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SEWAGE GARDENS – CONSTRUCTED WETLANDS FOR SINGLE FAMILY HOUSEHOLDS

During the last 30 years the increase of interest in low-cost decentralized and small wastewater treatment plants (WWTP) is observed in Europe. For this purpose, sand filters, stabilization ponds, mini reactors with activated sludge, trickling filters and treatment wetlands are used. Among the listed facilities, treatment wetlands (TWs) offer effective and reliable treatment efficiency, being at the same time low-cost and simple in operation. This is a sustainable treatment technology which does not generate secondary sewage sludge. In the paper, design concept and performance of nine TWs constructed in 2009 for single-family households in Kashubian Lake District is discussed. The treatment efficiency of three different TW configurations is compared. The findings of the study provide a basis for future design and implementation of TWs in agricultural areas.

1. INTRODUCTION

Treatment wetlands (TWs) have already found a wide application in municipal management all over the world. TWs are first of all used for second stage treatment of domestic wastewater but also for the treatment of industrial wastewater (e.g. from wineries and dairies), stormwater, landfill leachate as well as renaturalization of treated effluent from conventional WWTPs [1–3]. In many European countries, TWs are advised as the best available technology (BAT) for single family households and local treatment facilities for less than 2000 person equivalent (pe) [4]. In spite of the fact that the method has been used for over forty years, the optimal design and configuration of TWs to guarantee both reliability and pollutant removal is still a contentious issue. According to Langergraber [5], the effluents of a one-stage vertical subsurface flow (VSSF) bed of a unit surface area equal to 4 m²/pe and organic matter loading equal to 20 g/(m²·d), meet rigorous Austrian

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outflow standards (below 90 mg COD/dm³ and 25 mg BOD₅/dm³), regardless of the season and air temperature. Simple guidelines for designing TWs for less than 30 pe with single VSSF bed were introduced in Denmark in 2005 [6]. In France, two sequential VSSF beds have been successfully used for the treatment of raw sewage (without primary mechanical treatment) for over 20 years [7, 8]. According to Molle et al. [8] the unit area should be equal to 1.2 m²/pe for the first bed and only 1.0 m²/pe for the second bed. Such configuration of VSSF beds allows the reduction of pollutant concentrations to the following levels: COD – 60 mg/dm³, TSS – 15 mg/dm³, Kjeldahl nitrogen – 8.0 mg/dm³. Molle et al. [8] recommended that the hydraulic loading of the beds working in batches should be below 600 mm/d. In Norway, a very effective primary treatment of wastewater is applied. A three-chamber septic tank is recommended for TWs [9]. Effluent from the tank is first pre-treated by the biofilter (pre-filter) before entering the wetland bed. The pre-filter is a vertical flow bed filled with LECA material (light-weight expanded clay aggregates) which has very good filtration properties. Another function of the pre-filter is aeration of sewage. The last step of domestic wastewater treatment occurs in a HSSF bed (horizontal subsurface flow). This bed is mainly constructed for removal of phosphorus and pathogens. For efficient phosphorus removal in TWs, the use of Filtralite[®]P as a filter media with high P-binding capacity is recommended [9]. Effective phosphorus removal requires a minimum retention time of 7–10 days in a HSSF bed. Due to the cold climate, HSSF beds in Norway are deeper (0.9 m) than it is recommended in other European countries [10].

The European experience also shows that TWs can be successfully used for the stabilization and disposal of sewage sludge in the so called sludge treatment reed beds (STRBs) [11]. The STRB is a system consisting of beds made of concrete, prefabricates or soil screened with an impermeable membrane and drainage pipes for collecting the leachate at the bottom. The beds are filled with gravel (for effective sludge dewatering and bed ventilation) covered by sand (to support plant growth). Macrophytes (usually *Phragmites australis*) are implemented to grow on overlying layers of deposited sludge (with low content of dry matter, ca. 0.5–1%) [12–14]. Estimated costs of dewatering sludge in STRBs are relatively low and constitute only 5–10% of the overall operational costs of conventional methods of sludge utilization [15].

