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Long-term operation of Kickuth-type constructed wetland applied to municipal wastewater treatment in temperate climate

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ABSTRACT

The purpose of this paper is to discuss the problem of changes of effectiveness of Kickuth-type constructed wetland with subsurface flow applied to domestic wastewater treatment. This study is based on an example of a wetland 3000 m^2 in surface, serving 800 inhabitants, located in Poland. The results of chemical analysis showed that after an initial year of 'start-up time', the efficiency of pollutant removal gradually increased to reach an apex in the 6th year of operation. Such maximum efficiency continued up to the 10th year of operation; afterwards it gradually dropped. Moreover, after 12 years of operation, a serious problem with overland flow was observed, which indicated the porous media clogging processes.

KEYWORDS Constructed wetland; wastewater treatment; common reed; Kickuth design; effectiveness

1. Introduction

Due to environmental concern as well as enforcement of European Union regulations, there is a strong demand for construction of new and upgrading of existing small and middle size wastewater treatment plants in Poland and in other European countries [1]. Moreover, Poland, being one of the contracting parties of the HELCOM, is obliged to fulfill the provisions of the Baltic Sea Action Plan adopted in 2007 in Cracow during the HELCOM Ministerial Meeting [2]. One of the main goals of that plan was to protect the Baltic Sea against excessive eutrophication, recognized as the most significant problem, in order to reach good environmental status for the Baltic Sea by 2021. HELCOM recommendations concerning the reduction of nutrient loaded to the Baltic Sea are stricter than the obligations arising from Polish membership in the European Union. Among other statements, the Helsinki Commission estimates that in order to reach good environmental status of the Baltic Sea, introduction of requirements for wastewater management for small- and medium-sized municipalities (300–10,000 Persons Equivalent [PE]) is necessary.

Treatment Wetland (TW) technology seems to be an excellent environmentally sound approach, which could be implemented in any place to solve the problem of small- and medium-sized municipalities. While both scientists and professionals, as well as the general public, accept TWs as an excellent ecological solution for wastewater treatment, there is still concern about the length of time at which the system can be efficiently operated [3–8]. Such a question is particularly often addressed for Kickuth-type wetlands. This is mainly due to the very specific design of the porous media bed characterized by low porosity, small size of pores, and organic layers in the bed. The concept of Kickuth's system is based on cohesive material (often originated at the construction site) as a substrate, very often with high content of clay. This technology is known in textbooks as the Rood Zone Method (RZM), closer to the traditional understanding of a soil treatment of sewage [9,10]. The role of the plant in RZM was to improve the hydraulic conductivity of substrate. According to Kickuth [11], the vegetated area of the bed in RZM should be only 2 m^2/PE.

Since the late 1970s, RZM has spread to other European countries (among others Denmark and Poland). Unfortunately, operational problems during wastewater treatment resulted in discontinued operation of facilities in this technology. Moreover, RZM technology used subsurface horizontal flow (SSHF) beds, which are dedicated to removal of total suspended solids, organic matter, and nitrogen, but only in the denitrification process due to the limited oxygen supply [5, 10–13]. Thus, in this context (and according to our current knowledge), RZM would not fulfill the requirements that are now in force in EU countries according to the Water Framework Directive (2000/60/EEC) [14] and Council Directive of 21 May 1991 (91/271/EEC) [15] which are as follows: Biochemical Oxygen Demand$_5$ (BOD_5) < 25 mg/l; chemical oxygen demand (COD) < 125 mg/l; and total suspended solids (TSS) < 35 mg/l. In Poland there are less strict demands in force for settlements below 2000 PE like BOD_5 < 40 mg/l; COD < 150 mg/l; and TSS < 50 mg/l (Polish regulation, 24 July 2006 [No. 137 item 984] and 28 January 2009 [No. 27 item 169] and 18 November 2014 [No. 2014 item 1800]) [16]. According to this regulation in Poland, removal of nitrogen and phosphorous compounds is required only for sensitive areas, and thus for the whole of Poland, since 99% of it belongs to the Baltic Sea catchment and is assumed as potentially sensitive for eutrophication (N < 30 mg/l and P < 5 mg/l).

The objective of this research was to assess long-term performance of such wetland applied to municipal wastewater treatment for a community of about 800 inhabitants, including efficiency of removal of most important pollutants (organic matter and nutrients such as nitrogen and phosphorous) as well as some effects of bed clogging. Achieved results enable better understanding of the processes of pollutant removal in SSHF TWs over a long time of performance.

2. Site description

The research was carried out on an SSHF wetland designed and constructed under supervision of a Danish consulting company and located in the southern part of Poland. Discharged wastewater was collected from several surrounding small communities of 800 PE. The facility was designed for daily average flow of 116 m^3/d and a maximum $Q = 180$ m^3/d. Since its opening in 1997, it has been the largest wastewater treatment plant in Kickuth's technology in Poland (according to a Danish project). TW consists of four compartments of 750 m^2 of surface each (see Figure 1), with each compartment of 25 m by 30 m. The system was of one stage and it means that compartments were working in parallel. The wetland was designed with unit area equal to 3.75 m^2/PE (by hydraulic loading 4 m^2/PE). It is the largest Kickuth-type wetland in Poland applied for wastewater treatment.

