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Kinetics of pollutants removal in vertical and horizontal flow constructed wetlands in temperate climate

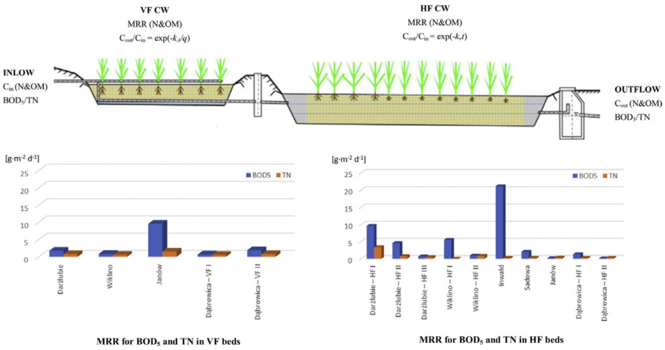
Magdalena Gajewska [a], Katarzyna Skrzypiec [a], Krzysztof Jóźwiakowski [b],*, Zbigniew Mucha [c], Włodzimierz Wójcik [d], Agnieszka Karczmarczyk [e], Piotr Bugajski [f]

[a] *Dept. of Water and Wastewater Technology, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Narutowicza St. 11/12, 80-233 Gdańsk, Poland*
[b] *Dept. of Environmental Engineering and Geodesy, Faculty of Production Engineering, University of Life Sciences in Lublin, Akademicka St. 13, 20-950 Lublin, Poland*
[c] *Dept. of Environmental Technologies, Faculty of Environmental Engineering, Cracow University of Technology, Warszawska St. 24, 31-155 Kraków, Poland*
[d] *Dept. of Civil Engineering, Krosno State College, Rynek St. 1, 38–400 Krosno, Poland*
[e] *Dept. of Environmental Development, Institute of Environmental Engineering, Warsaw University of Life Sciences-SGGW, Nowoursynowska St. 159, 02–776 Warsaw, Poland*
[f] *Dept. of Sanitary Engineering and Water Management, University of Agriculture in Kraków, Al. Mickiewicza St. 24/28, 30-059 Kraków, Poland*

HIGHLIGHTS

- Describing N and OM removal process in constructed wetland by a first-order decay laws
- Variations in total nitrogen and organic matter k-values in constructed wetlands
- Insignificant impact of the BOD5/COD and BOD5/TN ratios on the mass removal rate
- Nomographs for constant removal of total nitrogen for horizontal and vertical beds

GRAPHICAL ABSTRACT



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ABSTRACT

This paper reports a comparative study on kinetics of organic matter expressed as BOD_5 and nitrogen removal in constructed wetlands operated in Poland. Analyzed data were collected at eight wetland systems, composed of subsurface flow beds: horizontal flow (HF) and vertical flow (VF), in different number and sequences. The analysis involved particularly mass removal rates (MRR) and first-order removal rate coefficients of BOD_5 and total nitrogen (k_A and k_v for VF and HF filters, respectively, and k_{20} as a parameter averaged for a temperature of 20 °C). It was found that the higher the load of pollutants applied to the beds, the higher MRR values were obtained. The average k-rates in analyzed systems were mostly lower than those reported in the literature, especially in the case of total nitrogen. Its removal obtained in horizontal flow beds was $k_v = 0.002–0.042\ d^{-1}$, while in vertical flow systems k_A varied from $0.007\ m\ d^{-1}$ to $0.0037\ m\ d^{-1}$. According to data given by previous studies, first-order reaction rates for nitrogen removal varied in range from $k_v = 0.048\ d^{-1}$ to $k_v = 0.19\ d^{-1}$ and k_A from 0.007 to $0.1\ m\ d^{-1}$ in HF and VF beds, respectively. Regarding BOD_5 shown in literature, removal rate k_v for HF beds varied from 0.071 to $6.11\ d^{-1}$, and k_A for VF beds varied from 0.019 to $1.0\ m\ d^{-1}$, while in this study lower k-rates were obtained: $k_v = 0.005–0.085\ d^{-1}$ and $k_A = 0.015–0.130\ m\ d^{-1}$. Relatively long monitoring period, for some of constructed wetland up to 16 years, resulted in good data set and enables creation of the graphs,

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* Corresponding author.
E-mail address: krzysztof.jozwiakowski@up.lublin.pl (K. Jóźwiakowski).

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which could be helpful in evaluation and designing of constructed wetlands for PE bigger than 50, in moderate climate conditions.

1. Introduction

Constructed wetlands (CWs) comprise a suite of recognized eco-technologies that are designed and constructed to mimic and manipulate the simultaneous physical, chemical, and biological processes occurring in natural wetlands. Constructed wetlands are nowadays a well-known technology for wastewater treatment. They are recognized to be effective in removal of dissolved organics and suspended solids. Many current research studies are dedicated to nitrogen compounds removal processes and the rate of nitrogen removal in different types of constructed wetlands (Kadlec and Knight, 1996; Vymazal, 2005; Kadlec and Wallace, 2009; Wu et al., 2018).

