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Efficiency of Wastewater Treatment in Single-Family Constructed Wetlands in Kaszuby Lake District

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1. Introduction

According to the report of Environmental Protection Inspection about the condition of Polish waters indicates that the protection of waters against eutrophication is one of the most significant issues. In order to solve the problem of the eutrophication of waters in Poland, strategies not only for big agglomerations but, first of all, for rural areas with dispersed farms and buildings have to be developed. Surface waters are especially exposed to eutrophication due to the way of land is used in rural areas. One of the most important reasons of this is discharging of untreated or only partly treated wastewater in this regions. Also sanitation of Polish villages is the most curtail task in the light of the newest EU Water Directive demands.

According to the EU directive the problem of wastewater treatment in non-urbanised areas (mainly rural) must be resolved by 2015. In Polish countryside, the difficulties with wastewater management are mainly caused by dispersed settlements, located far away from the conventional sewage system, what results in high investment costs for new sewerage lines. Another problem is a construction of sewage systems without any wastewater treatment plants (WWTPs). Although, the number of WWTPs serving for villages increased from 433 to 2 341, from 1995 to 2010 respectively, still only 25.7% of rural population was served by sewer system and municipal WWTPs in 2010. Due to the above facts, an immense interest has been focused on developing and establishing decentralised wastewater treatment systems (DWWTSs). Consequently, 82,632 DWWTSs were constructed in Poland, in 2010. However, due to the dispersed character of rural settlements, it is estimated that in the next few years over 587,000 individual DWWTSs may be constructed [11]. It is postulated that decentralised systems should have integrated both wastewater and sludge management.

Treatment wetlands (TWs) can be an alternative solution to sewage treatment in rural communities, schools, at campsites and in individual houses. These systems are simple in operation, cheap and effective and they can have landscape and educational values. Although TWs in Europe are usually designed to serve up to 2000 inhabitants, most of the existing facilities receive sewage from fewer than 50 inhabitants or even from individual farms. TWs for more than 1000 inhabitants are scarce [23, 12, 24, 7, 15] In spite of being in use for more than 20 years still different configurations of TWs are applied all over the Europe for domestic wastewater [24]. In Norway enhance pretreatment in septic tank and pre filter with LECA is applied before one stage horizontal subsurface flow bed (HSSF) [8, 10, 20]. While in France raw domestic wastewater (without any pretreatment, only grinding down) is discharged directly into two stage vertical subsurface flow beds (VSSF) [1, 16]. Also in Denmark VSSF beds for small amount of wastewater (up to 30 p.e) are advised. There are special, very simple guidelines for dimensioning of one stage SS VF bed depending on quantity of people living in household to be served by TWs [2]. Since it is estimated that about 1500 single family TWs both with one stage HSSF or VSSF have been constructed in Poland, thus arise a question which of them are more effective in pollutants removal and should be advice to implementation. Within the research project *Innovative Solutions for Wastewater Management in Rural Areas* supported from the EEA Financial Mechanism and Norwegian Financial Mechanism (PL 0271), and the Polish Ministry of Science and Higher Education (E033/P01/2008/02) the conception of sewage treatment and sewage sludge utilization at the TWs for individual households in a rural area was created. After the review of existing TWs in Poland and in Europe, three configurations of hydrophyte beds are proposed. These facilities were constructed in summer 2009 in Kaszuby Lake District, and the result of two years of monitoring are presented in this paper.

2. Materials and methods

2.1. Single family TWs characteristic

The proposal of an innovative sanitary system is basing on an idea of a closed cycle of water and organic matter in the environment. The nutrient substances: N, P, K compounds present in wastewater should be used as soil fertilizers. Wastewater from individual households are treated at individual treatment plants for a single household. The benefit of treatment wetlands (TWs) arises from the fact that no excessive sludge is generated during wastewater treatment. Primary treatment of wastewater takes place in septic tanks. Then, the wastewater is discharged to TWs working with three configurations. The important aspect of the undertaken research is the selection of the optimal configuration of hydrophyte beds, which will depend on the local conditions. Within the project, nine individual farms were selected in the analysed catchment area. The farms were already equipped in the septic tank. The investors (farmers) accepted the project conditions. Within the Project the formal questions were settled up at the local administration level and the necessary materials for TWs construction were purchased. The construction of TWs was carried out by the farmers themselves. Three configurations were proposed: two with vertical subsurface flow (VSSF) beds and the third one with a horizontal subsurface flow (HSSF) bed preceded by a pre-filter (Fig. 1). There were three facilities working in each configuration [19].