Before being sent to the wetland, raw wastewater is pretreated with a cache-type screen for separation of particles larger than 3 cm, and then undergoes sedimentation in a three-compartment septic tank with a total volume of 200 m^3, which results in average detention time of about 40 h. Afterwards wastewater was pumped to the wetland with a possibility to control a uniform hydraulic loading with a valve before each compartment. Distribution of wastewater was achieved through a perforated pipe located on the bottom of a bed inlet. The perforated pipe and the first 1.5 m were covered with stones of 4–7 cm diameter. Such large diameters lead to large-sized pores. Since the wetland was designed and constructed according to Kickuth's solution, the bed had sequential layers of humus, straw, and local soil (in the Polish condition of this region it was mainly loamy sand or loam) [17]. The filtration coefficient of used loam sand was 10^{-8} to 10^{-6} m/s. It was assumed by the designer that the plants' roots would increase bed porosity during the wetland operation.

The depth of a bed was 0.6 m and the bottom was sealed with a plastic liner for protection from contamination of groundwater. The beds were planted with common reed (*Phragmites australis (Cav.) Trin. ex Steud.*). There were no data of plant density at the beginning of the operation but the current density of planted reed is 340 plants/m^2. During the first several years, the Danish firm requested and supervised chemical control of growth of plants other than reeds. Later, the operator continued such control by hand harvesting, including removal of any plant at the inlet and outlet zones.

The wastewater depth was maintained at about 5 cm below the bed surface, but flooded from time to time for better weed control, following the designer's recommendations.

3. Methods

Monthly monitoring of wastewater quality allowed to collect the data showing the changes of effectiveness of the wetland during 15 years of plant operation (from 1997 till 2012). The samples were collected at the inlet before the screen and at the outlet of the wetland (discharge to the stream). It was estimated in the project based on textbook that the pretreatment resulted in about 35% of BOD_5 and COD as well as 50% of TSS and up to 30% of nitrogen and phosphorous removal. Thus for calculation of decay rates, the initial concentration of the analyzed parameter was reduced by an appropriate degree of reduction in this stage.

Sampling, sample transportation, processing, and analysis have been done according to relative Polish Standards of Wastewater Examination which are in accordance with APHA 1992 and 2005 [18,19].

Flow rates were measured at the outlet with weir and ultrasound measurement for monitoring wastewater depth. It should be noted that flow rate at the outlet could be sufficiently different than at the inlet due to

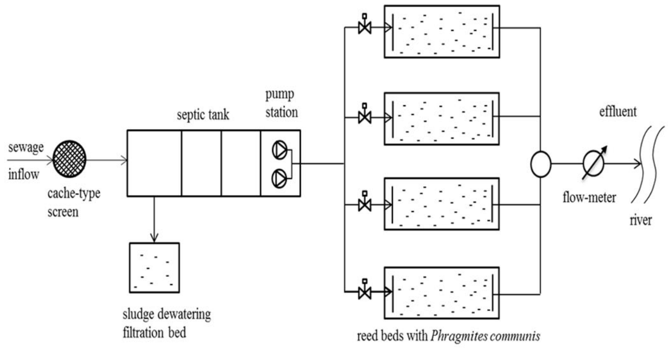


Figure 1. Scheme of technology of the analyzed wastewater treatment plant with the application of Kickuth-type wetland and Google view.

evapotranspiration, particularly during the plant growing season, which peaks in May and June in Poland.

Moreover, observations of wastewater depth at the wetland were conducted for monitoring any overland flow. The collected data were analyzed monthly (ca. 170 months) and yearly as an average of monthly data (15 years of monitoring).

Due to the changes in both flow and pollutants' concentration, the efficiency removal was calculated based on appropriated load of pollutants. Removal efficiency was calculated as a quotient of pollutants load difference in influent (L_{in}) and outflow (L_{out}) in SSHF and load in influent (L_{in}), $\eta = (L_{in} - L_{out})/L_{out}$.

The first-order decay rates of organic matter (BOD_5) and nitrogen (as a total nitrogen (TN)) were calculated according to the equation proposed by Kickuth [8] widely used for sizing of SSHF TW systems for domestic sewage treatment:

$$A_h = Qd(\ln C_{in} - \ln C_{out})/k, \tag{1}$$

where A_h is the surface flow of the bed (m^2), Qd is the average flow (m^3/d), C_{in} is the influent contaminant (respectively BOD_5 or TN (mg/l), C_{out} is the effluent contaminant (respectively BOD_5 or TN (mg/l), and k is the rate constant for TN or BOD_5 (m/d).

4. Results and discussion

4.1. Fluctuation of flow and temperature

Wastewater discharged to the plant varied from 26 to 119 m^3/d while the system was designed for average 116 m^3/d. Thus the flow never exceeded the maximum value of 180 m^3/d (Figure 2). During the first six years of operation (up to 70 months), the flow was much lower (68 m^3/d) than the designed one and in consequence the hydraulic load equaled 22.7 mm/d. This created preferable conditions for the start-up period of the facility and an environment favorable for the growth of microorganisms responsible for pollutants' removal processes. After six years of operation, when all households were connected to the wastewater treatment plant, the average flow was equal to 113 m^3/d, which corresponded to 37.7 mm/d of hydraulic load. According to many authors, hydraulic load plays a very important role in ensuring effective removal of pollutants

