DEVELOPMENT OF REED BED SYSTEMS

- A EUROPEAN PERSPECTIVE

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ABSTRACT

Nowadays subsurface flow wetlands (SSFW) are a common alternative in Europe for the treatment of wastewater in rural areas. Mainly in the last 10 to 12 years there has been a significant growth in number and size of the systems in use. This paper presents general considerations for SSFW, giving additional information about the principal systems of vertical and horizontal flow wetlands. Special attention is drawn to the removal of nutrients. For this purpose are mentioned various combined systems. One part of the paper discusses the problems of modeling SSFW. Finally sludge mineralization beds, a special form of constructed wetlands, are explained.

KEYWORDS

constructed wetland; denitrification; horizontal-flow bed; nitrification; subsurface flow; vertical-flow bed; sludge mineralization bed, modeling

INTRODUCTION

The principal development of Reed bed systems in Europe begun in the late 60th as a means of secondary wastewater treatment for rural areas. Since than a large variety of design lines has been established. Especially in the last 10 to 12 years there has been a significant interest in reed beds. This paper does not review the historical development. The aim of this paper is to present the main ideas of development in the last years and some promising approaches to the problem of secondary wastewater treatment in constructed wetlands in Europe.

Talking about constructed wetlands it is necessary to keep in mind that over 95% of the constructed wetlands in Europe are subsurface flow wetlands (SSFB). Therefore this paper does not refer to surface flow wetlands. It is to be expected that the total number of SSFB in Europe exceeds 10.000 plants, of which more than 90% are in a size range of 4 to 10 pe. After solving the problem of the removal of organic compounds in SSFB, research in the last years has concentrated on finding dimensioning criteria for nutrient removal.

GENERAL CLASSIFICATION

Among the SFFBs does exist a wide range of lines of development:

- direction of flow: horizontal flow, vertical downflow, (vertical upflow)
- type of material for filtration: gravel, sand, sand-soil mix, (soil)
- design approach: m²/pe; Organic load/m²,d; TKN-load/m²,d; mm/d; oxygen consumption and input; load (organic or nutrients)/ m³,d

The main type of wetland applied in a certain country varies widely depending on the country in Europe and their main lines of development.

There are some general considerations about planning wetlands, which have been developed over the years (none of them accepted by all plant designers):

- The substrate used should not contain loam, silt or other fine material, nor should it consist of material with sharp edges.
- The substrate used in general is sand with a hydraulic capacity (k_f-value) of about 10^{-4} to 10^{-3} m/s
- The SSFBs have to have a uniform distribution of the wastewater in the inlet area).
- A sufficient hydraulic capacity of the beds has to be proven by application of Darcy´s law or other appropriate methods of calculation.
- The surface of the beds should be flat to omit unequal distribution or surface run off.
- Short circuits have to be avoided.
- Plants do play an important role in reed beds, but the purification process is a combination of microbial degradation and chemical processes.
- Phragmites communis (common reed) is the most used plant because of its characteristics of subsurface biomass growth and strong resistance against diseases.
- Basic design of SSFB has to take into account suspended solids and organic load.
- SSFBs considering nitrification and denitrification have to be designed using oxygen consumption, soil aeration, and availability of carbon source as additional criteria.
- Many SSFB do present a high efficiency for phosphorous removal but a general design for phosphorous removal has not yet been developed.
- The use of k-values for the description of nutrient removal is incorrect. The ”Kickuth Equation”, based on the Monod kinetics, was developed for reactions of 1st order. As the nitrification process in conventional wastewater treatment is usually of zero order, this equation cannot be used. 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.

Besides the development of horizontal or vertical flow wetlands for wastewater treatment, the use of wetlands for sludge treatment has been very successful in Europe. Some special design lines offer the retention of microbiological organisms in constructed wetlands, the treatment of agricultural wastewater, treatment of some kinds of industrial wastewater, and the control of diffuse pollution.

HORIZONTAL FLOW BEDS (HFB)

As the strong development of SSFB was based on the application of HFBs, these are still the most applied plants. In the beginning HFBs showed some problems with surface run off and therefore poor purification results, but nowadays well-designed HFBs are widely accepted as a robust and low maintenance treatment system for secondary wastewater. The size of the beds is about 5 – 10 m²/pe.

