REMOVAL PERFORMANCE AND CLOGGING INVESTIGATION OF AN HYBRID TREATMENT WETLAND IN MEDITERRANEAN AREA

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Big Sky Resort, Montana, USA
Objectives

Evaluate the reliability of a **hybrid-TW system** (which includes three beds in series - one horizontal, HF and two vertical beds, V1 and V2) used as secondary wastewater treatment system of a retail store (IKEA) in South Italy, in term of:

- **removal efficiency** (based on physical-chemical and bacteriological concentration of the wastewater with respect to Italian Regulation for wastewater discharge into water bodies (LD 152/06) and agricultural reuse (MD 185/03);

- **potential clogging risk** by:
  - hydraulic conductivity measurements *in situ* ($K_s$)
  - flow paths visualization by means of tracer tests
  - 2-D electrical resistivity tomography (ERT) imaging
Area location: IKEA store

- Restaurant, bar, toilets
- ~ 300 employees
- ~ 6,000 visitors per day
- ~ over 16,000 visitors on Sunday/holydays (23,000 visitors on Dec 8th 2016)
- ~ 800 meals served per day (up to 2,000 per day)
Onsite wastewater treatment plant

Wastewater toilets restaurant Bar

- Grease&Oil-water separation
- Coarse Screen + Equalization tank
- Sequential Batch Reactor (SBR)
- River disposal

Wastewater to toilets, restaurant, bar

<table>
<thead>
<tr>
<th>SBR Design Parameters</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum daily flow (Qi)</td>
<td>m³/day</td>
<td>30</td>
</tr>
<tr>
<td>Mean flow (24 hours)</td>
<td>m³/day</td>
<td>1,3</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/L</td>
<td>350</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>500</td>
</tr>
<tr>
<td>BOD</td>
<td>mg/L</td>
<td>300</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>mg/L</td>
<td>135</td>
</tr>
<tr>
<td>Total Phosphorus (P)</td>
<td>mg/L</td>
<td>15</td>
</tr>
</tbody>
</table>

- 2 cycles per day (2013-2014)
- 3 cycles per day (2015- April 2017)
- 4 cycles per day (since April 2017)

High fluctuations of hydraulic load

High fluctuations in pollutant load

Considerable differences with the SBR design parameters
Wastewater volume

The daily wastewater volume from toilets, showers, kitchen sinks, ecc. has been measured by two flow meters.

Maximum design daily flow $Q = 30 \, m^3/day$

<table>
<thead>
<tr>
<th></th>
<th>Min value</th>
<th>Max value</th>
<th>Range</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m$^3$/day</td>
<td>m$^3$/day</td>
<td>m$^3$/day</td>
<td>m$^3$/day</td>
</tr>
<tr>
<td>Working days</td>
<td></td>
<td>7</td>
<td>20</td>
<td>14,73</td>
</tr>
<tr>
<td>Non-working days</td>
<td></td>
<td>27</td>
<td>25</td>
<td>27,85</td>
</tr>
</tbody>
</table>

- Maximum design flow rate = 5 m$^3$/h
- In some days a flow rate of 10-12 m$^3$/h has been recorded
Rough wastewater characteristics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>mg/L</td>
<td>68</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>mg/L</td>
<td>295</td>
<td>980</td>
<td>532</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>600</td>
<td>1450</td>
<td>940</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>mg/L</td>
<td>12</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>Ammonium (NH$_4$)</td>
<td>mg/L</td>
<td>20</td>
<td>231</td>
<td>114</td>
</tr>
</tbody>
</table>

Design concentration of Total Nitrogen was 135 mg/L

Plant description

Design COD value = 500 mg/L
Layout of Hybrid CW plant (implemented in June 2014)
### Wetland characteristics: HF

<table>
<thead>
<tr>
<th>Constructed wetland</th>
<th>Area (m²)</th>
<th>W (m)</th>
<th>L (m)</th>
<th>Q (m³/day)</th>
<th>Gravel</th>
<th>Macrophytes</th>
<th>Density (rhizomes /m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF (I stage)</td>
<td>400</td>
<td>12</td>
<td>34</td>
<td>45-50</td>
<td>Volcanic gravel</td>
<td>Phragmites australis</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Gravel**
- **Type**: Volcanic gravel
- **Size (mm)**: 8-15
- **Depth (m)**: 0.6

