The impact of sewage composition on the soil clogging phenomena of vertical flow constructed wetlands

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Abstract The infiltration rate and therefore the principal function of a sand based vertical flow constructed wetland (VFCW) is influenced by the content of suspended solids (SS) and chemical oxygen demand (COD) of the waste water supply. In this study there were three operating conditions defined as "No Clogging"; "Partly Clogging" and "Clogging". Investigations on 21 VFCWs approved analytical differences between these conditions. The content of SS and especially particles > 50 µm are considered to play a key role. These particles are of the same size as the pores in which seepage mainly occurs. Thus their potential for surface blocking is high. It is concluded that the construction and size of the primary settling has to ensure that the mean concentration of SS after settling does not exceed 100 mg l^{-1}. The results of this study indicate that the area of the VFCW should be designed for a maximum loading rate of 5 g m^{-2} d^{-1} and the COD load should not exceed 20 g m^{-2} d^{-1}.

Keywords COD; mass loading; particle distribution; soil clogging; subsurface flow constructed wetlands; suspended solids

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Introduction

A precondition for the function of a vertical flow constructed wetland (VFCW) is a sufficient hydraulic conductivity of the infiltration zone. Prolonged clogging leads to permanent ponding and to anaerobic conditions within VFCW. A general decrease of performance and especially of nitrification rate can be observed. The reasons for the reduction of the percolation rate can be very complex and there is no simple cause-and-effect chain. In literature several possibilities are discussed:

- Blocking of the pore space by deposition of organic and inorganic particles (Hill, 1983; Börner, 1992; Ellis and Aydin, 1995; Müller and Lützner, 1999; Nguyen, 2000)
- Precipitation and deposition of $CaCO_3$ (Baveye *et al.*, 1998; Blazejewski and Murat-Blazejewska, 1997)
- Clogging of the pores from microbial biomass (Kristiansen, 1981; Okubo and Matsumoto, 1983; Baake, 1985; Vandevivere and Baveye, 1992; Ronner and Wong, 1994; Bihan and Lessard, 2000)
- Root influence (Börner, 1992)
- Mechanical compaction of the soil (Otis, 1985; Kristiansen, 1982)
- Entrapped gas blocking the pores (Rice, 1974; Soares *et al.*, 1989)

The clogging phenomenon always occurs at the filter surface or at soil layer changes (Otis, 1985; Rice, 1974; Thomas *et al.*, 1966; Siegrist and Boyle, 1987; Platzer and Mauch, 1997).

This paper discusses the influence of the influent composition especially regarding the COD and SS content on the hydraulic properties of the filter bed. The composition of waste water of 21 VFCW in Germany was investigated. As told by the operators or taken from design documents the filter material of all constructed wetlands except one gravel bed filter was a coarse sand with $U = d_{60}/d_{10} \leq 5$ and $k_f \approx 10^{-4}$–10^{-3} m s^{-1} in accordance with the

German guideline (ATV A 262). The d_{10} were between 0.08 and 0.3 mm, except for the gravel filter where the d_{10} is unknown. The plants investigated had operation times from 2 to 8 years but in none of them was an aggregation of the sand observed. They all showed single grain texture. Primary settling was either done by multiple chamber tanks (14), Imhoff tanks (3), or by filtration through fabric material such as straw or reed (3). In one case there was direct charging on a gravel bed filter without primary settling. The distribution systems varied from fishbone structured pipes to circular structures with different densities. The effective surface area used for infiltration varies between the treatment plants.

The operating conditions were split into three different categories, depending on the observed area of ponding or building of puddles on the surface of the constructed wetland:

Clogging:	more than 80% of the surface is permanently ponded between two loads
Partly clogging:	between 30 and 80% of the surface is ponded between two loads
No clogging:	None or less than 30% of the surface is ponded between two loads

The classification into the three categories was subjectively done by walking across the filter beds and measuring the area ponded. Ponding of the surface directly after a loading cycle didn't bring the plant automatically into the category "Clogging". Therefore the ponding had to last until the next loading took place so that the soil air was disconnected from the oxygen supply.