Some special design considerations for HFB are:

- Do not plan a slope on top in order to avoid short circuits.
- As the hydraulic capacity is limited, special attention has to be paid to proper hydraulic dimensioning. Due to this fact a bed length of more than 15 m is uncommon in Germany, other design lines use lengths up to 25 m.
- A bed width above 30 m is critical for uniform distribution.
- The inlet zone is the critical point for the proper functioning of HFBs, therefore special attention is needed to prevent surface run off.
- In order to control weed growth it is recommendable to have the possibility to dam up the beds completely.
- In order to guarantee a sufficient aeration of the bed it is recommendable to have the possibility to lower the water level to the bottom of the HFB.
- The oxygen transport into HFB is limited; therefore nitrification in HFBs is often poor.
- Denitrification in HFBs is very efficient, even at very low C/N ratios.

The experiences made by Green et al. (1998) in Great Britain concerning the application of HFBs played a very important role for the development of HFBs for tertiary treatment and stormwater treatment. HFBs for this purpose are built using mainly gravel as filter material.

Especially in locations without energy and low hydraulic gradients, the HFBs are recommendable for basic purification purposes. , but they do occupy larger areas than VFBs. As tertiary treatment they offer the possibility of post-denitrification without addition of an external carbon source. However, HFBs occupy larger areas than VFBs.

VERTICAL FLOW BEDS (VFBs)

The development of VFBs has been very strong since the publication of first results at IAWQ conference in Cambridge (Cooper & Findlater, 1990). Due to their high purification capacity concerning organic load and nitrification VFBs were a kind of “top of the art” during the last years. Being operated properly the beds proved to have very high purification rates (Cooper et al., 1996; Platzer, 1996; Felde v. & Kunst, 1996; Bahlo, 1997). But designing these systems it has to be considered that this type of bed has its limitations as well, which have to be taken into account. The still widely used dimensioning by m²/pe is not sufficient.

An extremely important aspect of VFBs is the potential risk of soil clogging which provokes a general failure of the system. At first only a few authors reported about this (Cooper & Green 1994; Platzer & Mauch, 1996). Currently there are various research projects in Germany concerning this aspect (i.e. Goetz & Winter, 2000). The experiences with these beds are differing widely and due to the various lines of dimensioning, it is difficult to formulate general considerations. Therefore the following considerations have to be seen as a proposal for such considerations:

- The main factor for the proper functioning of VFBs is a sufficient soil aeration.
- VFB have to be loaded intermittently in order to provoke soil aeration.
- A uniform distribution of the wastewater is indispensable for good results.
- In order to guarantee soil aeration, soil clogging of the beds has to be avoided.
- The organic load should be limited to avoid soil clogging (25 g COD/m², d)
- The plants play a very important role in maintaining and restoring soil conductivity.
- A treatment plant with VFBs should use at least 4 beds in order to be able to rest the beds on a regular basis (i.e. 6 weeks in operation and 2 weeks of rest).
- To achieve nitrification a calculation of oxygen consumption and input is indispensable.
- The use of gravel in VFB for secondary wastewater treatment is not recommendable due to short cuts in the filter.

Concerning nitrification in VFBs the experiences by Cooper et al. (1996) were very important. They reported good nitrification results with very high ammonia loading up to 48 g NH_4-N/m²,d (three beds in rest) in tertiary treatment with BOD_5 influent concentrations below 30 mg/l. Unfortunately the experimental site was operated only a couple of years, therefore there is a lack of information about long-term performance with these loads. Based on these experiments and theoretical approaches Cooper (1998) developed a dimensioning for nitrification in VFBs. It is based on oxygen demand. A similar approach was developed by Platzer (1998) combining his results concerning oxygen demand with his results concerning soil aeration in order to carry out an oxygen balance. In his experiments with secondary wastewater he did not exceed a limit of 6.5 g TKN/m²,d and a reasonable organic load. In order to achieve complete nitrification the oxygen demand and the oxygen input have to be calculated. The total oxygen input (OI) has to be higher than the oxygen demand (OD). The resulting dimensioning criterion is fairly simple. It is expressed in Equation 1.

