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Original Research

Treatment of Landfill Leachate by Constructed Wetlands: Three Case Studies

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Abstract

The performance of three constructed wetland systems treating landfill leachate, two located in northern Poland (Szadółki near Gdańsk and Gatka near Miastko) and one in southern Sweden (Örebro), is discussed. The CWs differ in size, hydraulic regime, type of hydrophytic plants, and type of leachate pre-treatment before discharging to the CW. The CW in Szadółki consists of two parallel beds with sub-surface, horizontal flow of leachate (HSSF) planted with reed. The leachate is discharged to the CW without pre-treatment. The facility in Gatka is a willow plantation that receives leachate after preliminary sedimentation in a retention pond. The system at Örebro consists of a series of ponds with a surface flow of leachate (the free water surface - FWS wetland), preceded by pre-treatment in an aerated tank with nitrogen stripping. A comparison of treatment conditions and results is presented. The best treatment efficiencies were observed at the CW Örebro (98% TSS, 91% BOD, 65% COD, 99.5% N-NH_4^+), which resulted from:

(i) an effective pre-treatment of leachate before it was discharged to the CW, and
(ii) the CW type – with surface flow of leachate (FWS).

At the sub-surface flow wetlands (Szadółki, Gatka), clogging problems occurred due to lack of or unsatisfactory pre-treatment of leachate, resulting in lower treatment efficiencies. The ammonia nitrogen was still removed at the clogged facilities with the efficiencies varying from 52 to 89%, while the organics removal efficiencies were substantially lower (27-61% for BOD_5 and 2-35% for COD).

Keywords: clogging, constructed wetlands, design, landfill leachate, operation and maintenance

Introduction

Treatment of landfill leachate has become one of the most important environmental problems due to fluctuating composition and quantity as well as high concentrations of specific pollutants (polycyclic aromatic hydrocarbons PAH, absorbable organic halogens AOX, polychlorinated biphenyls PCB, heavy metals) and very high ammonia nitrogen and COD concentrations. Considerable variations in the quality of leachate from different landfills has been reported in the literature [1]. The leachate from young landfills (where the acetogenic biodegradation phase is active) is characterized by high chemical oxygen demand (COD), biological oxygen demand (BOD), and Na^+, Cl^- and NH_4^+ content, while the leachate produced in the subsequent methanogenic phase is characterized by relatively low COD, BOD, and NH_4^+ content and higher pH [2, 3]. The composition of leachates from 35 landfill sites with acetogenic and 29 with methanogenic conditions given by the British Department of the Environment (1995) is cited by Jones et al. [2]. The average COD and BOD values for "acetogenic" leachates were 36,817 mg O_2/l (the range 2,740-152,000) and 18,632 (the range 2,000-68,000) mg O_2/l,

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respectively, while in "methanogenic" leachates these values decreased to 2,307 mg O_2/l (622- 8,000) for COD and 374 mg O_2/l (97-1,770) for BOD. Apart from the organics, ammonia nitrogen is the principal pollutant in the leachate. Ammonia nitrogen is present in the leachate from young landfills owing to the deamination of amino acids during destruction of organic compounds [3]. Leachate from older landfills is rich in ammonia nitrogen due to hydrolysis and fermentation of the nitrogenous fractions of biodegradable substrates. Ammonia concentrations in leachate from different landfills may vary from tens or hundreds of mg N-NH_4^+/l [1] to even over 10,000 mg N-NH_4^+/l [4].

High-tech solutions applied for leachate treatment (i.e. reverse osmosis or ozonation) are expensive and energy consuming, thus they are not suitable at many landfill sites, especially in rural areas. Constructed wetlands (CWs) provide an alternative method of either treating or polishing the landfill leachate, which is inexpensive, simple to operate, and has potential to remove not only organic carbon and nitrogen compounds, but xenobiotics and heavy metals as well [5-7]. The natural process occurring in CWs can aid in leachate treatment. Volatile organics are removed by volatilization or biodegradation. Ammonia nitrogen can be released to the atmosphere directly or after transformation to the dinitrogen gas in the nitrification and denitrification processes. According to Reddy and d'Angelo [8] volatilization of nitrogen is negligible at neutral pH, thus nitrification and denitrification are key removal processes. Metals are accumulated by the hydrophytes (mostly at the underground parts) [5, 9-12], precipitate in the form of insoluble sulphides and hydroxides, or undergo ion exchange processes in the bottom sediments. Hydrophytes are tolerant to the high concentrations of typical pollutants present in the leachate, as well as heavy metals and PAHs [5, 7, 10, 11, 13, 14]. High leachate salinity may disturb some aquatic plants, although according to literature reports, the plant most commonly used in the constructed wetland systems, *Phragmites australis*, can withstand relatively high Cl concentrations [10, 15-17]. Constructed wetlands have been successfully applied for leachate treatment in the USA [18-22], and in European countries (Norway, UK, Slovenia, Sweden) [5, 23-27]. Different types and configurations of CWs are applied for leachate treatment (with surface and sub-surface flow of sewage, several treatment stages with different flow conditions) [20, 23, 28, 29]. While CWs in Poland have gained popularity for sewage treatment, experience with landfill leachate treatment is still developing. In some cases, lack of knowledge in design, construction and operation leads to problems and unsatisfactory treatment results.