In all TWs additional pumps were used. A timer, overrun by a float switch, controls the dosing pump. The depth of vertical flow beds was 0.7 m. The bottom was laid with HDPE foil (1 mm thickness). Common reed was planted on the beds surface with the density of 4 plants per m^2.

Each of the investors individually arranged the aesthetical appearance of his TW and was allowed to extend the area of the polishing pond. The only “strong” recommendations were to keep the gravitational outflow of wastewater from the bed to the pond and to isolate of the significant part of the pond’s bottom from the subsoil with the 1 mm HDPE foil. The role of the pond is removal of nitrates (V) (in denitrification process), further removal or the liquid organics, fine suspended solids and colloids. Additionally, the pond will provide retention during the winter period. In the vegetation season the treated wastewater will feed the plants growing on the pond's edges. In order to promote biodiversity, it was recommended to plant the pond with possibly large number of aquatic plant species and to systematically remove the extensive vegetation to avoid recontamination of the treated wastewater. The TWs were built in summer and autumn 2009 in Kaszuby Lake District.

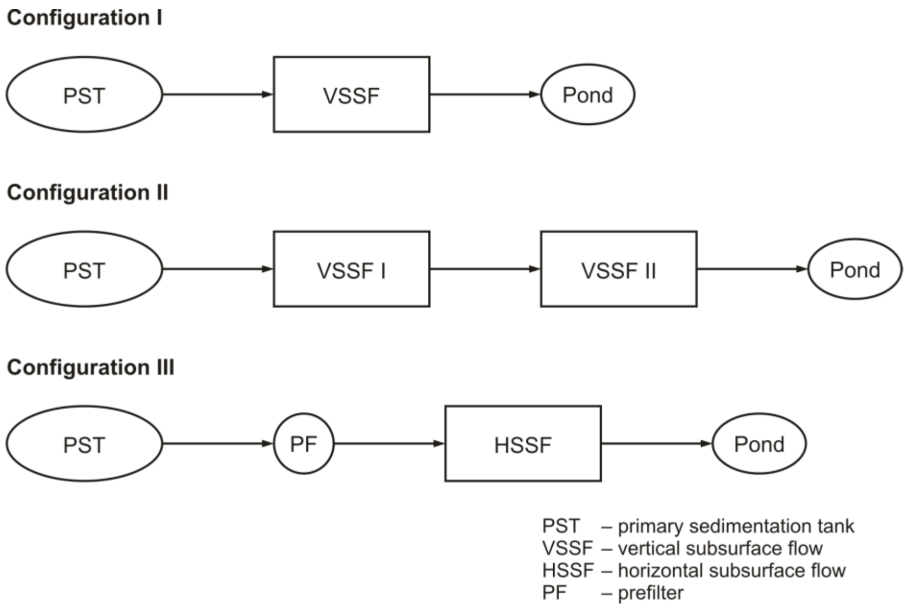

Fig. 1. Schemes of applied configurations
Rys. 1. Schematy zastosowanych konfiguracji

2.2. Laboratory analyses

The samples of wastewater in inflow and outflow were collected from October 2009 till October 2011 (eight sampling events in each single family TW). The wastewater samples were collected from the manholes or pumping chambers, which ensured retention time of 6–12 hours. The air temperature during sampling events was varying from +6.5°C to +24.3°C.