Most processes that occur in constructed wetlands can be expressed in terms of a first-order removal rate coefficient (*k*). This means that the rate of pollutant removal is dependent on the concentration of the pollutant (Sun and Saeed, 2009; Saeed and Sun, 2011; Arias et al., 2017). Temperature is another external factor that has a significant impact on the removal rate of contaminants. In this paper the influence of temperature on *k*-rate coefficients in wetland beds was taken into account as well (Jóźwiakowski, 2012; Gajewska et al., 2015).

The processes taking place in particular constructed wetland beds are different due to the diversity of kinetics expressed in removal rates. Different wetlands have different *k* rates, but sometimes central tendencies can be observed (Akratos et al., 2009; Langergraber et al., 2010; Gajewska et al., 2018).

The reaction rate constants determined by different authors (Table 1) vary in a wide range: for total nitrogen $k_A = 0.007–0.1$ m d^{-1} and $k_v = 0.048–0.19$ d^{-1} and for BOD_5 $k_A = 0.019–1.0$ m d^{-1} and $k_v = 0.071–6.11$ d^{-1}. The above fluctuations may indicate a significant variation in the individual processes leading to the removal of nitrogen compounds and organic matter in HF and VF beds.

Constant removal rate depends on i.e. bed matrix, porosity and flow rate. The porosity of the bed material is critical for the hydraulic loading rate and retention time of effluent passing through it, which in turn determines the efficiency/the speed of pollutants removal (Molle et al., 2008; Gajewska and Ambroch, 2012).

The vast majority of scientific publications describing MRR and kinetics of pollutants removal rates were released in the 1990s. Since then, significant improvements have been made in the design and construction of subsurface flow constructed wetland systems. Many current systems work under specific configurations, required unit area was significantly reduced, and a wide range of filtration materials is available for selection. Nowadays, trends promoting natural based solutions for wastewater treatment have resulted in renewed interest in CWs and thus the need to verify their parameters in different climatic conditions.

The aim of the study was to investigate kinetic parameters of contaminants removal in constructed wetland beds with subsurface horizontal and vertical flow. This research was conducted for moderate climatic conditions in Poland, and the results could be applicable in similar climate condition in Europe.

2. Methods

The research was carried out in eight hybrid constructed wetlands (HCWs) situated in different localities in Poland. These systems consist of beds with subsurface horizontal (HF) and vertical (VF) flow with different configuration. The measurement period varied for different HCWs, all of them have been monitored longer than 3 years and few even 16 years.

Sampling, sample transportation, processing and analysis have been done according to relative Polish Standards of Wastewater Examination Polish Standards According Limits for Discharged Sewage and Environmental Protection which are in accordance to American Public Health Association (APHA),1992 and American Public Health Association (APHA), 2005.

Characterization of analyzed systems is given in the Table 2. Hybrid constructed wetlands operated in Dąbrowica I and Dąbrowica II are particularly noteworthy, as they differ only in the applied configuration of wetland beds (opposite configuration). The location, surface area, quantity and composition of influent wastewater are the same in these two systems.

Most of the wetlands presented in the Table 2 were planted with common reed (*Phragmites australis*). Only HF beds in Janów, Dąbrowica I and Dąbrowica II were planted with willow (*Salix viminalis*).

Mass removal rate (MRR), which is the main parameter that determines 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. Thus MRR was calculated on the basis of the following equation:

$$MRR = [(C_{in} \text{ x } Q_{in}) - (C_{out} \text{ x } Q_{out})]/A \left[\text{g m}^{-2}\text{ d}^{-1}\right] \quad (1)$$

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; Jóźwiakowski, 2012).

In order to examine the efficacy of the investigated systems, and in particular the rate of removal of contaminants, the analysis of removal processes kinetics was carried out. The first-order kinetics model was used as a reliable basis for removal rates analysis.

The first-order decay rates of organic matter (BOD_5) and total nitrogen (as a TN) were calculated according to the Eq. (2) widely used for sizing of subsurface horizontal (HF) flow constructed wetland systems for domestic sewage treatment. Eq. (2) is one of the simplest and most user-friendly design equations. The key parameter (*k*) was first determined in 1990, based on regressions of inlet and outlet BOD_5 values in existing reed beds in the UK and Denmark (Brix and Johansen, 1999; Sun and Saeed, 2009):

$$A_h = Q_d \text{ x } (\ln C_{in} - \ln C_{out})/k \quad (2)$$

where A_h is the surface of bed (m^2), Q_d is the average flow rate (m^3 d^{-1}), C_{in} is the influent pollutant concentration i.e. BOD_5 or TN (mg L^{-1}), C_{out} is the effluent pollutant concentration i.e. BOD_5 or TN (mg L^{-1}), k is the rate constant for TN or BOD_5 (m d^{-1}).

To estimate removal performance, 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. On the basis of the retention time, flow rates, surface bed area and concentrations of organic matter and nitrogen, the decomposition constant coefficients (k) for wastewater treated in HF beds and VF beds were calculated. First order equation form presented in (3), which uses k_v rate in d^{-1} and the hydraulic retention time (*t*) in days, is dedicated for HF beds:

$$C_{out}/C_{in} = \exp.(-k_v t) \quad (3)$$

The more commonly applied k_A rate is presented in the following equation. It is considered to be dedicated to calculations for k-rates in

Table 1
First order removal constant regarding BOD_5 and TN in HF and VF beds.