In this paper, the design and performance of three CWs for leachate treatment, two located in northern Poland (Szadółki near Gdańsk and Gatka near Miastko) and one in southern Sweden (Atleverket near Örebro) is discussed. The CWs differ in size, hydraulic regime, type of hydrophytic plant, and type of leachate pre-treatment before discharging to the CW. Performance and operation problems of the CWs are discussed.

Table 1. Characteristics of investigated CWs for landfill leachate treatment.

CW location	Year of landfill construction/ year of CW construction	Wastes received per year [t/year]	Leachate inflow to CW [m^3/d]	CW configuration	Plants	Type of leachate pretreatment	Remarks to CW operation
Szadółki, Poland	1973/2001*	2,310	6-240	two parallel HF-CW beds, area 50×50 m each, depth 0.6 m	reed *Phragmites australis*	none	low hydraulic conductivity ($2.55 \cdot 10^{-5}$ m/s) clogging
Gatka, Poland	1993/1997	220,000	5	willow plantation (filter 43×31 m, depth 0.8 m)	willow *Salix*, orchard grass *Dactylis glomerata* L.	retention tank, 1,000 m^3 vol.	low hydraulic conductivity ($5.87 \cdot 10^{-5}$ m/s), clogging
Örebro, Sweden	1979/2003	15,000	max 22	10 hydrophyte ponds with a surface flow of leachate, total volume 53,000 m^3/d, water depth 0.5-1 m	duckweed *Lemna*, reed *Phragmites australis*, bulrush *Scirpus palla*, cattail *Typha latifolia*, sedge *Carex*	cyclically aerated tank 20,000 m^3 vol. with ammonia stripping	CW operated only in vegetation season (April-October); during winter the leachate is recirculated to the landfill

*modernization of beds took place in the period 2006-08.

Experimental

Study Facilities

Investigations were performed at three constructed wetlands: two in northern Poland (Szadółki near Gdańsk and Gatka near Miastko) and one in southern Sweden (Atleverket near Örebro). Both Polish CWs experienced serious clogging problems resulting from unstable leachate composition and quantity, as well as the use of fine grained materials as filter materials (hydraulic conductivity $2.55 \cdot 10^{-5}$ m/s in Szadółki and $5.87 \cdot 10^{-5}$ m/s in Gatka). These questions were not properly considered and solved at the design stage, which had a crucial impact on future operation and treatment efficiency of both CWs [30]. Poor operation of CW Szadółki made it impossible to discharge the treated leachate to the surface receiver as planned. Finally, the clogged bed materials were replaced by a new medium, thanks to which treatment processes were restored. However, the hydraulic conductivity of the new filtration material was similar to the replaced clogged material, which may negatively impact future CW performance.

Methods

Performance monitoring was based on analyses of the leachate flowing into and out of the CW systems. In the case of the CW at Gatka, there was no outflow due to high transpiration. In order to evaluate the treatment processes taking place at the filter, two poliethylene wells were installed at the filter to assemble pore water sample collection (Fig. 1, sampling points III, IV). The leachate percolating through the filter gathered at the bottom of the pipes and could be collected using a syphon.

For the CWs working as the final treatment stage, the raw leachate quality (before pre-treatment) was also assessed. Leachate samples were collected from 2004 to 2005 at Szadółki, from December 2005 to November 2006 at Gatka, and from January 2004 to October 2006 at Örebro. Concentrations of the following pollutants were measured: TSS, BOD_5, COD_{Cr}, N-NH_4, N-NO_3^-, N_{tot}, P_{tot}, total alkalinity, and Cl^-. All measurements were performed according to Polish Standard Methods as well as U.S. standards [31].

