Water Footprint of Constructed Wetlands – Lutopecny Case Study

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Abstract. Constructed wetlands (CWs) are effective low-cost applications of nature-based solutions to the treatment of wastewater from small municipalities and isolated dwellings. One type of evaluation of CWs is focused on the effectiveness of wastewater treatment. Another type of CWs evaluation is focused on water balance because wetland plants are adapted to growth in conditions of unlimited water availability, which is associated with a high rate of evapotranspiration. In this study, the water footprint (WF) was used for joining these two evaluations. The blue WF describes water loss from CWs. The grey WF is an indicator of the effectiveness of CW in terms of pollution reduction. This is the first study of CWs that compares the importance of blue and grey WF under different climatic conditions during the year. Data from different seasons were used to calculate the WF of the CW in a temperate climate zone. During cold days, the grey WF is several times higher than the blue WF. Another situation occurs on hot summer days when the blue WF is higher than the grey WF. On all assessed days, the grey WF reduction was higher than the blue WF reduction; it means that the CW saves more clean water in the recipient (needed to dilute discharged pollution) than losses by evapotranspiration.

1 Introduction

Constructed wetlands (CWs) are effective low-cost applications of nature-based solutions to the treatment of wastewater from small municipalities and isolated dwellings [1]. The first CW, used as a wastewater treatment plant (WWTP), was in the Czech Republic established in 1989 [2]. In Europe, the beginning of their use date back to the 1950s [3,4]. Natural-based solutions are mainly used for wastewater treatment from decentralized houses, small settlements, dwellings, hotels, recreational facilities, restaurants and summer camps, smaller municipalities, or their parts, usually up to 2000 PE. According to the composition of wastewater, these methods are also applicable for the treatment of industrial wastewater from the food processing industry, trade facilities (workshops) and selected small industrial plants,

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landfill leachate treatment, organically low-loaded agricultural runoff and wastewater agricultural facilities, polluted stormwater runoff, erosion washes of polluted surface water. The CW advantages lie mainly in relatively simple technological implementation, lower operating costs, low energy consumption, the possibility of being overloaded by ballast water, relatively rapid incorporation of the treatment process, and achievement of the performance efficiency quality target in a short period of time after the start of the operation, treatment of organically low-loaded wastewater that cannot be treated by conventional methods (treatment plants based on activation processes).

Many guidance and handbooks have brought information for the design, construction, operation, and maintenance of all types of the CW since the beginning of their implementation in wastewater management, e.g. Kadlec et al. [5], Kadlec and Wallace [6] and Vymazal & Kröpfelová [7]. CW performance is affected by a range of factors such as operation mode (loading rate, continuous or batch-load) and environmental conditions (climate, season) [8–10]. Temperature is one of the main characteristics affecting removal efficiency [11].

In the Czech Republic, horizontally and vertically flowing CWs are among the most frequently used methods of wastewater treatment in small municipalities. The quality of the treated wastewater from well-functioning CWs can reach the quality of the treated wastewater from a mechanical-biological wastewater treatment plant [12]. Typical CWs consist of one or more filters connected in series or in parallel. Horizontally flowing filters are usually planted with suitable wetland vegetation, most often *Phalaris* and *Phragmites*. An essential part of these technologies is a well-functioning mechanical pre-treatment, which protects the filter media's own biological stage from clogging by solid particles. The most often types of pretreatment are septic tanks and the Imhoff tanks.

Basic design criteria for reed bed systems (horizontal subsurface flow CW), earth filters, vertical flow CWs, and wastewater stabilization ponds (WSP) are given by the Czech technical guidance for WWTP design (ČSN 75 6402). Requirements for mechanical pretreatment, orientation requirements on the grain size distribution of the filtration medium, and the depth of filters are set. The area of 5.0 m^2 in horizontal subsurface flow CWs per one PE, and 1.0-5.0 m^2 per 1 PE in earth filters are recommended. The hydraulic load should be 0.10-0.20 $m.day^{-1}$ ($m^3.m^{-2}.day^{-1}$) for filters and the mass load should be 6 - 10 g BOD_5 per $m^2.day^{-1}$ for filters with the horizontal subsurface flow and 10 - 40 g BOD_5 per $m^2.day^{-1}$ for filters with the vertical flow. These design criteria have been used for CWs used for wastewater treatment in the Czech Republic since the beginning of their implementation after 1990.

Wastewater stabilization ponds have been an important element in wastewater treatment longer than CWs, since the end of the 19th century, and are widely used for wastewater treatment in the world [13], and in the Czech Republic [14]. Since 1990, with the development of the use of natural-based solutions for wastewater treatment in Czech municipalities, a combination of both technologies has been used, where the primary purpose of including a WSP is to increase the efficiency of ammonia nitrogen removal. At the same time, the reduction of outflow concentrations of total nitrogen and total phosphorus is expected.