HF			VF		
	k_v [d^{-1}]	Bibliography		k_A [$m\ d^{-1}$]	Bibliography
BOD_5					
Scope	0.8–1.1	Crites, 1994	Scope	0.085–1.0	Kadlec and Knight, 1996
	1.104	Reed and Brown, 1995		0.49	Kadlec, 1997
	0.17–0.22	Tanner et al., 1995a, 1995b		0.19	Vymazal, 1998a, 1998b
	0.86–1.84	Wood, 1995		0.118	Brix, 1996
	0.3–6.11	Kadlec and Knight, 1996		0.083	Schierup et al. 1990
	0.86	Liu et al., 2011		0.067–0.1	Cooper, 1990
	0.071–0.27	Obarska-Pempkowiak and Gajewska, 2005		0.16	Brix, 1994
	0.15–0.29	Gajewska and Ambroch, 2012		0.068	Brix, 1994
				0.07–0.31	Kadlec et al., 2000
				0.06–0.31	Cooper et al., 1997
				0.019–0.03	Obarska-Pempkowiak and Gajewska, 2005
				0.04	Gajewska and Ambroch, 2012
TN					
Scope	0.16	Tanner et al., 1995a, 1995b	Scope	0.007–0.1	Kadlec and Knight, 1996
	0.06	Wittgren and Maehlum, 1997		0.028	Kadlec et al., 2000
	0.048–0.127	Obarska-Pempkowiak and Gajewska, 2005		0.018–0.025	Obarska-Pempkowiak and Gajewska, 2005
	0.09–0.19	Gajewska and Ambroch, 2012		0.03	Gajewska and Ambroch, 2012

VF beds:

$$C_{out}/C_{in} = \exp.(-k_A/q) \qquad (4)$$

where q is the hydraulic loading rate in m d^{-1} (calculated as the ratio of the flow rate, Q in $m^3\ d^{-1}$ and surface area, A in m^2) and k_A is the decomposition constant in m d^{-1} (Brix and Johansen, 1999; Gajewska et al., 2018).

Most processes in wetlands are dependent on wetland area, so k-rates used in the wetland literature are often area-based coefficients (k_A – as surface area, A, is present in the formula for q in (4)) (Arias et al., 2017). It should be noted that the Eqs. (2)–(4) are various forms of the same equation, which could be transformed to calculate missing data like surface area [A] when all other data are provided.

As wastewater temperature effects k-rate coefficients, they can be adjusted for temperature using parameter (θ). K rates are usually corrected to a temperature standard of 20 °C in the literature. The temperature (T) effect in Eqs. (3) and (4) is expressed by the constant k_T (k_A or k_v), which is determined by the use of an Arrhenious equation, as follows (Akratos et al., 2009; Arias et al., 2017):

$$k_T = k_{20}\ (\theta)^{T-20} \qquad (5)$$

where k_T is the rate constant at the measured temperature $T = T$ °C, k_{20} is the rate constant at 20 °C, θ is Arrhenius coefficient (temperature coefficient).

3. Results and discussion

The BOD_5/COD ratio is an indicator of organic matter biodegradability. Its value above 0.5 indicates that the organic matter is easily biodegradable, whereas, a ratio lower than 0.3 signifies that the organic

Table 2
The operation conditions of hybrid constructed wetland systems.

Plant	Flow [$m^3\ d^{-1}$] (PE)	Configuration	Area [m^2]	Depth of bed [m]	Hydraulic load [mm d^{-1}]	BOD_5 load [g O_2 $m^{-2}d^{-1}$]
Darżlubie (north Poland)	56.6	HF I	1200	0.6	47.3	6.80
	(650)	Cascade bed	400	0.6	141.2	
		HF II	500	1.0	113.4	
		VF	250	0.6	226.8	
		HF III	1000		56.7	
			Σ3350			
Wiklino (north Poland)	18.6	HF I	1050	0.6	19.5	2.20
	(202)	VF I	624	0.4	65.7	
		HF II	540	0.6	38.0	
			Σ 2214			
Pilot Wschód[a] (north Poland)	0.24	VF I	7.5	0.6	3.2	8.44
	(5)	VF II	5.0	0.6	4.8	3.56
		HF	3.9	0.6	16.3/23.5	2.19
			Σ 16.4			
Inwałd (south Poland)	26–119	HF	3000	0.6	22.7–37.7	19.07
	(800)					
Sadowa (central Poland)	16–20	HF	1980	0.6	24.0	5.88
	(150)					
Janów (eastern Poland)	0.66	VF	18	0.8	37.0	10.17
	(3)	HF	30	1.2		
			Σ 48			
Dąbrowica I (eastern Poland)	0.3	HF	24	1.0	12.0	3.23
	(3)	VF	24	0.8		
			Σ 48			
Dąbrowica II (eastern Poland)	0.3	VF	24	0.8	12.0	3.23
	(3)	HF	24	1.0		
			Σ 48			

[a] The system for treatment of leachate from sludge dewatering process.

matter is difficult to degrade in wastewater treatment process. In most of the constructed wetlands, analyzed BOD_5/COD ratios rarely exceeded 0.5 (Canga et al., 2011; Saeed and Sun, 2011).