The granulometric analyses of filtration bed media and hydraulic conductivity were performed in Szadółki (2004) and Gatka (2006). The analyses were done for already clogged media (no data concerning the initial structure and type of filling material is available). Two types of soils samples were collected: the disturbed-structure samples for grain size analyses (from depths below 30 cm) and the undisturbed-structure samples for the measurement of permeability coefficient (from 30-40 cm). The analyses were carried out according to Polish Norm PN-88/B0481. Construction soils – soil sample analyses as well as Geotechnical Engineering Handbook [32].

Results and Discussion

The concentrations of pollutants in raw and treated leachates (mean values and standard deviations) are shown in Table 2.

A measure of bioavailability of organics in the leachate is the BOD_5/COD ratio. At young landfills (landfilled wastes not older than 3-5 years) the BOD_5/COD ratio is high, reaching even 0.7, indicating high biodegradability of organics in the leachate. In such cases, COD and BOD_5 concentrations are high (over 4,000 mg O_2/l and over 6,000 mg O_2/l, respectively). The pH is acidic (<6.5) indicating that acetogenic fermentation phase products (volatile fatty acids) are present. At the mature landfills (5-10 years) the BOD_5/COD ratio decreases to 0.5-0.3, since the easily biodegradable organics (BOD_5) are consumed. The pH increases to 6.5-7.5. The leachate from old landfills (over 10 years) is characterized by low BOD_5/COD ratios (< 0.1) and pH over 7.5 [1, 4].

Although the three landfills in this study have been in operation for several years, the age of landfilled wastes at each site varies, and all of the landfills are still receiving new waste. Despite their ages, the decomposition processes within the landfill have not yet finished. The leachate from Szadółki is characterized by the highest COD and the highest BOD/COD ratio (0.49), whereas the pH of the Szadółki leachate is the lowest of the analyzed leachates (7.5). In view of the landfill leachate characteristics given above, these parameters correspond to leachate from mature landfills, with partly decomposed organic wastes.

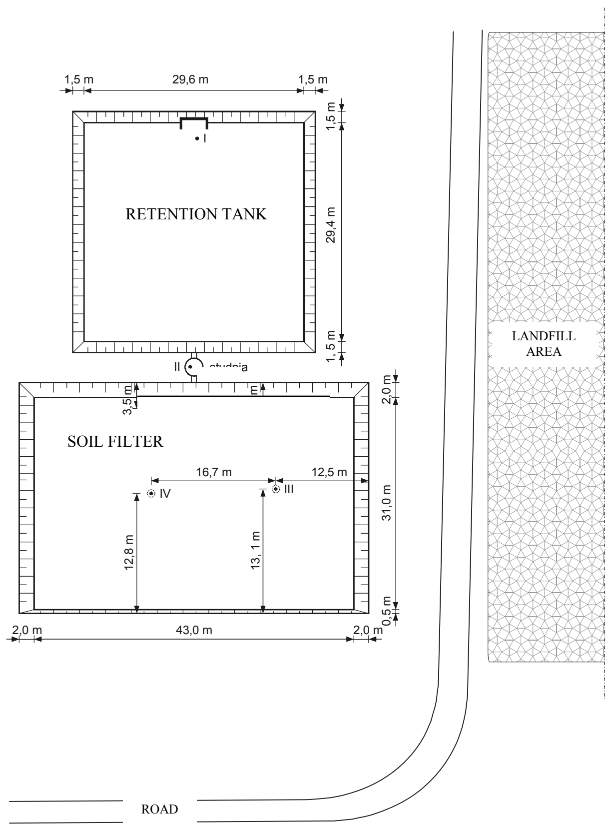

Fig. 1. The landfill leachate treament plant in Gatka.

Leachate from the Örebro site has the second highest COD concentration as well as BOD/COD ratio (0.21), and pH 8.0. The ammonia nitrogen concentration of the Örebro leachate is even higher than that of Szadółki. The quality of raw leachate from the Gatka landfill is much better than that of the other two sites.

Apart from the organics, ammonia nitrogen is a typical pollutant of landfill leachates. The concentrations of ammonia nitrogen in municipal leachates fluctuate from several hundred to over 10,000 mg/l [3, 33]. The concentrations of ammonia nitrogen in the analyzed leachates were typical, as were the chloride concentrations. In case of the leachate from Gatka the TSS concentrations were relatively high.