**Macrophytes**
- **Species**: Phragmites australis
- **Density (rhizomes /m²)**: 4
### Wetland characteristics: VF

<table>
<thead>
<tr>
<th>Constructed wetlands</th>
<th>Area (m²)</th>
<th>Flow rate (m³)</th>
<th>HLR (m³/m²/day)</th>
<th>Gravel</th>
<th>macrophytes</th>
<th>Density (rhizomes /m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF1 (II stage)</td>
<td>530</td>
<td>≈ 8÷10 m³ 6 times per day (every 4 hours)</td>
<td>≈ 0.09</td>
<td>Volcanic Sand</td>
<td>25-40</td>
<td>Cyperus Papyrus, Canna Indica L.</td>
</tr>
<tr>
<td>VF2 (III stage)</td>
<td></td>
<td></td>
<td></td>
<td>Volcanic Gravel</td>
<td>30</td>
<td>Iris pseudacorus</td>
</tr>
</tbody>
</table>

- **VF1 (II stage)**: Gravel type "Volcanic Sand" with a size of 5-15 mm and a depth of 45 cm; associated macrophytes include *Cyperus Papyrus* and *Canna Indica L.*
- **VF2 (III stage)**: Gravel type "Volcanic Gravel" with a size of 25-40 mm and a depth of 30 cm; associated macrophytes include *Typha latifolia* and *Iris pseudacorus*.
Methodology

REMOVAL PERFORMANCE AND CLOGGING INVESTIGATION OF AN HYBRID TREATMENT WETLAND IN MEDITERRANEAN AREA
Removal efficiency

- **Wastewater sampling period:**
  - from January 2015 - May 2017 at 30-day intervals

- **Wastewater sampling points:**

- **Wastewater analysis:**
  - physicochemical parameters (mg/L): TSS, BOD$_5$, COD, NH$_4$, P$_{tot}$
  - microbiological parameter (Ulog): *E. Coli, Salmonella*

Methodology

Legend
- 1: CWs inlet
- 2: HF outlet
- 3: VF$_1$ outlet
- 4: VF$_2$ outlet
Clogging investigation: HF unit - $K_s$ measurements

- **hydraulic conductivity at saturation ($K_s$) in situ**
- flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

**Methodology**

**Measurements:**
- **hydraulic conductivity** ($m \cdot d^{-1}$) was measured using the falling-head test method (NAVFAC, 1986, Pedescoll et al., 2009)
- 36 measurement points

**Monitoring campaigns:**
- 2016 – 2017
- one survey per year

![Diagram](image-url)

- 36 sampling points for hydraulic conductivity
- N. piezometers


Giuseppe Cirelli - 7th International Symposium for Wetland Pollutant Dynamics and Control (WETPOL), 21-25 August 2017, Montana, USA
Clogging investigation: HF unit - $K_s$ measurements

- hydraulic conductivity at saturation ($K_s$) measurements *in situ*
- flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

**In each point:** A steel tube was inserted into the wetted material and was filled with water in a pulse mode using a bucket. A pressure probe, connected to a laptop, measured and recorded automatically pressure variations proportional to the water column height.

A small hole was dug in the granular medium until the water level was reached.
Clogging investigation: HF unit - $K_s$ measurements

- hydraulic conductivity at saturation ($K_s$) measurements *in situ*
- flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

Combining the observed measurements and the geometric characteristics of the tube, **saturated hydraulic conductivity** ($K_s$) was determined according to Lefranc’s formula:

$$K_s = \frac{d^2 \ln \left(2L/d\right)}{8Lt} \ln \left(\frac{h_1}{h_2}\right)$$

- Diameter of permeameter
- Water height at time zero
- Water height at time $t$
- Length of the submerged part of the tube (perforated zone)
Clogging investigation: HF unit - tracer tests

- Hydraulic conductivity at saturation (Ks) measurements *in situ*
- Flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

- **Tracer:** 50 kg sodium chloride (NaCl) dissolved in 150 L

- **Measurements:**
  - *Electrical conductivity* (S·m⁻¹) was measured and recorded automatically by a probe with a data logger (Delta OHM-HD 2106.2) at the wetland outlet and in the piezometers
  - 10 measurement points