In collected samples of waste water the pH and concentrations of BOD_5, COD, TSS and total nitrogen (TN), ammonia nitrogen, organic nitrogen, nitrates (V) and total phosphorus (TP) were determined. The analytical procedure recommended by Hach Chemical Company and Dr

Lange GmbH was used. The analyses were performed according to Polish norms and guidelines given the Regulation of the Ministry of the Environment of 24 July 2006.

3. Results and discussion

3.1. Pollutants concentration

The average concentrations of pollutants at single family TWs are given in Figures 2, 3 and 4.

a) b)

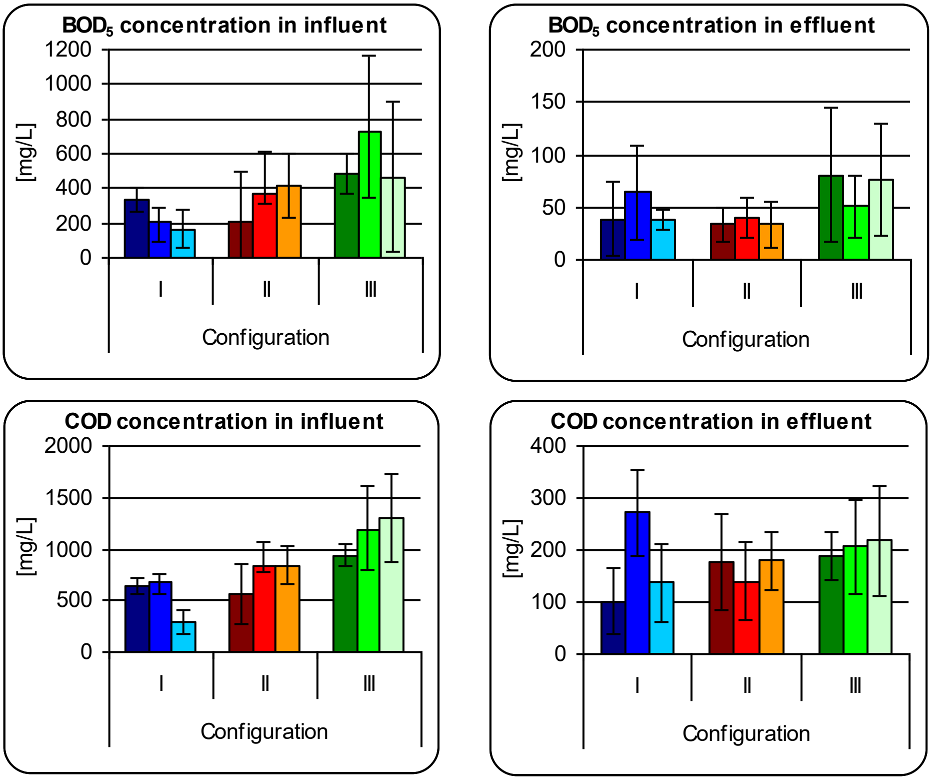

Fig. 2. The concentration of organic matter with standard deviation in influent (a) and effluent (b)

Rys. 2. Stężenia substancji organicznej wraz z odchyleniami standardowymi w a) dopływie, b) odpływie

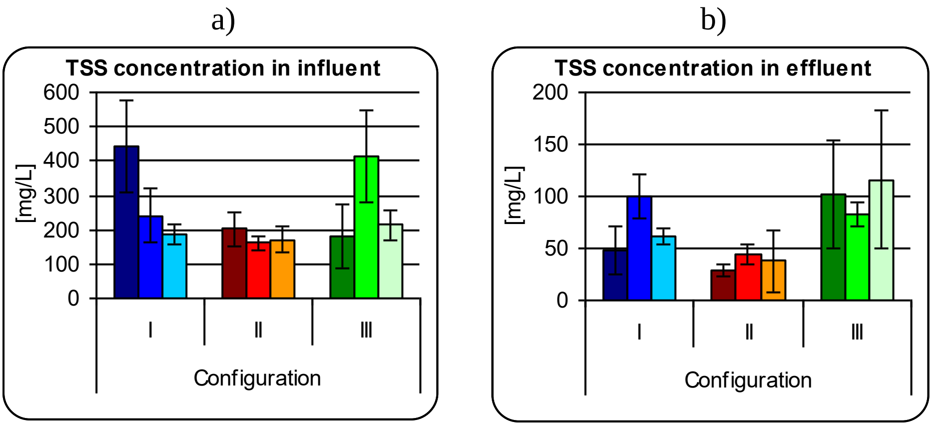

Fig. 3. The concentration of total suspended solids with standard deviation influent (a) and effluent (b)