$$\text{OI by diffusion} + \text{OI by convection} - \text{OD} > 0 \text{ [g/d]} \qquad (1)$$

The oxygen demand results in Equation (2)

$$\text{Oxygen demand (OD) [g/d]} = (0.85 \cdot 0.7 \cdot \text{CSBinf [g/d]} + 4.3 \cdot \text{TKNinf [g/d]} - 0.1 \cdot 2.9 \cdot \text{TKNinf [g/d]} \qquad (2)$$

The equation is based on a COD removal of 85 % with an oxygen consumption of 0.7 g O_2/g COD. For nitrificaion the OD is calculated with 4.3 g O_2/g TKN. Recovery of oxygen from denitrification was calculated with 2.9 g O_2/g NO_3-$N_{denitrified}$ assuming a denitrification of 10%. In cases of wastewater with very low organic load this term has to be omitted.

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

The input by diffusion can be calculated with Equation 3.

OI by diffusion [g/d] = 1 [g O_2/(h·m²)] · bed area [m²] · (24 [h] – 1.5 [h] · number of loadings) (3)

Due to experiments the OI by diffusion is calculated with 1 g O_2/m².h. OI by diffusion can not take place in a period of about 1.5 hours after each puls loading of the bed. This time of water saturation after a pulse loading has to be subtracted from the time between two pulses. Therefore the maximum input by diffusion depends on the number of loadings.

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 4)

OI by convection [g/d] = 0.3 [g O_2/l] · volume of water applied [m³/d] ·1000 [l/m³] (4)

It has to be taken into account that this equation can not be used if application and infiltration take place over longer periods of time. In this case the wastewater leaving the filter during application has to be subtracted from the total water applied.

HYBRID SYSTEMS

With rising interest in nitrogen removal there has been a growing interest in combined or hybrid systems. In these systems the advantages and disadvantages of HFB and VFB can be combined to complement each other. Some design approaches have been made using such combinations.