Sampling and methods

Samples from influent were taken out of the pumping pit after primary settling by an automatic sampler every 5 minutes for 2 hours. The composite samples were stored at 4°C and parts of it kept frozen before analyses.

SS were separated by a cross flow filtration unit into three different size classes: 0.45–10 µm; 10–50 µm and >50 µm. It was necessary to filter 10 to 20 l to get a suitable amount for investigations. The SS were freeze-dried, weighed and analysed for C, N and volatile solids. The overall amount of SS was analysed in parallel by pressure filtration through a 0.45 µm filter according to DIN 38 409 –2. COD was determined from homogenised non-filtered sewage samples with standardised tests by photometry.

There are uncertainties in the calculation of the loading of the VFCWs. In 17of 21 treatment plants the hydraulic load was not measured directly or could not be calculated by pumping times. The hydraulic loading rates in these cases were taken from the data set which was estimated by Geller *et al.* (2002) based on a detailed evaluation of sites and documents.

Box and Whisker plots were used for statistical description of the data. The boxes represent the values of 50% of all results. The horizontal line indicates the median whereas the mean is shown as a cross. The whiskers mark the 1.5 interquartile ranges from the lower and upper quartiles. Values bigger than 1.5 and 3.0 times (crossed quadrate) of the 25% and 75% percentile are indicated as statistical outliers by little quadrates.

Results and discussion

Suspended solids

The soil clogging tendency is correlated with the concentration of total suspended solids (TSS) in the inflow. As shown in Figure 1, the concentration of TSS was lowest in the inflow of those treatment plants which did not show any clogging tendencies. Constructed wetlands with clogging or partly clogging phenomena were loaded with higher concentrations of TSS. Although there is an overlapping of the whiskers of non-clogging and clogging constructed wetlands, the classification of three different operating conditions is useful: non-clogging constructed wetland filters were characterised by low loading rates and low input concentrations, partly clogging filters also had low mass loading rates but higher input concentrations whereas clogging filters were charged with high concentrations as well as high loading rates.

Table 1 shows the composition of SS in the inflow of the investigated VFCWs. Generally the amount of SS is lower if measured with cross flow filtration compared to pressure filtration. Therefore the median values in Table 1 are slightly smaller than in Figure 1. The overall loading rate as well as the loading of particles > 50 μm is highest at constructed wetlands regularly showing clogging effects (Table 1). The high variation coefficients indicate that beside the particle loading other effects can also lead to soil clogging.

50 μm or bigger is the diameter of pores (wide coarse pores) in which percolation takes place. In pores of a size between 10–50 μm (narrow wide pores) only slow leaching occurs and pores smaller than 10 μm (medium and fine pores) hold water against gravity. Particles > 50 μm get filtered out at the surface and block the pore space which then leads to clogging. The wide coarse pore system is not a continuum. At narrows of the pore channels smaller particles also get filtered so that the pore space gets even smaller. Because of this sieving effect the pores at the surface can be blocked rapidly and the infiltration rate decreases. This leads to inundation so that the oxygen transport into the VFCW by diffusion and mass transport is disconnected. The biological degradation of the particulate organic carbon decreases and the state of clogging becomes stabilised.

In the inflow of clogging constructed wetlands the concentration of volatile solids and of organic carbon of SS tended to be lower whereas the C/N ratio was higher than with no clogging constructed wetlands (Table 2).

After primary settling only very fine (≤ 10 μm) and colloidal dissolved particles should be found within the inflow of the VFCW. High amounts of TSS as well as large concentrations of coarse particles and low volatile solids are a sign of insufficient primary settling. In the case of combined sewerage systems storm water can lead to high hydraulic and mass loads because of whirling up of sludge particles. The same happens if the sludge level is too high because of a lack of maintenance.

