Effectiveness of septage pre-treatment in vertical flow constructed wetlands
Beata Karolinczak and Wojciech Dąbrowski

ABSTRACT
Septage is wastewater stored temporarily in cesspools. A periodic supply of its significant quantities to small municipal wastewater treatment plants (WWTPs) may cause many operational problems. In the frame of the research, it has been proposed to utilize vertical flow constructed wetlands for pre-treatment of septage prior to its input to the biological stage of a WWTP. The aim of the work was to assess the effectiveness of pre-treatment in relation to factors such as: seasonality, hydraulic load, pollutants load of the VF bed and interactions between these factors. The results proved that application of a VF bed to septage pre-treatment can significantly reduce the concentration of pollutants (biochemical oxygen demand (BOD5): 82%, chemical oxygen demand (COD): 82%, total suspended solids (TSS): 91%, total nitrogen (TN): 47%, ammonia nitrogen (NH4-N): 70%), and thus decrease the loading of the biological stage of a WWTP. The mathematical models of mass removal process were created. They indicate that in case of all analysed parameters, removed load goes up with the increase of load in the influent. However, with the increase of hydraulic load, a decrease of the removed BOD5, COD, TSS and total phosphorus, and in vegetation period an increase of TN, can be observed in terms of load. There are no statistically significant effects of seasonality.

Key words | pre-treatment, septage, septic tank, treatment modelling, vertical flow constructed wetlands (VF-CW, SS VF)

INTRODUCTION
Septic tanks are a widespread solution in rural areas of Poland, since only 37% of the population use the sewage system (GUS 2015). Septage quality is significantly different from the quality of municipal and household wastewater because of long term storage and abnormalities in cesspools’ management.

Periodic supply of significant quantities of septage to small wastewater treatment plants (WWTPs) in rural areas may cause many operational problems, such as: increase of the contamination load and its irregularity, an increase of energy consumption, increase of the sludge quantity as well as accumulation of foam in aeration chambers and sedimentation tanks. As a result, there are difficulties in meeting the required effluent standards and there are problems with the reliability of WWTPs. The problem has not been solved despite the installation of septage receiving stations and retention tanks (US EPA 1994; Liénard & Payrastre 1996; Strauss et al. 1997; Paing & Voisin 2005; Al-Sa‘ed & Hithnawi 2006).

It is estimated that the problem of overloading small WWTPs will grow with the increasing amount of treated septage (GUS 2015; Troesch et al. 2009). Introduction of more effective legal regulations in the field of septage management causes an increase of the amount of treated septage, which worsens the changes of compliance (Liénard & Payrastre 1996; Paing & Voisin 2005; Troesch et al. 2009). Due to this fact, many small WWTPs will require modernization.

A possible solution is using VF beds to pre-treat septage prior to its input to the biological stage of WWTPs. Before feeding the bed, septage goes to a receiving station equipped with a device for mechanical treatment, and then to a retention tank. According to Science Direct, no studies on septage pre-treatment in VF beds in the climatic conditions of Eastern Europe have been carried out thus far (date of search: 1 April 2017, keywords: septage, constructed wetlands (CWs)).

The usage of CWs for septage treatment has been researched in Western and Southern Europe (Liénard & Payrastre 1996; Paing & Voisin 2005; Troesch et al. 2009; Vincent et al. 2011), North America (Kinsley & Crolla...
In the autumn period, VF beds are rested for 5 weeks; the applied SLR possibility of transferring the experiments with sewage once a week. The load was increased to 300 TSS kg m⁻² y⁻¹. Troesch et al. (2009) examined the possibility of transferring the experiments with sewage sludge dewatering to treating septage. The research was conducted on beds filled up to 0.45 m, planted with Phragmites australis, with a casing reaching 0.8 m above their surfaces. In the first year of the plants' vegetation, SLR was at 30 kg TSS m⁻² y⁻¹. The beds were supplied with septage for 3 days, then they rested for 20 days. The research was continued by Vincent et al. (2011) in order to examine the influence of TSS load on septage treatment effectiveness. The aim of the research conducted in Africa was to determine the possibility of septage dewatering in a VF bed planted with Antelope grass (Echinocloa Pyramidalis) (Kengne et al. 2009). With the load between 100 to 200 kg TSS m⁻² y⁻¹, the system functioned properly in terms of separating liquid and solid fraction, reaching over 30% effectiveness in dewatering. Clogging was observed when the load was increased to 300 TSS kg m⁻² y⁻¹.