The data presented in Table 2 allows for analyses of pre-treatment efficiency and its effect on treatment processes in the CW. At Gatka, pre-treatment in the retention tank was not effective, since the concentrations of pollutants, especially TSS, were almost the same before and after this stage. This was due to the fact that the gathered sludge was never removed from the tank. Probably the resuspension of the settled sludge took place, leading to high TSS at the tank effluent. The extremely high TSS concentrations discharged to the vegetation filter caused partial clogging of the filter and periodic flooding of the lower part of the filter (around point IV, Fig. 1), followed by changes of the vegetation type (at the lower part of the filter willow *Salix* was replaced by orchard grass *Dactylis glomerata* L.).

At Örebro the pre-treatment took place in the aeration tank with nitrogen stripping. High removal efficiencies were observed: 71% for BOD_5, 46% for COD and 68% for $N\text{-}NH_4^+$. However, the TSS concentrations increased by over 100%.

At Szadółki, raw leachate was discharged directly to the CW. Due to lack of a sedimentation tank upstream from the CW at Szadółki, the leachate flowing into the CW contained very high concentrations of BOD and COD as well as ammonia nitrogen, which had a remarkable impact on the treatment results. A sedimentation tank would enable not only partial elimination of TSS and probably organics or volatilization of ammonia nitrogen, but it would allow for averaging the concentrations of pollutants and the leachate inflow as well.

Of the three CW systems studied, the most successful in terms of pollution reduction was the CW at Örebro. At the other sites operational problems connected with clogging (Szadółki, Gatka), fluctuations of the leachate amount, and quality (Szadółki) and excessive pollutant concentrations in the leachate discharged to the CWs (due to lack of or unsatisfactory pre-treatment) occurred, influencing the treatment results [30].

The most “problematic” of the CWs was the pair of beds at Szadółki, where all of the above operational problems appeared, caused by errors at the design and construction stage. There was no data concerning the filling material used for bed construction; the only analyses were performed for already clogged media and described in earlier publications [30]. It was found that the fine-grained soil was used for bed construction (0.0007-0.0024 mm). High uniformity coefficients (174-583) were explained using the landfilled wastes and debris, as well as the local soil (clay, loam), for the bed filling, which was visible during the visits to the CW. This resulted in very low hydraulic conductivity of the beds (permeability coefficient k_{10} = $2.55\text{-}5.77 \cdot 10^{-5}$ m/s). The total hydraulic capacity of the CW system, evaluated on the basis of soil analyses (clogged media), was only 1.72 m^3/d, while the hydraulic loading of the beds varied from 6 to 240 m^3/d. Since there was no pre-treatment of the leachate discharged to the CW, the beds were particularly prone to clogging, not only because of the average TSS concentration at Szadółki (150 mg/l), but also due to high organics content (792 mg/l BOD and 1,616 mg/l COD). Assuming the mean leachate flow of 123 m^3/d, the incoming loads of pollutants were as follows: 3.7 g $TSS/m^2{\cdot}d$, 19.5 g $BOD_5/m^2{\cdot}d$ and 39.8 g $COD/m^2{\cdot}d$. The recommended values to avoid clogging risk are 5.4 g $TSS/m^2{\cdot}d$ [34], 6 g $BOD_5/m^2{\cdot}d$ [35, 36] and 15-20 g $COD/m^2{\cdot}d$ [34].

According the TSS concentration, some authors and the German Guideline ATV-A62 recommend that the incoming concentrations should be below 100 mg TSS/l. Beyond any doubt the organic loads discharged to the CW Szadółki were too high and the TSS load contributed to the bed clogging as well. Also, the value of BOD_5/COD ratio at Szadółki (0.49) was quite high comparing to leachates from other landfills. However, it was smaller than the typical value for wastewater, indicating the presences of recalcitrant substance. This means that the organics once accumulated at the beds were resistant to biodegradation and remained at the beds, reducing the effective porosity. Another contributor to the poor hydraulic capacity was related to high concentration of Fe in the raw leachate (mean 22.6 mg/l; range 11 to 38 mg/l). Contact with oxygen brought to the beds via the roots and rhizomes of reed, the Fe^{2+} ions will get oxygenated to the insoluble Fe^{3+} ions that will be deposited in the bed, reducing the effective pore size. High iron concentrations ought to be removed before the leachate is directed to the CW beds.

