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OXYGEN TRANSFER RATE AND BOD REMOVAL EFFICIENCY OF CONSTRUCTED WETLANDS WITH DEPENDENCE ON CONSTRUCTION

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Abstract. Most cases of wastewater treatment involve three main types of constructed wetlands (CW). They are free-water surface wetlands (FWF) and subsurface flow CW including filters of vertical flow (SVF) and horizontal flow (SHF). The objectives of the article deal with the summarization of the data received from the investigations in Lithuania and the evaluation of constructed wetlands performance of different construction. The analysis of the filters' efficiency was performed due to the estimation of the filter load for analysed pollutants and their removed amount for an area unit. According to the removal efficiency of organic pollutants (BOD_5) filters could be put into the following order: SVF – SHF – FWF. At the load of all filters, according to BOD_5 4.0 g m^{-2} d^{-1} the following treatment efficiency 93.5, 77.5 and 42.2%, respectively was reached. This directly correlates with the oxygen transfer rate according to which filters are ranged at the following ratio: SVF : SHF : FWF – 1.0 : 0.6 : 0.3.

Keywords: constructed wetlands, removal efficiency, BOD, oxygen transfer rate.

1. Introduction

Constructed wetland (CW) treatment systems are engineered systems designed to treat wastewater with the usage of the same processes that occur in natural wetlands. However it is done within a more controlled environment.

The full-scale investigations of free-water surface wetlands (FWF), subsurface flow filters including filters of vertical flow (SVF) and horizontal flow (SHF) were carried out in Lithuania. Due to construction differences wastewater treatment conditions in filters are not identical, and it has the influence upon the pollutant removal efficiency.

In free water filters the wastewater is directly "exposed" to atmosphere. Such kind of filter contains a filtration body (plant roots + soil) with an isolated bottom for the protection of subsurface water from pollution. Free water filters often include a pre-settling basin and a number of compartments with a shallow water layer (0.2–0.4 m) planted up with helophytes such as *Phragmites*, *Typha* or *Scirpus* spp. (Verhoeven *et al.* 1999). In the USA and other countries, free water filters are usually used in secondary and tertiary wastewater treatment stages. They may also be used for the treatment of surface runoff water from agricultural land areas (Koskiaho 2003).

In filters of subsurface flow the wastewater is flowing under the ground surface. The filters consist of excavated beds filled with soil in which marshy plants are growing; water level is below the ground surface in such filters. In filters of horizontal flow the wastewater flows horizontally from the inflow zone through the body of the filter (i.e. roots of marshy plants, rhizomes and soil), where it is purified. The functioning principle of vertical filters is similar, only here the wastewater is spread on the surface of the filter; then it flows vertically through a 0.6-1.0-m deep sand layer into the collection pipes.

Subsurface flow filters are investigated under different climatic conditions all over the world. Such filters are distinct for their efficient removal of organic matter. According to BOD_7 (biochemical oxygen demand), treatment efficiency in such filters reaches 80-98% (Schierup *et al.* 1990; Cooper 1990; Haberl *et al.* 1995; Mander *et al.* 1997; Vymazal 2001). The results from the Czech horizontal filters showed an average treatment efficiency of 86.6% with an average effluent BOD_5 concentration of 13.2 mg L^{-1} with an average BOD_5 loading of 33.5 kg ha^{-1} d^{-1}. The results also indicated that the removal of BOD_5 is not temperature dependent and is steady throughout the year (Vymazal 1999). According to (Uhl *et al.* 2005) COD (chemical oxygen demand) and SS (suspended solids) removal rates of 85–99% can be expected from vertical type of filter. Considering the study data collected by (Paing *et al.* 2005), vertical filters achieved high removal of SS, BOD and COD (mean respectively 96%, 98%, 92%). Performance was not significantly influenced by variations of organic, hydraulic load and seasonal variations. As (Bahlo 2000) has observed, when vertical filters load according to BOD_5 is 6.4 g m^{-2} d^{-1} and COD

11.7 g m^{-2} d^{-1}, after treatment the concentration of BOD_5 was fluctuating within the range of 2-7 mgO_2 L^{-1}, while the concentration of COD was changing within the range of 15-27 mgO_2 L^{-1}.

