainable", it has become very attractive treatment alternative in the current context (Cooper, 2009). Although it has started to be seen as a treatment for sewer effluent from small agglomerations, they are recently used in the treatment of all types of effluents and all over the globe. However, the main objective of the process should always be kept in mind, which is the treatment of wastewater such that the treated effluent can be discharged in accordance with the standards set by the regulator, avoiding adverse impacts on the ecosystem of the receiving environment (Silveira, 2009). For that reason, it is relevant to analyse the treatment level offered by constructed wetlands in the treatment of CSO, aiming to control the pollution level of streams in a economical and sustainable way.

2 CONSTRUCTED WETLANDS TREATMENT

Currently one of the natural process most used in water treatment, in Portugal, are constructed wetlands (CW). These treatment consist in a recreation of a natural system with physical, chemical and biological processes identical to those shown in natural wetlands, although in a more controlled environment (EPA, 1999).
2.1 General Characterization

A constructed wetland consists in a shallow impermeable basis (usually less than one meter height) with a downstream level control, in order to keep both retention time and level has desired (EPA, 1999). A constructed wetland can be classified according to three factors (Figure 2.1): if is planted (and in that case the type of macrophyte it has), if the flow is free surface or sub-surface, and in case of a sub-surface flow the direction it takes (horizontal or vertical) (Malaviya and Singh, 2012; Vymazal, 2010). If the constructed wetland has a vertical subsurface flow, it can still be classified by the direction of the effluent (ascending or descending vertical flow) (Vymazal, 2010).

![Figure 2.1 – Classification of a CW](image)

In a CW, the inflow takes place at one end (or in the top of the beds, in case of vertical flow) and after crossing the bed, where physical-chemical processes take place, discharged at the opposite one with a reduction in pollutant load.

The surface flow (SF) CW are not widely used in Europe, although they are relatively common in North America and Australia (Vymazal, 2010), given the danger of contact with the untreated effluent, the strong attraction of mosquitoes and also the increased problems with smells. Note that, although the attraction of mosquitoes is mostly a matter of well-being, some species may be carriers of disease (EPA, 1999). Subsurface flow (SSF) constructed wetlands feature a better cold resistance, bigger treatment ratio/area and minimal smells when compared with SF CW (Davis, 1995; Nelson et al. 2008). Since the flow takes place under the surface, the problems associated with human contact are also minimized. However, there are certain additional difficulties due to the need to ensure that the flow is exclusively sub-surface and the substrate doesn’t clog, which would undermine not only the efficiency but also the safety of the surroundings. In terms of maintenance, repair and construction costs, these types of CW are more expensive than SF CW (Davis, 1995).

The treatment of a constructed wetland is diverse and interactive, combining physical, chemical and biological processes (Van Moortel et al., 2009; Vymazal, 2010). The treatment mechanisms present in a constructed wetland are: sedimentation of particulate matter; filtration and chemical precipitation; chemical transformation; absorption of pollutants and nutrients by microorganisms and plants and also predation and natural death of pathogens (Davis, 1995; Faulwetter et al., 2009; Galvao et al., 2005). In a CW initial phase of operation the pollutant sedimentation and adsorption is greater due to the high adsorption ability of the brand media. While the equilibrium adsorption and desorption cycle is not reached, the system acts as a heat sink from contaminants. Once reached the equilibrium, contaminants continue to undergo adsorption on a smaller scale, and in this case, retained by a reversible adsorption process.

It is generally recommended a minimum and maximum load to be applied on CW, to ensure the stability and treatment efficiency of the system. However, a study performed in SSHF (subsurface horizontal flow) CW, where they apply differentiated effluent load from a tannery, have shown a good response to shock load and alimentation interruption in terms of efficiency (Calheiros et al., 2009). Sometimes the macrophytes suffer high mortality rates, which is related to three main factors: plugged media, build up of toxic elements and water stress caused by lack of water (Gustafson et al. 2002).