Large multistage systems (Darżlubie and Wiklino) as well as single-stage systems (in Sadowa) generally provided more stable effluent quality than small, single-household systems, in which a wide range of pollutants concentrations in the outflow was obtained (e.g. Dąbrowica I and II) (Table 3).

The BOD_5 and TN removal k-rates in horizontal and vertical flow beds in subsequent years of operation were calculated and given separately for each year (see Figs. 1–3).

The results of organic matter (BOD_5) removal in HF beds presented in the Fig. 1 do not clearly indicate a dependence of the k-rates on the time of operation. In the small-scale constructed wetlands operated in Dąbrowica I, II and Janów, removal rate coefficient of BOD_5 was unstable in time. The longest monitored facility was Inwałd – a large-scale horizontal flow system – after an initial year of 'start-up time', the rate of BOD5 removal gradually increased to reach an apex in the 11th and 12th year of operation, afterwards it gradually dropped. In the beds operating for over a dozen years the k-rates were more stable and did not change significantly. The highest values for this period of operation, apart from Inwałd, were recorded for the second-stage HF bed in Darżlubie.

The calculated first-order reaction rates constant for TN in horizontal flow filters fluctuated in time. The highest values, though with a decline in trend, were obtained in the 4th, 5th and 6th year of operation in Wiklino, especially in the second-stage bed. The results from the initial period in Dąbrowica and the following years in Wiklino also confirmed higher efficiency of the second-stage bed.

During the initial years of operation higher rate coefficients of BOD_5 and TN were achieved in vertical flow beds located at the first stage of treatment. In the systems tested after a long period of time, better results occurred in the VF bed subjected to higher pollutant loading rates but lower hydraulic loads (Darżlubie). Under opposite operating conditions in Wiklino, the maximum coefficients for BOD_5 and TN occurred in the 6th year of operation.

Our results confirmed previous investigations and literature data that first-order removal rate constants are not a constant in time. It varies with age of a system, hydraulic loading as well as organic and nutrient loadings (Trang et al., 2010; Kadlec and Wallace, 2009; Gajewska and Ambroch, 2012; Mucha et al., 2018). For the system working with similar hydraulic and pollutants regimes the values of k- rates fluctuates in time of operation. For studied HCW, both horizontal and vertical bed systems, k-rates were lower in the first years of operation, what could be explained by not fully developed root system, which is needed for creation of adequate environment for the microorganisms to grow. Received results indicate that in third year of operation k-values are 20% higher on average in comparison to k-values in first year of operation for both VF and HF beds. In subsequent years of operation the k-values fluctuation is rather connected with the way of system operation, like changing hydraulic load or organic load, which happen in Polish condition quite often due to e.g. connection of new residential buildings (Gajewska and Obarska-Pempkowiak, 2011; Mucha et al., 2018). In working condition of Polish HCW, organic and nutrient composition of wastewater seems to play an important role. Thus we elaborate further the mass removal rates, BOD_5/COD and BOD_5/TN ratio and k-values.

Table 3
Influent and effluent concentrations of BOD_5 and TN in analyzed CW system (min–max).

Plant	Influent		Effluent	
	BOD_5 [mg L^{-1}]	TN [mg L^{-1}]	BOD_5 [mg L^{-1}]	TN [mg L^{-1}]
Darżlubie	340–390	114–129	28–32	9–11
Wiklino	281–500	118–148	11–20	18–28
Pilot Wschód[a]	320–501	710–860	11–25	121–188
Inwałd	80–2750	26–211	10–280	30–135
Sadowa	120–440	26–61	10–200	9–29
Janów	104–389	37–97	1–74	16–40
Dąbrowica I	99–338	109–202	1–39	35–136
Dąbrowica II	99–338	109–202	0–98	16–112

[a] The system for treatment of leachate from sludge dewatering process.

In this research mass removal rates (MRR) after each stage of treatment were analyzed, in HF as well as VF beds. The results including MRR and *k*-values for total nitrogen and biochemical oxygen demand are presented in Table 4 (for HF beds) and Table 5 (for VF beds). In addition, the following data are presented in relation to influent loads, hydraulic retention time (HRT) and wastewater temperature.

The MRR values obtained in HF beds indicate that organic matter decomposition was the most advanced process, while TN removal was slightly less effective. A very unique, high MRR of BOD_5 (21 g O_2 m^{-2} d^{-1}) was obtained in one-stage system in Inwałd. It is also reflected in its high k_{20}-value (0.129 d^{-1}). Such results can be associated with large surface area of the system and relatively good BOD_5/COD ratio around 0.45.

