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Sustainability of the Constructed Wetland Based on the Characteristics in Effluent

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Abstract

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The constructed wetland (CW) in the settlement of Gložan is the first system of its kind for wastewater treatment constructed in Vojvodina (Serbia), aimed at treating local municipal wastewater. The common reed *Phragmites australis*, naturally growing at the CW location, was used as biofiltering vegetation. The monitoring effectiveness of the CW was based on removing suspended solids and reducing the amount of organic matter. The eight-year long study shows that the age of the constructed wetland does not significantly affect the changes (increase) in concentration of suspended particles and organic compounds from the wastewater effluent. We proved that measured values of variables, suspended solids, and biochemical oxygen demand (BOD_5) of effluent belong to the same population. The chronological data series of suspended solids and BOD5 of effluent were processed using statistical tests of homogeneity, both parametric (Student's *t*-test with Fisher's *F*-test) and nonparametric (Mann-Whitney's *U*-test). The results of testing homogeneity of the data confirm that the constructed wetland has not been compromised, and that the removal of suspended solids is 93–96% and reduction of organic compounds, expressed in terms of BOD_5, is up to 79–84%.

Keywords: BOD_5; purification; suspended solids; wastewater

Constructed wetlands (CWs) are used to remove a wide range of pollutants such as organic compounds, suspended solids, pathogens, metals, and excess nutrients (e.g. N and P) from various wastewaters including storm water runoff and municipal wastewater (Ghermandi *et al.* 2007; Vymazal 2007; Snow *et al.* 2008; Cooper 2009; Kadlec 2009; Chen 2011). Because of high removal efficiency, low cost, water and nutrient reuse, and other ancillary benefits, CWs have become a popular option for wastewater treatment (Ghermandi *et al.* 2007; Rousseau *et al.* 2008; Kadlec 2009; Llorens *et al.* 2009). Since the 1990s, wetland systems have been used for treating numerous domestic and industrial waste streams including those from tannery and textile industry, abattoirs, pulp and paper production, agriculture (animal farms and fish farm effluents), and various runoff waters (agriculture, airports, highway, and storm water) (Haberl *at al.* 2003; Lee *et al.* 2006; Vymazal 2007; Carty *et al.* 2008; Diaz *et al.* 2012).

The treatment efficiencies of constructed wetlands vary depending on the wetland design, the type of wetland system, climate, vegetation, and microbial communities (Vacca *at al.* 2005; Picek *et al.* 2007; Ström & Christensen 2007; Weishampel *at al.* 2009). The design of CWs is based on free water surface flow (FWS), horizontal subsurface flow (HF), or vertical subsurface flow (VF) (Kadlec 2009).

Nowadays, the most popular are CWs with subsurface flow. They consist of gravel or rock beds sealed by an impermeable layer and planted with wetland vegetation. The wastewater is fed at the inlet and flows through the porous medium under the surface of the bed in a more or less horizontal path

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until it reaches the outlet zone, where it is collected and discharged. In the filtration beds, pollution is removed by microbial degradation and chemical and physical processes in a network of aerobic, anoxic, anaerobic zones with aerobic zones being restricted to the areas adjacent to roots where oxygen leaks to the substrate (Vymazal 2010).

Suspened solids concentration and biochemical oxygen consumption measurements are widely used in wastewater treatment, since they very well illustrate water quality. Generally, wastewater is characterized by high suspended solids concentrations and organic compounds, which need to be removed before releasing water into the recepient. The various types of constructed wetlands differ in their main design characteristics as well as in the processes which are responsible for the pollution removal.

The present paper shows monitoring results of suspended solids and BOD_5 on the CW Gložan (Vojvodina Province). The aim is to determine whether there has been a significant change in the effluent concentration after eight years of operation. For this purpose, the test data homogeneity of suspended solids and BOD_5 effluent is calculated.

Study area. The population of Vojvodina accounts for more than two million inhabitants who live in 467 settlements. Out of this number, there are more settlements with less than 2000 inhabitants. In these settlements septic tanks are still in use, so that their leaks contaminate groundwater, whose level in this region is rather high.