Rys. 3. Stężenie zawiesiny ogólnej wraz z odchyleniami standardowymi w a) dopływie b) odpływie

The quality of wastewater delivered to treatment wetlands facilities after mechanical treatment in septic tanks differed significantly with reference to all analyzed pollutants. Moreover, they were much higher than reported by [22, 8, 21, 10]. The highest organic matter concentrations were detected in the operating facilities according to Configuration III. The average BOD_5 concentration changed from 500 to 700 mg O_2/l whereas in case of COD it was from 900 to 1300 mg O_2/l. Enormous concentrations of organics (both COD and BOD_5) were discharged to TWs – at four out of nine analysed farms. COD was exceeding 1000 mg/l and at another one was 970 mg/l. The inflow BOD_5 concentrations were also high, reaching 1300 mg/l.

So high inflow concentrations could be caused either by improper maintenance and operation of septic tanks or the inflow of high strength wastewater (manure, run-off from the fields or leakages from farmyard) as well as in some cases smaller water consumption [25].

Significant differences were observed in the concentration of TSSS, particularly in the facilities working in Configuration I and III (Fig. 3). On that basis and after the inspection of the facilities it was found out that the operation of preliminary tanks was incorrect due to too rare empting of sludge chambers. As a result TWs were supplied with higher load of organic matter than it was assumed.

Facilities in Configuration II were supplied with wastewater of lower concentration of TSS, which resulted in its removal with average efficiency amounting to 78.0%. In the final assessment, the operation of TWs enabled from 20.0 up to 40.0 mg/l at the outflow, so it fulfilled the requirements in force [4].

Wastewater delivered to TWs was characterized by high concentration of total nitrogen from 60 up to 160 mg TN/l (Fig. 4).