Wetland technology could also be used for solving problems in wastewater and sludge management in rural areas. It is called green technology, due to the use of vegetation and its low energy demand (very often systems work without any energy consumption). TWs create a similar environment to natural wetlands, promoting biodiversity. For these reasons, this treatment method is regarded environmentally friendly and sustainable [16]. Moreover, TWs fit perfectly within a village landscape and can easily be arranged as sewage gardens without producing any negative impacts (like odors or mosquitoes), even in close proximity to households.

According to the EU directive, the problem of wastewater treatment in non-urbanized areas must be solved by 2015. To meet these demands, three different concepts of



approaching wastewater treatment and sludge utilization in rural areas were developed by Polish researchers from the Gdansk University of Technology in cooperation with Norwegian researchers from the Bioforsk, Soil and Environment Division in Aas within the research project *Innovative Solutions for Wastewater Management in Rural Areas*. These concepts followed the main idea of the research project aimed at implementing innovative and sustainable technologies for management and treatment of domestic wastewater and sludge in rural areas.

The aim of this paper is to present the results of an innovative wastewater and sludge management system for single households that was designed and implemented in 2009 in the scope of the research project *Innovative Solutions for Wastewater Management in Rural Areas* (financed by Polish Ministry of Science and Higher Education E033/P01/2008/02 and EOG Financial Mechanism, and Norwegian Financial Mechanism PL0271). The proposal of an innovative sanitary system is based on the idea of a closed cycle of matter in the environment. The compounds of nutrient substances: N, P, K present in wastewater should be used as soil fertilizers. Wastewater from single households is treated at individual treatment plants. One of the benefits of TWs is no excessive (secondary) sludge generation during wastewater treatment. Primary treatment takes place in septic tanks. Then the wastewater is discharged to treatment wetlands working in one of three configurations. According to the project, sewage sludge gathered in septic tanks was to be periodically removed and discharged to reed treatment beds, where intensified natural dewatering and stabilization would take place. The filtrate generated in the dewatering process is recirculated to TWs and treated together with wastewater (Fig. 1). The dewatered and stabilized sewage sludge would become a valuable humus substance, that could be used as soil fertilizer at the farm lands. In this way, the matter cycle is closed. The sewage treatment technology as well as sludge processing is simple in operation.

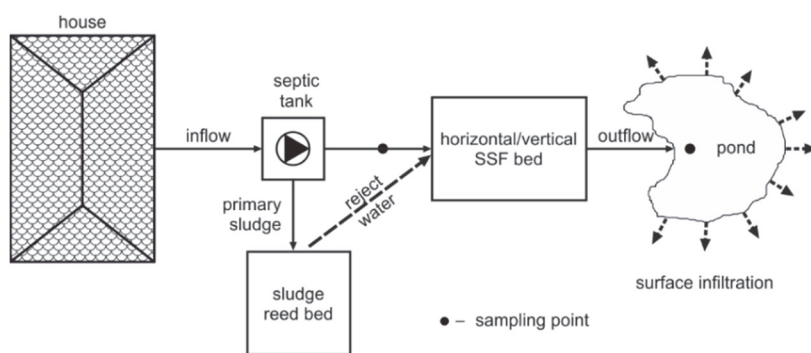


Fig. 1. The concept of innovative wastewater and sludge management for a single household

The innovation of the proposed solution was the discharge of the effluent to a polishing pond to increase the retention of water in a small catchment area as well as the

application of sludge treatment reed beds (STRBs) for primary sludge produced in the septic tank. In practice, it turned out that farmers had a negative attitude towards the use of STRBs. The facilities were built according to the design project, however none of the farmers involved in the project ever decided to use them. Instead, the sludge from septic tanks is periodically pumped out and transported to a central wastewater treatment plant.