Water Footprint (WF) is often used for evaluation of WWTPs. In case of conventional biological WWTPs the grey WF plays a crucial role in the total WF. Operation of CWs is linked with important amount of evapotranspiration by plants in CWs. The aim of the study is a preliminary assessment of the importance of blue water footprint in the case of the use of CWs as WWTPs. It represents a combination of natural-based technologies described above. They are also typical rural settlements' WWTPs of the period 1990 – 2015, before a larger implementation of the combination of horizontal subsurface flow CWs and vertical flow CWs with pulse water distribution as the biological step of WWTPs.

2 Study Area

Lutopecny is a village in Kroměříž District in the Zlín Region in the east part of the Czech Republic. The WWTP in Lutopecny (49.3044N, 17.3476E) is designed for a capacity of 640 PE. There are 600 inhabitants connected to the WWTP. The average annual amount of treated wastewater is 65 000 m^3; the average flow rate is 2 l.s^{-1}. Wastewater is diluted by ballast water (combined sewerage in the village) and affected by nitrified water (overflows from septic tanks) - therefore a CW was designed as a method of wastewater treatment in the village. The WWTP has a mechanical and a biological part. The mechanical pre-treatment consists of a screen, a grit separator, and an Imhoff tank. The biological part consists of 8 horizontal subsurface flow filter beds with a total area of 3,000 m^2 (4 beds of 17.5x20 m, and 4 beds of 20x20 m). Beds are connected in parallel, each has its own separately controlled inlet and they alternate in operation. The depth of the filter beds is 0.95 m, and they are filled with material of a fraction of 4-8 mm. The beds are planted with common reed (*Phragmites australis*). The annual average hydraulic load of the beds is 5.9 cm.day^{-1}. Treated wastewater is led from the constructed wetland to the WSP. The area of the WSP is 2400 m^2. From the WSP, water is discharged into the local stream called “Věžecký potok”. The schema of WWTP is shown in **Fig.** 1. The WWTP testing operation started in October 2006, the regular operation started in September 2007. The flow rate measurement is performed automatically, once a day in measuring shafts at the inflow when filling the filter beds and at the outflow from beds. Both places are fitted with plastic Parshall flumes with electronic flow rate monitoring. An ultrasonic sensor measures the immediate and the total volumetric flow rates.

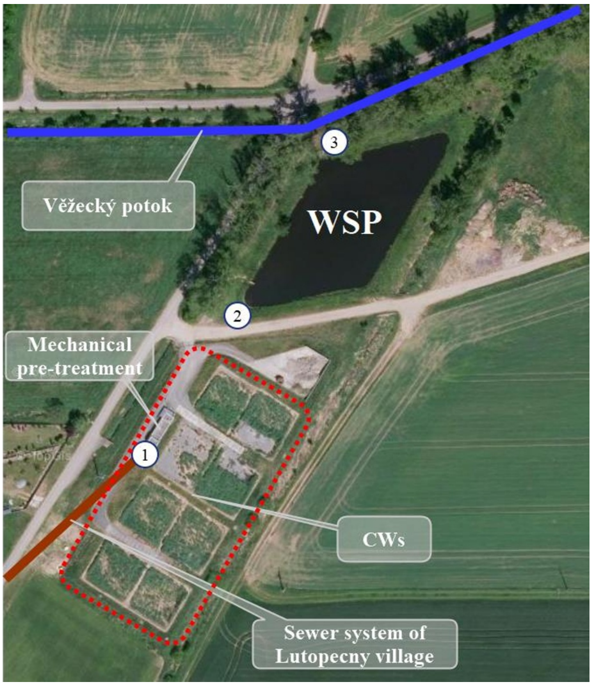


Fig. 1. Situation of Lutopecny WWTP – numbered circles represent profiles where the water footprint was calculated (source of background picture: mapy.cz)

3 Data and Water Footprint Calculation

For this preliminary assessment, data from 4 days in 2017 were collected (**Table 1**). These data were used for the calculation of the grey and blue water footprints. The grey water footprint (GWF) was calculated according to Eq. 1. As an accumulation capacity in Eq. 2 were used values from our former studies [15] (**Table 2**).

$$GWF = \max \{GWF_1, GWF_2 \ldots, GWF_n\} \tag{1}$$

where $GWF_{i=1\ldots n}$ is calculated according to Eq. 2:

$$GWF_i = \frac{L_i}{c_{max,i} - c_{nat,i}} \tag{2}$$

where L_i is the quantity of pollutant i being emitted into water [weight unit per time unit]; $c_{max,i}$ is the maximum permissible concentration of the substance i in receiving water [weight unit per volume unit]; $c_{nat,i}$ is the natural concentration of the substance i in receiving water [weight unit per volume unit].