Nitrogen within primary settled domestic wastewater typically consists of 75% ammonium and 25% organic nitrogen compounds. Organic nitrogen compounds entering subsurface flow wetlands are converted into NH_4-N through biological ammonification (Hammer 1991). NH_4 is then used as an energy source by obligately aerobic chemosynthetic nitrifying bacteria, producing nitrate (NO_3) as an endproduct. Finally, denitrification, an obligately anaerobic heterotrophic respiratory pathway, uses NO_3 as a terminal electron acceptor, reducing it into N_2 gas (Focht *et al.* 1975). The subsurface filters environment is predominantly anaerobic or anoxic containing small aerobic microzones surrounding the rhizomes of planted macrophytes. Consequently, nitrification is often the rate limiting step in the removal of nitrogen from filters (Brix *et al.* 1996; Tanner *et al.* 1999).

Since 1994, the first experimental wastewater treatment facilities containing constructed wetlands have been constructed in Lithuania (Gasiunas *et al.* 2003). The first full-scale constructed wetland comprising horizontal subsurface flow reed bed filters was built in 1995. Detailed long-term investigations on wastewater treatment efficiency were carried out in those wastewater treatment facilities as well as in those constructed later (Gasiunas *et al.* 2005). Since 2003 the investigations on vertical filters has started. (Struseviciené *et al.* 1994) has investigated the application of free water filters for the treatment of polluted surface water.

The objectives of the article are to summarize the data of the performed investigations and evaluate the performance of constructed wetlands of different construction.

2. Materials and methods

The investigations of constructed wetlands were performed in climatic conditions of Lithuania, which is known as a cold climate country. The amount of precipitation is 670 mm, and average air temperature is 6.2 ^{o}C. The coldest month is January (-5.1 ^{o}C). Average temperatures are: in winter -4 ^{o}C, in spring 5.5 ^{o}C, in summer 16 ^{o}C, in autumn 7 ^{o}C. In the winter period snow cover is 10-20 cm deep, and frozen ground can reach 50-70 cm in depth.

The database of investigations on constructed wetlands of different construction collected within the study period of 1995-2009 was used for the estimation of BOD_5, nitrogen and phosphorus removal efficiency.

For horizontal filters, the studies were carried out in 6 wastewater treatment facilities where wastewater of different chemical composition was treated. All objects under investigation contain filters of common construction. After the primary treatment wastewater is distributed into the filter via a distribution manhole. Chippings prisms arranged in filters contain distribution pipes. Here water is distributed evenly within the whole filter. Then wastewater is filtered horizontally through a semi-coarse sand medium with the filtration coefficient of 5-8 m d^{-1}. Size of sand particles d_{10} is fluctuating between 0.15 and 0.17 mm, the ratio d_{60}/d_{10} is 2-5. The depth of filters is 0.8 m, filtration distance 4.5 – 5.5 m. Filters are planted up with common reed (*Phragmites australis*).

The investigations of vertical filters systems were carried out in wastewater treatment facilities arranged in motels "Nikola", "Pastogė" and village Aristava, Kėdainiai district within the period of 2003-2009. After the purification in septic tanks, wastewater is directed into vertical filters for secondary (biological) treatment. Surface areas of filters are 300, 250 and 950 m^2 in motels "Nikola" "Pastogė" and Aristava respectively. With the help of a pump, wastewater from septic tanks is distributed into a distribution manhole. Further wastewater is directed into distribution pipes, and finally it is sprayed into a layer of chippings arranged on the surface of the filter. Vertical filters contain a 20-cm thick layer of fine chippings with distribution pipes arranged at the spacing of 1 m. With the help of a pump, wastewater is distributed from the pump shaft into the distribution pipes. Further wastewater is spread throughout the chippings layer and is filtered downwards in a vertical direction via a 0.8-m deep sand layer into the collecting pipes arranged on the bottom of the filter. Sand filtration coefficient is 35.5 ± 5.9 m d^{-1}, the ratio of sand particles d_{60}/d_{10} is 5-6. Filters are planted up with common reed (*Phragmites australis*).