In the research performed by Randerson and Slater [37] on treatment of leachate from a closed landfill site, the first stage of treatment was leachate aeration at a 3 m high tower filled with lightweight polypropylene media, were dissolved Fe^{2+} was rapidly oxidized to solid Fe^{3+} and precipitated as a film on the media, then the leachate was directed into a lagoon, where further iron settlement took place. Still, in the next stage of treatment performed at small reed beds (with intermittent leachate inflow), iron settlement occurred. To avoid clogging problems it was necessary to clear the accumulated iron deposits, which was achieved by excavating the gravel from the reed beds and washing out the iron sludge with a pressure hose. The washed gravel was then returned to the beds and the reed rhizomes replanted. This operation was performed once a year.

Another problem at Szadółki was connected with unstable leachate composition and lack of any collecting tank prior to the CW that would enable averaging of the leachate composition. Finally, high Cl^- concentration was present in

Table 2. Raw and treated leachate characteristics (means, standard deviations) for the landfill leachate treatment CWs.

Parameter	Effluent standards in Poland	Szadolki						Gatka[1)]								Örebro					
		Raw leachate	SD	outflow bed I	SD	outflow bed II	SD	Raw leachate	SD	Inflow to the CW	SD	point III[2)]	SD	point IV[3)]	SD	Raw leachate	SD	Inflow to the CW	SD	Outflow	SD
BOD5 [mg O_2/l]	30	792	969	303	69	576	116	76	21	60	17	44	9.9	54	11.7	275	23.2	79	5.6	7	1.8
COD [mg O_2/l]	150	1,616	1,645	1,045	281	1,422	426	804	271	648	55	788	20.4	576	14.1	1,338	323	716	141	246	92
BOD/COD		0.49	-	0.29	-	0.41	-	0.10	-	0.09	-	0.06	-	0.09	-	0.21	-	0.11	-	0.03	-
Ptot [mg/l]	5	-	-	-	-	-	-	5.0	1	5.2	1	1.1	0.6	1.7	1.7	4.65	2.89	4.22	2.07	0.10	0.03
Ntot [mg/l]	30	433	92	148.4	23	208.6	45	182	74	116	17	34.2	6.2	25.9	8.1	497	176	286	82.2	27.6	5.4
N-NH_4^+[mg/l]	6	302	206	98.4	11	146.1	27	85	42	75	7	16.5	0.6	8.8	0.5	415	76.8	134	45.5	0.62	0.07
N-NO_3^- [mg/l]	1	-	-	-	-	-	-	4.4	3	2.0	1	1.4	0.3	1.3	0.3	2.29	0.9	96	20.8	19	4.5
TSS [mg/l]	50	150	134	84.8	17	124.1	37	2,714	139	2,596	171	311.9	141.5	412.5	369.2	99	23.3	234	40.8	4.8	1.1
Cl^- [mg/l]	1,000	749	163	-	-	-	-	446	107	320	45	581.4	17.8	17.8	211.4	679	83.3	579	50.8	-	-
pH	6.5-9.0	7.5	0	7.2	-	7.3	-	8.4	0	8.4	0.3	7.2	0.2	7.4	0.1	8	0.3	7.9	0.2	7.8	0.2

[1)] willow plantation without outflow; analysis of pore water samples from the vegetation filter;
[2)] pore water sampling point in the vegetation filter; the part of filter covered by willow;
[3)] pore water sampling point in the vegetation filter; the part of filter covered by orchard grass.

the leachate (mean 749 mg/l; range 530 to 922 mg/l). The combination of these factors led to flooding of the beds and *P. australis* die-off, with consequently poor treatment efficiency (Table 2). The leachate at Szadółki cannot be discharged to surface waters and is recirculated to the landfill site.

The concentrations of pollutants measured in the pore water samples collected at the willow plantation at Gatka were quite low in terms of BOD, total nitrogen, and ammonia nitrogen concentrations. In contrast, the COD and TSS concentrations are high. Nevertheless, the leachate discharged to the vegetation filter was transpired to the atmosphere by *Salix* and *Dactylis glomerata* L. plants and there was no problem with effluent quality. The BOD and COD removal in the vegetation filter was below expectations, but good efficiencies of N and P removal were observed. The ammonia nitrogen removal efficiency was about 70-78% (Fig. 1), indicating an effective nitrification process. There is some indirect evidence that the data presented in Table 2 may not reflect the real denitrification capacity. It is likely that an intensive transpiration by willow growing around sampling point III caused depletion of water and an increase of the pollutant concentrations. This is confirmed by an increase of chloride concentration at point III in comparison to the inflow that cannot be explained by any other reason. If it was so, the nitrate concentration at sampling point III may also be overvalued due to water loss.