Table 1 Median load and variation coefficient of SS differentiated by operating conditions and size classes measured with cross flow filtration

Particle size	No clogging		Partly clogging		Clogging	
	Load [g m^{-2} d^{-1}]	Variation coefficient [%]	Load [g m^{-2} d^{-1}]	Variation coefficient [%]	Load [g m^{-2} d^{-1}]	Variation coefficient [%]
0.45–10 μm	1.5	94	1.6	54	4.3	61
10–50 μm	0.3	192	0.2	117	0.4	150
>50 μm	0.3	82	0.7	86	1.4	186
Summary	2.1		2.5		6.1	

Table 2 Median of volatile solids (VS), organic carbon (C), nitrogen composition (N) and CN ratio of the particles found in the influent of the investigated constructed wetlands

Particle size	No clogging				Partly clogging				Clogging			
	VS [%]	C [%]	N [%]	C/N [%]	VS [%]	C [%]	N [%]	C/N [%]	VS [%]	C [%]	N [%]	C/N [%]
0.45–10 μm	80	41.8	8.2	5.1	81	44.6	6.6	6.8	70	38.4	6.0	6.4
10–50 μm	67	29.3	4.6	6.4	58	29.1	3.3	8.8	64	25.0	4.0	6.25
>50 μm	64	31.6	4.6	6.9	69	31.0	3.3	9.4	59	25.6	2.6	9.8

COD

Vertical flow constructed wetlands with a clogging tendency were charged on average with higher COD values (Figure 2). This had to be expected because the COD usually correlates with TSS. The box of the COD concentration of the partly clogging constructed wetlands overlaps the boxes of the non-clogging and clogging filters even more than it does for TSS. Comparing the load of the partly clogging plants with the other operating conditions shows that these plants were charged with comparable loads to non-clogging plants. Again, only the concentration reached the dimensions of the clogging plants. Constructed wetlands tending to soil clogging got the highest COD load. High COD concentrations with low hydraulic load lead to short overloads and partial ponding occurs. When hydraulic loads are small the surface gets dry, pores open and oxygen supply rises. Thus the higher aerobic degradation leads to a hydraulic regeneration of the filter bed. The amount of total and dissolved organic carbon (TOC, DOC) of the inflow shows the same tendencies as the COD.

Areal mass loading

Investigations of constructed wetlands in Germany, Austria and Switzerland showed a mean COD load of 75 g per capita and day after primary settling (Geller *et al*., 2002). Resulting from different design and operating conditions a broad distribution of areal COD mass loading rates ranging from 2 to 50 g m^{-2} d^{-1} were found. The loading rates in this study always refer to overall surface area. It is likely that an alternating operation of several filter beds allows a higher load for one bed because accumulated organic substances can be degraded during resting periods. Only 3 of the investigated 21 VFCWs were run with alternating operation so that there was not enough data to study this influence. One of the 3 investigated VFCW with alternating operation had permanent clogging problems so that this operation modus alone does not prevent clogging.

In Figures 1 and 2 the difference between boxes of non-clogging and clogging constructed wetlands is significant. 75% of surveyed mass loading rates of the wetlands without clogging problems were below, and 75% of all the wetlands with clogging problems were above this transition zone of a COD load of 20 g m^{-2} d^{-1} and a TSS load of 5 g m^{-2} d^{-1}.

