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Research article

Oxygen profile and clogging in vertical flow sand filters for on-site wastewater treatment

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ABSTRACT

13 million people (about 20% of the population) use on-site wastewater treatment in France. Buried vertical sand filters are often built, especially when the soil permeability is not sufficient for septic tank effluent infiltration in undisturbed soil. Clogging is one of the main problems deteriorating the operation of vertical flow filters for wastewater treatment. The extent of clogging is not easily assessed, especially in buried vertical flow sand filters. We suggest examining two possible ways of detecting early clogging: (1) NH_4–N/NO_3–N outlet concentration ratio, and (2) oxygen measurement within the porous media. Two pilot-scale filters were equipped with probes for oxygen concentration measurements and samples were taken at different depths for pollutant characterization. Influent and effluent grab-samples were taken three times a week. The systems were operated using batch-feeding of septic tank effluent. Qualitative description of oxygen transfer processes under unclogged and clogged conditions is presented. NH_4–N outlet concentration appears to be useless for early clogging detection. However, NO_3–N outlet concentration and oxygen content allows us to diagnose the early clogging of the system.

1. Introduction

Vertical unsaturated subsurface flow filters are widely used for the treatment of wastewater, whether from individual houses or small communities. These unsaturated porous media provide bacteria with a growth substrate that makes these systems particularly robust to organic and hydraulic load variation. Furthermore, hydraulic and pollutant loads being low compared to those encountered in conventional treatment, passive aeration is usually sufficient to maintain aerobic conditions in the system. The oxygen demand is due to the aerobic degradation of reduced forms of carbon and nitrogen found in domestic wastewater. Former surveys on these systems highlighted very good rates of TSS (Total Suspended Solids) retention, oxidation of organic matter, and nitrification (e.g., Kadlec and Wallace, 2009).

The main cause of malfunction of vertical flow sand filters is clogging, which is the temporary or definitive reduction of their hydraulic conductivity. Severe cases reduce the efficiency of systems to the extent that treatment is no longer feasible. Clogging is due to the accumulation of suspended solids, chemical and bacterial growth products on or directly beneath (within the porous media) the surface of the filter. It is most important to understand that the processes involved in the development of clogging are precisely those required for wastewater treatment. Therefore it is not advisable to eliminate the causes of clogging, but rather to distinguish between normal operation and dysfunctional clogging.

Knowles et al. (2011) listed the main causes leading to clogging: (1) solid entrapment, linked to TSS retention; (2) biofilm growth, due to biological activity and hence to biodegradation; (3) vegetation growth, the effects of which have not yet been clearly identified; (4) chemical effects, that mainly consist of precipitation and adsorption.

Design and operational characteristics influence the occurrence of clogging: (1) wastewater characteristics (Winter and Goetz, 2003); (2) loading rates (Langergraber et al., 2003) and frequency (Molle et al., 2005); (3) media characteristics (Lowe and Siegrist, 2008); (4) inlet distribution system (Pavelic et al., 2011).

They also impact oxygen transfer in vertical flow filters. Indeed, the wastewater characteristics determine both oxygen demand and aerobic bacterial activity. The loading frequency affects the time available for diffusive fluxes through the surface of the filter. Media characteristics constrain transfer rates within the filter. Finally, the inlet distribution system influences the potential transfer of oxygen

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through the surface of the filter. Oxygen content in the filters is acknowledged to be an observable parameter linked to the clogging phenomenon (Rolland et al., 2009). However this relationship, depending on strongly interdependent physical and biological phenomena (Kayser and Kunst, 2005), is not well understood. For some authors, clogging leads to the reduction of the air-free fraction of the filter, which precludes gaseous oxygen transfer and thus aerobic activity (Platzer and Mauch, 1997). This phenomenon is called "physical clogging". For other authors, low oxygen concentrations in the filter are the result of high bacterial consumption (exceeding the filter's oxygen renewal capacity); the situation results in mineralization, eventually clogging the filter through the accumulation of biological matter (McKinley and Siegrist, 2010; Nevo and Mitchell, 1967). This phenomenon is called "biological clogging".

The problem of distinguishing between normal operation and dysfunctional clogging is particularly acute for systems that do not offer access to the surface of the filter, as it is the case for buried filters for onsite wastewater treatment. Consequently, clogging issues are often discovered late, when the system is completely blocked, leaving no other option than its replacement. In this paper, the authors suggest examining two possible ways of detecting dysfunctional clogging as early as possible: (1) NH_4–N/NO_3–N outlet concentration ratio. This ratio depends on the nitrification process occurring in the filter. Nitrification is very sensitive to oxygenation and its lack might be linked to clogging; (2) Direct measurement of oxygen content within the porous media. This information can be obtained by gas analysis of the filter's air phase (Platzer and Mauch, 1997; Rolland et al., 2009). A low value means that the filter might be encountering re-oxygenation problems depending on the degree of filter clogging.