Since autumn 2004, the municipal wastewaters of Gložan have been treated in the CW with common reed as phytofilter. The geographic coordinates of Gložan are 45°17'N latitude and 19°33'E longitude, while the altitude is 80–82 m a.s.l. The regional surface water is represented by the Danube River and land drainage canals. The settlement is located at a distance of 6 km from the Danube.

Between the settlement and the Danube there is an inundation area which is protected from high waters by a dike, along with the constructed drainage system. According to its geographic position, Gložan is in the belt of moderate continental climate. Gložan is an urbanized settlement of Pannonia type, with 2275 inhabitants. Waterworks were constructed in 1973, and until the construction of a sewerage system in 2004, septic tanks had been in use.

The CW is located in the inundation zone of the Danube alluvial plane, in the south of the Gložan settlement, between two land drainage canals. The terrain is almost horizontal, and its altitude is 76.50 m a.s.l. The location can be characterized as a marshy landscape.

The CW consists of three cells of a total area of 9400 m^2. The CW is a horizontal subsurface flow. The substrate consists of gravel beds, 0.6 m wide and 0.6 m deep, which alternate in succession of the belts of natural soil, 1.0 m wide (Figure 1). The surface layer consists of gravel mixed with earth, along with the reed vegetation. The lining is made of an impermeable clay layer that existed on the wetland location. The treatment of wastewater is carried out by passing it through three fields, the residence times being 24, 48, and 33 h in fields I, II, and III respectively. The technological process encompasses collecting and conducting of used water, its treatment in the CW, and its discharge into the recipient, a canal connected with the Danube. The system has a section for treatment of raw sewage prior to entering the wetlands.

The previous results (2005–2008) confirm that the CW Gložan can remove more than 90% of suspended solids

Figure 1. The wetland under construction (2004)

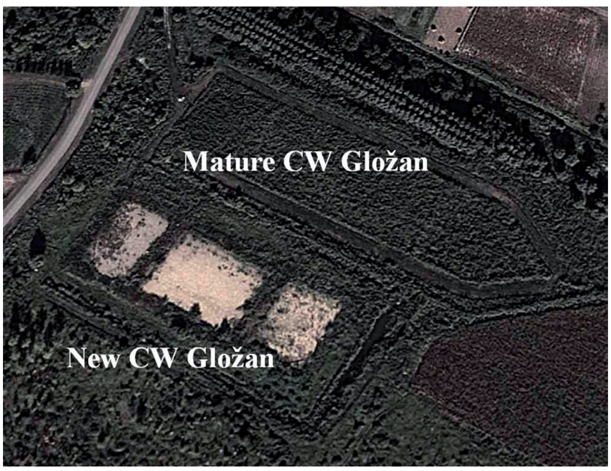

Figure 2. Location of the newly constructed wetland

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while organic matter reduction, expressed in terms of biochemical oxygen demand (BOD_5), is more than 80%. The efficiency of removal of nitrogen compounds ranged from 47.3% for nitrates, 47.5% for ammonium, to 78.3% for nitrites, and the efficiency of total phosphorus removal was 29.1%. Chemical analysis of the reed composition confirmed the bioaccumulation of nutrients in the plant organs. It was found out that a certain proportion of nitrogen was taken up by reed and accumulated in its particular parts, mostly in the leaves, where nitrogen content varied between 28.3 to 42.7 g/kg dry matter (DM) (Josimov-Dundjerski *et al.* 2011). The reed bloom most accumulated P, its content was up to 2.1 g/kg DM. The CW Gložan retained 292 kg P and 2920 kg N per year on average (Josimov-Dundjerski *et al.* 2012).

However, the age of the CW is a topical question. Taking this into consideration, a new CW is in preparation, located next to the still functioning mature CW (Figure 2).

MATERIAL AND METHODS

The investigation of the CW operation was carried out in the 2005–2012 period, with an interruption in the period 2009–2010. Measurements at the CW covered both influent and effluent the samples of which were taken for analysis of suspended solids and BOD_5.

