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Kinetics of pollutants removal in hybrid treatment wetlands – Case study comparison

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ABSTRACT

Recent years have seen an increasing interest in hybrid constructed wetland (HCW) systems for domestic sewage treatment. This paper is focused on kinetics of removal of the main pollutants occurring in wastewater i.e. organics expressed as chemical oxygen demand, biochemical oxygen demand and total nitrogen. The purpose of the article is to compare different HCW configurations in terms of mass removal rates (MRR) and removal rate coefficients (k_A and k_v). Analysed data have been collected at two wetland systems, each composed by two subsurface flow beds: horizontal flow (HF) and vertical flow (VF). Reliable evaluation was achieved by using the same composition of influent wastewater in both HCWs. Performance of opposite configurations HF + VF vs. VF + HF was compared after each stage and the overall HCW system. The average mass removal rates of COD, BOD_5 and TN in both systems were similar, respectively: 2.30, 0.98 and 0.40 $g\,m^{-2}\,d^{-1}$. However, removal rates differ between single wetland beds after each treatment stage.

1. Introduction

Constructed wetlands (CWs) have received a high level of interest over the past decades due to their efficiency, low investment and operating costs and positive environmental impact. For this reason, these facilities have started to be used as a sustainable method of wastewater treatment for small communities and individual households. In terms of the complexity of the processes occurring, constructed wetlands create a more diverse environment compared to conventional treatment technologies (Gajewska and Obarska-Pempkowiak, 2011; Gómez Cerezo et al., 2001; Langergraber et al., 2010; Vymazal, 2005; Vymazal, 2013).

Subsurface hybrid CW systems are composed of filters with different sewage flow patterns: vertical (VF) or horizontal (HF). These systems prove to achieve higher efficiency of pollutants removal combining the benefits of both types of beds. Processes in vertical flow beds are dominated by mineralization of organic matter and ammonia nitrification thanks to better oxygen conditions compared to the horizontal flow beds ensuring better quality of final effluent (lower concentration of organic matter, complete nitrification and partial denitrification). The processes occurring in vertical and horizontal flow beds differ in magnitude depending on the design and mode of operation. In general, VF beds are unsaturated units usually fed periodically, resulting in high oxygen transfer capacity, thereby favoring the process of nitrification within the wetland bed. On the other hand, HF beds are operated mostly under anoxic/anaerobic conditions due to constant saturation of the beds, which makes it a likely environment for denitrification. Horizontal flow beds are also responsible for effective removal of suspended solids and organic matter (Gajewska and Obarska-Pempkowiak, 2011; Jóźwiakowski et al., 2017; Kadlec and Knight, 1996; Kadlec and Wallace, 2009; Reed et al., 1995).

The results of many studies revealed that the mass removal rate (MRR) of NH_4-N varies only between 2.13 ± 1.72 $g\,m^{-2}\,d^{-1}$ for HF + VF constructed wetlands and 2.48 ± 2.83 $g\,m^{-2}\,d^{-1}$ for VF + HF CWs. Hybrid constructed wetlands with multiple stages of VF and HF beds removed on average 2.33 ± 2.61 g NH_4-N $m^{-2}\,d^{-1}$. Considering total nitrogen, HF + VF and VF + HF beds combinations are able to achieve MRR on average 2.74 ± 1.86 and 2.31 ± 2.10 g TN $m^{-2}\,d^{-1}$, respectively. It should be noted that all removal rates exceed the average MRR of single HF systems (1.13 ± 2.01 g TN $m^{-2}\,d^{-1}$) or single VF CWs (1.85 ± 3.66 g TN $m^{-2}\,d^{-1}$). In terms of BOD_5, COD, TSS, the mass removal rates in hybrid constructed wetlands did not vary and, also did not differ substantially from single VF and HF constructed wetlands

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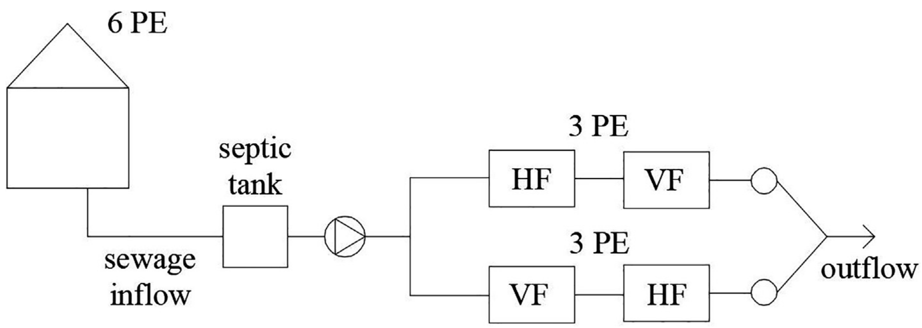

Fig. 1. Constructed wetland system in Dąbrowica – general scheme (author's own work).