Considering multi-stage systems operated in Darżlubie and Wiklino, the nitrogen removal rate in horizontal flow beds varied from 0.506 to 3.360 g m^{-2} d^{-1}, and from 0.842 to 1.119 g m^{-2} d^{-1}, respectively. HF beds in Darżlubie and Wiklino worked most effectively at the first treatment stage. It was noted that with the subsequent stages the MRR value was gradually decreasing. This trend is reflected in the BOD_5/TN ratio, as in the inflow it was about 3.0, which is below the minimal optimal value ensuring effective nitrogen removal (optimal is around 4.0), and after subsequent treatment stages the ratio decreased to about 1.0 for Wiklino and 2.2 for Darżlubie. Determination of BOD_5/COD ratio helped to recognize the biodegradability of pollutants (Gajewska et al., 2015). In the case of these two plants, this ratio also decreased with the successive treatment steps: from 0.4–0.5 to 0.25 on average, which indicates a decline in the amount of readily biodegradable contaminants affecting the denitrification process in particular.

Interestingly, relatively low k-values were recorded for TN in the last five systems listed in the table above (Table 4), from 0.003 to 0.016 d^{-1}. However, it is not confirmed by the favorable ratios of BOD_5/TN (8.97 and 6.51) and BOD_5/COD (0.45 and 0.7) in the systems located in Inwałd and Sadowa. This may indicate that the removal of nitrogen compounds depends not only on the quality of wastewater, but also on the conditions occurring in wetland, such as availability of oxygen, retention time and configuration of beds in the system.

In vertical flow beds the differences of MRR values of nitrogen and organic matter are much smaller and balanced. A very high rate of BOD_5 (9.57 g m^{-2} d^{-1}) removal in the two-stage treatment plant in Janów occurred in the VF bed, which was operated as the first stage of treatment. This is reflected in the high BOD_5/COD ratio, which was equal to 0.55 in the influent.

On the basis of the graph showed in Fig. 4, where BOD_5 and TN mass removal rates for the analyzed constructed wetlands (both HF and VF beds) are presented, it is possible to determine which types of beds are more efficient.

The performance of HF beds in Dąbrowica I and Dąbrowica II also indicates the first treatment stage as a more effective one, especially for organic matter removal (1.30 g m^{-2} d^{-1} and 0.08 g m^{-2} d^{-1}, respectively). A very low BOD_5/TN ratio (0.56) in the influent to the HF bed working as second stage also confirms low rate of nitrogen removal in this case.

When analysing HF and VF beds for the removal of organic compounds expressed by k-rates, the performance of vertical flow beds was slightly more effective than that of horizontal flow beds. In the case of total nitrogen removal, k-rates values in horizontal and vertical flow beds were relatively even and comparable. Also, in multistage constructed wetland systems (in Darżlubie and Wiklino), HF beds were slightly more efficient in the removal of TN and BOD_5 than VF beds (Tables 4 and 5).

Although the k-values are not stable in time of operation of the system, which we also confirmed in our investigation we decided to

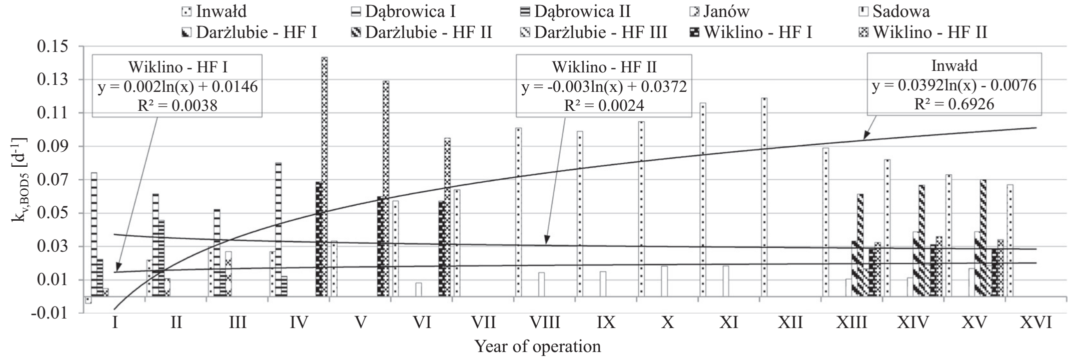

Fig. 1. BOD_5 removal k-rates in horizontal flow beds in subsequent years of operation. Regression lines and corresponding equations and correlation coefficients are presented.

elaborate the nomographs. These nomographs could be helpful during the prediction of performance or dimensioning of the constructed wetland system for wastewater treatment for more than 50 PE. As a justification for our decision to using all data and averaging them, could be the assumption of trend line appointed for both VF and HF beds working in HCWs, for which we had monitoring data form at least 9 years of operation. These trend lines revealed relatively stable rates of yearly k-values (Figs. 1–3) in long monitoring period (longer than 9 years).

The nomographs presented below allow to determine k-rate coefficients for nitrogen removal depending on the temperature of wastewater and the expected retention time in horizontal flow beds (Fig. 5).

The ranges of hydraulic retention time and temperature given in the graph in the Fig. 5 are 2.1–16 d and 5–18 °C, respectively. The given values of wastewater temperature refer to a temperate climate. As can be seen in the Fig. 5, wastewater temperature has a predominant influence on k_{20TN} values, although the increase in HRT also directly contributes to higher removal rates.