JUS ISO 5667-1 standard was applied for water sampling, SRPS H.Z1.160 for suspended solids determination and SRPS ISO 5815 for BOD_5.

Based on the suspended solids and BOD_5 measured data in influent and effluent chronological series of variables were formed. Series of suspended solids concentrations and BOD_5 were divided into three equal parts: n_1 (period 2005–2006), n_2 (2007–2008), and n_3 (2011–2012). Numerical characteristics of variables were obtained by average values, variance, standard deviation, and coefficient of variation. Removal effects were calculated on the basis of average values.

It can be noticed that data are inhomogeneous, which is the consequence of natural changes (e.g. storm water or floods), or man-made changes (e.g. uncontrolled disposal of wastewater into constructed wetland, dysfunction of sedimentation tank, etc.). Analysis, whether the facility has reached the end of its life cycle or not, was done by the comparison of the differences for the suspended solids and BOD_5 in the effluent. The zero hypothesis H_0 was defined: measured values of variables, suspended solids, and BOD_5 belong to the same population. Homogeneity of the n_1, n_2, and n_3 series was tested by parametric Student's t-test. The hypothesis that the variances are equal was checked using the Fisher's F-test. The nonparametric Men-Whitney's U-test, which includes the previously confirmed hypothesis of normal distribution of variables, was also applied. Statistical analyses were checked at the significance level of $\alpha = 0.05$ and $\alpha = 0.01$.

RESULTS AND DISCUSSION

Monitoring analysis of suspended solids and BOD_5 has proven the fact that the mature CW Gložan is still effective in the wastewater treatment. Measured concentrations of suspended solids and BOD_5 for time series n_1, n_2, and n_3 are presented in Figures 3 and 4, where the horizontal lines show average values. The results of suspended solids and BOD_5 statistical analysis in the periods n_1, n_2, and n_3, and the efficiency of pollutants removal in the CW Gložan are shown in Table 1.

The calculated values of statistical variables t, F, and U for homogeneity test of suspended solids and BOD_5 in the effluent and critical values of t, F, and U

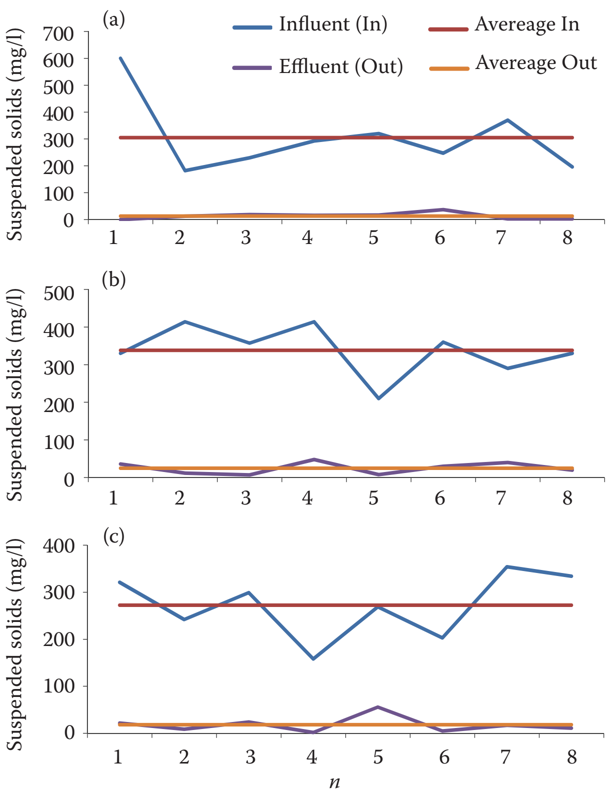

Figure 3. Suspended solids (mg/l) in influent and effluent in periods n_1 (a), n_2 (b) and n_3 (c)

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Table 1. Statistics and efficiency of removing suspended solids and organic compounds (BOD_5) of the constructed wetland Gložan