### Planted vs. not planted

In the begging there was a general belief that the entire purification process resided in the plants themselves. However, it is now recognized the key role of the biofilm throughout the entire biological
treatment, as well as all other treatment processes based on the nature of the filter media, gradually blocking it (Cooper, 2009). The plant most commonly used in CW wastewater treatment is undoubtedly the Phragmites australis (Vymazal, 2011b). This common reed is used throughout Europe, Canada, Australia and most Asian and African territory. In order to achieve your maximum potential is usually given a period of "maturation" of about three years (Chazarenc and Brisson, 2009). The major difference between CW with or without plant lies in the hydraulic cycle of the system, with the notable difference between the effluent volume of a planted bed in comparison to an unplanted one, due to the evapotranspiration phenomenon (Sperling et al., 2005).

The use of plants can sometimes be unrelated to the performance of the system but with its aesthetic, whereas in this case some ornamentals plants are used. In developing countries the use of unconventional plants can in fact represent an economic benefit that goes beyond the simple treatment of wastewater.

### 2.2 Advantages / disadvantages

Generically, natural systems have great advantages over the methods conventionally used as activated sludge and trickling beds. The wastewater treatment through constructed wetlands is no exception to the rule, presented several advantages and some disadvantages (Davis, 1995; Foladori et al., 2012; Malaviya and Singh, 2012; Nelson et al., 2008; Pereira and Miranda, 2006; Ribeiro, 2007, Rousseau et al., 2005; Vymazal, 2010; Zurita et al., 2009):

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Low construction costs</td>
<td>Low removal/m² ratio</td>
</tr>
<tr>
<td>Low operational costs</td>
<td>Clogging of the media</td>
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<tr>
<td>Tolerance to variations of flow and organic load</td>
<td>Seasonal efficiency</td>
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<tr>
<td>Relatively simple maintenance</td>
<td>Hydric stress</td>
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<tr>
<td>Ecological solution with great integration into the landscape</td>
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<tr>
<td>Production of oxygen and CO₂ consumption by the plants</td>
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<tr>
<td>Easy treatment-reuse of water</td>
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<tr>
<td>Use of flowers/plants with commercial value</td>
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</table>

### 2.3 k-C* model

Recognizing the deficiencies presented by a single parameter model, when applied to organic decay within a CW, Kadlec and Knight (1996) proposed a modified first-order model, often called the k-C* model (Stein et al. 2006). This model assumes the existence of a residual concentration (C*), modifying the concept of a zero low limit. This constant (C*) reflect the organic matter produced inside the CW through deposition of particulate matter from atmospheric sources, soil, or a fraction of recalcitrant organic matter in the effluent (Stein et al. 2006).

The k-C* model expresses the organic matter decay inside a CW as the hydraulic retention time increases (Wong and Geiger, 1997). The model assumes steady flow conditions and is usually expressed as (Vymazal, 2011a; Wong and Geiger, 1997):

\[
\frac{C_0 - C^*}{C_1 - C^*} = e^{-k_v t} \rightarrow C(t) = C^* + C_0 e^{-k_v t}
\]

With:
- \(C_0\) – Outflow concentration (mg/L)
- \(C_1\) – Inflow concentration (mg/L)
- \(k_v\) – Volumetric parameter (d⁻¹)
- \(C^*\) – Residual concentration (mg/L)
- \(t\) – Hydraulic retention time (d)
There isn’t much information available about the value of C*. However, Kadlec and Knight (1996) suggest 1.7 ≤ C * ≤ 18.2 mg/L as expected range of values with a mean of 9.9 in assessing removal of organic matter through the BOD parameter. As for Shepherd et al. (2001) a range of values of 23 ≤ C * ≤ 450 mg/L is reported for winery treatment with horizontal subsurface flow CW, when the analysis of organic matter is based on COD or BOD.

3 EXPERIMENTAL WORK

This work is the continuation of a previous study conducted by Amaral (2011), which analyzes the response of constructed wetlands (with and without plants) regarding the treatment of CSO from Frielas WWTP. This type of effluent is associated with rainfall events in a combined sewer system, as is the case of the sewer system that brings the wastewaters to Frielas WWTP. The analysed parameters were the COD (chemical oxygen demand), TSS (total suspended solids) and Enterococci.