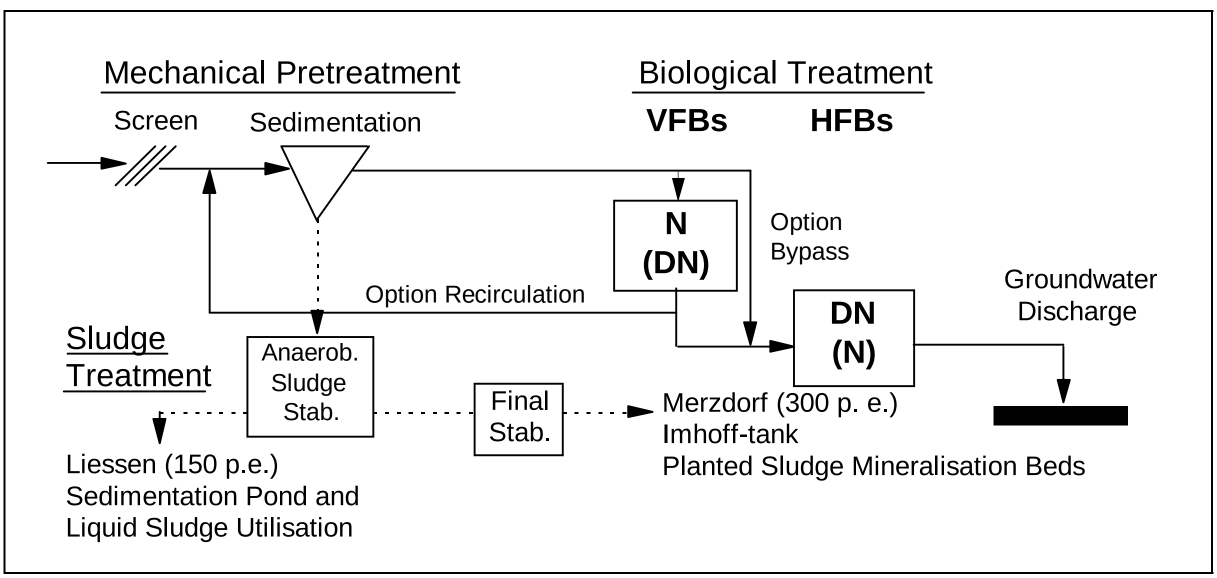

Figure 1:Flow scheme of a combined system treatment plant

In Germany a large research program with respect to enhanced nitrogen elimination (nitrification/denitrification) was carried out by Platzer (1998) over 4 years. The principal design of the combined system is shown in figure 1. The basic idea of this concept is to achieve the removal of organic compounds and a nitrification in the vertical flow bed, and a denitrification in the horizontal flow bed. Based on the results there was built a plant with very high effluent standards concerning total nitrogen (Rustige & Platzer, 2000).

In France Boutin et al. (2000) used a VFB – HFB combination as well and compared it with a double VFB (standard French system). The layout of the research system can be taken from figure 2.

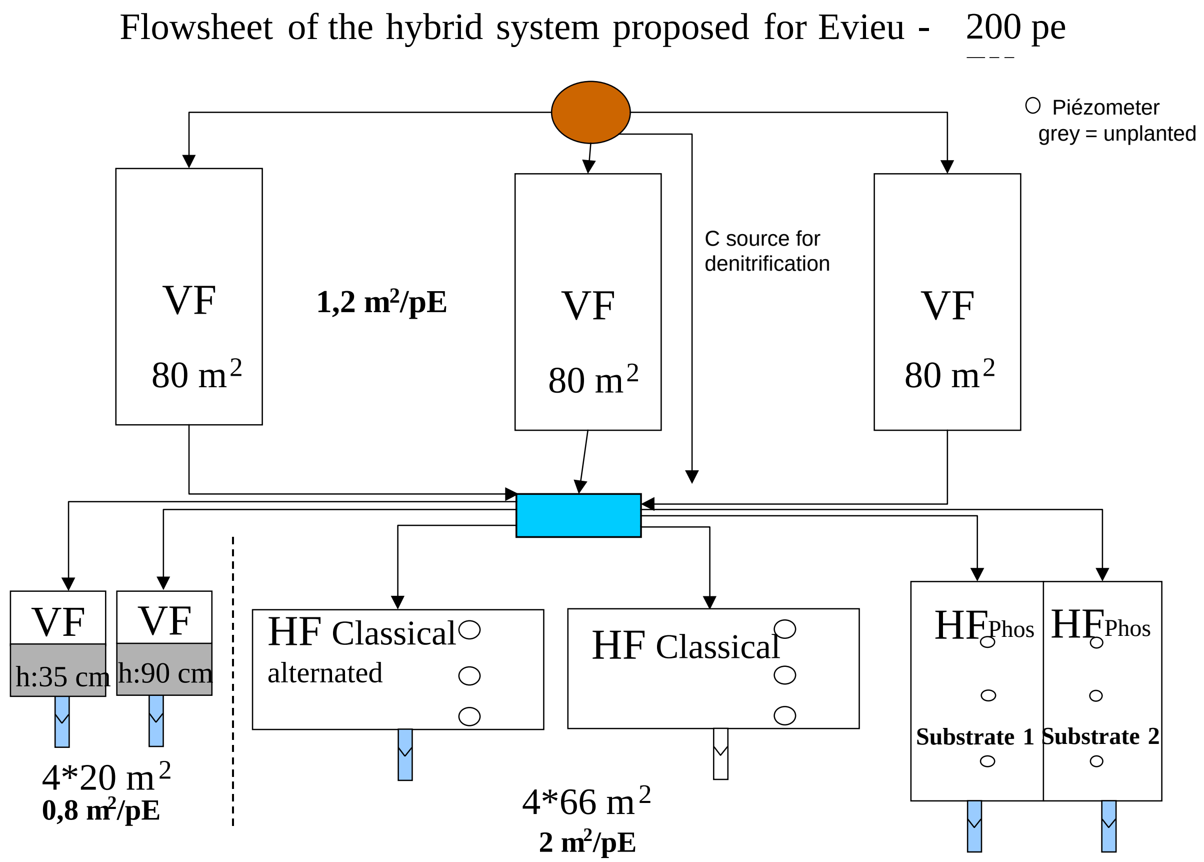

Figure 2 Flowsheet of the hybrid system proposed for Evieu (Boutin et al., 2000)

Another design approach was made by Johansen and Brix (1996), who used a large HFB for organic removal and partial nitrification, followed by a small VFB for nitrification. For denitrification purposes they proposed a recirculation to the HFB. This concept was built several times in Poland.

