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Influence of soil physical parameters on removal efficiency and hydraulic conductivity of vertical flow constructed wetlands

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ABSTRACT

Low cost filter materials for efficient waste water treatment in constructed wetlands are worldwide in demand. However, information on soil physical parameters needed for efficient treatment is scarce. We investigated 5 different lava and one fluviatile operating sand filters in Germany for their differences in pore size distribution spectra, specific inner surface area and cumulative pore volume. While these soil physical parameters did have an influence on purification capacity and hydraulic conductivity, differences in mineralogy (presence of zeolites), waste water distribution systems (baffle plates versus pipes) and loading rates were the dominating factors determining filter efficiency. Lava sands convince with high purification capacities during permanent loading rates of >100 mm d^{-1}, average loading rates of 20 g COD m^{-2} d^{-1} (chemical oxygen demand) and approximate effective loading rates of up to 250 g COD m^{-2} d^{-1}.

1. Introduction

Work and cost efficient waste water treatment is globally and regionally of crucial importance and might become one of the most demanding tasks in urban areas in many regions of the world in the near future (IPCC, 2007). The usefulness and suitability of constructed wetlands for waste water treatment have been increasingly recognized worldwide in recent years and have a more than five decade history in Europe (for overview see Vymazal, 2011; Knowles et al., 2011). The most common filter materials for constructed wetlands in the industrialized countries are fluviatile sands, because they are efficient filter materials, chemically relatively inert, connected to low costs and easily available. In Germany, constructed wetlands have a long history for more than hundred years (for an historic overview see Boerner et al., 1998, and Geller, 1997). Because vertical flow operated systems (Fig. 1) are generally less prone to clogging (due to a more uniform distribution of the waste water combined with intermittent loading resulting in alternating oxic and anoxic phases) than horizontal flow subsurface systems they became the more popular operating system in Germany (see review Knowles et al., 2011). After the official regulatory design guidelines were published in the late 1980s and 1990s (ATV, 1989, 1998), tens of thousands of constructed wetlands were built (mostly as reed bed soil filters) and operated successfully in different federal states of Germany. However, the commonly used fluviatile sand filters were criticized for their relatively short life span due to clogging (Blazejewski and Murat-Blazejewska, 1997; Engelmann et al., 2003, see an European comparison in Knowles et al., 2011), especially if connected to high organic loading (Winter and Goetz, 2001; Tuszynska and Obarska-Pempkowiak, 2008). The latter causes the need of sand renewal, which is connected to comparably high operational costs. The overall discussion resulted in new official regulatory design guidelines, which require considerably higher pre-filter elimination volumes (between 500 and 1,500 L PE^{-1} (PE = population equivalent)) and bigger surface areas of the filters (2.5–4 m^2 PE^{-1}) (DWA, 2006; FLL, 2008).

Generally, life span of sand filters are reported to exceed several decades (with an exception for phosphorous or heavy metal sorption in some of them but no decline in biological purification capacity), as long as loading rates of 80 mm d^{-1} are not exceeded (DWA, 2006). However, loading rates of ≤80 mm d^{-1} is often not sufficient for urban waste water treatment – especially

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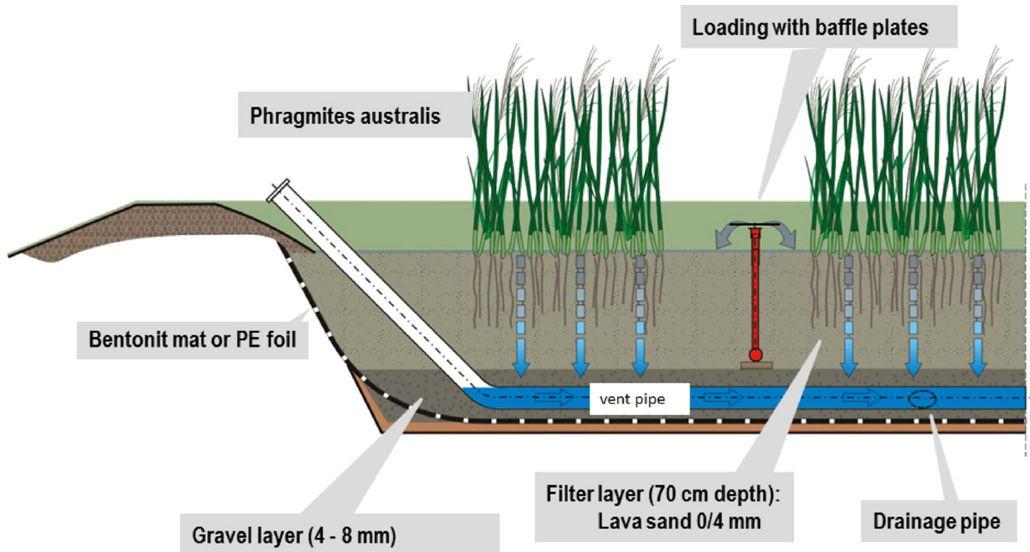

Fig. 1. Scheme of vertical flow constructed wetlands for the baffle plate type filters. Plants are *Phragmites autralis* planted with 4 plants per m^2.

for wastewater of mixed sewer systems – where only limited space is available and finances cannot afford a spacy filter design.