In North America, Kinsley & Crolla (2013) conducted research on beds filled up to 0.75 m and planted with common Phragmites australis. The casing rose 2 m above their surfaces and its role was to accumulate sludge for 7 to 10 years. The bed's average hydraulic load was 3.5 m y⁻¹ (around 0.01 m d⁻¹). The average load of suspended solids exceeded 80 kg TSS m⁻² y⁻¹. The exploitation guidelines suggested supplying the bed with 0.075 to 0.15 m of septage once a week.

While analyzing the guidelines for beds' loads resulting from the research conducted so far, some major differences can be noticed: in temperate climate conditions 40 kg TSS m⁻² y⁻¹ (Liénard & Payrastre 1996), 30 kg TSS m⁻² y⁻¹ during bed startup, later 50 TSS kg m⁻² y⁻¹ (Vincent et al. 2011), 80 kg TSS m⁻² y⁻¹ (Kinsley & Crolla 2013). In tropical climate conditions the load might increase even up to 250 kg TSS m⁻² y⁻¹ (Koottatep et al. 2005). The assumed pollutants load indicator for a bed was based on a solid load rate. Such an assumption was based on very high concentrations of TSS: 12,900 ± 10,110 mg l⁻¹ in Thailand (Koottatep et al. 2005), 28,158 ± 11,094 mg l⁻¹ in France (Troesch et al. 2009) and 19,500 ± 2,700 mg l⁻¹ in Canada (Kinsley & Crolla 2013). The beds were supplied with septage once every 6–20 days. For this reason, the beds' construction and exploitation was similar to sludge treatment reed beds. In the research presented in this article, the applied wastewater wetland is typical for sewage treatment, not sludge treatment. The bed was supplied for 5 days with one batch per day (HLR 0.1 or 0.05 m d⁻¹), then it rested for 2 days. The bed was supplied with septage after sedimentation, unlike in the French system, where the primary treatment is omitted.

The aim of the work was to assess the effectiveness of septage pre-treatment in VF beds typical for sewage treatment. The mathematical mass models of removed load in relation to factors such as seasonality, hydraulic load, pollutants load and interactions between these factors were elaborated. The aim of the article includes future research directions formulated by Tan et al. (2015) in their article Septage treatment using vertical-flow engineered wetland: a critical review. The authors noticed that the current models of pollutants removal concern the application of municipal wastewater treatment, whereas there is no such model for septage treatment, although it is necessary to ensure the efficient performance of VF beds.

**METHODS**

The research was conducted over a 12-month period using a pilot-scale plant built in the Municipal WWTP in Sokółka (Podlasie Province) (Figure 1). The plant was designed and built by the authors. Its main element is a VF bed with a 5 m² surface area and 0.65 m depth. In addition, the installation includes two buffer tanks, a 5 mm sieve, pump, feeding system and control wells.

The bed was built of three layers: 1 – stones (16–60 mm): 0.15 m, II – gravel (2–16 mm): 0.55 m and III – sand (0.5–2 mm): 0.15 m. The bottom and sides were covered with...
tiles and sealed with waterproof membranes in order to support the whole construction. A supplying system constructed with ø50 mm PVC pipes was installed on the surface. In order to prevent the filling matter in the bed from being washed out by the stream of septage, the outflow of the pipe was secured with concrete tiles. A collecting system constructed with ø50 mm drainage pipes and covered with stones was installed on the bed’s bottom. A system of six vertical pipes, connected with the collecting system, ensured passive ventilation.