For free water filter, the investigation object included the Babėnai wastewater treatment facilities (Kėdainiai town) that have been re-constructed from the aeration wastewater treatment plant into the natural one. A free water filter has been arranged for the additional wastewater treatment. The filter was set up in 2003. Currently it is completely overgrown with reed and cat's tail. The area of the filter is 675 m^2. Water depth in the filter may be regulated from 0.1 to 0.8 m. Water depth is maintained to be at the depth of 10-20 cm in warm period of the year and at the depth of 50 cm in winter. Due to the entrance of surplus water into the wastewater network, its discharge is fluctuating from 10 to 90 m^3 d^{-1}. The data of measurements taken in different study periods (2003-2006) was used for the analysis. Another examined free water filter set in village Aristava was used for the secondary wastewater treatment after the wastewater treatment in the vertical filter. The filter was set-up in 2004. The area of the filter comprises 130 m^2. The amount of wastewater varies from 10 to 30 m^3 d^{-1}. Water levels are the same as in Babėnai examined object. A free water filter is completely overgrown with cat's tail.

Further analysis of wastewater treatment efficiency is performed only from the beginning of influent into the filters. To evaluate BOD_5, removal efficiency, for statistical data analysis 182 for SHF, 90 - SVF and 55 for FWF of measurement data of different periods were taken.

All constructed wetland systems can be considered to be attached-growth biological reactors, and their performance can be estimated with first-order plug flow kinetics for BOD and nitrogen removal. The relationship for plug flow reactors is given by (Eq. (1)) (Reed *et al.* 1995):

$$\frac{C_e}{C_o} = \exp(-\frac{K_T}{HLR}) \quad (1)$$

where: C_e - effluent pollutant concentration, mg L^{-1}; C_o - influent pollutant concentration, mg L^{-1}; K_T - temperature-dependent first-order reaction rate constant, d^{-1}; HLR - average daily hydraulic loading rate, m d^{-1} .

$$K_T = K_{20}\theta^{(T-20)} \quad (2)$$

where: K_T - the reaction rate coefficient at temperature, °C; K_{20} - the reaction rate coefficient at 20°C; Θ - the temperature factor; T – temperature, °C.

Since the biological reactions involved in treatment are temperature dependent, it is necessary for proper design to estimate the water temperature in the wetland. The value used for K_T in (Eq. (2)) depends on the pollutant requiring removal and on the temperature. The temperature conditions in a wetland affect both the physical and biological activities in the system. The biological reactions responsible for BOD removal, nitrification, and denitrification are known to be temperature dependent. However, in many cases the BOD removal performance of existing wetland systems in cold climates has not demonstrated obvious temperature dependence. This is believed due to the long hydraulic residence time provided by these systems, which tends to compensate for the lower reaction rates during the winter months (Reed *et al.* 1995). The data of our performed investigations have not determined a statistically reliable difference between the efficiency of wastewater treatment in warm and cold seasons as well. Thus we equate a constant K_T to a rate constant K_{bod}.

The efficiency of pollutant removal according to BOD may also be determined using (Eq. (3)):

$$\varepsilon = \frac{C_o - C_e}{C_o} \quad (3)$$

ε – removal efficiency in unit parts.

Both equations (1 and 3) and appropriate calculations provide the (Eq.(4)):

$$-\ln(1-\varepsilon) = \frac{K_{bod}}{HLR} \quad (4)$$

From the (Eq. (4)) a rate constant K_{bod} can be calculated:

$$K_{bod} = -\ln(1-\varepsilon)HLR \quad (5)$$

The necessary filter area for the removal of pollutants according to BOD_5 can be calculated by the following equation (Cooper 2001):

$$A = \frac{Q(\ln C_0 - \ln C_e)}{K_{bod}} \quad (6)$$

where: A - surface area of filter, m^2; Q - the influent flow, m^3 day^{-1}; C_o - average BOD_5 concentration in influent, mgO_2 L^{-1}; C_e – normative average BOD_5 concentration of effluent, mgO_2 L^{-1};K_{bod} - the area-based first order rate constant for BOD removal, m d^{-1}

$$K_{bod} = \frac{Q(\ln C_0 - \ln C_e)}{A} \quad (7)$$

The removal of organic pollutants and nitrification processes in CW depend upon aeration capacity or so called oxygen transfer rate of filter body. In subsurface filters it is the sand with planted macrophytes and their roots and in free water filters – water and plants growing in it. The horizontal subsurface flow constructed wetland in Kodijärve, Estonia, showed aeration capacity 2.7 -3.1 gO_2 m^{-2} d^{-1} (Noorvee 2005).