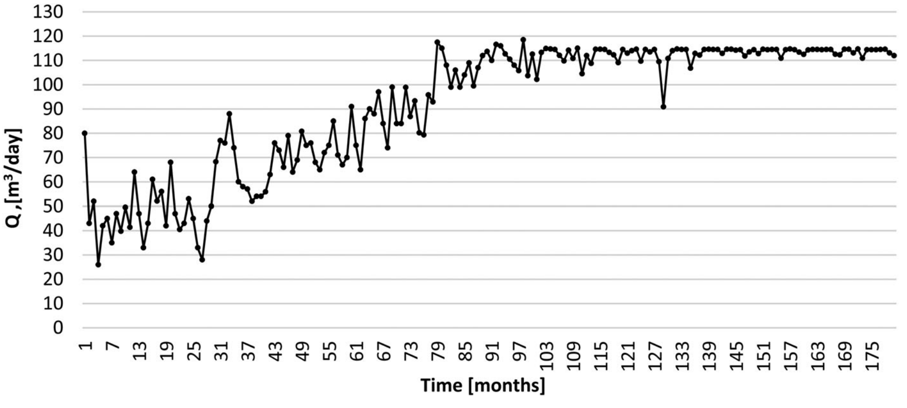
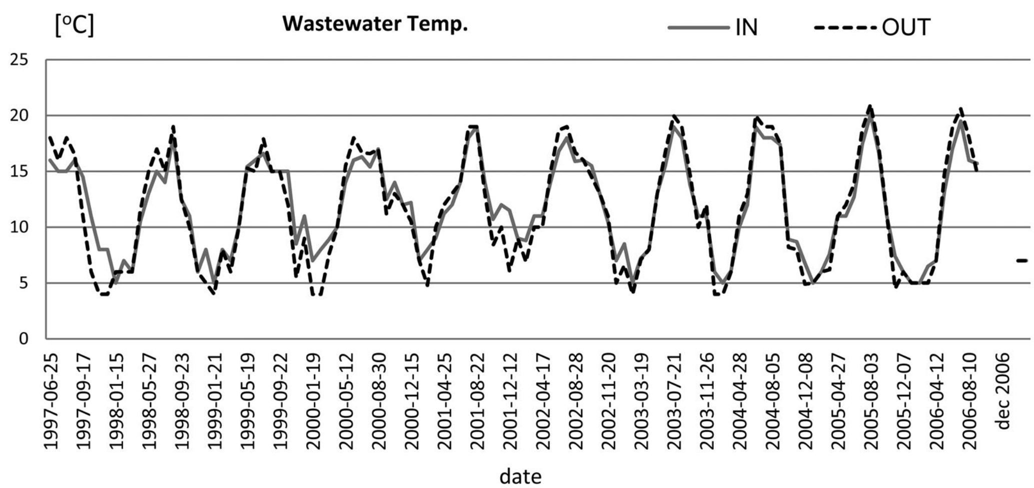


Figure 2. Fluctuation of the hydraulic loading at the TW in Inwałd, Poland.

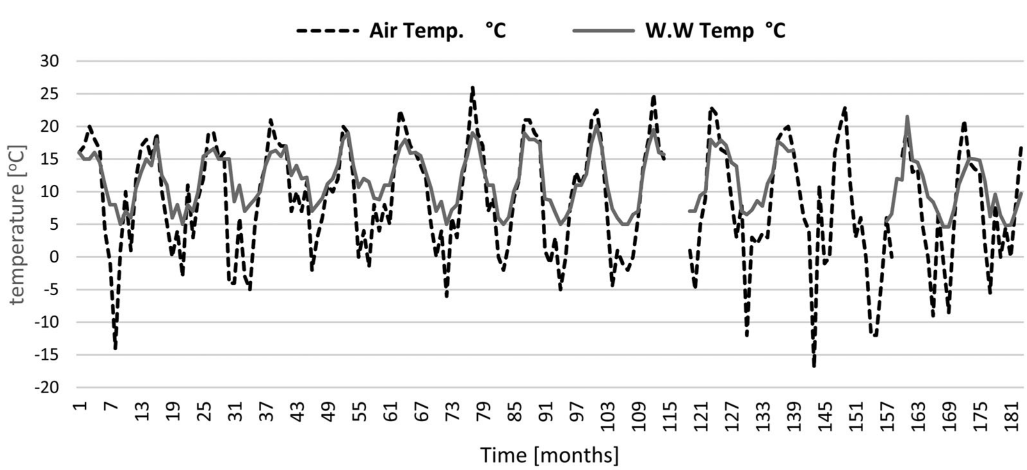
Figure 3. Clogging effect after 12 years of operation (winter season) at the TW in Inwałd, Poland.

[8,20]. When the SSHF system is overloaded by discharged wastewater, surface flow can change and in consequence could cause improper conditions for biochemical processes responsible for contamination removal in subsurface flow [10,21]. In case of analyzed TW, surface flow was observed after 12 years of exploitation, which was most likely a consequence of the clogging of the first part of the SSHF beds (see Figure 3).

During a long period of operation, the temperature of wastewater in inflow and, most importantly, in effluent did not drop down below +4°C, which is the temperature limiting removal of nitrogen processes. The results presented in Figure 4(a,b) clearly confirm: (1) the seasonal pattern typical for latitude of temperate climate and (2) only a small influence of TW on the temperature of wastewater (Figure 4(a)). During winter period TW cooled down, while summer warmed up the wastewater, but in both cases the differences were very small and only up to 2°C. From Figure 4(b), it can be concluded that even very low air temperatures during winter time, typical for this part of Poland (started in December



a) of wastewater in inflow and outflow from TW in Inwałd



b) temperature of air and wastewater in inflow

Figure 4. Fluctuation of temperature at the TW in Inwałd, Poland. (a) Temperature of wastewater in inflow and outflow from TW in Inwałd and (b) temperature of air and wastewater in inflow.