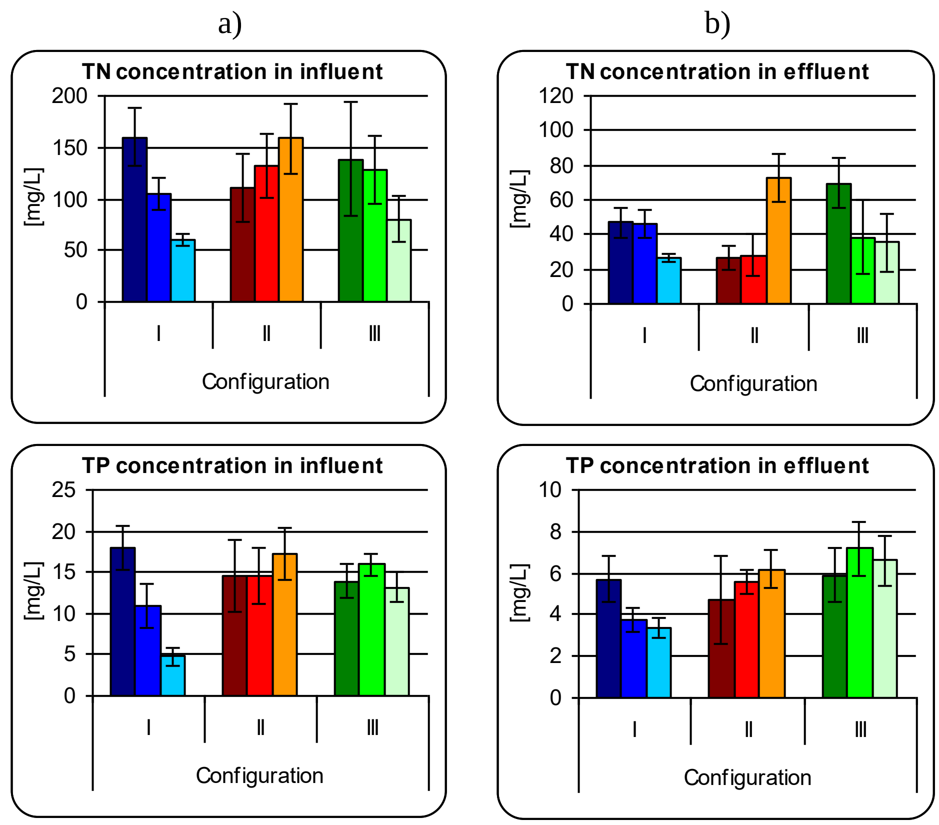

Fig. 4. The concentration of nitrogen and phosphorous with standard deviation influent (a) and effluent (b)

Rys. 4. Stężenia azotu ogólnego i fosforu ogólnego wraz z odchyleniami standardowymi w a) dopływie b) odpływie

These concentrations were two- three times higher in comparison to the values (36.3 to 77.5 mg/l) reported by [8, 23]. Similar high concentration of nitrogen were present in the septic tank effluent in Podlasie Region of Poland [18, 6]. Such differences in TN influent concentration indicates that the activities carried out in individual households had domestic character in some cases while in others the character was typical for production and agricultural activities. It had influence on the final concentration of pollutants at the outflow. The facilities supplied with wastewater of lower concentration of TN (similar to household sewage) made it possible to obtain lower concentration at the outflow (from 22 to 38 mg TN/l) (Fig. 4).

As far as TP is concerned, the highest variability was observed at the inflow in case of facilities operating in configuration I: from 5 to 18 mg TP/l while in case of other configurations the quality of delivered wastewater was more stable. The range of changes was 14.0–17.5 mg TP/l (Fig. 4).

3.2. Efficiency Removal

In spite of so high inflow pollutants concentrations, quite effective removal of pollutants was observed at most TWs. The removal efficiency for organic matter is given in Table 1. The biological part (namely TWs) provided for high and stable efficiency in removing delivered pollutants similar to high-effective methods (like tricking) applied for treatment of small amount of wastewater [9].

Table 1. The organic matter efficiency removal in TWs working in analyzed configurations
Tabela 1. Skuteczność usuwania substancji organicznej w analizowanych konfiguracjach oczyszczalni hydrofitowych

Facility	**BOD_5**			**COD**		
	Configuration					
	I	II	III	I	II	III
1	88.3	83.5	83.3	84.1	68.6	79.9
2	69.7	88.9	93.0	60.0	83.1	82.5
3	77.4	91.8	83.5	53.1	78.6	83.3
MEAN	78.5	88.1	86.6	65.7	76.8	81.9

The effectiveness of BOD_5 and COD removal varied from 77.0 up to 83.0%, and from 62.0 up to 80.0%, respectively. BOD_5 was removed with slightly higher efficiency than COD, what is characteristic for both conventional and natural wastewater treatment technologies. The highest effectiveness of BOD_5 removal (88.1%) was observed for Configuration II. It was also observed that long retention time in HSSF bed applied in configuration III favoured the decomposition of COD.

The analysed TWs showed high variation in TSS removal efficiency (from 43.6 to 89.1%). Lower efficiency of TSS removal was caused by high concentration at the inflow. TWs, are most effective in removal of pollutants in dissolved and colloidal form, as well as in residual suspended solid after preliminary tanks. High concentrations of TSS at the outflow from the tanks reduced efficiency of the whole system. Facilities in configuration II were supplied with wastewater of lower concentration of TSS, which resulted in its removal with average efficiency amounting to 78.6% (Table 2).

The highest TN removal efficiency was observed in case of facilities operating in Configuration II (69.70% on average) while in case of configuration I and III it was 60.7 and 58.50%, respectively. The facilities supplied with wastewater of high concentration of TN, characteristic for agriculture and service activities, should have greater area, due to kinetics of microbiological changes of nitrogen. The highest efficiency of TP removal was achieved also in facilities operating in configuration II – 62.4% on average, which provided concentration from 4.5 to 6.2 mg TP/L at the outflow.