3.1 Constructed Wetlands Pilot Plant

The experimental setup was created at the start of the SONATE project and installed in Frielas WWTP, in Lisbon, managed by SIMTEJO, S.A. The location was chosen so that the beds were under the actual conditions, in terms of local climatic and environmental conditions, such as the characteristics of the effluent (as it was always pumped screened effluent from the WWTP).

The pilot plant consists of 4 PVC beds (555x361x400 mm), all of them simulating constructed wetlands with subsurface horizontal flow. The beads were named LM1 to LM4 and grouped according to the load received in each event with LM1 and LM2 in group A, which were fed with 10 L/event and the beds LM3 and LM4 in group B, fed with twice the load. The deferent load events aimed to analyse the system treatment response when subjected to different hydraulic and organic loads (group A and B). Each group had a bed with and without plants, so that we could analyse the effect of the macrophytes in the treatment process. As for the media, it was applied a 8,4 mm gravel with a 40cm height and a 30% porosity. The feeding was conducted through a perforated pipe installed inside the bed and the draining of the beds was done by a throttle structure at the opposite end.

3.2 Materials and Methods

The experimental procedure was developed in two distinct phases. The first phase was conducted between April 3 and June 8, 2012, in which the beds were fed once per week and effluent samples were collected twice (one and seven days after feeding) and later compared with the same period of the previous year (Amaral (2011) study). Afterwards, we proceeded to a second experimental phase in which the sequence of CSO of Frielas WWTP during the winter of 2010/2011 was reproduced. This period was chosen because it was considered representative of a winter "typical" in terms of CSO discharge.

Since there were days without rainfall, it was necessary to simulate CSO, similar to the methodology adopted in Amaral (2011), with a proportion of 1/3 of sewage to 2/3 of drinking water. In order to ensure that the minimum chlorine would be applied, which could affect the level of treatment, the volume of tap water needed has always been previously stored the day prior to feeding, ensuring the chlorine release of remaining chlorine.

4 RESULTS AND DISCUSSION

In order to analyse the treatment efficiency, the effluent quality was measured by the following parameters:

- Enterococci
- TSS
- COD
- Level
- Porosity

Regarding the macrophytes evolution, it was found in previous study, conducted in 2011, a increased growth of macrophytes in CW4 compared to CW2. This growth difference may be related to water stress in CW2, which has always received a smaller volume of effluent. The following year, 2012, probably due to the strong drought that the beds were exposed, followed by an unusually dry winter further aggravated the growth and survival of the CW2 vegetation during the first experimental phase of the campaigns.
Figure 4.1 shows the drastic reduction felt between 2011 and 2012 in CW2, and a normal growth and a high survival rate as seen for CW4.

Figure 4.1 – Macrophytes evolution from 2011 to 2012

In terms of beds porosity, in phase I, CW1 obtained bigger values (30-45%) and CW4 the lowest ones (20-25%). As for CW2 and CW3 porosity, the majority of the results demonstrate a higher porosity in CW3. Therefore suggesting that the existence of plants and a higher load leads to a porosity decrease, which may be related to filtration and propagation of roots in the media.

Figure 4.2 - Beds porosity during phase I

In fact, when installing a perforated pipe in CW4 to check the water level inside the bed, before the start of campaigns in 2012, a very high root density was observed, which was also reflected whenever the bed was fed, with a much lower emptying speed, indicating a clogging of the media.

In terms of evapotranspiration, it was analysed in a more qualitatively way, based on the water level reading during the campaigns. The first experimental phase, in which the temperatures were higher and the macrophytes were in a growing phase, showed a strong plant effect on the hydrology of the system. In fact, when comparing the planted beds (CW2 and CW4) with non planted (CW1 and CW3) there was a much higher decrease in the water level in the first one.