Oxygen transfer rate (OTR) was calculated using the following equation, modified from (Cooper 1999):

$$OTR = \frac{Q[(BOD_{in} - BOD_{out}) + ((NH_4 - N)_{in} - (NH_4 - N)_{out}) \times 4.3]}{A} \quad (8)$$

where: BOD_{in} - BOD_7 in the influent, mgO_2 L^{-1}; BOD_{out} - BOD_7 in the effluent, mgO_2 L^{-1}; NH_4-N_{in} - NH_4-N in the influent, mg L^{-1}; NH_4-N_{out} - NH_4-N in the effluent, mg L^{-1}; Q - the influent flow (m^3 day^{-1}); A - filter area, m^2.

Note: collected data of BOD_5 were transformed to BOD_7 with the following equation:

$$BOD_7 = 1.15 \times BOD_5 \quad (9)$$

3. Results and discussion

When calculating removal capacity of organic pollutants according to BOD_5, the analysis of the constructed wetlands has been made, i.e. it has been estimated which proportion of pollutants was removed from the filter with respect to its load. Data of correlation analysis are presented in Fig. 1. The average load of studied SHF according to BOD_5 was 3.7±2.7, SVF – 5.0±3.2 and FWF – 3.1±2.8 g m^{-2} d^{-1}. To compare the treatment efficiency, the calculations of pollutants removal efficiency have been made at the same load of all filters, i.e. BOD_5 4.0 g m^{-2} d^{-1}. To make the calculations, the results of relationships presented in Fig. 1 have been used. In this case the treatment efficiency of vertical, horizontal and free water filters reaches 93.5, 77.5 and 42.2% respectively.

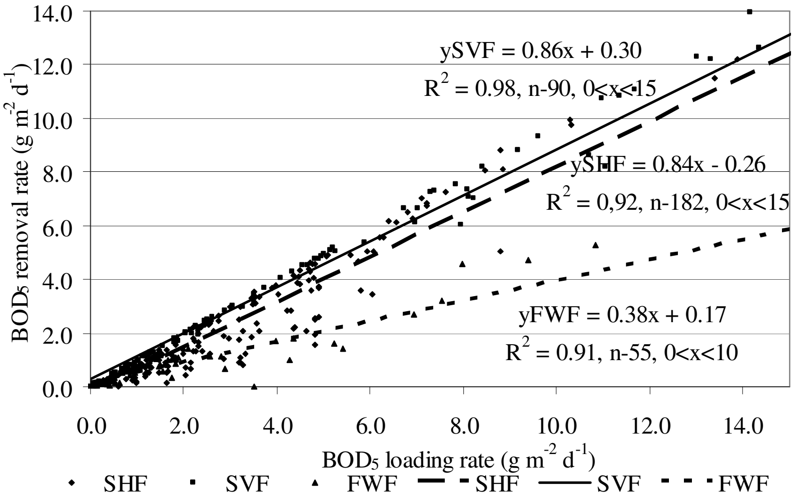

Fig 1. Removal rates of pollutants according to BOD_5 in different filters with respect to the load

Using the experiment data a rate constant K_{bod} is calculated according to (Eq.(5) and (7)). The identical calculation results are received. This reveals that the necessary filter area of CW with different construction can be calculated by (Eq.(6)) using the received average K_{bod} values for SVF - 0.097, SHF – 0.054 and in FWF – 0.045. In the United Kingdom while designing horizontal filters the rate constant K_{bod} – 0.06 m d^{-1} is used (Cooper 2001). According to the rate constant values it is possible to judge that the most efficient purification of organic pollutant according to BOD_5 is in SVF. In order to achieve the same purification efficiency, SHF has to be 1.8, and FWF – 2.2 times greater in the surface area in comparison to vertical filters.