2. METHODS

Study facilities. Three different configurations of SSF systems were applied to test whether vertical or horizontal flow beds perform better in Polish countryside conditions. In all configurations, a septic tank was applied as a mechanical treatment and the last stage of treatment was performed in a polishing pond. In configuration I, a single VSSF bed with a unit area of $4\text{m}^2/\text{pe}$ was applied while in configuration II sequentially working VSSF beds were applied with the total unit surface area of $2.5\text{m}^2/\text{pe}$. The configurations with a single VSSF bed and two VSSF beds working in a series were tested to investigate how double contact time affects the efficiency of pollutant removal. Configuration III was designed according to the Norwegian scheme and consisted of a pre-filter followed by a HSSF bed. Instead of LECA, a local material – Pollytag made of fly ashes from thermal-electric power plants was used (Table 1).

Table 1. Characteristics of the analyzed single family TWs

Configuration	HRT in primary tank [day]	Unit area/pe [m^2]	Filling material of the bed	Pond surface area [m^2] ^a
I with single VSSF	maximum 3	3.0	20 cm – drainage layer 16–32 mm 40 cm – filtration layer 2–8 mm up to 10 cm – mixture of peat and wooden bark	Minimal $1\text{m}^2/\text{pe}$ with the depth maximum 1.2 m
II with two VSSF	5–7 days	I VSSF – 1.5 II VSSF – 1.0	20 cm – drainage layer 16–32 mm 20 cm – filtration layer 8–16 mm 20 cm – filtration layer 2–8 mm up to 10 cm – mixture of peat and wooden bark ^b	
III with pre-filter and HSSF	3–7 days	5.0	distribution and collection zone 16–32 mm main filtration layer 2–8 mm	

^aMinimal designed (recommended) dimension – all farmers decided to build ponds as recipients of treated sewage.

^bThe same layers for I and the II stage beds.

An important feature of the implemented wastewater treatment plants is that all of them have been implemented in 2009 as full-scale facilities under real field-operational



conditions. Therefore the outcomes on the removal of wastewater pollutants truly reflect the treatment efficiency of these facilities.

Sampling and laboratory analyses. The sampling period was divided into two sub-periods: I – in years 2010 and 2011 with seven sampling events and II – from October 2012 to May 2013 with three sampling events. The second period should be regarded a post-vegetation one. The averaged samples of wastewater inflowing to the HSSF/VSSF beds (after septic tanks) were collected from the collecting wells (Fig. 1). The size of the wells ensured 6 h of wastewater retention. Outflow samples were collected from the ponds. In the collected samples COD, TSS, total nitrogen (TN) and total phosphorus (TP) were determined. The analytical procedures followed the recommendations of the Hach Chemical Company and Dr Lange GmbH. The analyses were performed according to Polish Norms and guidelines as set out in the Polish Environmental Ministry Regulation of 24 July 2006 [17].

3. RESULTS

3.1. POLLUTANTS CONCENTRATION IN WASTEWATER IN SINGLE FAMILY TWs

Figures 2 and 3 present the average concentrations of pollutants in wastewater at the inflow and at the outflow of the analyzed TWs in both monitoring periods (I and II). The results are given for three TW configurations. In each configuration three facilities (described with Nos. 1, 2 and 3) are shown with different shaded bars.

The quality of wastewater delivered to the TWs after mechanical treatment in the septic tanks differed significantly in regards to COD, TSS, TN and TP concentrations (Fig. 2). In both sampling periods, the highest concentrations of COD were observed in the facilities operating according to configuration III. The concentrations of COD in configuration III varied from 900 to 1300 mg O₂/dm³ while in configurations I and II they were below 800 mg O₂/dm³. The high concentrations of COD were not associated with particulate organic matter since the concentrations of TSS were much lower and varied from 160 to 450 mg/dm³. Thus most of organic matter incoming into TWs was in the soluble or colloidal form. It was also observed that in the second sampling period the concentration of TSS decreased significantly, most probably due to better maintenance of septic tanks, while the COD concentrations remained high.