- **Monitoring campaigns:** 2016 – 2017 one tracer test per year
Residence Time Distribution (Levenspiel, 1972)

\[ \tau = \int_0^\infty t \cdot f(t) dt = \frac{\int t \cdot C(t) dt}{\int C(t) dt} \]

Actual residence times (first absolute moment)

\[ \sigma^2 = \int_0^\infty (t - \tau)^2 \cdot f(t) dt = \frac{\int (t - \tau)^2 \cdot C(t) dt}{\int C(t) dt} \]

variance (second absolute moment)

\[ \sigma_\theta^2 = \frac{\sigma^2}{\tau^2} \]

dimensionless variance

\[ f(t) = \frac{C(t)}{\int_0^\infty C(t) dt} \]
Dispersion Number (D) and hydraulic efficiency

- The equation for D (Dispersion Number) estimation, by trial and error, was:
  \[ \sigma^2_\theta = 2D - 2D^2 \left[ 1 - \exp\left( -\frac{1}{D} \right) \right] \]

- The hydraulic efficiency of wetlands (\(\lambda\)) was determined according to Persson et al. (1999)
  \[ \lambda = \frac{t_p}{HRT} \]
Clogging investigation: HF unit - ERT surveys

- Hydraulic conductivity at saturation ($K_s$) measurements *in situ*
- Flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

**Methodology**

- **Measurements:**
  - 168 superficial electrodes, spacing 10 cm, 2 m far from the inlet for a total length of 16.7 m
  - *electrical resistances* values (ohm, $\Omega$) were measured by a resistivity meter (dipole-dipole scheme) through electrical resistivity tomography technique (ERT, Binley and Kemna, 2005) and inverted to calculate the *electrical resistivity distribution* ($\Omega$ m)

- **Monitoring campaigns:**
  - 2017
  - two surveys (ERT1 and ERT2)

**Electrical resistivity distribution ($\Omega$ m)**

Clogging investigation: HF unit

- hydraulic conductivity at saturation ($K_s$) measurements *in situ*
- flow paths visualization by means of tracer tests
- 2-D electrical resistivity tomography (ERT) imaging

Setup of the HF unit with the indication of the measurements points

Legends:
- Red circles: 36 sampling points for hydraulic conductivity
- Black squares: 10 sampling points for tracer test
- Green lines: ERT lines (length of 16.7 m)
- Light grey squares: N. piezometers

HF unit setup diagram with measurement points labeled.
Results

REMOVAL PERFORMANCE AND CLOGGING INVESTIGATION OF AN HYBRID TREATMENT WETLAND IN MEDITERRANEAN AREA
hybrid CW performance

**Results**

Despite high variations of the influent pollutant concentration, the effluent concentration of the hybrid system remained low and stable.
hybrid CW performance

- the main part of BOD\(_5\), COD and TSS removal occurs in the 1st stage (HF)
- ammonification of N-org and the denitrification of the nitrates occurs effectively throughout the HF bed.
- the freshly formed ammonia is then almost completely oxidised by the two VF beds → high concentration of NO\(_3\) in the final effluent
- a progressive reduction in the concentrations of \textit{E. coli}: 1.8 Ulog decrease between the inlet and the HF outlet, and a further 1.0 Ulog and 1.2 decrease after VF1 and VF2 treatment
### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>WW Italian limits to discharge in surface water body</th>
<th>WW Italian limits for agriculture reuse</th>
<th>Hybrid CW out</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% samples under discharge limits</td>
<td>% samples under reuse limits</td>
<td></td>
</tr>
<tr>
<td>TSS</td>
<td>80 mg/L</td>
<td>10 mg/L</td>
<td>100</td>
</tr>
<tr>
<td>BOD₅</td>
<td>40 mg/L</td>
<td>20 mg/L</td>
<td>100</td>
</tr>
<tr>
<td>COD</td>
<td>160 mg/L</td>
<td>100 mg/L</td>
<td>100</td>
</tr>
<tr>
<td>NH₄</td>
<td>15 mg/L</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>NO₃</td>
<td>20 mg/L</td>
<td>-</td>
<td>41</td>
</tr>
<tr>
<td>NO₂</td>
<td>0.6 mg/L</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>TN</td>
<td>-</td>
<td>35</td>
<td>-</td>
</tr>
<tr>
<td>TP</td>
<td>10 mg/L</td>
<td>10 mg/L</td>
<td>100</td>
</tr>
<tr>
<td>E. coli</td>
<td>5000 UFC/100 mL (1)</td>
<td>50 UFC/100 mL (2)</td>
<td>100</td>
</tr>
</tbody>
</table>