Variables (mg/l)	*n*	Influent				Effluent				Fff (%)
		average	SD	s^2	CV	average	SD	s^2	CV	
n_1										
Suspended solids	8	304.75	135.02	18231.08	0.225	13.50	11.98	143.43	0.887	96
BOD_5	8	379.44	140.27	19675.67	0.282	61.85	46.53	2165.04	0.582	84
n_2										
Suspended solids	8	338.13	66.78	4458.98	0.202	25.13	15.62	243.84	0.622	93
BOD_5	8	624.48	192.74	37148.71	0.257	130.08	80.36	6457.73	0.317	79
n_3										
Suspended solids	8	272.50	46.45	2157.60	0.171	18.25	11.70	136.89	0.641	93
BOD_5	8	385.63	105.49	11128.14	0.274	61.75	50.67	2567.45	0.821	84

n – No. of observations; SD – standard deviation; s^2 – variance; CV – coefficient of variation; Eff – removal efficiencies

for appropriate degree of freedom and significance threshold (α = 0.05 and α = 0.01) are shown in Table 2.

Influent water quality monitoring at the CW Gložan has determined that suspended solids concentration during the investigation periods (Figure 3) and BOD_5 in the n_2 period (Figure 4) were generally higher as compared to those reported in the literature for domestic wastewater. The highest mean concentrations were observed in period n_2 for suspended solids (338.13 mg/l) and for BOD_5 (624.48 mg/l) (Table 1).

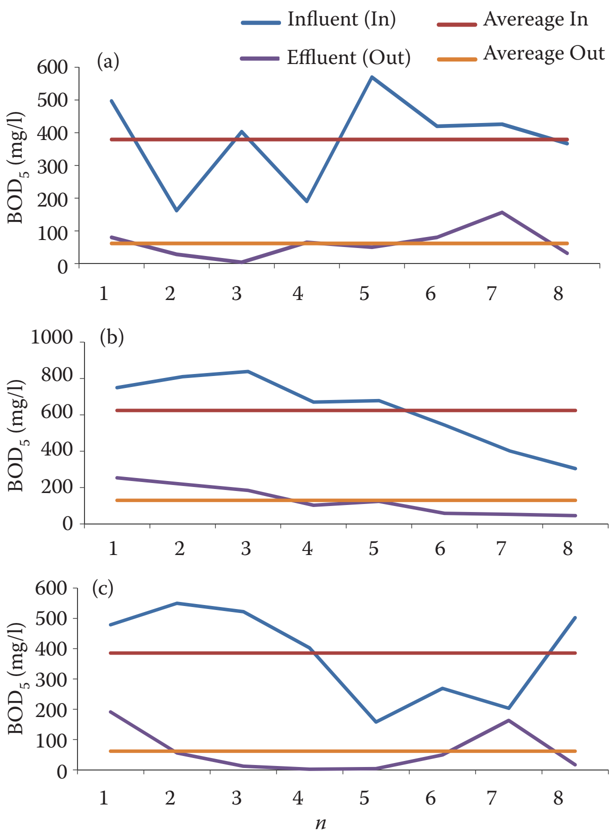

Figure 4. Biochemical oxygen demand (BOD_5) of influent and effluent in periods n_1 (a), n_2 (b) and n_3 (c)

Suspended solids concentrations in influent are relatively unified (Figure 3) with average values of 304.75 mg/l for n_1, 338.13 mg/l for n_2, and 272.50 mg/l for n_3 (Table 1). The standard deviation of influent suspended solids for period n_3 has shown small variability of data when compared to periods n_1 and n_2.

The CW Gložan reduces the concentration of suspended solids. In the first period efficiency was 96%, and in the second and third period it was 93% (Table 1). Suspended solids are retained predominantly by filtration and sedimentation and the removal efficiency is usually very high (Vymazal 2009; Vymazal & Kröpfelová 2009). Average influent and effluent concentrations and removal efficiency of suspended solids in some CWs in other countries are shown in Table 3 (Babatunde *et al.* 2008).