Table 2. The total suspended solids efficiency removal in TWs working in analyzed configurations
Tabela 2. Skuteczność usuwania zawiesiny ogólnej w analizowanych konfiguracjach oczyszczalni hydrofitowych

Facility	**TSS**		
	Configuration I	Configuration II	Configuration III
1	89.1	85.5	43.6
2	58.3	72.3	79.9
3	67.1	78.0	45.8
MEAN	71.5	78.6	56.4

Table 3. The nutrients efficiency removal in TWs working in analyzed configurations
Tabela 3. Skuteczność usuwania pierwiastków biogennych w analizowanych konfiguracjach oczyszczalni hydrofitowych

Facility	TN			TP		
	Configuration					
	I	II	III	I	II	III
1	70.6	75.9	49.7	68.2	67.8	57.6
2	55.9	79.0	69.9	65.4	61.4	54.7
3	55.6	54.3	55.8	29.1	64.0	50.0
MEAN	60.7	69.7	58.5	54.3	64.4	54.1

Lower concentration at the outflow was received in case of facilities operating in configuration I – from 3.8 up to 5.8 mg TP/l due to receiving the lowest concentrations in influent (Fig. 4).

3.3. Discussion

The obtained results confirm that TWs were not successful in removal of TP from delivered wastewater due to high concentration of volatile suspended solids. TWs are adopted to removal of inorganic phosphorus compounds coming from detergents. Whereas TP should be retained together with the suspended solid in the mechanical part.

The pollutants removal efficiency in TWs in Kaszuby Lake District is similar to the monitoring results of the individual household TWs in Poland. It was indicated that the HSSF facilities working at the second stage of sewage treatment provided effective removal of BOD_5 and COD as well as TSS. The effectiveness of BOD_5 removal varied from 25.6 to 99.1% (average 62.4%) for the loadings from 11.2 to 115 kg/(ha·d). However, the removal effectiveness of the total nitrogen was lower and varied from 22.4 to 84.2% (average 44.5%), for the loadings from 8.5 to 34.0 kg/(ha·d) [18, 5]. Many authors confirms that VSSF beds are more effective in removal pollutants and provide better quality of treated effluents [2, 3, 13, 14, 17].

The analysis performed in Germany showed the average concentrations of COD and ammonia nitrogen in the effluent of the VSSF facility were equal to 68.2 mg O_2/L and 9.5 mg/l, respectively, and were lower than the corresponding values for the HSSF facilities (102.5 mg O_2/L and

36.0 mg/l, respectively) [14]. According to [13] the effluents of one-stage VSSF beds in a unit area equal to 4 m^2/p.e and organic matter load equal to 20 g/($m^2 \cdot d$) can meet rigorous Austrian outflow standards (below 90 mg/l COD and 25 mg/l BOD_5), regardless of the season of a year and air temperature. According to [16], two sequential VSSF beds, periodically supplied with raw sewage, provide effective treatment. This configuration of VSSF beds allows for reducing pollutant concentrations to the following level: COD – 60 mg/l, TSS – 15 mg/l, Kjeldahl nitrogen – 8.0 mg/l. In France there are over 200 TWs constructed according to this scheme. More than 60 of these facilities were built in 2003. In 2005 the analysis of the operation of 81 TWs (53 with sequential VSSF I and VSSF II beds) was performed. The treatment effectiveness of the analyzed facilities was very high: over 91.0% for COD, 95.0% for TSS and 85.0% for Kjeldahl nitrogen. Due to high treatment effectiveness, the concentrations of pollutants in treated sewage were very low: 66.0 mg/l COD, 15 mg/l TSS and 13.0 mg/l $N_{Kjeldahl}$. The removal effectiveness of Kjeldahl nitrogen in the first stage of treatment was equal to 50.0%.