Elevated organic loads can cause oxygen deficits and organic matter accumulates in the filter bed which decreases the pore space (Müller and Lützner, 1999). High biological

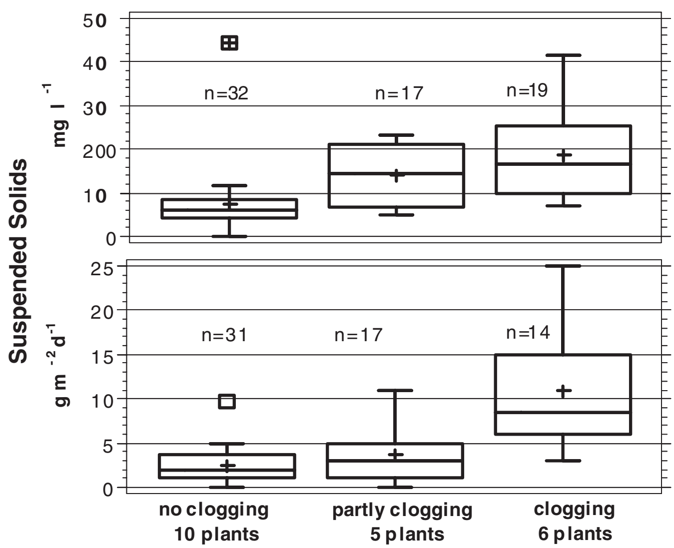

Figure 1 Inflow concentration and areal load of TSS differentiated by operating conditions measured with pressure filtration (n = number of samples)

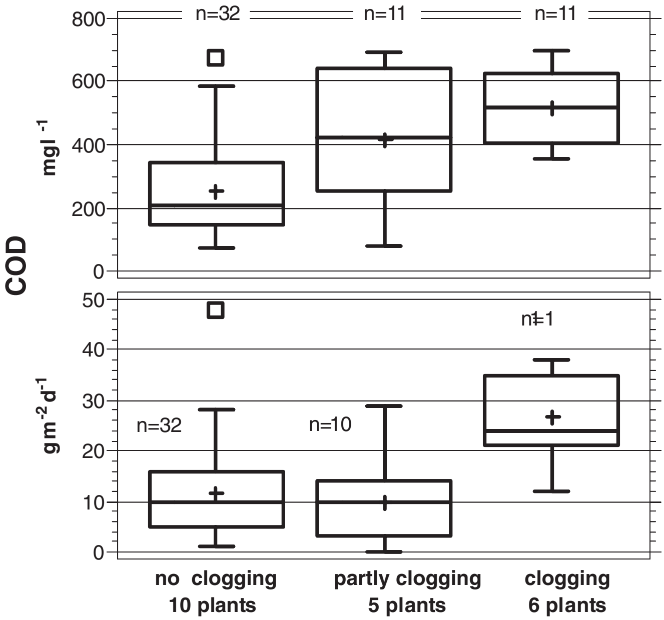

Figure 2 Concentration and load of COD differentiated by operating conditions (n = number of samples)

activity in combination with high organic loads may lead to an overproduction of voluminous extracellular polymer substances (EPS) which can also cause an effective pore blocking. Kristiansen (1982) suspected a relation between high SS loading and the growth of EPS.

Conclusions

The investigations on 21 VFCWs show that the waste water composition has a major effect on the clogging tendencies of the plants. VFCWs with clogging problems were charged with higher COD and TSS concentrations and loading rates.

The results of this study indicate that:

- An effective primary settling is a requirement for a trouble free run of a vertical flow constructed wetland system.
- The average concentration of TSS in the inflow should not exceed 100 mg l^{-1}. Especially particles > 50 μm can lead to surface blocking of the pores.
- The COD and TSS load should not exceed 20 g m^{-2} d^{-1} and 5 g m^{-2} d^{-1} respectively under the climatic conditions of Central Europe.

The clogging process is reversible. In order to prevent the system from long term clogging and in order to be more flexible it is useful to have at least 2 and preferably 4 filters so that, for example, 3 can be loaded while one is on rest (alternating loading). The length of the required resting period depends on the climate. It must last long enough to supply a sufficient oxygen amount in order to oxidise the black precipitation of iron sulfide which usually forms after a longer inundation. Iron sulfide itself does not lead to pore clogging but in this case it is an easy to control indicator.

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