The bed was planted with *Phragmites australis* reeds. Three-year-old seedlings were used, which allowed a faster start-up of the operation. The start-up period lasted about 1 year (from March 2010 until April 2011). In the initial period of exploitation, according to the guidelines provided by Troesch et al. (2009) and Kinsley & Crolla (2013), in order for the plants to adapt well, the bed was first supplied with treated sewage (1 month), then with raw sewage (2 months) and finally with septage (9 months). After winter, dry stems were cut and removed from the bed. Maintaining a high level of bed filling was possible due to applying a regulated outflow. The rise in air temperature enabled the reed to grow intensively and new sprouts to appear. It was recognized as the beginning of the proper exploitation phase (Heinss & Koottatep 1998) and thus the beginning of the research. The study was carried out over a 12 month period (V 2011-IV 2012). Twenty four sampling series were collected with the hydraulic load of 0.05 and 0.1 m d⁻¹. The bed was loaded with a single batch for 5 days a week followed by 2 days of resting period (weekends). Only domestic septage fed the bed. The average air temperature during the vegetation period (May–October) was 18.4 °C. In the non-vegetation period (November–April) it was 2.9 °C.

The basic physical and chemical analyses were performed: biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), TSS, total Kjeldahl nitrogen (TKN), ammonia nitrogen NH₄-N, nitrate nitrogen (V) NO₃-N, and total phosphorus (TP). Pollutants loads in influent and effluent were used to calculate the removed load. Determinations were conducted in a certified laboratory in accordance with the procedures set out in the Regulation of the Environmental Protection Minister from 18 November 2014 (Rozporządzenie Ministra Środowiska z dnia 18 listopada 2014) and in accordance with the American Public Health Association (2005). Removal efficiency was calculated as a concentration reduction, according to the terminology given by Kadlec & Wallace (2009). Results were evaluated statistically in order to determine the effect of all factors (hydraulic load HLR, contaminations load ɪᵣᵦ, seasonality veg and their interactions) on the size of the removed pollutants load. The linear regression with t-test of the significance coefficients was applied, following Hocking’s (1976) and Thompson’s (1978) recommendation. The analysis was performed separately for each of the parameters BOD₅, COD, TSS, total nitrogen (TN), TP:

\[
\begin{align*}
\text{ɪᵣᵦ} \cdot \text{veg} &= a \cdot \text{ɪᵦ} + b \cdot \text{HLR} + c \cdot \text{veg} + d \cdot \text{ɪᵦ} \cdot \text{veg} \\
+ e \cdot \text{ɪᵦ} \cdot \text{HLR} + f \cdot \text{HLR} \cdot \text{veg} + g \cdot \text{ɪᵦ} \cdot \text{HLR} \cdot \text{veg} + h
\end{align*}
\]

ɪᵦ - unit removed load [g m⁻² d⁻¹],
ɪᵦ - unit influent load [g m⁻² d⁻¹],
HLR - hydraulic load rate [m d⁻¹],
veg - seasonality [(1) vegetation period, (0) non-vegetation period],
ɪᵦ · veg, ɪᵦ · HL, HLR · veg, ɪᵦ · HLR · veg - interactions,
a, b, c, d, e, f, g - coefficients of linear regression,
h - free term.
In case of NH4-N and TKN, a linear regression was obtained on a logarithmic scale.

\[
\ln(l_{\text{in-out}}) = a \cdot \ln(l_{\text{in}}) + b \cdot \text{HLR} + c \cdot \text{veg} + d \cdot \ln(l_{\text{in}}) \cdot \text{veg} + e \cdot \ln(l_{\text{in}}) \cdot \text{HLR} + f \cdot \text{HLR} \cdot \text{veg} + g \cdot \ln(l_{\text{in}}) \cdot \text{HLR} \cdot \text{veg} + h
\]

That is:

\[
l_{\text{in-out}} = (l_{\text{in}})^a \cdot e^{b \cdot \text{HLR}} \cdot e^{c \cdot \text{veg}} \cdot (l_{\text{in}})^d \cdot \text{veg} \cdot (l_{\text{in}})^e \cdot \text{HLR} \cdot e^{f \cdot \text{HLR} \cdot \text{veg}} \cdot (l_{\text{in}})^g \cdot \text{HLR} \cdot \text{veg} + h
\]