Research done in CWs with subsurface flow has also shown that the output can reach the level of suspended solids in the range of 15–20 mg/l, and even for higher inputs, suspended solids removal is acceptable. Besides, the age of the system does not significantly influence the output suspended solids concentrations in the effluent (Vymazal 2002). Up to two-year-old objects have shown suspended solids removal of 94 ± 4%, and objects 2–6 year old had removal of 95 ± 2%.

According to US EPA (2000), suspended solids removal is good for loads lower than 20 g/m^2 per day, calculated with the monthly maximum of total

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Table 2. Homogeneity testing of effluent using Student's *t*-test, Fisher's *F*-test, and Men-Whitney's *U*-test

Periods	Suspended solids			BOD_5		
	F	*t*	*U*	*F*	*t*	*U*
n_1 and n_2	1.700	–1.564	–1.471	2.983	–1.944	–1.786
n_1 and n_3	1.048	–0.751	–0.630	1.186	0.004	–0.630
n_2 and n_3	1.781	0.933	–0.945	2.515	1.903	–1.891
Critical values for α = 0.05	3.787	± 2.145	± 2.145	3.787	± 2.145	± 2.145
Critical values for α = 0.01	6.993	± 2.977	± 2.576	6.993	± 2.977	± 2.576

Hypothesis H_0 is accepted

suspended solids. The CW Gložan has a load of 9 g/m^2 per day at the monthly maximum that has determined suspended solids removal efficiency of 93–96%.

Amplitude measured concentrations of BOD_5 in influent range from 158.0 mg/l (in n_3) to 838.40 mg/l (in n_2) (Figure 4). The BOD_5 for municipal sewage water goes up to 400 mg/l, which was also proven with the research in periods n_1 and n_3 with the average values of 379.44 and 385.63 mg/l (Table 1). However, in the period n_2 organic pollutants had significantly higher concentrations with the average value of BOD_5 at 624.48 mg/l (Table 1). In this period measured values in influent in all samples but one exceeded the average value for sanitary communal sewer water. High concentrations in influent have shown that not only households were discharging water to the communal sewer system. Logically, high influent concentrations of BOD_5 affected the concentration in the effluent (Figure 4).

According to USEPA (2000), removal of organic pollutants is considered successful if maximum BOD_5 is less than 4.5 g/m^2 per day in influent for effluent with 20 mg/l, and 6 g/m^2 per day in influent for effluent with 30 mg/l. In the CW Gložan reduction of BOD_5 by 84% in the periods n_1 and n_3, and by 79% in the period n_2 were achieved (Table 1). The average value of BOD_5 in influent was 7.4 g/m^2 per day for period n_1, for period n_3 it was 7.5 g/m^2 per day, and for period n_2 it was 12.1 g/m^2 per day. The results from the Czech Republic in the CWs of the same type showed an average treatment efficiency of 86.6%. The BOD_5 loading of vegetated beds varied between 2.6 and 99.6 kg/ha per day with an average of 33.5 kg/ha per day (Vymazal 1999). Average influent and effluent concentrations and removal efficiency of BOD_5 in some CWs in other countries are shown in Table 4 (Babatunde *et al.* 2008).

Organic compounds are effectively degraded mainly by microbial degradation anoxic/anaerobic conditions, as the concentration of dissolved oxygen is very limited in constructed wetlands with subsurface flow (Vymazal & Kröpfelová 2009). The highest values in effluent in the period n_2 were measured during winter and spring with small inflow at the level of 1.5 l/s. The number of microorganisms is in correlation with the level of organic pollutants and ecological factors, namely temperature (Josimov-Dundjerski *et al.* 2012). Relatively low air temperatures in winter and spring in Gložan (average 5.9°C,

Table 3. Average influent (In) and effluent (Out) suspended solids and removal efficiencies (Eff) (Babatunde *et al.* 2008)