With the help of the next graph (Fig. 6) it is possible to estimate the rate of nitrogen removal in vertical flow beds in relation to the applied hydraulic load (in this case in the range 13–113 mm d^{-1}) and wastewater temperature (5–20 °C).

So far, the constant values of $k_{\nu,TN}$ and $k_{A,TN}$ for such a large range of temperatures and retention times or hydraulic loads in HF and VF wetlands have not been presented in literature. This causes difficulties in comparing and evaluating the results obtained with available data. Trends presented in the literature indicate that the constant $k_{\nu,TN}$ assumes higher

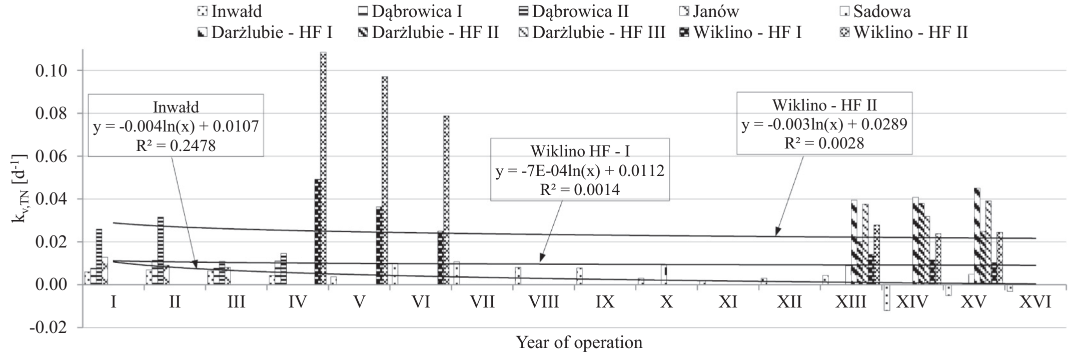

Fig. 2. Total nitrogen removal k-rates in horizontal flow beds in subsequent years of operation. Regression lines and corresponding equations and correlation coefficients are presented.

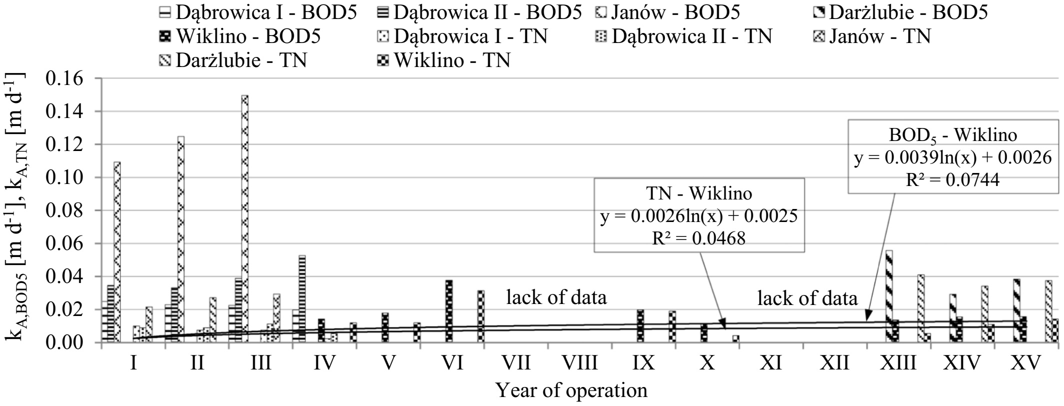

Fig. 3. Total nitrogen and BOD_5 removal k-rates in vertical flow beds in subsequent years of operation. Regression lines and corresponding equations and correlation coefficients are presented.

Table 4
Average parameters of BOD_5 and TN removal rates in analyzed HF beds.

			HF							
Plant	Temperature	HRT	BOD_5				TN			
			Influent loading rate	MRR	k_v	k_{20}	Influent loading rate	MRR	k_v	k_{20}
	°C	d	$g\ O_2\ m^{-2}\ d^{-1}$	$g\ O_2\ m^{-2}\ d^{-1}$	d^{-1}	d^{-1}	$g\ N\ m^{-2}\ d^{-1}$	$g\ N\ m^{-2}\ d^{-1}$	d^{-1}	d^{-1}
Darżlubie HF I	12.5	5.1	17.41	9.56	0.038	0.056	5.710	3.360	0.042	0.064
HF II		2.1	18.83	4.56	0.067	0.101	5.620	0.736	0.029	0.040
HF III		4.2	2.38	0.66	0.018	0.026	1.070	0.506	0.036	0.053
Wiklino HF I	11.8	12.3	6.77	5.52	0.030	0.047	2.310	1.119	0.012	0.019
HF II		6.3	1.47	0.92	0.034	0.052	1.630	0.843	0.025	0.038
Inwałd	11.4	7.5	19.22	21.14	0.085	0.129	3.020	0.231	0.006	0.009
Sadowa	10.2	13.2	2.66	2.04	0.015	0.025	0.410	0.245	0.008	0.016
Janów	12.5	13.4	0.37	0.13	0.015	0.021	0.890	0.322	0.010	0.016
Dąbrowica I	12.2	16.0	2.11	1.30	0.013	0.020	1.679	0.238	0.002	0.003
Dąbrowica II	12.2	16.0	0.23	0.08	0.005	0.007	0.896	0.217	0.004	0.006

Table 5
Average parameters of BOD_5 and TN removal rates in analyzed VF beds.