At the beginning, the full models containing all dependent variables (HLR; veg.: 0 – no, 1 – yes; \( l_{\text{in}} \)) and their possible interactions \( l_{\text{in}}^a \cdot \text{veg}, l_{\text{in}}^a \cdot \text{HLR}, \text{veg}^a \cdot \text{HLR}, l_{\text{in}}^a \cdot \text{veg}^a \cdot \text{HLR} \) were created. In the following steps, the least significant variables were removed. The final model was built in a maximum six steps, as there were six coefficients in the full model. In each step, the statistical significance was assessed for all current regression coefficients. The part of the model with the least statistically significant coefficient was removed. Modelling proceeded with other parts of the model to the next step, until the statistical significance of every coefficient was less than 1%. A high significance level was chosen in order to make the final model less sensitive to data randomness. The final models included only statistically significant variables. Moreover, in each step the fulfilment of linear regression assumptions was tested: normality of the residuals by means of the Shapiro–Wilk test and the independence of the distribution of residues of matching values on the scatter plot.

Due to the fact that the models were built on the basis of empirical data, they have a defined range of applicability. The applicability range was determined based on hydraulic and pollutants loads during the research period.

**RESULTS AND DISCUSSION**

**Septage characteristic and VF bed pre-treatment effectiveness**

The concentrations of pollutants in influent to the SS VF bed were at (median ± st. deviation): 1,094 ± 3,841 mg TSS l\(^{-1}\), 1,280 ± 2,174 mg BOD\(_5\) l\(^{-1}\), 2,599 ± 3,763 mg COD l\(^{-1}\), 143.0 ± 70.1 mg N – NH\(_4\)-N l\(^{-1}\), 221.0 ± 103.7 mg TKN l\(^{-1}\), 226.2 ± 103.7 mg TN l\(^{-1}\), 30.2 ± 22.7 mg TP l\(^{-1}\).

Looking at the concentrations of pollutants in raw septage, it can be noticed that they are lower than reported in other countries (US EPA 1994; Koottatep et al. 2005; Vincent et al. 2011; Kinsley & Crolla 2013; Krithika et al. 2017). Only domestic septage delivered from household septic tanks, which were emptied at least once a year (as required by law), was used in the research.

However, these values are definitely higher than the ones observed in raw sewage treated in the analyzed WWTP in Sokółka, as well as typical domestic and municipal sewage treated in CWs (Gajewska et al. 2015; Obarska-Pempkowiak et al. 2015a). The differences in septage quality given by other authors may be caused by combining household and industrial septage in some cases. The most important factors affecting its quality are: climate, hygienic habits of inhabitants, type of sanitation as well as how leak proof the cesspools were and the frequency of their emptying. According to the US EPA (1994) such a wide variation of septage quality requires local research on its treatment process. It was also pointed out by the authors of the article *Septage treatment using vertical-flow engineered wetland: a critical review* (Tan et al. 2015).

The concentrations of pollutants in effluent from the SS VF bed were at (median ± st. deviation): 100 ± 59 mg TSS l\(^{-1}\), 200 ± 116 mg BOD\(_5\) l\(^{-1}\), 408 ± 171 mg COD l\(^{-1}\), 24.6 ± 59.4 mg NH\(_4\)-N l\(^{-1}\), 41.8 ± 48.1 mg TKN l\(^{-1}\), 94.8 ± 53.5 mg TN l\(^{-1}\), 6.5 ± 3.7 mg TP l\(^{-1}\).

The concentrations of pollutants in pre-treated septage were similar to those observed in raw sewage treated in the examined WWTP in Sokółka (mean values: 209 mg TSS l\(^{-1}\), 280 mg BOD\(_5\) l\(^{-1}\), 581 mg COD l\(^{-1}\), 58 mg N-NH\(_4\)-N l\(^{-1}\), 70 mg TKN l\(^{-1}\), 73 mg TN l\(^{-1}\), 30 mg TP l\(^{-1}\)). Therefore, it can be concluded that the input of septage pre-treated in an SS VF bed will not harm the processes in the biological stage of WWTPs.