CW4 recorded the lowest water levels, in a result of their high macrophytes density, which contributed to the reduction of effluent volume. In fact, in Week 2-8 May there was a general increase in water level due to local precipitation and CW4 bed showed a decrease from 32.5 to 4.2 cm, indicating a strong evapotranspiration rate.

As for the beds porosity during phase II (Figure 4.3), a porosity increase in most beds was observed, continuing to be CW4 the bed with the lowest porosity, with values between 33-35%. The remaining beds porosities were very similar, with values close to 40%.
This overall porosity increase can be related to resting period between the beginning of June and beginning of December, during which the solids present in the media may have been digested.

### 4.1 First Experimental Phase

In terms of pathogens, it was analysed the intestinal enterococci parameter, showed in Figure 4.4 in a logarithmic scale. In an initial stage the values slightly differed between beds, achieving after two weeks of campaign a more uniform treatment. This initial period may be related with the biofilm stabilization, which was possibly not fully developed due to the dry period, leading up to the beginning of the campaign, that the beds were subjected.

As for the comparative analysis of the treatment level between the four beds, no significant differences were identified. Therefore it can be concluded that both the load applied and either the presence or not of macrophytes don’t effect, at least not in a noticeable way, the WSSF CW pathogens treatment. Note that the decay of enterococci appears to be linear in a logarithmic scale.

The Enterococci removal in Amaral (2011) (Figure 4.5) achieved higher efficiencies than the ones observed in the phase I, with a increase tendency throughout the two experimental studies. On the other hand, the results obtained in the 1st phase of this experimental study, when compared to the start-up period, appear to exhibit greater stability in terms of treatment efficiency.
The TSS treatment, present in Figure 4.6, shows similarities to the Intestinal Enterococci treatment, with a small variation at an initial phase, which may be, once again, due to a biofilm development. When analysing the obtained results, there is a clear TSS removal within 24 hours after feeding. This rapid decrease is probably related to filtration and adsorption processes by media.

Amaral (2011) presented initial efficiencies greater than 90% for TSS removal, unlike the 1st experimental phase, in which the initial efficiencies were between 50-90% (Figure 4.7). However there was a gradual increase in TSS treatment until the end of the campaign, with efficiencies close to 100%.
For a HRT=7 days the COD removal efficiency (Figure 4.8) was noticeably different between the beds with vegetation (CW2 and CW4) vs. the ones without vegetation (CW1 and CW3), being the vegetated the ones with the lower efficiencies (50-80’s% vs. 90’s%). This difference was not observed in Amaral (2011), where the treatment efficiency was more or less the same for all beds.

4.2 Second Experimental Phase

In the second campaign phase was registered a difference between the level of treatment in an initial and in a final stage, in which the effluent COD concentrations were higher. Such fact may be due to the high feeding frequency, during the final days of phase II, which can lead to a saturation of the treatment system, thereby decreasing their efficiency. Another factor to consider is the fact that the feeding was realized with pure sewage in the final stage of the campaign, which could also led to a reduction of the system efficiency. The treatment efficiency in terms of organic removal (Figure 4.9), the CW4 bed obtained the lowest efficiency among the analysed beds.

4.3 k-C* Model

When applied the k-C* model to Amaral (2011), phase I and phase II (values in Table 1) is noticeable the similarity COD decay between the first two studies. In Amaral (2011) the residual concentrations of all beds were lower than 50 mg/L, which may be due to the fact that the CW were in the starting phase, where the biofilm wasn’t fully stabilized and the plants hadn’t completed a cycle, and therefore hadn’t yet released organic matter in the senescence phase. As for phase II, the residual concentrations were higher, specially in the bed fed with a higher load/event. However when calculating the expression for each bed, more data with HRT=1 was used, which can lead to a bias adjustment of the model parameters.
Table 1 – Obtained values for the k-C* model when applied for all the experimental beds and studies.