The effluent from the CW Örebro contained very low BOD and $N\text{-}NH_4^+$ concentrations. However, the total nitrogen concentrations were similar to the treated leachate from Gatka. The predominant form of nitrogen in the effluent from Örebro was nitrate nitrogen. The CW Örebro was characterized by the highest treatment efficiency among the analyzed facilities. This resulted from:

(i) an effective pre-treatment of leachate before it was discharged to the CW, and
(ii) the CW type – FWS (free water surface).

The raw leachate from the Örebro landfill site contained the highest concentration of $N\text{-}NH_4^+$ of the analyzed leachates. The ammonia stripping process in the aerated tank prior to the CW system was quite effective and allowed for the average $N\text{-}NH_4^+$ concentration decrease from 415 to 134 mg/l (Table 2). Also, BOD and COD concentrations decrease in the aerated tank. In contrast, the average TSS concentrations increased from 99 to 234 mg/l. Clogging problems inside the wetland did not occur however, since this was the FWS wetland with surface flow of leachate, which is generally less prone to clogging than the sub-surface flow wetlands.

Fig. 2 compares the BOD, COD, TSS and ammonia nitrogen removal efficiencies for the three CWs. For the CW Szadółki, removal efficiencies for both parallel working beds (I and II) are shown. In Gatka, removal efficiencies were calculated separately for pore water sampling points III (the area covered by willow) and IV (orchard grass). Although the treated leachate quality from Gatka and Szadółki is worse than at Örebro, the treatment efficiencies observed at Gatka and even at Szadółki (especially at bed I) are quite good. This is due to the fact that both Polish CWs

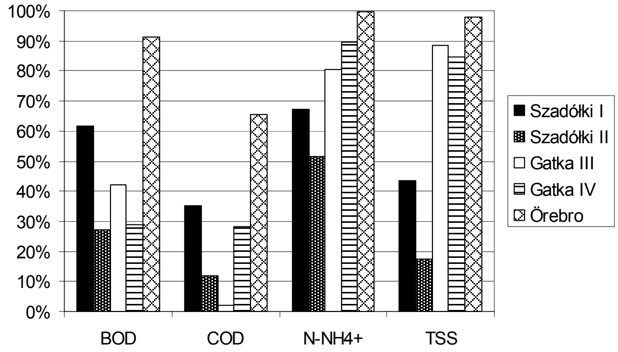

Fig. 2. Average leachate treatment removal efficiencies for the analyzed CW systems.

receive raw leachate (at Szadółki there is no pre-treatment at all, while the only function of the retention tank at Gatka is averaging of the leachate volume and composition – the pollutant concentrations do not decrease).

Conclusions

Analysis of the operational results of three CW systems for leachate treatment located in northern Poland (2 sites) and southern Sweden (1 site) shows that constructed wetland systems can effectively treat landfill leachate. The hydrophytes are tolerant to the high concentrations of COD, BOD, $N\text{-}NH_4^+$ and Cl^- present in the leachate; however, there may be problems with huge fluctuations in the composition and quantity typical of the landfill leachates. Thus, we recommend that retention tanks precede CW systems treating landfill leachate. Another role of retention tanks would be removal of TSS in order to avoid clogging of wetland cells, which is especially important in the case of subsurface flow wetlands. Since high concentrations of Fe (III) contribute to the clogging, Fe (III) removal prior to the wetland systems should be considered. Although constructed wetlands can deal even with raw leachate, using the two-stage leachate treatment systems with CW as the final stage, achieves high quality effluent that can be discharged to surface waters (Örebro). The pre-treatment can occur in a combination of aeration and sedimentation units. The design and construction stage of the CW systems is very important, which is apparent in the case of the CW at Szadółki. As leachate composition, volume and quality fluctuations are site-specific, the system design should be adapted to these site specific conditions. Otherwise, future problems with the operation of CW systems and poor treatment results will cause landfill operators to reject the idea of leachate treatment with CWs.

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