Wastewater delivered to the treatment wetlands was characterized by a high concentration of total nitrogen, from 60 to 160 mg TN/dm³, in both periods (Fig. 2c). These concentrations were two–three times higher in comparison to the values reported by Vymazal [18] and Heistad et al. [19] (36.3 to 77.5 mg TN/dm³). Similar high concentrations of nitrogen were observed in septic tank effluents in the Podlasie region of Poland [20, 21]. Such differences in TN influent concentration indicate that in some cases domestic wastewater was contaminated with liquid manure or other liquid wastes from the farmyards.



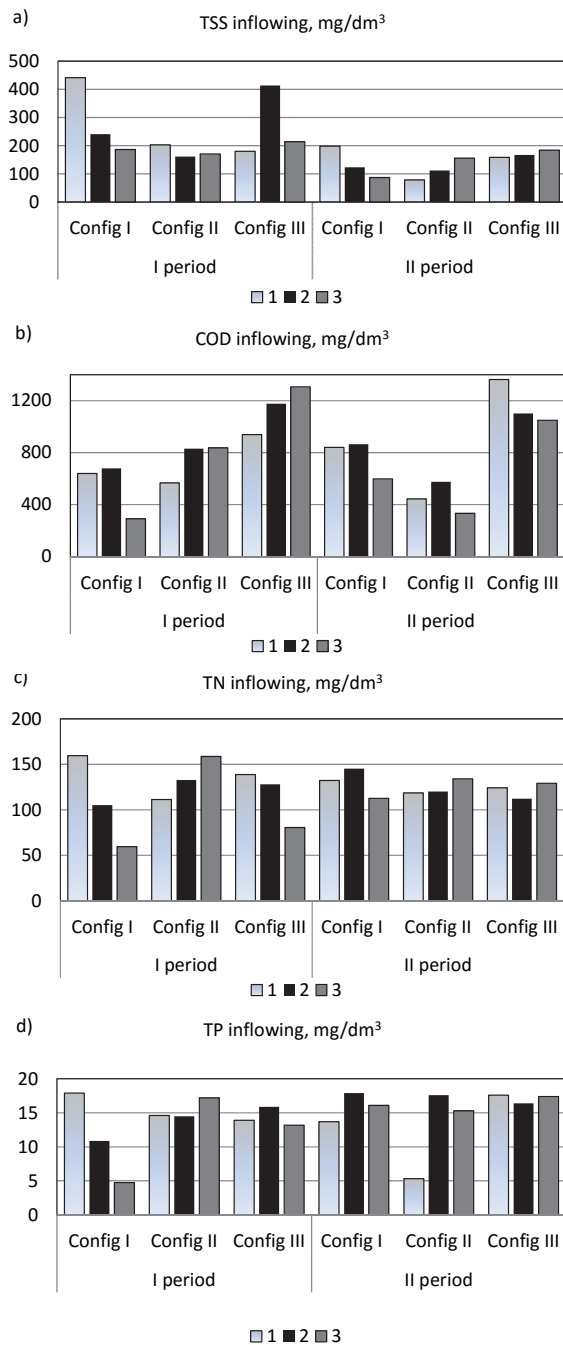


Fig. 2. Concentrations of pollutants discharged to single family TWs
a) TSS, b) COD, c) TN, d) TP; 1–3 – numbers of facilities in each configuration