The one-stage vertical flow systems had not been used until 2004 in Poland, when they were implemented as a solution to wastewater problem in the rural area in Podlasie region (east part of Poland). The VSSF TWs in Podlasie are being monitored by several research institutes, however, the monitoring results differ. The analyses performed by the authors of the article indicated that the analysed facilities were very effective in pollutant removal. The removal effectiveness of BOD_5 varied from 86% to 98%, and of COD – from 79% to 94%. The results of the analyses confirmed the low effectiveness of total phosphorus removal (from 13.4 to 41.3%) [18]. Additionally, it was found out that the effluent concentrations of TSS exceeded the admissible value of 50 mg/l (Environment Ministry Regulation from 24 July 2006). The share of organic suspended solids in the total suspended solids at the effluent varied from 49 to 95%. Very good conditions for the nitrification process existed in the treatment facilities. This is confirmed by the very low concentrations of ammonia nitrogen at the effluents of the three analyzed facilities. However, the removal of total nitrogen was substantially lower in comparison to that of ammonia nitrogen. As a result, nitrates V were the dominant form of nitrogen at the effluents, which indicates that the denitrification pond failed to play its role [18].

Comparison of all three configurations so far indicated the best performing for Configuration II consisted of two sequential VSSF beds followed by a pond. Since the contact time in sequentially working VSSF beds is twice as long as in a single VSSF bed with bigger unit area, it can be concluded that elongation of the contact time has more positive impact on treatment results than application of larger unit area of a single VSSF beds. This finding is in accordance with the newest tendency to minimise the unit area of hydrophytes bed but appalling two or even more stage of treatment in TWs [7, 17, 21, 23].

4. Conclusions

The results obtained during the 2-years operation period of single-family TWs indicate stable and effective removal of pollutants. Thus application of TWs for single-family sewage utilization can be a good solution to wastewater treatment problem in the rural areas. The TWs operated in Poland receive much higher concentration of pollutants in comparison to the TWs operated in Europe and USA.

Good treatment effectiveness BOD 64.0–92.0%, TN 44.0–77.0%, TP 24.0–66.0% was observed. Comparing the achieved efficiency removal in three applied configuration shows:

- importance of TSS removal in pre-filter before application of TWs
- double contact time in sequentially working VSSF beds improve the efficiency removal up to 20% in comparison to the efficiency of single VSSF with bigger unit area.

The lowest concentration of pollutants, and at the same time the highest efficiency of treatment was provided by the facilities operating according to Configuration II. The operation of facilities according to Configuration I and III was also efficient. Nevertheless, in the final comparison it is confirmed that facilities operating in configuration II were the most efficient (it means using two sequential vegetated beds with vertical wastewater flow).

Individual construction of the treatment facilities by farmers under the supervision of technical personnel make the framers aware of the significance of each element of the treatment process and guarantees proper future operation of the system.

Further investigations of pollutants removal effectiveness in the single-family TWs, with special focus on the winter periods as well as long-term operation should be performed.

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Skuteczność oczyszczania ścieków bytowych w przydomowych oczyszczalniach hydrofitowych na Pojezierzu Kaszubskim

Streszczenie

W pracy zaprezentowano wyniki badań trzech różnych konfiguracji oczyszczalni hydrofitowych stosowanych do oczyszczania ścieków bytowych z indywidualnych gospodarstw domowych. Wykazano, m.in., że zastosowanie oczyszczalni hydrofitowych jest zrównoważonym i stabilnym rozwiązaniem problemu gospodarowania ściekami na terenach o rozproszonej zabudowie. Oczyszczalnie przydomowe w Polsce otrzymują wyższe stężenia zanieczyszczeń niż odpowiednie oczyszczalnie w Europie czy USA, po mimo to analizowane obiekty zapewniały skuteczne usuwanie substancji organicznej: BZT_5 do 92,0% i substancji biogennych: N_{og} do 77,0% i P_{og} do 66,0%. Konfiguracja II składająca się z dwóch charakteryzowała się najwyższą skutecznością usuwania zanieczyszczeń i w konsekwencji zapewniała najniższe stężenia zanieczyszczeń w oczyszczonych ściekach.