Suspended solids	In ± SD	Out ± SD	Eff (%)
	(mg/l)		
Ireland	228 ± 197.8	20.5 ± 18.8	91.0
Czech Republic	64.8 ± 46.7	10.2 ± 6.9	84.3
Denmark and UK	98.6 ± 81.6	13.6 ± 11.1	86.2
Poland	140 ± 77.2	38.6 ± 23.5	77.4

SD – standard deviation

Table 4. Average influent (In) and effluent (Out) biochemical oxygen demand (BOD_5) and removal efficiencies (Eff) (Babatunde *et al.* 2008)

BOD_5	In ± SD	Out ± SD	Eff (%)
	(mg/l)		
Ireland	361 ± 259.7	21.3 ± 17.2	94.1
Czech Republic	87.2 ± 63.1	10.5 ± 9.9	88.0
Denmark and UK	97.0 ± 81.0	13.1 ± 12.6	86.5
Poland	110 ± 87.8	18.1 ± 14.3	73.5

SD – standard deviation

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minimal average –4.7°C) slowed down microbiological processes, which can be one of the causes for high BOD_5 in effluent.

In order to achieve efficient water treatment in the constructed wetland system, retention time has to be longer or equal to the time that is needed to achieve the desired effluent concentrations. According to literature, retention time for constructed wetland systems with above ground or underground water flow is 4–15 days, depending on the pollution type and concentration (Carty *et al.* 2008; Diaz *et al.* 2012). Total retention time of the wastewater in the CW Gložan is relatively short (4.4 days), although the influent pollution is high, especially in the period n_2. It is highly probable that hydraulic characteristics of CW and influent pollution can affect and determine relatively high BOD_5 in effluent.

Statistical parameters analysis of effluent variables has unambiguously shown increase of concentrations in the period n_2. However, statistical analysis of samples has shown that CW has not aged at the significance level of $\alpha = 0.05$ and $\alpha = 0.01$ (Table 2). Applied statistical tests have proven homogeneity of effluent at the mature CW Gložan to the level of hydro technical significance. The age of the CW did not reduce the efficiency of wastewater treatment. The CW Gložan has shown a very good treatment performance, despite of being mature.

The results have shown that the removal of pollutants is very effective. It confirms the general idea that the organic matter removal rate increases depending on the constructed wetland age (Kadlec 1999). Higher age of a wetland is also associated with an increase in microbial population (Picard *et al.* 2005). Both new and mature CWs successfully remove traditional pollutants such as BOD and suspended solids from domestic wastewater. However, the biochemical oxygen demand, chemical oxygen demand, suspended solids, and ammonia-nitrogen concentrations were reduced within the mature constructed wetland system even after approximately 5 years of operation (Kayranli *et al.* 2010).

CONCLUSION

During the CWs design the key task is to properly define the area and select the largest one, consider loads and pollutants, and analyze all of them one by one. Considering the variables of the suspended solids in the CW Gložan, the designed area was properly sized and it provided good results. While considering BOD_5, it can be said that the system was designed for average loads of the treated water. Measurements proved high concentration of organic compounds, with relatively low retention time, which is reflected in the effluent concentrations and the treatment efficiency.

Although from the technical point of view, CW looks like a simple structure, it is a very fragile system because it has to be hydro-technically effective for a long time, i.e. enabling large amounts of water to pass through. At the same time, it must ensure good conditions for water treatment. At the CW Gložan suspended solids and BOD_5 homogeneity variables testing showed that there were no statistically significant changes in the pollutants removal during the research period. The mature CW Gložan provides successful water treatment.

The results presented for the CW Gložan demonstrate durability, reliability, and usability of such systems under the conditions of moderate continental climate, which could be an essential contribution to the sustainable development and environmental protection. The CW Gložan successfully removes suspended solid and organic compounds and thus reduces their concentration in wastewater, which after treatment flows into the Danube as the final recipient. It is very important to sustain "very good" water quality of the Danube, in accordance with the category A1 of the Directive 75/440/EEC for surface waters quality (Mladenović-Ranisavljević *et al.* 2013).

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