<table>
<thead>
<tr>
<th></th>
<th>CW1</th>
<th>CW2</th>
<th>CW3</th>
<th>CW4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k (d⁻¹)</td>
<td>C* (mg/L)</td>
<td>k (d⁻¹)</td>
<td>C* (mg/L)</td>
</tr>
<tr>
<td>1st phase</td>
<td>-2,817</td>
<td>24,667</td>
<td>-2,615</td>
<td>41,444</td>
</tr>
<tr>
<td>2nd phase</td>
<td>-1,774</td>
<td>41,212</td>
<td>-2,233</td>
<td>52,994</td>
</tr>
</tbody>
</table>

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

During the first experimental phase, a high evapotranspiration was registered in planted beds, as observed by Sperling et al. (2005), especially in CW4, which had a higher macrophytes density. The analysis of the evaporation rate is crucial to ensure a minimum level of effluent for the survival of the macrophytes, avoiding any water stress that may occur.

The apparent porosity of beds increased in the second phase of the campaigns, which may be related to the rest period (June to December) during which the solids present in the media may have been digested. Among the four beds, CW4 showed the lower porosity levels, both in the first and second experimental phase.

As for Enterococci removal, analyzed in the first experimental phase, it was similar to the previous study (Amaral, 2011), with a linear decay in a logarithmic scale. As for their removal efficiency, they were in the order of 4-5 log, which is lower than the obtained efficiency during Amaral (2011). However, the beds have demonstrated a more stable removal of pathogens when compared to the previous study.

In terms of the TSS, high removal efficiencies were obtained, similar to Amaral (2011), with a tendency to increase over time, reaching values close to 100% in the last events.

In general, the efficiencies obtained in terms of COD removal were good, being attenuated over time. There was also observed a clear removal in the first 24 hours of treatment, with removal efficiencies in the first phase between 68-84% for HRT=1 d and 74-90% for HRT=7 d and for the second phase (with diluted effluent) 63-85% for HRT = 1.

In phase I, CW4 was the one with the lowest removal efficiency. However, it also presented a lower effluent volume, which would result in discharge with lower pollutant load.

At the end of phase II, the COD removal decreased, indicating some saturation of the treatment system, with efficiencies as low as 20%. Also, in the period of December 2012 to January 2013, a higher COD treatment instability was recorded, especially in CW4.

The organic decay changed from the first to the second phase, with particular change in the residual concentration, being in the first phase 25 mg/L in CW3 e CW1 and 50 mg/L CW2 and CW4 to 40-50 mg/L in the CW1 and CW2, 77mg/L in the CW3 and 140 mg/L in CW4 during the second phase. Note that the increase of C * may be related to the calculation of the decay expression with a higher number of data with HRT=1.

In summary, in the first phase a higher COD removal efficiency for the planted beds was observed as for the second phase the CW fed with lower loads were more efficient. This differentiation in the first phase between planted and non planted beds may be due to a period of maturation of the system required so the roots may developed, as recommended by Chazarenc and Brisson (2009) (advising a period of 3 years).

Future Work

As a result of clogging, especially in CW3 and CW4 which received throughout the hole experiment twice the load, it is suggested the study of a systems with a sedimentation basin before the HSSF CW. This way the particles can sediment, helping to control the filling of the media and ensuring a uniform flow distribution along the bed.

The feeding frequency of the beds should also be controlled, ensuring a minimum rest period when there is a higher frequency of CSO from the WWTP. This not only prevents the clogging of the CW but also avoids a possible saturation of the treatment system, as seen at the end of the phase II.
Given the low survival rate of the macrophytes in CW2 from 2011 to 2012, the feeding of the beds with WWTP effluent in case of absence of CSO it’s highly recommended, ensuring the minimum volume to face the evapotranspiration rate. Also, the prevention of water stress in the system ensures the level of treatment in the future and the reduction of effluent discharged into the waterlines, translating into a higher efficiency of the treatment plant.

Because the treatment plant discharges the treated effluent in a close by waterline, it’s suggested the study of the level of treatment of a CW with the native plants from this river, in order to examine its self-treatment capacity.

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