DESIGN RECOMMENDATIONS FOR SUBSURFACE FLOW CONSTRUCTED WETLANDS FOR NITRIFICATION AND DENITRIFICATION

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ABSTRACT

The paper presents a design for nitrogen removal in subsurface flow wetlands. The nitrification in the vertical-flow beds (VFBs) is clearly determined by the oxygen balance in the filter. Full nitrification can only be achieved when the oxygen balance is positive. For sizing purposes equations for the calculation of oxygen demand and oxygen input are given. Three possibilities to achieve sufficient soil aeration are presented and explained.

For the denitrification two possibilities are presented. From technical wastewater treatment plants pre-denitrification is well known. Return rates up to 200 % can be used without hydraulic problems for the VFBs. In cases of low C/N ratios an additional application of HFBs has to be used. The design can be carried out using a design of 1 g NO_3-N/m²,d achieving a 65 % removal in more than 90 % of the cases.

The paper discusses some of the equations presented internationally. The suitability of the use of k-values for the processes nitrification and denitrification is especially questioned.

KEYWORDS

constructed wetland; denitrification; horizontal-flow bed; nitrification; subsurface flow; vertical-flow bed;

INTRODUCTION

After solving the problem of organic removal in subsurface flow wetlands (SFW), research for the last years has concentrated on finding dimensioning criteria for removal of nutrients.

This paper presents a preliminary sizing method for nitrification and denitrification, using a combination of vertical and horizontal-flow wetlands. The conclusions are drawn from a three year monitoring period at two SFWs. The idea was to combine the advantages of vertical-flow beds (VFBs) with those of the horizontal-flow beds (HFBs). The VFBs do have a very high nitrification capacity whereas the HFBs show very efficient denitrification even at low C/N ratios.

DESCRIPTION OF PLANTS

The research plants are described elsewhere, for detailed description see Platzer (1996). They were designed for 150 p.e. (plant at Ließen) and 300 p.e. (plant at Merzdorf). The design of the reed beds is almost the same in both plants (Figure 1).