(Kadlec and Knight, 1996; Kadlec and Wallace, 2009; Canga et al., 2011; Vymazal, 2013).

The aim of the paper is to provide an evaluation of performance of HCW with opposite configurations of the beds in respect of pollutants removal rates. Mass removal rates (MRR) and rate constants (k) were analysed after each stage of treatment. Within this paper, a statistical analysis of research results was carried out. The division of discharged wastewater into two streams treated in HCWs in two configurations enabled for reliable estimation and very unique results.

2. Materials and methods

The investigations were carried out at two constructed wetlands (Dąbrowica I and Dąbrowica II) in Dąbrowica, Poland, southeast part of the country. Analysed systems were built in 2006 and were designated for the treatment of domestic wastewater from a single household.

In this case subsurface vertical flow (VF) and horizontal flow (HF) beds were used. The scheme of the investigated wetland systems is shown in Fig. 1.

The analysed wetlands differ from each other in the order of subsequent stages. The characteristic of the systems with configuration of the beds is given in Table 1.

Each HCWs system comprised of two beds arranged in series. All beds had dimensions of 6 × 4 m. In the presented case, opposite bed configurations used in these two systems (HF + VF vs. VF + HF) were very valuable for comparison of treatment efficiency due to the identical dimensions of the beds and the same composition of influent wastewater.

Longitudinal sections of the analysed plants are shown on Figs. 2 and 3.

As a filter media, gravel and medium sand were selected for both wetland systems. The surface layer of HF bed consists of a humus layer with a thickness of 0.1 m. The following is a 0.6 m layer of sand (grain diameter 1–2 mm). The lower horizontal layer of the bed is 0.2 m thick and consists of gravel with a granulation range of 10–50 mm. Underneath, there is a layer of sand of about 4 cm. VF wetlands are made in the same arrangement of layers, with the difference that the thickness of the sand layer lying under the humus layer is 0.4 m. All wetland beds are isolated from the natural ground using 0.5 mm PEHD geomembrane.

The method of sewage discharge into HF beds is gravitational and feeding regime is continuous, whilst VF beds are fed periodically by means of submersible pumps installed in the wells. Volume of a single loading is 0.3 m^3 with loading intervals set to once per hour. The designed retention time in HF and VF beds was 16 and 9.6 days, respectively. The retention time can be calculated on the basis of the following equation:

$$t_r = (L \times W \times n \times d)/Q \tag{1}$$

where: L – length of the bed (m), W – width of the bed (m), n – porosity of the material from the bed, d – depth of bed (height of the filter bed filled with sewage) (m), Q – average daily inflow of sewage ($m^3\ d^{-1}$) (Cooper, 1998; Jóźwiakowski, 2012).

Horizontal flow beds in the systems were planted with willow (*Salix viminalis*), and for vertical flow beds common reed (*Phragmites australis*) was used.

Data from HCW systems in Dąbrowica I and Dąbrowica II was collected in 2007–2010. Averaged samples of influent and after subsequent stages of treatment in the CW systems were analysed. Number of series of analyses in this study was sixteen as sampling interval amounted to four times a year (February, May, August and November). Overall number of samples taken was 106. In order to evaluate the removal efficiencies, the following parameters were measured: organic matter (COD and BOD_5) and total nitrogen (TN), according to the methods of Polish Standards in accordance with the standard methods (APHA, 2005). Removal efficiency was calculated as a quotient of contaminants concentration difference in influent and effluent after subsequent stages of constructed wetland and concentration in influent. Mass removal rate (MRR) was calculated on the basis of the following equation:

$$MRR = [(C_{in} \times Q_{in}) - (C_{out} \times Q_{out})]/A\ [g\ m^{-2}\ d^{-1}] \tag{2}$$

where A is the area of constructed wetland bed [m^2], Q_{in} and Q_{out} are the average influent and effluent flow rates, respectively [$m^3\ d^{-1}$], C_{in} and C_{out} are average influent and effluent pollutant concentrations, respectively [$mg\ L^{-1}$] (Gajewska and Obarska-Pempkowiak, 2011; Jozwiakowski, 2012).

To estimate the rates of removal, the rates of organic matter decay and total nitrogen removal were calculated. It was assumed that the rate coefficients can be described by means of a first-order decay laws.

Table 1
The operation conditions of the wetland systems.

Plant	Flow [$m^3\ day^{-1}$] (pe)	Configuration	Area [m^2]	Depth of bed [m]	Hydraulic load [$mm\ d^{-1}$]	Organics loading rate [$g\ COD\ m^{-2}\ d^{-1}$]
Dąbrowica I	0.3; (3)	HF VF	24 24 Σ 48	1.0 0.8	12.0	7.021
Dąbrowica II	0.3; (3)	VF HF	24 24 Σ 48	0.8 1.0	12.0	7.021