Lava sands with similar average pore sizes (0–4 mm) as the discussed fluviatile sands seemed to be the solution for the problem, since clogging was not observed even with a hydraulic loading of up to 225 mm d^{-1} (Hasselbach, 2013). Thus, with comparable or even better purification capacity, lava sands have a tenfold higher hydraulic conductivity compared to fluviatile sands (Bruch et al., 2011). As such, the Entsorgungsverband Saar (EVS), an association of interest of all 52 municipalities of the Saarland, one of the federal states of Germany, developed an official regulatory design approach for the waste water management with lava sands as filter materials (Drescher et al., 2007), which differs from the commonly used approach for fluviatile sands and allows higher loading rates.

Information on lava sands as filter materials in constructed wetlands is so far scarce in the international literature, despite their intriguing characteristics and capacities. Machate et al. (1999) find high removal rates of nitrate, nitrite as well as organic contaminants from contaminated groundwater in a lava sand filtered constructed wetland. Bruch et al. (2011) concluded that zeolites play a crucial role in improving the purification capacity of lava sand filters. However, suitability and purification capacity of lava sands have been discussed in the grey literature of Germany (e.g., Alfs and Reinhardt, 1999; Drescher and Hasselbach, 2010). But with the exception of Bruch et al. (2011), who investigated soil chemical parameters, none of the published studies on lava sands tried to scrutinize the material properties in search for a mechanistic understanding of removal efficiency and hydraulic properties.

The role of porosity and grain sizes in filter materials has been pointed out by Baeder-Bederski et al. (2004) when they compared sand filters to a mixture of sand-clay in constructed wetlands in Germany. The factors promoting or causing clogging have already been described several times in detail during the last four decades ranging from grain sizes, biofilm growth, vegetation growth, organic or inorganic accumulation of organic matter including microbial polysaccharides, accumulation of calcium–silica-gels, $CaCO_3$, suspended solids or soil colloids or the collapse of macro pores and operating systems (e.g. Nevo and Mitchell, 1967; de Vries, 1972; Blazejewski and Murat-Blazejewska, 1997; Pedescoll et al., 2011a; Knowles et al., 2011). However, even though the role of the pore sizes, the pore size distribution and the specific inner surface area has been acknowledged as important regulating factors, only de Vries (1972) actually gave information on these parameters. Even an intensive in depth review of the factors influencing clogging of constructed treatment wetlands on a European scale (Knowles et al., 2011), did not address the role of the above mentioned soil physical characteristics. The authors point out, that the dynamic mechanisms of clogging cannot be addressed at the moment, because the necessary detailed scientific studies are lacking (Knowles et al., 2011).

Very recent literature points again to the importance of soil physical parameters. In laboratory experiments, Harris et al. (2012) found that different genotypic and phenotypic structures of biological communities were reliably generated by the engineering of their physical environment in terms of structural complexity (as determined by particle size distribution and therefore pore size distribution). Theoretical consideration and modelling studies demonstrate that the heterogeneity of the pore-size distribution has a significant impact on bioavailability of contaminants while the heterogeneity of the biomass distribution only (Gharasoo et al., 2012) or the inclusion of plant roots oxygen release leads to minor effects (Samso and Garcia, 2013). Furthermore, the pore size distribution is crucial when it comes to porosity reduction due to bacteria growth and accumulation of particulate components (Giraldi et al., 2010). As such, soil physical parameters should play a crucial role for the purification capacity and longevity of constructed wetlands.

The aim of this study was to investigate the role of material porosity and Brunauer–Emmett–Teller specific inner surface area (BET) for the removal efficiency and hydraulic properties of sand filters. We compared three different lava sands within one constructed wetland (Riesweiler, Saarland) to study the influence of soil physical parameters on hydraulic conductivity. We further investigated the dependency of purification capacities of vertical flow constructed wetlands from soil physical parameters and different distribution systems of the filters at Riesweiler with those of two other lava sand filters (Medelsheim, near Gersheim and Büschdorf, near Perl, Saarland) and a fluviatile sand filter at St. Alban (near Alzey, Rhineland-Palatinate).

2. Sites

All constructed wetlands are used as municipal plants operating in vertical flow regime (Fig. 1) to treat wastewater of mixed sewer systems (please note that St. Alban and Büschdorf have a