Table 1. Wastewater quality at the inlet and outlet during the 15 years of operations ($n = 170$ samples) of the treatment wetland in Inwald, Poland.

	Inlet – raw wastewater			Outlet – effluent from the wetland		
Parameters	Range	Average	Standard deviation	Range	Average	Standard deviation
BOD_5 (g O_2/m^3)	70–2750	572	495	10–215	48	31
COD (g O_2/m^3)	169–6512	1287	1193	36–366	131	67
TSS (g/m^3)	40–5490	731	925	4–130	32	25
TN (g/m^3)	26–211	86	32	26–132	71	20
TP (g/m^3)	1.94–30.2	13	6	1.0–25	10	5

Note. TP: total phosphorous.

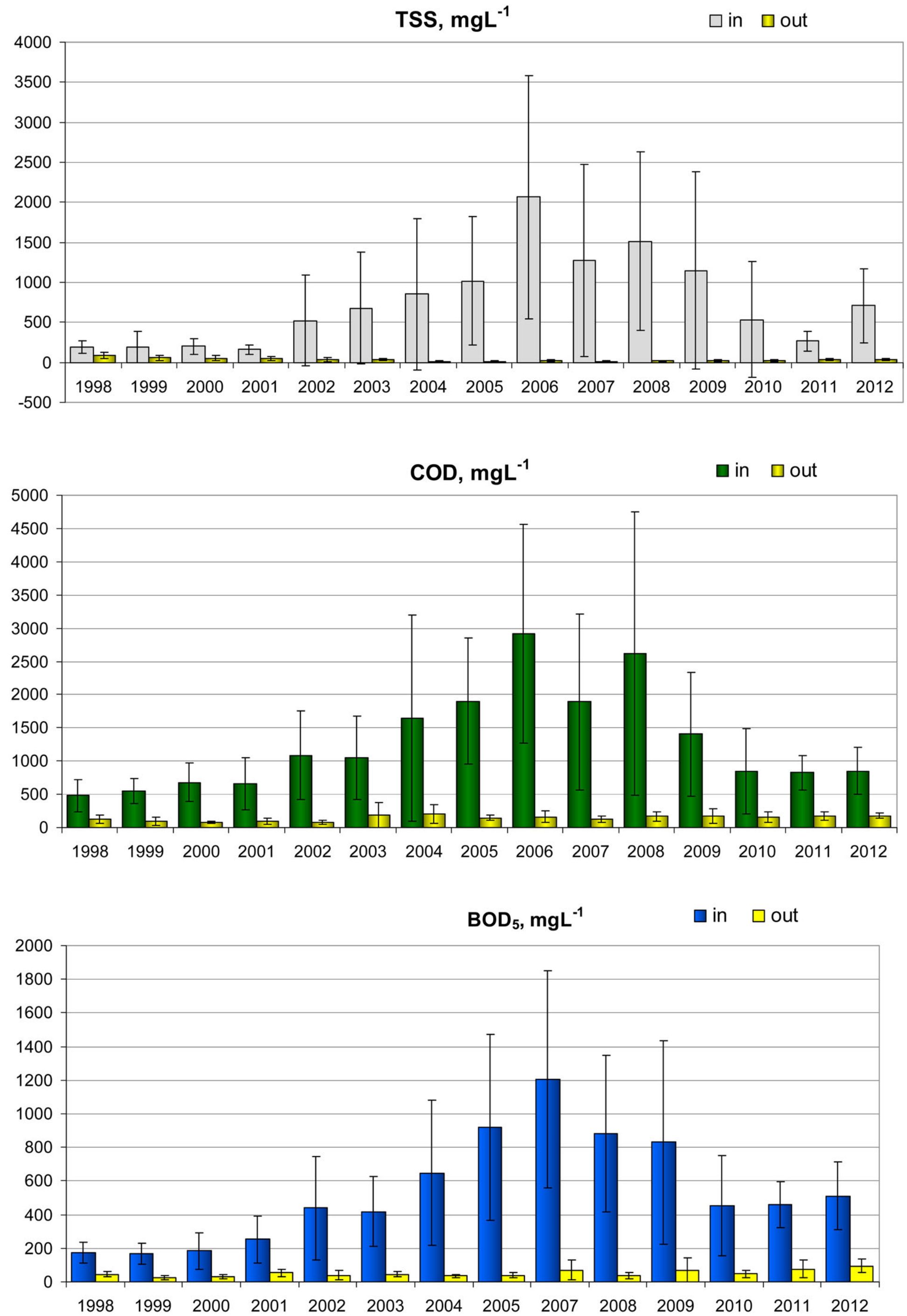


Figure 5. Average annual concentration of pollutants in inflow and outflow at the TW in Inwałd in years 1998–2012.