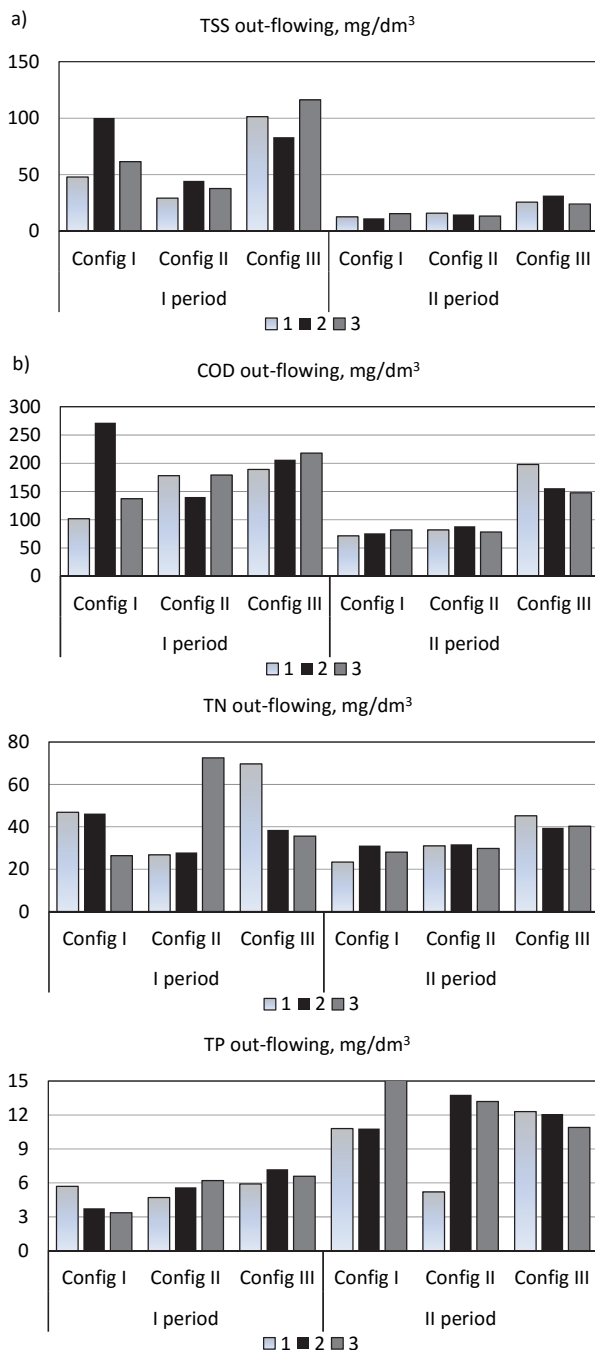


Fig. 3. Concentrations of the pollutant in the effluent from single family TWs:
 a) TSS, b) COD, c) TN, d) TP. 1–3 – numbers of facilities in each configuration



The highest variability in inflow total phosphorus concentrations was observed at facilities working in configuration I: from 5 to 18 mg TP/dm³ in the first period and for configuration II during the second period. For other configurations, the quality of delivered wastewater was more constant. The range of TP concentrations was 14.0–17.5 mg TP/dm³ (Fig. 2d).

The quality of treated wastewater is shown in Fig. 3. Although the concentrations of pollutants decreased, the sewage samples collected from the last stage of treatment (the pond) in many cases did not fulfil the requirements of the Regulation of Environmental Ministry [17] during the first monitoring period. The relatively low quality of the treated effluent in this period was likely be the result of a short period of the TWs operation (poor development of roots and rhizomes as well as biofilms) and of the short period of wastewater retention in the pond [20]. During the second period (post-vegetation one) the quality of the effluent improved significantly and in many cases met the above mentioned requirements. Effluents from single family TWs working in configurations I and II met all the requirements except for concentrations of total phosphorus.

Effluent quality in configuration III was within the required value (50 mg/dm³) for TSS concentrations only. None of analyzed TWs ensured TP effluent concentration below the required 5 mg/dm³.

3.2. REMOVAL EFFICIENCY

Within most single family TWs, the removal of pollutants was quite effective, despite high their concentrations at the inflow. The efficiencies of analyzed pollutant removal in both monitoring periods are presented in Tables 2 and 3.