Box and whiskers plots have been chosen as a graphical interpretation of the statistical analysis of influent, effluent and removed loads (Figures 2 and 3). The average values for pollutants’ removal effectiveness (median ± standard deviation) are presented below the plots.

The SS VF bed showed the highest efficiency among the analysed parameters in removing TSS and organic matter (BOD\(_5\) and COD). TN was removed with the lowest efficiency. The research was carried out under the conditions of high load of organic matter expressed in BOD\(_5\); the unit surface of the bed did not exceed 1 m\(^2\) PE. The average loads of the bed were at: 163 g BOD\(_5\) m\(^{-2}\) d\(^{-1}\), 299 g COD m\(^{-2}\) d\(^{-1}\), 192 g TSS m\(^{-2}\) d\(^{-1}\), 11 g NH\(_4\)N m\(^{-2}\) d\(^{-1}\), 16 g TKN m\(^{-2}\) d\(^{-1}\), 17 g TN m\(^{-2}\) d\(^{-1}\), 3 g TP m\(^{-2}\) d\(^{-1}\).
Septage pre-treatment modelling

The results of the regression analysis allowed researchers to determine the factors that influence the removed pollutant load. On the basis of statistically significant variables, mathematical models have been formulated. The abbreviation \( \text{veg} \) which appears in interactions stands for seasonality. The value assigned for \( \text{veg} \) is ‘1’ in vegetation period and ‘0’ in...
non-vegetation period. Thus, the interaction with seasonality means that the model varies in form during the vegetation and non-vegetation periods. The elaborated models are presented in Table 1.

In cases of all models, high values of determination coefficient indicate their good fit. The established dependencies might be used in designing CWs for septage pre-treatment in the climatic conditions of Eastern Europe.

Table 2 presents the dependencies resulting from the models created for the parameters TSS, BOD₅, COD, NH₄-N, TKN, TN, TP.

Column 1 presents the influence of increased pollutant load on the removed load (↑ increase, ↓ decrease). Column 2 shows the influence of increased hydraulic load on the removed pollutants load (↑ increase, ↓ decrease, veg – vegetation period, non-veg. non-vegetation period). Columns 3, 4 and 5 present a comparison of interaction (+) or the lack of interaction (−) between the indicators.

For all the analysed parameters, the increase of load in influent causes the increase of removed load. When hydraulic load goes up, removed load goes down for all parameters except for nitrogen compounds. Removed load of TN goes up but only in the vegetation period. It means that the model has a different form during the vegetation period and beyond it. In the vegetation period, the removed load goes down for all parameters except for nitrogen compounds. Removed load of TN goes up together with the increase of influent load and hydraulic load. In the non-vegetation period, the removed mass depends only on the influent load. In the case of COD, there is also an interaction between hydraulic load and seasonality. The impact of hydraulic load is lower in the vegetation period. In the case of TP, there are two statistically significant interactions, between influent load and hydraulic load as well as interaction between all three factors. As before, the impact of the increase of hydraulic load and influent load is lower in the vegetation period.

Pollutants load

Loading of the bed rises with the increase of pollutants concentration in the inflow or with the increase of hydraulic load. The conducted research showed that the influence of pollutants concentration on the influent load was greater than the influence of hydraulic load, which had lower values (0.05 m d⁻¹, 0.1 m d⁻¹).