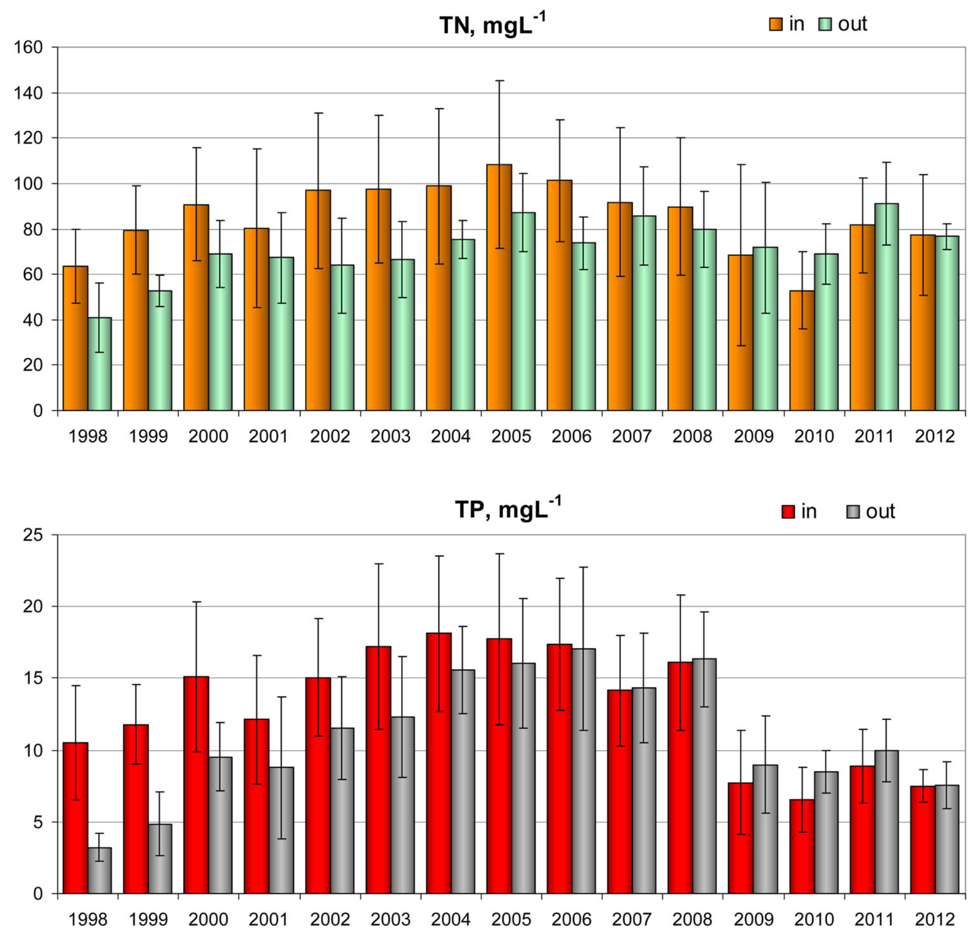


Figure 5. *Continued.*

1997 lasted for two months after seven months from start-up), did not cause any decrease of wastewater temperature below 5°C (Figure 4(a) – data 15 January 1998). Although there were no disorders of performants observed during winter period, the biggest problem could appear in the inlet zone when the soil and distribution system could be frozen. In case of the analyzed TW, there was no special equipment or procedure to handle this problem like it is given in literature [22].

4.2. Organic matter, nitrogen, and phosphorous

Average BOD_5, COD, and TSS of raw wastewater were 572 gO_2/m^3, 1287 gO_2/m^3, and 731 g/m^3, respectively (Table 1). Interestingly, standard deviations for those parameters were high: 495 gO_2/m^3 for BOD_5, 1193 gO_2/m^3 for COD, and 925 g/m^3 for TSS, which is due to typical quality variability for a small community.

Results indicated that the studied Kickuth-type constructed wetland exhibits an interesting and distinguished pattern. The results of BOD_5, COD, and TSS measurements showed that after the initial years of 'start-up time', efficiency of pollutant removal gradually increased to reach a climax in the sixth year of operation (Figure 5). The start-up time allowed for vegetation growth (including root mass) and biofilm build-up in the bed. It should be noted that the recommendation for this period is shorter, but a longer period is still beneficial. Maximum efficiency has been observed after 6 years since the beginning of this operation, which continues up to the 10th year of operation (Figure 6(a,b)). As mentioned in the previous sections, hydraulic loading and BOD_5 loading were both comparable with Kickuth's recommendations. Slow but gradual decrease of pollutants' removal efficiency after the 10th year of operation was observed. Moreover, after 12 years of operation (in 2009), a serious problem with overland flow was observed, which indicated the porous media clogging processes (see Figure 3). Another important conclusion could be an observation of no significant correlation between removal efficiency and temperature of both air and wastewater. Removal efficiency caused by winter season dropped up to 20% in case of organics and in case of suspended solids there was no influence of temperature (Figure 4). It seemed that TSS removal efficiency was more flow dependent – slow but constant