(1) Recommended value for P.E > 2000;  
(2) Maximum value to be detected in 80% samples;  
(3) Maximum limit;  

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**Results**

In May 2017, after an hydraulic setup of feeding operation the limits for irrigation reuse were achieved on 100% of samples (DATA NOT SHOWN).
Clogging investigation: HF unit - $K_s$ measurements

Average saturated **hydraulic conductivity** values along the length of HF wetland in 2016 and 2017

- **Similar trend** to both surveys, $K_s$ values tend to increase from the inlet to the central part of the bed (e.g. about half of the unit length) and to decrease a little bit at the HF outlet;
- In 2017, a general sharp decrease in $K_s$ was observed respect to 2016.

\[ K_{s_{2016}} = 270.3 \pm 127.3 \text{ m/d} \]
\[ K_{s_{2017}} = 170.5 \pm 89.8 \text{ m/d} \]

In 2017 $K_s$ values at the **inlet zone** were about 1 order magnitude **lower** respect those of the other transects, as a consequence of clogging of the granular medium.

[Graph showing hydraulic conductivity values along the HF unit length for 2016 and 2017 transects]
Clogging investigation: HF unit – Tracer test

**Results**

<table>
<thead>
<tr>
<th>Bed characteristics</th>
<th>Moment analysis results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time (years)</td>
<td>Area (m²)</td>
</tr>
<tr>
<td>2016</td>
<td>2</td>
</tr>
<tr>
<td>2017</td>
<td>3</td>
</tr>
</tbody>
</table>

*Significant degree of deviation from PF, D > 0.025*

Good hydraulic efficiency as values are $0.5 \leq \lambda < 0.75$
Overall, ERT patterns in the two tests are very similar, although in ERT1 the resistivity values are higher on the surface and therefore indicate the presence of unsaturated zones (the first 15 cm) of the substrate. But these zones could be also “death zones” due to the clogging or the effect of water uptake by root apparatus. In the ERT2 test, the lower resistivity values indicate a greater presence of water and/or sediments.

May 19, 2017 (ERT1)

Mean electrical resistivity: 20.8 ± 7.5 Ohm m

July 14, 2017 (ERT2)

Mean electrical resistivity: 19.2 ± 4.6 Ohm m *
Clogging investigation: $K_s$ measurements

- 4 mobile baskets (28 cm in diameter, 30 cm in height and laterals with openings spaced at 0.5 x 0.5 cm) were inserted within a HF.
- They were filled with the same substrate and painted in the same way of HF and remained inserted in the wetland bed at the same height.
- They were positioned at 22 m from the inlet of the units since May 2017, then will be removed from wetland and will be taken to the laboratory for measurement of $k_s$.

Conclusions

- The hybrid constructed wetland (horizontal subsurface flow + vertical subsurface flow + vertical subsurface flow) system, built for the treatment of wastewater produced by IKEA in Catania, efficiently removed main pollutants and it has been able to manage the pollutant load and hydraulic peaks.

- The hybrid constructed wetland was able to achieve high disinfection level (up to 4 Ulog), satisfactory removal of organic content and suspend solid (up to 70%) and good nitrification level (80%).

- The design system tested has proven to be a reliable treatment for the decentralised wastewater treatment (wastewater discharge and irrigation reuse standards almost satisfied)

- The assessment of the clogging risk of the TW system, by methods based on Ks measurements, tracer tests and ERT provide useful information. But in some cases they don’t fit in the same direction. Some of these methods are “time consuming” and may cause some disturbance of the TW beds, the minimally invasive ERT techniques could be a valid alternative, however further investigations are needed.
Thank you for your attention!!!

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