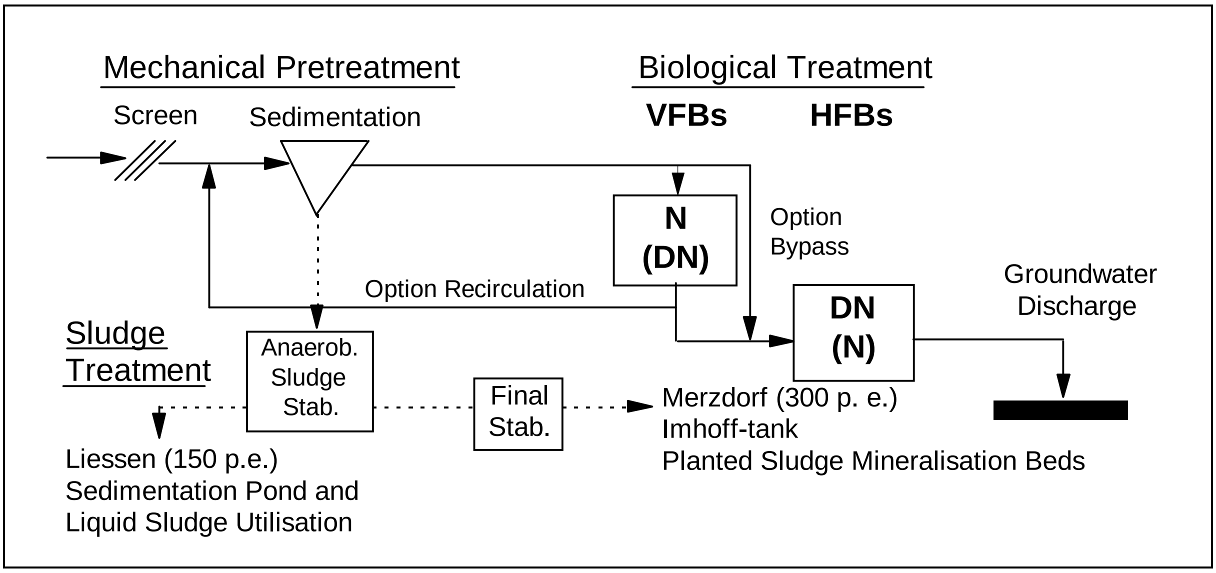

Figure 1: Flow scheme of the treatment plants

The vertical-flow beds (VFBs) in both plants consisted of 10 beds. The beds had a depth of 1 m and were filled with various types of sand. The characterization of the soils used is described in Platzer & Mauch (1997). The recommendations in this paper refer to results obtained on middle-coarse sands (d_{10}= 0,1-0,2 mm, uniformity U = 4, hydraulic capacity 1-4*10^{-4} m/s)

Since the horizontal-flow beds (HFBs) main task is the removal of N_{tot}, the beds were designed to have as little oxygen input as possible. For this reason the beds were fully dammed up. The hydraulic dimensioning was done according to Darcy´s law, resulting in a bed length of 6.2 m. Due to the short distance no bottom or top gradient was used and water movement was achieved by the hydraulic gradient, which is less than 10 cm. Each plant consisted of four (Ließen (Li)) or five (Merzdorf (Me)) HFBs.

All beds were planted with *Phragmites australis*.

METHODS

Wastewater concentrations and mass balance: Methods and gaining of results are described in Platzer (1996).

O_2 and CO_2 contents in the soil air: For measuring O_2 and CO_2 contents in the soil air a method of our own was developed. The samples are taken out of the soil at depths of 10, 30 and 50 cm using high-grade steel pipes of 5 mm diameter. In order not to influence the soil air balance the volume taken out has to be kept as small as possible. The experiments showed that a volume of 0.5 liter is sufficient for the analysis. For the analysis of the O_2-content a conventional oxygen electrode (WTW Oxi 96) for the measurement of oxygen in water is used, which was first tested for the application in air.

Calculation of the diffusion coefficient: As no method for the calculation of diffusion into a filter loaded with wastewater was available, amethod of our own was developed. The filter was taken out of operation after a last application of wastewater and only loaded again, when the oxygen concentrations in the soil reached 80 % of a bed which was out of operation more than 4 month. The oxygen concentrations of the soil air were measured in short time lags. The change in concentration over time and soil depth allowed the estimation of a diffusion coefficient directly in the beds using the 1. Fick's law. For a period of two days after the last wastewater application the changing soil moisture and the biological activity did not allow a reliable calculation of diffusion coefficients. This period was not taken into account.

RESULTS

The results of the VFBs in the monitoring program showed an almost complete nitrification using loadings below 6.5 g TKN/m²,d (figure 1, results of Liessen < 6.5 g TKN/m²,d in Platzer 1996) and guaranteeing a sufficient oxygen supply. In 95 % of the samples the effluent concentrations were below 10 mg NH_4-N/l. When using much higher concentrations but almost the same TKN loadings, nitrification was incomplete (Figure 1, results of Merzdorf > 10 °C in Platzer 1996).

In order to achieve complete nitrification the oxygen demand and the oxygen input have to be calculated. Therefore experiments concerning the Oxygen input (OI) were carried out.

Oxygen input paths

The oxygen input in VFBs consists of 3 main input paths:

- Input by convection
- Input over rhizomes (in our experiments included in the input by diffusion)
- Input by diffusion

Input by convection

Convection transport of gas results from a gradient of air pressures in the soil. In VFBs this gradient is a result of the effluent water which creates a vacuum which is equalized by air or wastewater.

If the time between beginning of application of wastewater and complete infiltration is short, the applied volume equals the volume of air entering the soil. The process was described in Platzer & Mauch (1997). As air contains about 300 mg O_2/l the oxygen input by convection can be calculated by multiplying the volume of applied water with the concentration of oxygen.

Input by diffusion

Especially using low hydraulic loadings or very high concentrations the oxygen input by diffusion plays an important role for the oxygen balance in the soil.