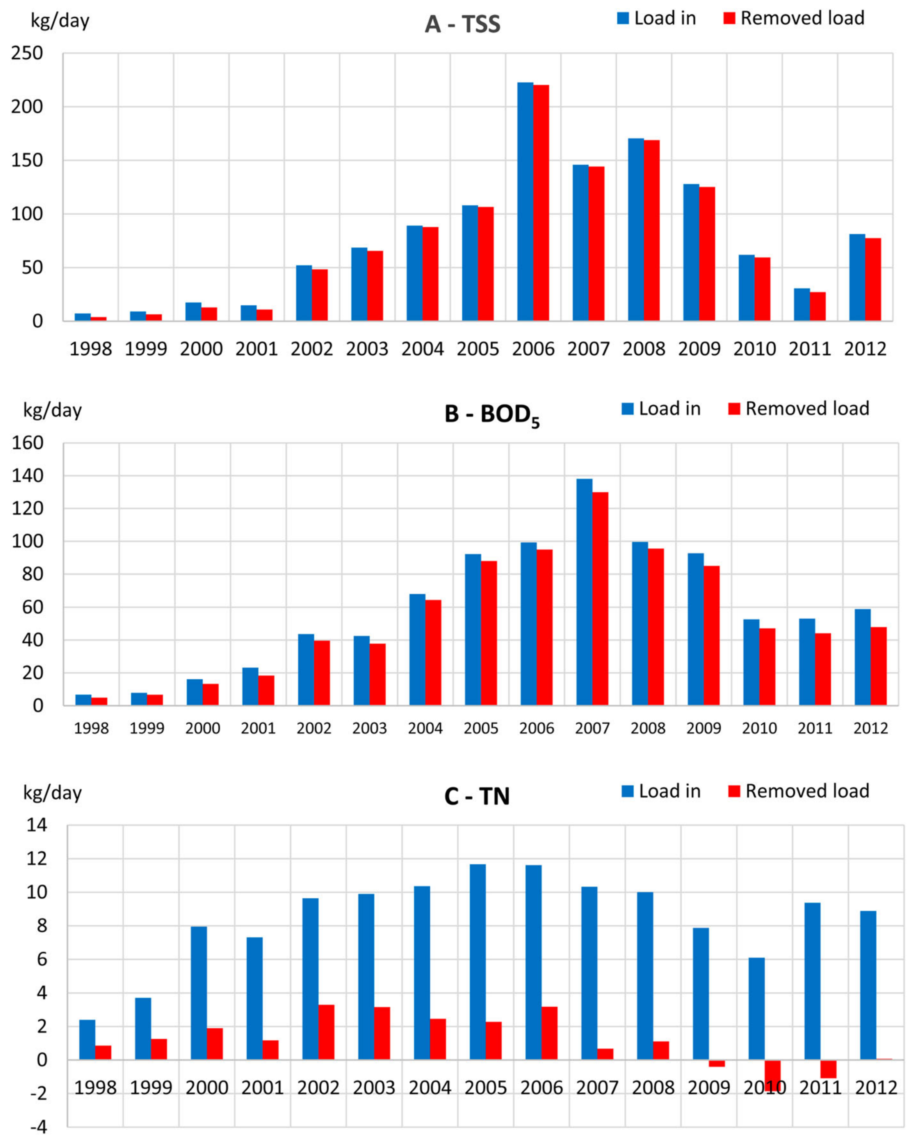


Figure 6. Fluctuation of mean load in influent and removed loads at the Inwałd plant in years 1998–2012.

increase of flow, which was observed within the first years of operation, caused variable effectiveness of suspended solids and had less influence on organics removal (Figures 2, 5, and 6). In the case of the analyzed TW both increase of flow and concentration of pollutants increased within the operation time (Figures 2 and 5) which led to series of operational problems and finally to decrease of removal efficiency of the object (Figure 5). These phenomena could be explained by typical sociologic and political issues like (i) when the treatment plant was constructed in 1997, more and more houses have been connected every year (ii). At the beginning, people tended to use more water, and both flow and concentration of pollutants have been increasing (iii), and finally in 2004 Poland become a member of the EU and since 2006 new tools like law and taxes have been introduced enhancing both single users and municipalities for better handling of wastewater [16,21].

The mean influent pollutant load during the investigation period was 110.6 kg COD/d, which corresponds to 37.0 g COD/m^2 d, while mean removed load was 90.6 kg COD/d (30.0 g COD/m^2 d). Average BOD_5 loading in raw wastewater was 57.2 kg/d, which amounted to 19 g/m^2 d meter of wetland, and average removed load was 42.8 kg BOD_5/d which was 14.2 g/m^2 d. Even though the system in Inwałd was highly loaded compared to the data given in literature [8,23], it has proven itself to have a very high potential for removal of organics (Figure 6(b)). The mean TN load was 8.48 kg N/d, which corresponds to 2.8 g TN/m^2 d, while mean removed load in years 1998–2008 was 1.94 g TN/m^2 d. Since 2009 the system has started to release previously accumulated nitrogen. The mean