Table 2

Total removal efficiency [%] of suspended solids and organic matter in single family TWs in both monitoring periods

Facility	TSS			COD		
	Configuration					
	I	II	III	I	II	III
First period						
1	89.1	85.5	43.6	84.1	68.6	79.9
2	58.3	72.3	79.9	60.0	83.1	82.5
3	67.1	78.0	45.8	53.1	78.6	83.3
Mean	71.5	78.6	56.4	65.7	76.8	81.9
Second period						
1	93.5	79.9	83.7	91.5	81.5	85.5
2	90.7	86.8	81.2	91.2	84.7	85.8
3	82.0	91.3	86.9	86.3	76.5	85.9
Mean	88.8	86.0	83.9	89.6	80.9	85.7



Table 3

Removal efficiency [%] of nutrient compounds (TN and TP)
in single family TWs in both monitoring periods

Facility	TN			TP		
	Configuration					
	I	II	III	I	II	III
First period						
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
Second period						
1	82.3	73.8	63.6	21.2	1.9	30.1
2	78.5	73.5	64.7	39.7	21.6	26.2
3	75.0	77.8	68.8	5.6	13.7	37.4
Mean	78.6	75.0	65.7	22.1	12.4	31.2

Generally the efficiency of pollutant removal (except phosphorus) improved with time in all configurations. The highest improvement was observed for configuration I with a single VSSF bed with the lowest loading rate. In the first period, TSS were generally more efficiently removed in facilities with vertical flow beds while in the second one, the removal efficiency of TSS in all facilities of configuration III improved significantly and was similar to those in other configurations. In the first monitoring period, configuration III was the most effective in respect to COD removal while in the second monitoring period COD was removed with the highest efficiency in configuration I.

Although the efficiency of TN removal in configuration III increased from 58.5% in the first monitoring period to 65.7% in the second one, it still remained lower than in the two other configurations. TP removal was very effective in the first monitoring period due to high sorption capacity of the substrate used. When the sorption capacity decreased in the second period, the removal occurred only due to bioaccumulation and did not exceed 30% of the incoming phosphorus load [2].

4. DISCUSSION

The pollutant concentrations in the wastewater discharged to the single family TWs were much higher than reported by numerous authors [18, 19, 22, 23]. Such high inflow concentrations seem to be typical of Polish rural areas and 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) and small water



consumption, at least in some cases [21, 24]. The observations based on the results of this study are in accordance with monitoring results in Europe. Many authors report that VSSF beds are more effective in terms of pollutant removal and provide effluents of better quality, as it was also confirmed in this study [23, 25–27].

The obtained results confirm that TWs were not successful in removing TP from wastewater due to a high concentration of P-compounds in volatile suspended solids. TWs are adapted to the removal of inorganic phosphorus compounds coming from detergents, while organic phosphorus should be retained together with the suspended solids in the mechanical treatment unit.

A comparison of all three configurations indicates superior performance of configurations with VSSF beds. Configuration I consisted of a single VSSF bed with a larger unit surface area in comparison to two sequential VSSF beds working in configuration II. In both configurations the beds were followed by a pond. The final pollutant concentrations within the effluent from both configurations were similar and fulfilled the requirements of the Regulation of Environmental Ministry [17]. Since the contact time in sequentially working VSSF beds was twice longer than in a single VSSF bed with bigger unit surface area, it can be concluded that an elongation of the contact time has a greater positive impact on treatment results than the application of a larger surface area single unit. This finding is in accordance with the newest tendency to minimize the unit area of TWs but applying two or even more treatment stages in TWs [2, 21, 24, 27].

5. CONCLUSIONS

The application of TWs for single-family effluent is an effective and sustainable solution for wastewater treatment in rural areas.

The TWs operated in Poland receive much higher concentrations of pollutants in comparison to the TWs operated in Europe and the USA.

In first two years of operation, satisfactory treatment effectiveness of BOD 64.0–92.0%, TN 44.0–77.0%, TP 24.0–66.0% was observed.

The efficiency removal of organics and TN, except for TP, increased between 12–20% after three years.

After three years of operation, the best quality of effluent was obtained in single VSSF's with a larger unit surface area and thus smaller loading ahead of sequentially working VSSF beds.

A negative attitude of the farmers can be an obstacle in the implementation of sludge treatment reed beds (STRBs). Thus STRBs at central WWTPs, receiving sludge from individual single-family treatment plants, should be considered instead.



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