The observed dependency between the growth of the removed pollutants load and the increase of pollutants load during wastewater treatment is confirmed by the results of the research conducted by Reed et al. (1995), Tanner (2001), Gajewska & Obarska-Pempkowiak (2009). Reed et al. (1995) explain it with the linear increase of reaction rate together with the growth of pollutants load. The biomass production is higher when the bed is more overloaded. A high

Table 1 | Mathematical models of septage pre-treatment in VF bed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mathematical models</th>
<th>The range of model applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lₘ-out = 0.99 lᵢn - 74.68 HLR</td>
<td>lᵢn = 10–1,260; HLR = 0.05–0.1</td>
</tr>
<tr>
<td>TSS</td>
<td>lₘ-out = 0.99 lᵢn - 206.68 HLR</td>
<td></td>
</tr>
<tr>
<td>BOD₅</td>
<td>lₘ-out = 0.99 lᵢn - 483.82 HLR + 169.64 HLR veg</td>
<td></td>
</tr>
<tr>
<td>COD</td>
<td>lₘ-out = 0.99 lᵢn - 314.18 HLR</td>
<td></td>
</tr>
<tr>
<td>Veg.</td>
<td>lₘ-out = 0.99 lᵢn - 483.82 HLR</td>
<td></td>
</tr>
<tr>
<td>Non-veg.</td>
<td>lₘ-out = 0.99 lᵢn - 483.82 HLR</td>
<td></td>
</tr>
<tr>
<td>N-NH₄⁺</td>
<td>lₘ-out = 0.83 lᵢn</td>
<td>lᵢn = 5–25; HLR = 0.05–0.1</td>
</tr>
<tr>
<td>TKN</td>
<td>lₘ-out = 0.87 lᵢn</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>lₘ-out = 0.75 lᵢn + 2.27 lᵢn HLR veg</td>
<td>lᵢn = 5–45; HLR = 0.05–0.1</td>
</tr>
<tr>
<td>Veg.</td>
<td>lₘ-out = 0.75 lᵢn + 2.27 lᵢn HLR</td>
<td></td>
</tr>
<tr>
<td>Non-veg.</td>
<td>lₘ-out = 0.75 lᵢn</td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>lₘ-out = 1.13 lᵢn - 3.09 lᵢn HLR + 1.65 lᵢn HRL veg - 0.36</td>
<td>lᵢn = 1–10; HLR = 0.05–0.1</td>
</tr>
<tr>
<td>Veg.</td>
<td>lₘ-out = 1.13 lᵢn - 3.09 lᵢn HLR + 1.65 lᵢn HRL - 0.36</td>
<td></td>
</tr>
<tr>
<td>Non-veg.</td>
<td>lₘ-out = 1.13 lᵢn - 3.09 lᵢn HLR - 0.36</td>
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</table>
load of beds filled with gravel does not lower their effectiveness in time, but even causes an increase. It is explained with the development of biological film and the plants’ growth (Liénard & Payrastre 1996). Tanner (2001) noticed a significant influence of hydrophytes on the removed load of ammonia nitrogen. However, the researchers’ opinions on the direct role of plants in removing nitrogen are divided. Vymazal et al. (1999) claims that its storage in plant tissues is insignificant and undergoes seasonal changes. Although the effectiveness of TSS removal increases with the growth of their load, the majority of authors suggest applying mechanical pre-treatment. It is one of the factors protecting the bed from clogging during septage treatment (Koottatep & Voisin 2005) and wastewater treatment (Obarska-Pempkowiak et al. 2013b).

The French system is an interesting case, as it does not have primary settling tanks. TSS form a crust on the surface layer of the bed, which contributes to pollutant elimination by providing extra adsorption sites, retaining solid organic pollutant fractions and providing growth of biofilm. Thus, deeper parts of the bed are protected from clogging (Molle et al. 2005; Molle 2014). The French system is an interesting case, as it does not have primary settling tanks. TSS form a crust on the surface layer of the bed, which contributes to pollutant elimination by providing extra adsorption sites, retaining solid organic pollutant fractions and providing growth of biofilm. Thus, deeper parts of the bed are protected from clogging (Molle et al. 2005; Molle 2014).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>Interactions</th>
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<tbody>
<tr>
<td>TSS</td>
<td>↑↑</td>
<td>↑</td>
<td>↑↓</td>
</tr>
<tr>
<td>BOD&lt;sub&gt;5&lt;/sub&gt;</td>
<td>↑↑</td>
<td>↑</td>
<td>↑↓</td>
</tr>
<tr>
<td>COD</td>
<td>↑↑</td>
<td>↑</td>
<td>↑↓</td>
</tr>
<tr>
<td>NH&lt;sub&gt;4&lt;/sub&gt;-N</td>
<td>↑↑</td>
<td>↑</td>
<td>↑↓</td>
</tr>
<tr>
<td>TKN</td>
<td>↑↑</td>
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<td>TN</td>
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<tr>
<td>TN</td>
<td>↑↑</td>
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<td>↑↓</td>
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<tr>
<td>TP</td>
<td>↑↑</td>
<td>↑</td>
<td>↑↓</td>
</tr>
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</table>

