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Hydraulic reliability of a horizontal wetland for wastewater treatment in Sicily

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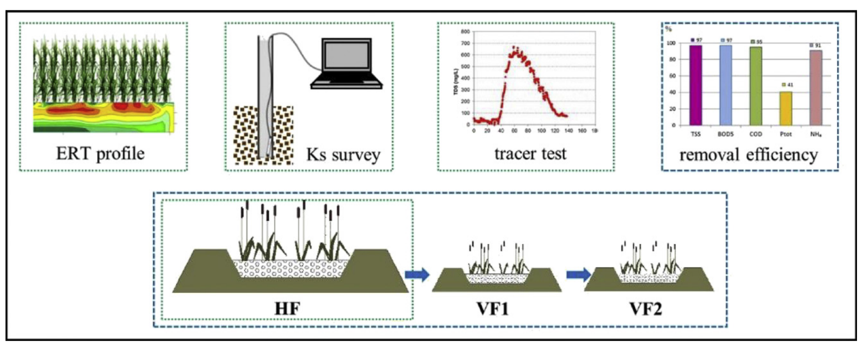
HIGHLIGHTS

- The wetland clogging was assessed by using traditional methods and geophysics.
- Partial clogging was identified by an integrated monitoring approach.
- Treatment reliability was not negatively affected by clogging.
- A hybrid wetland system was found reliable to treat civil wastewater.

GRAPHICAL ABSTRACT



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ABSTRACT

The purpose of this study was to evaluate how the hydraulic behavior of a horizontal subsurface wetland (HF), that is part of the hybrid wetland (hybrid-TW) of the IKEA® store in Eastern Sicily (Italy), influences the overall wastewater treatment performance. The HF unit experiences frequent overloading peaks due to the extreme variability in the number of visitors at the store, and after 2 years of operation it showed signals of partial clogging at the inlet area. The hydraulics of the HF unit has been monitored through measurements of hydraulic conductivity at saturation (Ks), tracer tests, and geophysical (*i.e.* electrical resistivity tomography—ERT) measurements carried out during the years 2016 and 2017. Results indicated a general good agreement between the performed measurement techniques, thus their combination, if adequately performed and calibrated, might be a reliable tool for detecting those wetland areas mainly affected by clogging conditions. The results also indicated that partial clogging had no significant effect on the quality of the discharged water.

1. Introduction

Effective wastewater (WW) management is essential for protecting public health, safeguarding the environment, adopting reuse strategies (Castorina et al., 2016; Angelakis, 2017; Salgot et al., 2017), and reducing the use of conventional water in agriculture (Toscano et al., 2013). WW treatment includes the use of centralized plants, which collect, treat, and discharge large amounts of effluent. Construction of these systems, which include large sewage collectors, are expensive and the costs are prohibitive in areas with low population density (Barbagallo et al., 2003; Barbagallo et al., 2012; Ye and Li, 2009).

In the last decade, decentralized WW treatment systems, such as treatment wetlands (TWs), have been increasingly used for small communities because of their low operation and maintenance requirements (Cirelli et al. 2007; Barbagallo et al. 2011). These decentralized

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treatment systems allow the collection, treatment, and disposal or reuse of effluent close to the WW point source (Massoud et al., 2009).

Thus, TWs are environmentally friendly systems that are now widely used to treat different type of WW with high range of organic and inorganic pollutants. TWs reduce these through a combination of physical and biochemical processes (Vymazal and Kröpfelová, 2008; Ávila et al., 2015). TWs are reliable, cost effective, and easily managed, and are therefore important options for small settlements, individual houses, and establishments (schools, shops, restaurants, hotels), especially when they are not connected to centralized sewage systems.

Recently developed hybrid-TW systems are now used to satisfy the more stringent standards for WW treatment processes, so that the effluent can be reused or discharged into public water bodies. These systems include various types of TWs (horizontal sub-surface flow, vertical subsurface flow, and free water surface flow) that are placed in series to increase the efficiency of the overall treatment process (Vymazal, 2005; Vymazal, 2011; Wu et al. 2014). However, clogging can reduce the life span of a TW (Barreto et al., 2015; García et al. 2016; Knowles et al., 2011; Stefanakis et al., 2014; Vymazal, 2018), mainly because of the reduction of hydraulic conductivity due to saturation of the TW porous media.

The biological, physical, and chemical treatment processes that occur in TWs may lead to a gradual clogging of the substrate, leading to hydraulic faults and/or reduced performance (Nivala et al., 2012). The process of clogging is inevitable due to sedimentation of suspended solids (SS) introduced with the water flow, biofilm formation in the filtering substrate, and invasion by plant roots (Vymazal, 2018). The traditional approaches used to monitor the extent and the impacts of clogging are measurements of hydraulic conductivity (Ks), tracer tests, and physical-chemical characterization of the clogging material. In general, Ks values are measured *in situ* to directly evaluate the severity of clogging. Tracer tests (using sodium chloride, rhodamine, or potassium bromide, fluoroscein) are used to monitor the effect of clogging on flow through the porous medium (Aiello et al. 2016). The major limitation of these two methods is the need for measurements at numerous time points. Furthermore, Ks measurements, which approximate the saturated hydraulic conductivity of the porous medium to the measured vertical conductivity, do not consider horizontal flow. In addition, a certain amount of compaction of the substrate occurs when inserting tubes used for Ks measurements (Pedescoll et al. 2011). Other disruptive methods performed on the clog permit quantification of the extent and nature of clogging in laboratory and/or *in situ*.