A pilot-scale experimental study was conducted to evaluate these two ways of detecting clogging in vertical flow filters.

2. Material and methods

2.1. The pilot-scale filter

Fig. 1 shows the pilot-scale filter. It is a 1 m high column, with a surface area of 0.1 m^2 (36 cm diameter). This study is based on the assumption of one-dimensional flow in vertical filters: neither water nor solute transport in the horizontal plane is considered. The active layer (60 cm) is composed of 0–4 mm alluvial sand ($d_{10} = 0.16$ and CU = 0.3, fines < 3%). A 10 cm layer of 10–20 mm gravel covered the sand layer in order to ensure equal distribution of the effluent. A 10 cm layer of the same gravel was put underneath the sand layer in order to avoid sand particles transport. The lower end of the column consists in a perforated plate allowing the treated wastewater to seep out. Two columns were used to test the repeatability of the results.

The weights of the influent and effluent tanks, as well as the column masses, were monitored using scales (NOBEL, France). The uncertainty on weight was below 0.05% for their respective ranges (50–300 kg and 1–60 kg for the column and tank balances respectively). PT100 probes were used to measure the temperature in the core of the filter and in the influent tank. All data were recorded minute by minute, using a data logger (Gantner, Austria).

2.2. Optical oxygen probes

The filter was equipped with oxygen optical probes (PreSens, Germany), intended to measure the oxygen content in both its water and air phases (John and Huber, 2005). The principle of this type of measurement is the fluorescence extinction of a complex fixed in sol–gel when exposed to oxygen.

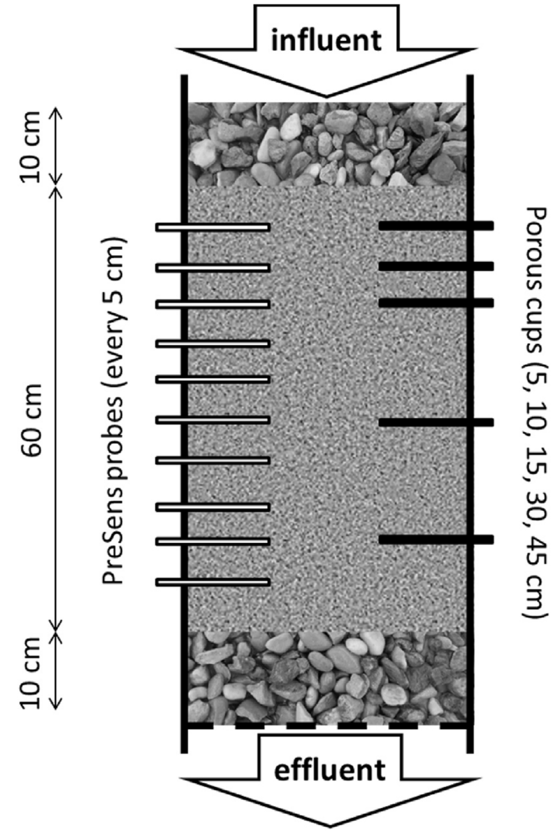

Fig. 1. Pilot-scale filter.

These probes are small, consume hardly any oxygen, have a response time of about one minute in water and excellent long-term stability (a few months of continuous operation without needing re-calibration). They have already been used successfully in sand filters by Turković and Fuchs (2010) and Wozniak et al. (2007).

However, proper measurement demands attention regarding the thermodynamic conditions near the probe (especially temperature, relative humidity, and gas-water oxygen concentration equilibrium). Indeed, the signal depends on temperature and is not continuously corrected as only manual correction is available. For the duration of all the experiments, the temperature in the columns varied between 20 °C and 24 °C. The sensors require constant water vapor-saturated conditions when the measurements are performed in an air phase. Finally, the measurements do not differ whether taken in the water or the air phase (both present in unsaturated porous media). Therefore, for the measurements to be taken into account in both phases, it was assumed that equilibrium between water and air oxygen concentrations (given by the Henry's law) was attained at all times. This last point increased the effective response time of the sensors when the concentrations in the two phases happened to be different, for instance due to the bacterial consumption in the water phase. This especially applies during highly transient phenomena occurring in vertical flow filters.

The oxygen concentrations are expressed as a percentage of the oxygen saturation, whether in the water or air phase. Oxygen content profiles are established from 10 measurements, using spatial linear interpolation.