A certain analysis aiming to determine the rate constant K_{bod} dependency upon filters load according to BOD_5 has been performed. The calculations did not reveal any correlation. Since K_{bod} fluctuated within certain boundaries, analyses of variance were used for the mathematical processing of data to determine the existence of the essential value difference of this constant among filters of different construction. According to the analysis, the statistically reliable difference between the averages was estimated. (LSD – least significant difference, LSD– 0.082, p=0.05).

The removal of N in constructed wetlands is dependent on the N cycle. As part of the cycle, the various forms of N are converted into gaseous components that are emitted into the atmosphere as nitrogen gas (N_2) or nitrous oxide (N_2O). Key processes in the N cycle include ammonification, nitrification, and denitrification. Nitrification - denitrification reactions are the dominant removal mechanisms of nitrogen in constructed wetlands.

Having performed the data analysis, it was determined that after the treatment process in filters, N contained in wastewater is of different forms and amounts. In SHF and FWF systems NH_4-N is prevailing, while in SVF systems NO_3-N is dominant. Composition of N-compounds in percent contained in the effluent water of filters is presented in Fig. 2

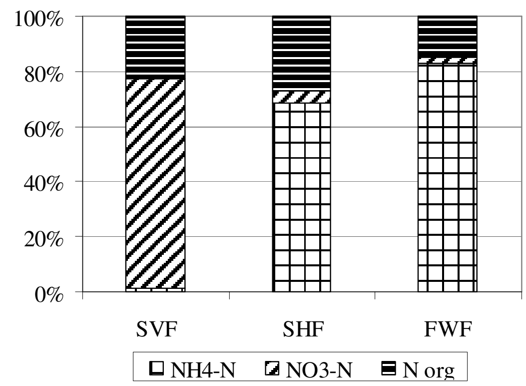

Fig 2. Composition of total N-compounds in percent contained in the effluent water of filters

CW of horizontal flow operate typically under anoxic conditions, thus their potential to oxidize ammonium is limited. On the other hand, in SVF constructed wetlands the biological denitrification demands anoxic conditions that are not prevalent in vertical flow constructed wetlands therefore their capacity to remove total nitrogen is limited. SHF is good for denitrification and poor for nitrification because of limited oxygen transfer capability; SVF is good for nitrification because of high oxygen transfer capability.

Other researchers have also noticed differences between N forms contained in wastewater after the treatment in SVF and SHF systems. Having analyzed 107 sand reed filters in Germany, it was determined that wastewater treated in SHF contained 58% of NH_4-N and 5.3 % of NO_3-N from the TN amount. After the treatment in filters of vertical flow, NH_4-N and NO_3-N made up 9.5 % and 86 % respectively of TN amount contained in wastewater after the treatment process (Felde et al.; 1996). Similar results were obtained by other researchers, too (Cooper, 1999; Cooper et al.; 1999).

Each construction filter group underwent a regressive analysis calculation of OTR dependency from load of the filters according to BOD_7 and NH_4-N. The regression equations are presented below:

$$OTR_{SHF} = -0.03 + X + 1.897Y \quad (10)$$

R^2-0.85; n-111

$$OTR_{SVF} = -0.569 + 0.971X + 4.399Y \quad (11)$$

R^2 – 0.95; n – 66

$$OTR_{FWF} = -0.150 + 0.368X + 1.071Y \quad (12)$$

R^2 – 0.94; n – 49

where: OTR – oxygen transfer rate in SHF – horizontal filters, SVF - vertical filters, FWF – free water filters, gO_2 m^{-2} d^{-1}; X – BOD_7 load of the filters, g m^{-2} d^{-1}; Y – NH_4 – N load of the filters, g m^{-2} d^{-1}; n – the number of observation data.

The received high coefficients of correlation show that OTR directly depends on BOD_7 and NH_4-N load. In order to reveal OTR differences due to filter construction, a special condition was established. It says that the filter load according to NH_4-N is twice lower in comparison to the load according to BOD_7.