The influence of OI by diffusion for wastewater treatment in SFS is sometimes not mentioned (Bahlo 1997, Green et al. 1996) and sometimes evaluated as the principal process (Guilloteau et al. 1993, Schwager & Boller 1997). Up to now no equation for the calculation of OI by diffusion for the application in wastewater has been published. For soil without wastewater application several models for the calculation of diffusion rates were published. The comparison of these models with the soil parameters used in the research plants led to a wide range of diffusion coefficients of $2 \cdot 10^{-3} – 6{,}5 \cdot 10^{-3}$ cm²/s.

The own experiments lead to an estimation of $3,5 \cdot 10^{-3}$ cm²/s for the diffusion coefficient (Figure 2).

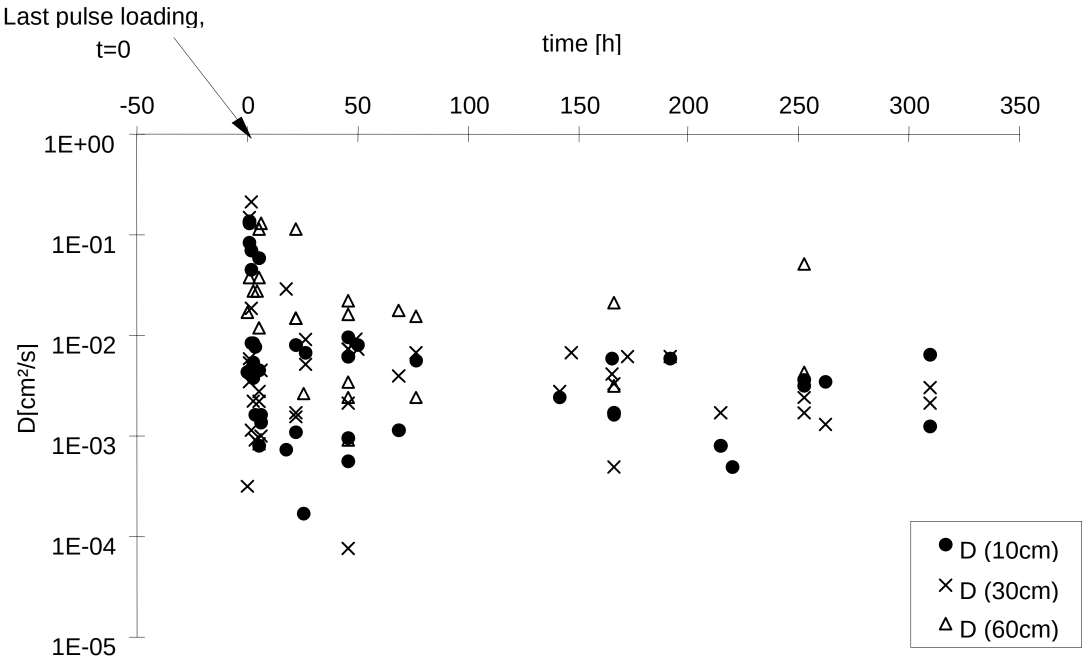

Figure 2 Diffusion coefficients (D_b) in dependence of time after the last loading at various depth (plant of Liessen) (Kubin 1997)

Out of these coefficients a transfer rate was calculated using the 1. Fick's law which resulted in 1 gO_2/m^2,h. It has to be taken into account that the diffusion rate is very dependent on the soil used. As the sand used was relatively fine (d_{10}= 0,11 mm), it can be expected that the use of the rate reported above does not overestimate the input by diffusion as long as the used sand is coarser.

DISCUSSION OF DIMENSIONING PROPOSALS OF OTHER AUTHORS

The number of available dimensioning proposals for nitrification and denitrification is limited. Most of the authors give a certain value using m²/p.e. or m³ /p.e., others use the ”Kickuth Equation” and k-values not only for organic removal but as well for nitrification and denitrification (Sikora et al. 1994, Hosomi et al. 1995).