Table 2 | Dependencies resulting from the models of septage pre-treatment in VF bed

A drop of effectiveness in removing organic matter together with an increase of hydraulic load was observed. Higher flow speed results in shorter contact with filtration media. The bed was supplied with a single batch once a day; the time duration of the contact between septage and the bed was equal to the time necessary for its filtering.

In the case of TSS, the increase of hydraulic load lowers the effectiveness of sedimentation and filtration. The drop in effectiveness of removing organic matter and TSS with the growth of hydraulic load was confirmed by Reed et al. (1995) and Jong & Tang (2014a, 2014b).

The influence of hydraulic load on the removed N = NH<sub>4</sub>-N and TKN loads was not observed. The lack of such dependence in an applied hydraulic load of 0.05 and 0.1 m d<sup>-1</sup> is confirmed by the results of the research conducted by Felde & Kunst (1997). However, increasing hydraulic load to 0.15 m d<sup>-1</sup> causes decreased effectiveness of NH<sub>4</sub>-N removal. On the other hand, the research conducted by Jong & Tang (2014b) showed that NH<sub>4</sub>-N removal effectiveness decreased significantly with SLR 250 kg TSS m<sup>-2</sup> y<sup>-1</sup>.

Higher effectiveness of TN removal was observed when hydraulic load was increased during the vegetation period. Increasing hydraulic load deteriorates its oxygen conditions, thus it allows a more effective denitrification process. Such dependency was not observed during the non-vegetation period, which might be a result of a different aeration mechanism occurring in the bed at that period. Jong & Tang (2014a) suggested impounding septage in the bed for a certain amount of time in order to create saturation conditions. Such an operating regime, supporting denitrification, is effective in terms of TN removal. The drop in effectiveness of TP removal with growing hydraulic load is explained by rinsing out phosphorate ions when the bed is hydraulically overloaded. The system has been operating for 2 years, so the saturation of adsorption sites might play a significant role.

**Seasonality**

The results of research conducted in Poland on domestic sewage confirm a statistically insignificant decrease of effectiveness of removing organic matter in the non-vegetation period (Gajewska & Obarska-Pempkowiak 2009). The lack of substantial influence of seasonality on the effectiveness of TSS removal comes from the lack of influence of temperature on the sedimentation and filtration processes.
An insignificant decrease in the effectiveness of NH$_4$-N removal in the non-vegetation period was also noticed by other authors conducting their research on wastewater treatment in VF beds located in the same region (Tomczuk & Ochrymiuk 2012).

The lack of significant influence of seasonality on the effectiveness of TN removal stems from the fact that it is removed in the vegetation period when the bed’s aeration is better. Suitable aeration of the bed causes problems with denitrification in the summer period.

In VF beds, TP is removed both in abiotic and biotic processes, which depend on the temperature. Lower effectiveness in TP removal observed in the non-vegetation period might be explained by lower effectiveness of biotic processes. During the vegetation period, when the bed is well aerated, the biosynthesis of phosphorous compounds is more intensive. Moreover, the presence of oxygen moderates phosphorous passing from sludge to the aquatic environment. During the non-vegetation period, release of phosphorous compounds stored in plants, beds and microorganisms takes place.