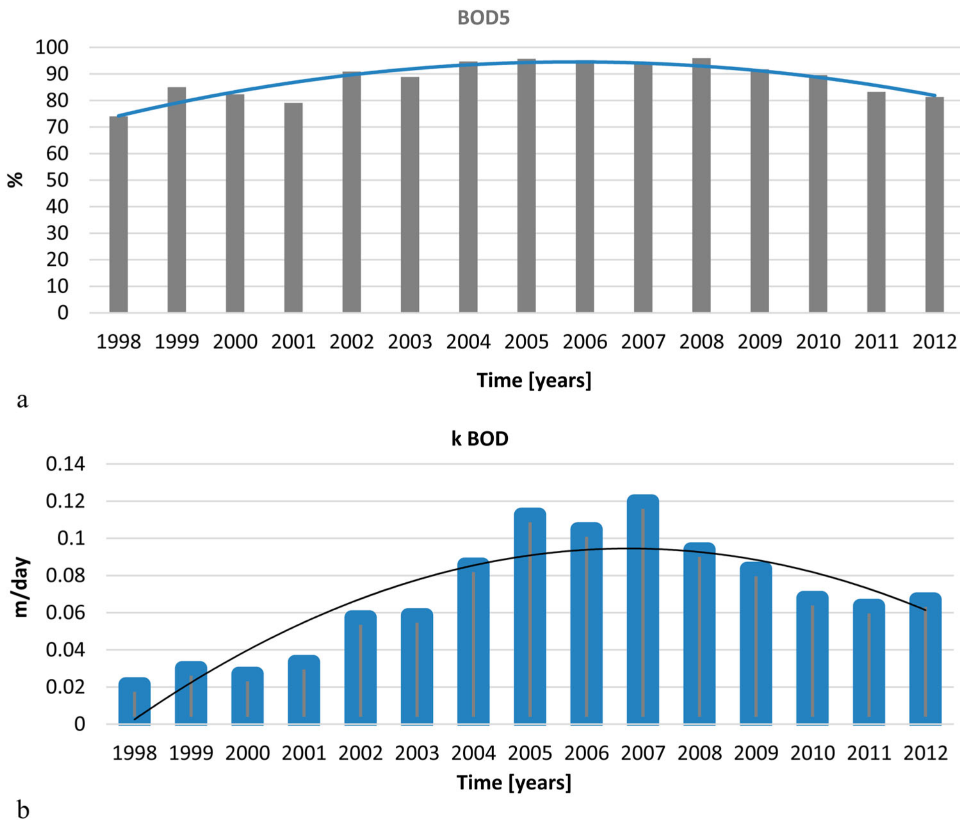


Figure 7. Fluctuation of (a) pollutant removal efficiency and (b) first-order reaction rates constant for BOD_5 at the Kickuth-type wetland in Inwałd.

load of withdrawal in years 2009–2011 was 1.1 g TN/m^2 d, with peak in 2010. Thus, in these years, the concentration of nitrogen in outflow was higher than in inflow (Figure 5). In 2012, the system again started to remove nitrogen with very small efficiency (Figures 6(c) and 8). Similar phenomena were observed in natural wetland studies [8,23].

In case of organics, the BOD_5 removal efficiency has indicated more fluctuation after 10 years of operation in comparison to COD removal efficiency which dropped down only 5% and was maintained at 84% which is relatively high for the SSHF bed constructed according to Kickuth's technology [8–11].

The most visible decries of removal efficiency were observed for nitrogen which according to many authors is the most sensitive for any operation problems [5,8,9,23].

Analyses of average efficiency removal and decay rates of organic matter (BOD_5) confirmed the observations in the objects (Figures 5 and 6). Since 2008 efficiency removal of BOD_5 started to fluctuate significantly and kinetic rate of BOD_5 decay has declined. Significant decrease of flow rate below designed hydraulic loading, which was introduced by operator of TW Inwałd, solved that problem, but only for a limited period of time. Not surprisingly, during overland flow the effluent did not meet parameters required by the Polish Regulation, 24 July 2006 [16]. Since 2008, in almost 88% of the taken samples of effluent the concentrations of organics, nitrogen, and phosphorous were exceeded. This finding together with visible problems with rapid decrease of hydraulic conductivity of the substrate resulting in pooling confirmed clogging [8,24].

According to data given by many authors, first-order reaction rates constant for BOD_5 for SSHF beds varied largely in scope [25]. The smallest value 0.02 m/d was confirmed by Brix [26] and the highest 0.49 m/d by Kadlec [27]. The rates constant for BOD_5 appointed for the Kickuth-type wetland in Inwaład are in accordance with the above-mentioned values and changed in scope from 0.021 to 0.12 m/d (Figure 7(b)).

In the analyzed Kickuth-type CW, removal rate of nitrogen and phosphorus was unstable in time and decreased over the years of operation (Figures 8 and 9). The efficiency removal and appointed first-order reaction rates constant for TN fluctuated in time. During the first two years of operation, they were a bit higher than in the third and fourth years, which could suggest that in the first two years, the main mechanism of TN removal was the sorption process due to underdeveloped root