VF										
Plant	Temperature	Unit hydraulic load q_A	BOD_5				TN			
			Influent loading rate	MRR	k_A	k_{20}	Influent loading rate	MRR	k_A	k_{20}
	°C	$mm\ m^{-2}$	$g\ O_2\ m^{-2}\ d^{-1}$	$g\ m^{-2}\ d^{-1}$	$m\ d^{-1}$	$m\ d^{-1}$	$g\ N\ m^{-2}\ d^{-1}$	$g\ m^{-2}\ d^{-1}$	$m\ d^{-1}$	$m\ d^{-1}$
Darżlubie	12.5	1.8	11.16	1.75	0.038	0.058	5.0	0.76	0.037	0.050
Wiklino	11.8	4.8	2.11	0.84	0.015	0.023	2.0	0.59	0.011	0.016
Janów	12.5	6.5	10.18	9.57	0.130	0.196	3.03	1.54	0.026	0.037
Dąbrowica I	12.2	9.6	0.81	0.66	0.023	0.035	1.44	0.56	0.007	0.011
Dąbrowica II	12.2	9.6	2.11	1.88	0.040	0.058	1.68	0.78	0.009	0.013

values at temperatures above 5 °C and increases with the retention time in HF bed, which is also confirmed by the data obtained in this study. Similarly, for VF beds, $k_{A,TN}$ constant values are inversely proportional to hydraulic load and directly proportional to temperatures.

In the results obtained in Dąbrowica I (HF-VF) and Dąbrowica II (VF-HF), which were operated in the same local conditions and with the same wastewater, the influence of the configuration on the kinetic removal rates was observed. In the system with the vertical flow bed at the beginning of treatment process (VF-HF) k-rates calculated for organic matter and nitrogen compounds removal were higher in general in comparison to HF-VF system. The only exception to the trend presented above was the removal of BOD_5 in horizontal flow beds, which was more effective with HF-VF configurations. In the systems operated in Dąbrowica I and II the BOD_5/COD ratio did not much affected

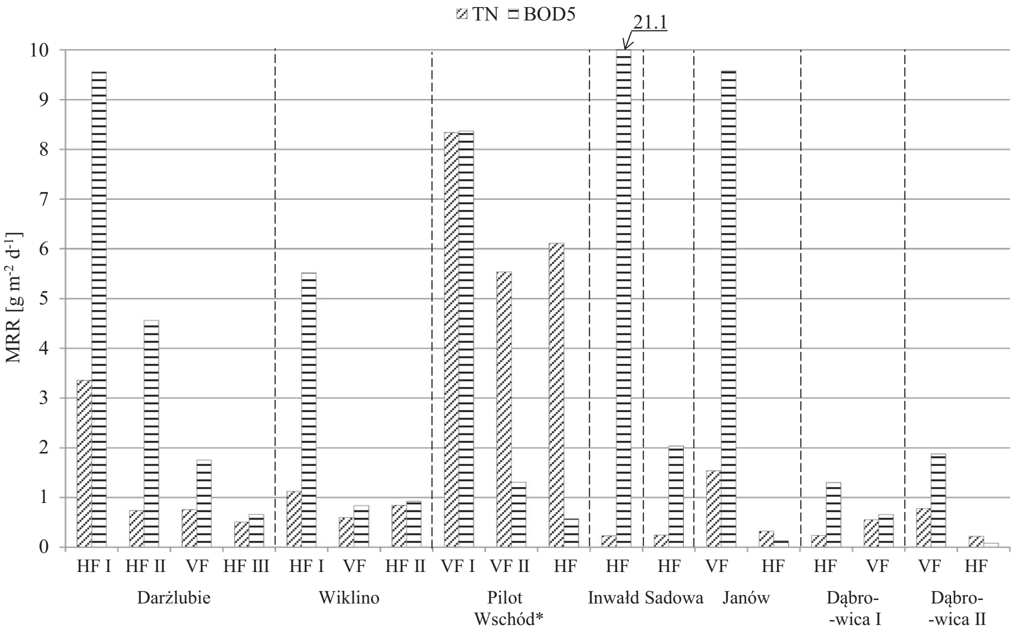

Fig. 4. Average mass removal rates (MRR, $g\ m^{-2}\ d^{-1}$) of TN and BOD_5 in analyzed HF and VF beds. *The system for treatment of leachate from sludge dewatering process.