Interactions

A range of interactions was observed. A higher influence of hydraulic load on removed load during the non-vegetation period was noticed in the case of COD. It drops with the increase of hydraulic load more than in the vegetation period. It might be explained with lower intensity of biochemical processes in that time. Higher hydraulic load also results in decreased treatment effectiveness, because of shorter contact time between pollutants and microbiological communities when the flow speed is higher.

The influence of hydraulic load on the removed load of TP during the vegetation period might be explained with plants’ greater ability to accumulate biogenic elements when their concentration in influent is higher. Moreover, the increase of hydraulic load deteriorates the oxygen conditions in the bed, which enhances the denitrification process.

Observed in the cases of COD and TP, a greater influence of hydraulic load increase on the removed load in non-vegetation period might be explained by the intensity of the biochemical processes, which together with shorter period of its contact with biological film, causes a decrease in the treatment effectiveness.

As observed in the cases of COD and TP, a greater influence of hydraulic load increase on the removed load in the non-vegetation period might be explained by the intensity of the biochemical processes. This situation, together with a shorter period of septage contact with the biological film, causes a decrease in the treatment effectiveness.

SS VF bed effectiveness in septage treatment

Comparing the obtained results with the data described in literature, similar effectiveness of removing organic matter, TSS and TKN was achieved by Liénard & Payrastre (1996). They conducted research on a vertical flow constructed wetlands bed of 0.25 m depth, with similar pollutants load and over 10 times lower hydraulic load. Still, the average effectiveness of TN and TP removal was higher and reached respectively 70% and 86%. The bed was located in a closed and heated room, which might have influenced its effectiveness.

Paing & Voisin (2005), who conducted studies on beds of 0.90 m depth, also achieved higher treatment effectiveness, respectively 99% for TSS, 98.5% for BOD$_5$, 95% for COD, 94% for TKN and 94% for TP. The research was carried out with similar pollutants load and over seven times lower hydraulic load. The bed operated for 7 days and rested for 5 weeks. The results of that research might point to a significant influence of the bed depth on the effectiveness of pollutants removal.

In their research conducted on a bed with 0.50 m depth, with 3 times higher pollutants load and 4 times lower hydraulic load, Troesch et al. (2009) obtained a slightly higher treatment effectiveness, which reached respectively 93% for COD, 95% for TSS, 91% for TKN, 90% for N – NH$_4$ and 95% for TP. The assumed regime of work for the bed included 3 days of feeding and 20 days of resting. The treatment process was therefore based on dewatering.

The assumed regime of the bed operation was 5 days of work during the week and 2 days resting (during the weekends). It corresponds with the conditions of small WWTPs located in rural areas. The problem of overloading with pollutants occurs during the week, when septage is delivered. Applying the suggested solution allows avoidance of difficulties in meeting the required effluent standards and problems with the stable working of small WWTPs.

CONCLUSIONS

1. The application of an SS VF bed to septage pre-treatment can significantly reduce the pollutants loads (BOD$_5$: 82%, COD: 82%, TSS: 91%, TN: 47%, N-NH$_4$: 70%), and thus decrease the loading of the biological stage of municipal WWTPs.
2. In the case of all analysed parameters, the removed load increases with the increase of load in the influent.
3. There is a statistically significant effect of hydraulic load on the removed pollutants load of BOD$_5$, COD, TSS, TN and TP. Except for TN, the increase of hydraulic load causes the decrease of unit removed load.
4. There are no statistically significant effects of seasonality on the removed load. In the case of COD, TN and TP, interaction of hydraulic load and seasonality is statistically significant.
5. The established models might be applied while designing CWs for pre-treatment of septage in the climatic conditions of Eastern Europe.

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Rozporządzenie Ministra Środowiska z dnia 18 listopada 2014 roku w sprawie warunków jakie należy spełnić przy wprowadzaniu ścieków do wód lub ziemii, oraz w sprawie substancji szczególnie szkodliwych dla środowiska wodnego (Regulation of the Minister of Environment from 18th of November 2014 on conditions to be met for disposal of treated sewage into water and soil and concerning substances harmful to the environment (Dz.U. 2014, no. 1800).


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