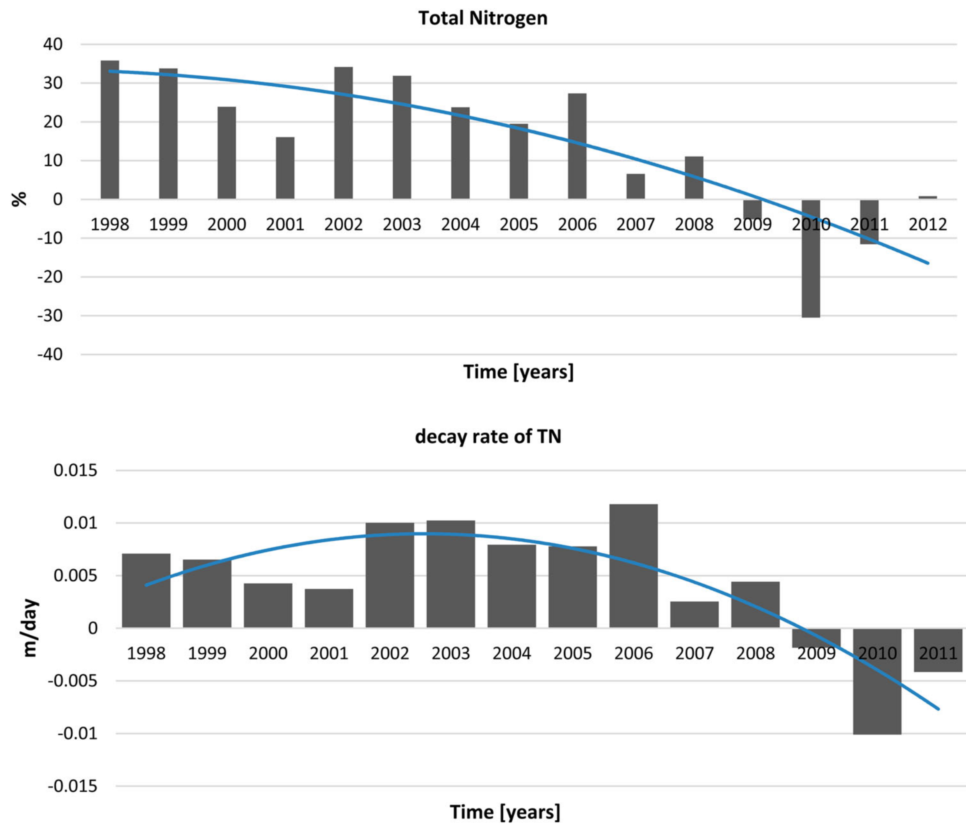


Figure 8. Fluctuation of (a) pollutant removal efficiency and (b) first-order reaction rates constant for total nitrogen at the Kickuth-type wetland in Inwałd.

zone system. After four years, both rates increased slightly but still the efficiency removal of TN was low (not exceeding 35%) in comparison to multistage CWs [5,8,12] or even single SSVF [3,4,13]. After six years of operation, the efficiency removal tended to decrease and finally, since 2009, the Kickuth-type CW in Inwałd has started to rely on previously accumulated nitrogen in the form of N-Org. Such phenomena are a common process observed in systems that suffer due to clogging [8]. The first-order reaction rates constant for TN changed in range of 0.007–0.0118 m/d and are in accordance with the values given by Kadlec &Knight [23] for single SSHF beds.

Total phosphorus removal was efficient only in the first two years of operation (concentration in outflow below 5 mg/l) and then tended to decrease rapidly with the workout of sorption capacity of the substrate. This phenomenon was probably also responsible for

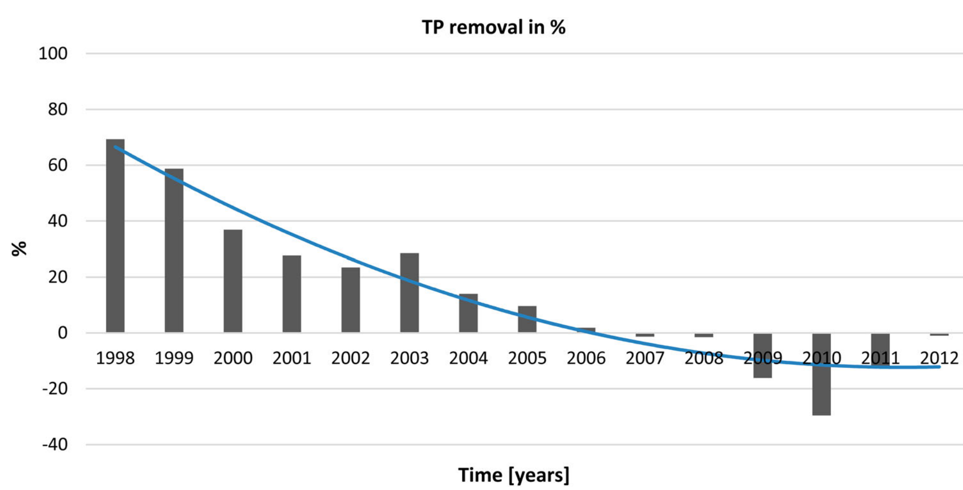


Figure 9. Fluctuation of total phosphorus removal efficiency at the Kickuth-type wetland in Inwałd.

the observed tendency since 2009 of releasing of previously accumulated phosphorus.

Our study confirmed previous ones of many authors, indicating that although the single system (more often SSHF) is characterized by high removal efficiency, it does not provide the required stability and efficiency of pollutant removal [7,9,10,24]. Single-stage systems with SSHF beds are more sensitive for changeable hydraulic and pollutant loads and, in consequence, fluctuations in the removal effectiveness are their natural apparent feature. Notwithstanding, SSHF beds are a very useful component of hybrid constructed wetland and in such configuration their disadvantages are mitigated [5,6,28,29].

5. Conclusions

Our findings showed that the studied single SSHF beds constructed according to Kickuth's technology, even with their noticeable relatively high removal efficiency of pollutants (organics up to 90% which corresponds to unit load removal of 30.0 g COD/m^2 d and 14.2 g BOD_5/m^2 d), are not able to ensure stable removal efficiency of pollutants over a long period of time, even for organic matter and for nitrogen as well as phosphorous.

One of the important conclusions from the assessment of monitored data is a noticeable length of time of operation after which a significant drop of treatment efficiency has been observed in the Kickuth-type wetland in Inwałd. The results showed that for BOD_5, TSS, and COD a 12-year time of operation was the limit of technical and economical operation for the Kickuth-type constructed wetlands applied to municipal wastewater treatment. Since the very beginning, the removal efficiency of nitrogen and phosphorus was too low to fulfill the Polish requirements. Both increase of flow and concentration of pollutants led to variable removal efficiencies and finally to beds clogging. The received results must be applied to other similar cases with additional care due to several factors which could affect treatment efficiency.

Disclosure statement

No potential conflict of interest was reported by the authors.

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