The parameter m²/p.e. does not include sufficient information. Every country has its own values for hydraulic, organic and nutrient load/p.e., but dimensioning for nitrification and denitrification has to differentiate between these parameters. Highly concentrated water has to be treated differently from wastewater with low concentrations.

For VFBs the parameter m³/p.e. is not correct. The main degradation of substances takes part in the upper 20 cm of a bed (Felde,v. & Kunst 1996, Platzer 1998). It is of no importance whether a bed has a depth of 0.8 m or 1.6 m although the volume has doubled.

The use of k-values for the description of nitrification is very questionable. The ”Kickuth Equation”, developed out of the Monod kinetics, was developed for reactions of 1st order. As the nitrification process in conventional wastewater treatment is usually of zero order, the Equation can not be used. Furthermore the extreme simplification of the Monod kinetics into one parameter has to be questioned. The k-value implies kinetic parameters (maximum growth of bacteria, yield coefficient) planning parameters (soil substrate, pore volume, bed depth) and operational parameters (temperature, oxygen supply). Therefore every plant has its ”own” k-value, which is not very helpful for dimensioning purposes.

Bahlo (1997) published a dimensioning proposal using a maximum load for each parameter in g/m³ bed volume. The proposal is interesting but the parameter g/m³ is not very helpful (see above). As the results were gained at relatively low concentrated wastewater, the conclusions drawn can not be transferred to highly concentrated wastewater.

DIMENSIONING PROPOSAL FOR NITROGEN ELIMINATION

The dimensioning proposal presented in this paper, is based on the most influential parameters for nitrification and denitrification in SFWs. The dimensioning is valid for effluent temperatures above 10°C, whereas good removal can still be expected at lower temperatures.

DIMENSIONING FOR NITRIFICATION

The monitoring results showed that fully nitrification can only be achieved in VFBs. A good nitrification in horizontal-flow beds (HFBs) is possible but the necessary bed area is usually extremely large as the maximum load in order to achieve nitrification should not exceed 0.2 g TKN/m²,d (Platzer 1998). Therefore VFBs will be chosen for economic reasons.

In order to achieve complete nitrification the oxygen demand and the oxygen input have to be calculated.

Calculation of oxygen demand

The oxygen demand is the sum of oxygen demand (OD) for decomposition of organic material and OD for nitrification. I here used the COD to calculate the OD for organic decomposition and took the results reported by Sengewein (1989). He calculated an OD of 0.7 g O_2/g COD. In our experiments the purification efficiency in the VFBs for COD was about 85 %.

From the results of Wiesmann (1994) the OD for nitrification is calculated with 4.3 g O_2/g TKN.

As the VFBs show a denitrification capacity of at least 10 % (up to 30 %), the recovery of oxygen from denitrification was calculated with 2.9 g O_2/g NO_3-$N_{denitrified}$. In cases of wastewater with very low organic load this term has to be omitted.

The complete oxygen demand results in Equation (1)

$$\text{Oxygen demand (OD)}_{[g/d]} = (0.85 \cdot 0.7 \cdot CSB_{inf\,[g/d]} + 4.3 \cdot TKN_{inf\,[g/d]} - 0.1 \cdot 2.9 \cdot TKN_{inf\,[g/d]} \qquad (1)$$

Calculation of oxygen input

The oxygen input (OI) in VFBs is the sum of input by diffusion and convection.

The OI by diffusion is calculated as described above with 1 g O_2/m².h. The time of water saturation after pulse loading a bed has to be subtracted from the time between two pulses. OI by diffusion can not take place in this period of about 1.5 hours after each loading (see Figure 1, Platzer & Mauch 1997). Therefore the maximum input by diffusion is dependent by the number of loadings. For example 8 loadings /d lead to a maximum time for diffusion of 12 h / d and therefore to 12 g $O_2/m^2.d$. The input by diffusion can be calculated with Equation 2.