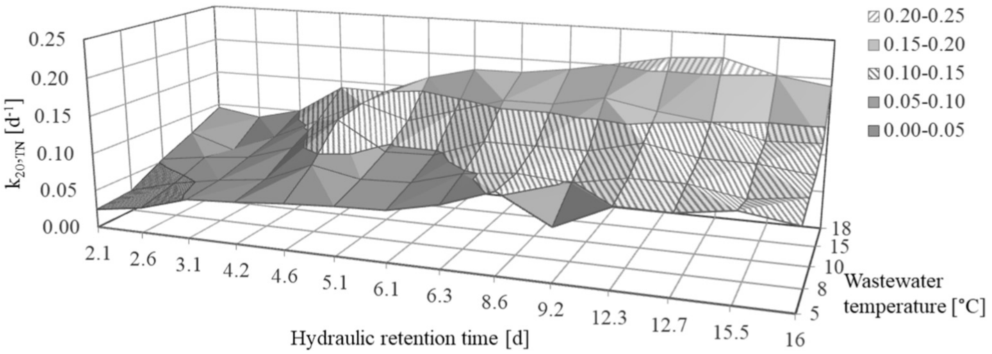

Fig. 5. Dependence of constant removal of total nitrogen ($k_{20,TN}$) on the temperature and hydraulic retention time in HF beds in analyzed systems.

treatment results. Generally, in HF beds there is no direct effect of BOD_5/COD ratio on higher removal rates.

Considering the literature data published by different authors (Table 1), average k-rates obtained in analyzed systems remained in the lower range of values in general. In horizontal flow beds the rate coefficients for BOD_5 and TN were in the range of 0.007–0.129 and 0.003–0.064, respectively (Table 4), and were mostly lower than those reported in the literature, especially in the case of total nitrogen. In vertical flow beds, the k-rates are comparable to the values quoted by other authors.

Hydraulic retention time (HRT) is an important parameter when considering the kinetics of chemical and microbial transformations in constructed wetlands. HRT within the range 2–10 d have been reported to improve nitrogen removal especially in HF beds and these values are dominant in analyzed Polish systems. Increased retention time occurring in Dąbrowica (16 d) is considered as a quite long detention time which is not so often observed. Significant increase of HRT did not much facilitate nitrogen removal in this system.

4. Conclusions

1. The obtained results confirmed variations of total nitrogen and organic matter *k*-values in time of operation of constructed wetlands for wastewater treatment in temperate climate. Although the yearly k-values fluctuations in time of operation did not exceed 20% for the analyzed HCW.
2. Much bigger differences of efficacy kinetics have been were observed for both VF and HF beds working in different analyzed HCWs. Nitrogen removal rate - k_{20} - in horizontal flow beds varied from 0.003 to 0.064 d^{-1} and for vertical flow beds varied from 0.011 to 0.05 m d^{-1}.
3. In general, the total nitrogen and organic matter k-values obtained in this investigation were lower than the values shown in literature, most likely due to much bigger unit area for a PE applied in HCWs in Poland (even up to 12 m^2 PE^{-1}).
4. Kinetic coefficients derived from first-order equation model coincided with higher pollutant loading, indicating that the coefficients varied probably due to the factors such as hydraulic loading and influent pollutant concentration.
5. The uneven values of pollutants removal rates in the analyzed systems reflected the complexity of processes in subsurface flow beds. Referring to mass removal rate indicator, it was found that the higher the load of pollutants applied to the beds, the higher MRR values were obtained. The impact of the BOD_5/COD and BOD_5/TN ratios on the MRR in analyzed horizontal and vertical constructed wetlands was not observed as significant.
6. Compiled graphs of removal of total nitrogen constant ($k_{20,TN}$) should be treated as approximate ranges of these values depending on the temperature and hydraulic load in VF or hydraulic retention time in HF beds.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

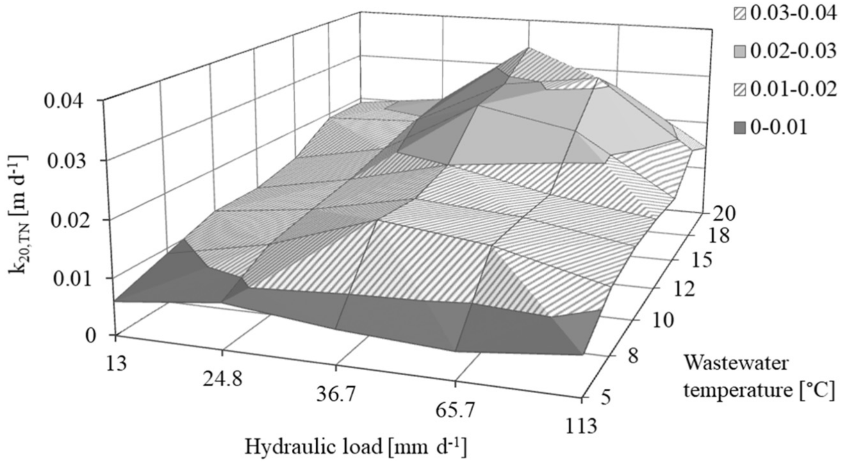

Fig. 6. Dependence of constant removal of total nitrogen ($k_{20,TN}$) on the temperature and hydraulic load in VF beds in analyzed systems.

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