At the moment several research attempts are made to overcome the problem of designing wetlands for phosphorous removal purposes. Almost every author dealing with P names the role of precipitation and adsorption in the soil. It is generally agreed that the concentrations of iron, aluminum or calcium are the main factors of influence. Since the process of adsorption is finite, it is important to know the cumulative loading at which a phosphorus concentration breaks through. Therefore much research concentrates on the prediction of the breakthrough point.

MODELLING OF SUBSURFACE FLOW WETLANDS

Numerous attempts have been made to predict the effluent concentrations in subsurface flow wetlands. In my opinion a modeling of subsurface flow wetlands with the aim of predicting effluent concentrations is not possible. The maximum is the development of design lines which guarantee certain concentrations i.e. ammonia. Usually the effluent concentrations should be far below the proposed concentration. Why that?

In order to achieve a proper modeling the biological and chemical reactions have to be described at every place of the reactor. Ideal wetlands have plug flow characteristics, therefore the concentration of the wastewater components changes with the flow direction. As the concentration changes, the conditions for the reactions change as well. Although we do understand most of the reactions we are not able to describe the innumerous reactions and processes influencing each other in all parts of the reactor, in addition to constantly changing conditions. The above described problem of the use of k-values fits into this aspect.

To give an example we tried to model a VFB in order to predict ammonia effluent concentrations. For this purpose we measured in various VFBs the ammonia, nitrate, nitrite, total N and oxygen concentrations at depths of 10, 30 and 50 cm and in the influent and effluent. Furthermore we evaluated the potential nitrification capacity of the soil at these depths. Based on the gained data we tried to develop a model consisting of three layers (0/20, 20/40, below 40 cm). The model did not even fit the results of the influent and effluent concentrations of the analyzed beds. What is the reason for this? Although we did know the cation exchange capacity of the sand, we were not able to predict the actual loading of this capacity. Therefore we have a storage capacity which influences largely the results. Furthermore we can not predict the oxygen concentrations in the soil which depend on the hydraulic loading, the loading cycle and most important, the state of clogging of the bed.

As a reliable prediction of all the influencing parameters is impossible we have to accept that subsurface flow constructed wetlands are natural systems, applicable for wastewater treatment, but not predictable until the last.

SLUDGE TREATMENT

Reed beds for sludge treatment are one of the main developments in Europe in the last years. Due to their high efficiency in reducing the total amount of sludge, the much higher quality of the final product and the very long sludge retention times (7 – 10 years), there has been build an increasing number of sludge treatment plants.

In France has been made a development for sludge treatment based on the experiences with the raw wastewater treatment beds. Boutin et al. (2000) report that the use of sludge drying reed beds has been a real success for years. About 30 working units were listed in 1998. At the end of 2000, 70 units are proposed. Their sizes are between 1.000 pe and 9.000 pe The SAUR, with whom Cemagref initiated studies about this subject between 1989 and 1992, has been the first one to commercialize, in the early 90's, this technique under the brand name "Rhizophyte" (Liénard, 1999). Today there are many requests that even other large French water companies are offering this system for communities of some thousand inhabitants.

Sludge treatment in reed beds is very common in Denmark as well. There has been a strong development based on the experiments made by Nielsen (1990). Johanson (2000) reports that the increase in the use of sludge treatment beds in Denmark has been significant.

The largest beds were built in Germany where the beds were highly successful in situations were sludge quality and quantity were the distinguishing factors. A dozen of beds in the size of 10.000 to 40.000 pe have been built. The largest bed is situated in the City of Emden. It treats the anaerobically digested sludge of 90.000 pe.

A new development is the multiple use of sludge treatment beds for storage of stormwater. In this case the unloaded beds are used to avoid hydraulic overloads of the wastewater works. In this cases special attention has to be paid to the drainage system and the distribution of the water.

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