The usage of given equations of regression made it possible to calculate OTR for each filter group with the same load. Calculation data are presented graphically in Fig. 3. As it is shown in the diagrams of Fig. 3, when filter load is according to BOD_7/NH_4-N - 2.0/1.0 g m^{-2} d^{-1} / g m^{-2} d^{-1}, in SVF – OTR is 5.77, in SHF – 3.87, and in FWF – 1.66 g m^{-2} d^{-1}. With the increase of the load to BOD_7/NH_4-N - 6.0/3.0 g m^{-2} d^{-1}/g m^{-2} d^{-1}, in SVF – OTR is 18.45, in SHF – 11.66, and in FWF – 5.27 gO_2 m^{-2} d^{-1}. These calculations, however, can only be applied until a certain load threshold is reached. As the load of filters in our experiment according to BOD_7 fluctuated in the range of 4.0 -6.0 gO2 m^{-2} d^{-1} our calculations would apply in the range of BOD_7/NH_4-N - 6.0/3.0 g m^{-2} d^{-1}/g m^{-2} d^{-1}.

When the load is BOD_7/NH_4-N - 2.0/1.0 g m^{-2} d^{-1}/g m^{-} d^{-1} we receive that oxygen transfer rate in vertical filters is 1.49 times bigger than in horizontal filters and 3.48 times bigger than in free water filters, and with the increased load BOD_7/NH_4-N - 6.0/3.0 g m^{-2} d^{-1}/g m^{-2} d^{-1}, this difference is correspondingly – 1.58 and 3.5 times. This reveals that with the proportional increase of load, oxygen transfer rate difference in filters of different construction is nonessential**.** Equalled the oxygen transfer rate in SVF to 1, ranging filters according to the oxygen transfer rate, the following sequence is received SVF : SHF : FWF – 1.0 : 0.6 : 0.3.

4. Conclusions

The analysis of the research data revealed that the pollutant removal efficiency in constructed wetlands depends not only on their load with the pollutants but also on their own construction.

According to removal efficiency of organic pollutants (BOD_5) filters could be put into the following order: SVF – SHF – FWF. At the same load of all filters, i.e. BOD_5 4.0 g m^{-2} d^{-1} the treatment efficiency of vertical, horizontal and free water filters reaches 93.5, 77.5 and 42.2% respectively.

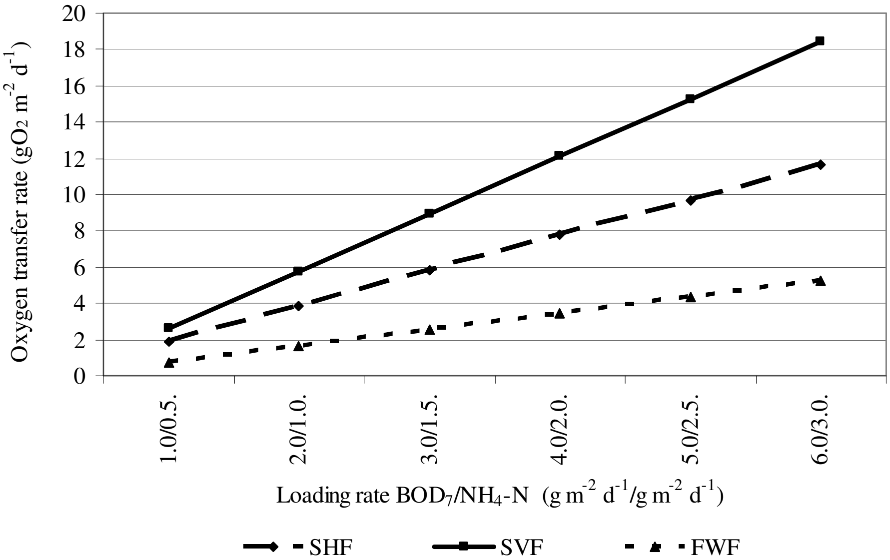

Fig 3. Relationship between oxygen transfer rate and load of filters according to BOD_7 and NH_4-N

The oxygen is required to ensure the removal of organic pollutants and the processes of nitrification. The calculations revealed that the biggest oxygen transfer rate (OTR) is contained in SVF. If their OTR is equalled to 1, accordingly the filters are put into the following order at the following ratio: SVF : SHF : FWF – 1.0 : 0.6 : 0.3.

As the analysis of the studies has shown, removal of organic pollutants is more efficient in vertical filters compared to horizontal or macrophytes filters. More efficient treatment results of vertical filters, still does not mean that filters with different constructions cannot be used. Having evaluated advantages and disadvantages of each construction it is possible to make certain combinations of all of the filters.

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