Despite the availability of different approaches, researchers have reported that no single method can provide comprehensive and quantitative assessments of clogging in TWs (Aiello et al., 2016; Nivala et al., 2012). Integrated approaches may therefore provide a better characterization of the complex hydrology and development of clogging in TWs. For example, Aiello et al. (2016) performed full-scale investigations of clogging phenomena in subsurface flow TWs by combining Ks measurements with quantification of clogging material and visualization of flow paths using tracer tests with NaCl. Other research used complementary *in situ* Ks measurements and rhodamine tracing experiments to evaluate the hydraulic conditions in a clogged TW used for tertiary WW treatment (Knowles et al. 2010). De Paoli and von Sperling (2013) characterized accumulated solids using hydraulic conductivity measurements at specific points, and compared planted and unplanted wetlands. Butterworth et al. (2016) compared the performance of four full-scale aerated horizontal flow TWs in terms of removal of ammonia, removal of solids, and hydraulic conductivity, by combining tracer tests with *in situ* measurements of Ks. However, all of the above-mentioned techniques are invasive, and involve some disturbance of the sample (Nivala et al., 2012).

Some limitations in the monitoring of clogging in TWs may be overcome by use of geophysical techniques, which rely on measurements of electric and electromagnetic properties of the porous medium. These methods are generally less disruptive than techniques that require sample extraction or taking the system offline. Moreover, geophysical surveys may provide information on a TW before clogging by detection of potential failures (Tapias et al., 2012). Recent research has shown that electrical resistivity tomography (ERT) is useful for investigation of the geometry of a subsurface flow TW, because it provides information on its internal structure, silting up, and clogging (Casas et al., 2012; Mahjoub et al., 2016). Therefore, use of ERT is a potentially effective approach for monitoring problems in TWs (Arjwech and Everett, 2015; Cassiani et al., 2006; Cassiani et al., 2015; Consoli et al., 2017; Vanella et al., 2018), such as evaluation of clogging, at high spatial resolution.

The study aims at: (i) evaluating the hydraulic performance of a horizontal sub-surface wetland (HF), part of the secondary hybrid-TW of the IKEA® retail store in Eastern Sicily (Italy), and (ii) observing any possible failure of the overall treatment efficiency at the hybrid TW due to the HF hydraulics behavior.

An evidence of partial clogging at the HF inlet (*e.g.* after two years of operation a progressive sludge matter deposition was detected) essentially motivated the study. The high fluctuation of customers visits at the store most probably caused an inadequate management of the existing conventional WW treatment system (*i.e.* sequential batch reactor—SBR). This was associated with an overloading of HF with untreated WW.

The hydraulics of the HF unit, accounting for partial clogging conditions, was therefore monitored by combining measurements of hydraulic conductivity at saturation (Ks) with the use of traditional tracer tests, and geophysical surveys (ERT).

2. Materials and methods

2.1. Hybrid-TW at the IKEA® store in Catania

The hybrid-TW system at the IKEA® store of Catania (Eastern Sicily, Italy; latitude 37° 26′ N, longitude 15° 01′ E, altitude 11 m a.s.l.) is the tertiary treatment unit for this store (Fig. 1).

It includes a screening system and a sequential batch reactor (SBR) (Fig. 2), as secondary treatment unit. This area of Sicily has a semi-arid climate, with average annual precipitation of about 500 mm, and the air temperature can reach 40 °C during summer. This SBR was designed for treatment of WW produced by toilets and the food area of the store. It has a maximum flow rate of 30 m^3 day^{-1} and a total nitrogen (TN) concentration of 135 mg L^{-1}. The screening unit and SBR operations started when the store opened in 2013.

The IKEA® Store in Catania opened in March 2013, employs 250 workers, has an average of about 6000 visitors per day, and up to 23,000 visitors on some days. The store has a wide shop space, bar, and restaurants, and has significant hydraulic and organic load variability during the day and year. In particular, during holidays, pre-holidays, and weekends, WW flow rate can be 2–4 times greater than that during normal working days, and NH_4 can be >200 mg L^{-1} on these busy days.

Due to these large fluctuations of organic load, the SBR system alone was inadequate as the sole treatment system. Thus, in August 2014 a hybrid-TW system that had 3 beds in series, was added. This hybrid-TW system is discontinuously fed. It was designed to receive 30 m^3 of daily effluent from the SBR and 20 m^3 of daily effluent from the screening unit, which bypasses the SBR unit during "overflow" (when the amount of WW exceeds the capacity of the SBR). In actual operation, the feeding phases did not match the design parameters. In fact, the incoming volumes ("total inflow") strictly followed the SBR discharge phase (related to overflow volumes), which occur during a few hours of the day (discharge peaks: 12.00–3.00 p.m. and 5.30–7.30 p.m.). From August 2014 to December 2015, the SBR discharge phase had 2 cycles per day; in 2016, to improve the feeding operation of the hybrid-TW system, it was modified to 3 cycles per day; in March 2017, it was modified again to 4 cycles per day by reducing the flow rate per hour. After the startup phase, the duration of SBR aeration was reduced, and this increased the sedimentation time and inactivated