OI by diffusion $_{[g/d]}$ = 1 $_{[g\ O_2/(h\cdot m^2)]}$ · bed area $_{[m^2]}$ · (24 $_{[h]}$ – 1.5 $_{[h]}$ · number of loadings) (2)

The OI by convection is calculated by the hydraulic load. For short periods of application and infiltration (< 10 min) it can be calculated that each liter of wastewater leaving the filter causes a suction of 1 liter of air into the soil. As the air contains 300 mg O_2/l, the input by convection can be calculated easily (Equation 3)

OI by convection $_{[g/d]}$ = 0.3 $_{[g\ O_2/l]}$ · volume of water applied $_{[m^3/d]}$ ·1000 $_{[l/m^3]}$ (3)

It has to be taken into account, that this equation can not be used if application and infiltration last over a longer period. In this case the wastewater leaving the filter during application has to be subtracted from the total water applied.

Dimensioning criterion

The resulting dimensioning criterion is expressed in Equation 4. The total oxygen input has to higher than the oxygen demand.

OI by diffusion + OI by convection – OD > 0 $_{[g/d]}$ (4)

In cases of negative result the possible options to enhance the oxygen input are:

- Reduction of the number of loadings. An optimal number of loadings are 2-3 applications a day.
- Enlargement of the bed size. This can by a good choice in cases of highly concentrated wastewaters, but usually in combination with the following,
- Installation of a wastewater recirculation. By this the input by convection rises directly with the amount of water recirculated.

Currently an upper limit of 6.5 g TKN $/m^2$,d should not be exceeded. This limitation has to be seen in combination with a reasonable organic load. Cooper et al. (1996) reported good results with loadings up to 48 g NH_4-N/m^2,d (three beds in rest) in tertiary treatment with BOD_5 influent concentrations below 30 mg/l.

In our experiments the hydraulic load was not limiting up to 250 mm/d.

DIMENSIONING FOR DENITRIFICATION

Denitrification in SSF can be achieved by two methods. In VFBs it is recommendable to use a recirculation into the primary treatment as a pre-denitrification. In cases of higher requirements it is necessary to add an HFB as an postdenitrification.

Pre-denitrification

Using a pre-denitrification for VFBs a sufficient high contact time of wastewater and biomass of denitrifiers has to be guaranteed. In this case the pre-denitrification in VFBs can be dimensioned as the classic pre-denitrification process in activated sludge plants (Equation 5).

$$n_{DN} = 1 - 1/(1+RV) \qquad (5)$$

RV = recirculation rate in relation to the influent volume
n_{DN} = elimination rate for nitrogen

This process was tested for septic tanks by Bahlo (1997), Laber et al. (1996) and Rustige (1997). Up to recirculation rates of 200 % the process was successful.

Schleypen (1993) and the Bayrische Landesamt (1996) proved the applicability of ponds as a method for pre-denitrification.

In cases of high strength wastewaters concerning nitrogen, the use of a pre-denitrification is not sufficient. The recirculation rates exceed 200 % and often the C/N ratio is not sufficient. In this case the pre-denitrification has to be combined with an post-denitrification.

Post-denitrification

The dimensioning of an post-denitrification in HFBs is very simple. The results of the HFBs showed an elimination of 80% for nitrified nitrogen. These results were achieved as well at very low C/N ratios (< 0.7) (Platzer 1996).

The transformation of these results into a dimensioning proposal by statistical means leads to a 65 % removal in 90 % of the cases. As the loadings during research did not exceed 1 g N/m²,d, no recommendation can be given for higher loadings.

For dimensioning purposes an elimination of 0.65 gN/m².d with a load of 1 gN/m².d has to be calculated. Therefore the $N_{nitrified}$ in g in the influent of the HFB equals the necessary area in square meters (Equation6).

$$\text{Necessary bed area } [m^2] = \text{influent } N_{tot}\text{-load to the HFB } [g/d] \,/\, 1\ [g/(m^2 \cdot d)] \qquad (6)$$

From the results of Wang et al. (1996) the hydraulic load should not be critical as long as the detention time in the HFBs is not shorter than 24 hours.

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