Table 1. Specific data of Column/Row

Profile	**Date**	**Inflow/Outflow** [m^3.day^{-1}]	**BOD$_5$** [mg.l^{-1}]	**COD** [mg.l^{-1}]	**SS** [mg.l^{-1}]
1	30.03.2017	99.7	59.2	185.0	114.0
1	09.06.2017	74.1	30.8	89.5	58.5
1	14.08.2017	51.7	53.2	200.0	56.2
1	10.10.2017	79.5	170.0	470	487.0
2	30.03.2017	75.0	20.3	64.1	33.3
2	09.06.2017	5.9	3.8	25.2	14.1
2	14.08.2017	8.5	3.0	20.0	12.6
2	10.10.2017	72.2	4.9	24.0	10.7
3	30.03.2017		12.9	41.3	4.3
3	09.06.2017		6.2	32.4	10.8
3	14.08.2017		3.7	16.1	3.6
3	10.10.2017		10.2	30.0	4.4

The blue water footprint (BWF) is represented by the evapotranspiration from subsurface flow filter beds and from the WSP. The evaporation from the grit separator, and from the Imhoff tank and the evapotranspiration from subsurface flow filter beds were expressed as a single value calculated as the difference between inflow on the WWTP (profile 1) and outflow from the subsurface flow filter beds (profile 2). The evapotranspiration from subsurface flow filter beds can be expected to be dominant in this technology system. For the estimation of evapotranspiration from the WSP was used web service EvapoSat (https://shiny.fzp.czu.cz/EvapoSat/) that uses satellite data [16] and evaporation from free water surface calculates by Eq. 3 [17]:

$$Ev = 0.5355 \times e^{0.1063 \times T_a} \tag{3}$$

where T_a is the average daily air temperature.

The WSP is located at coordinates 49.30508N and 17.34844E. Estimation of average evaporation per day in the summer was higher than inflow in the WSP. It means that the outflow from the WSP should be zero. Nevertheless, during very hot days in summer 2021, we still found outflow from the WSP. Maybe it is due to the full coverage of water level in the WSP by the aquatic vegetation or only approximation of real evapotranspiration due to the use of empirical equations and satellite data. Therefore, the evaporation estimation by web service EvapoSat was reduced to half in the summer months (**Table 4**). This mathematical adjustment increases the uncertainty of the results obtained.

Table 2. Assimilation capacity used for grey water footprint calculation

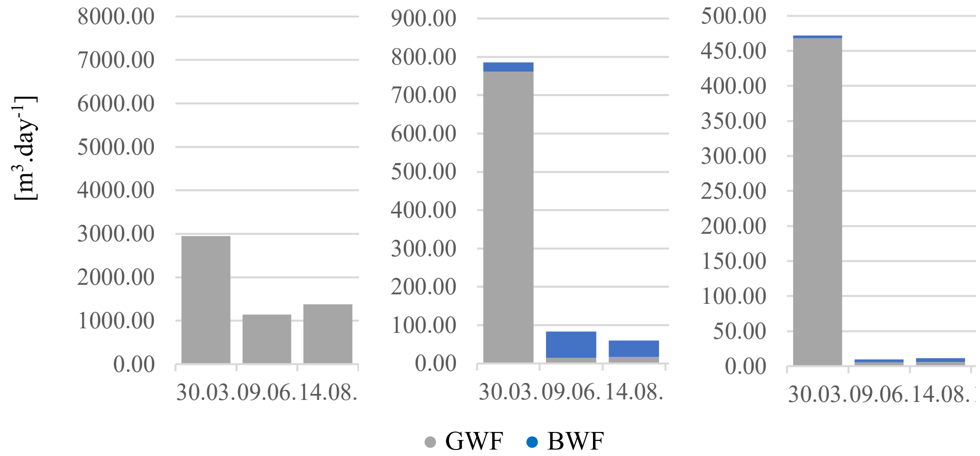
Parameter	**Symbol**	**Unit**	c_{max}	c_{nat}	**Assimilation capacity** ($c_{max} - c_{nat}$)
Biochemical oxygen demand	BOD_5	mg.l^{-1}	2	4	2
Chemical oxygen demand	COD	mg.l^{-1}	15	25	10
Suspended solids	SS	mg.l^{-1}	15	25	10

4 Results

The values of the GWF in individual profiles are shown in **Table 3**. The GWF of inflow to the WWTP represents the GWF without WWTP. The WWTP reduces of GWF of 84.1% to 99.6%. The values of BWF of subsurface flow filter beds and WSP are shown in **Table 4**. On the other hand, there is no BWF without WWTP (**Table 5**). **Figure 2** shows comparisons of BWF and GWF for individual profiles. In total, WWTP reduces WF from 83.2% to 96.0%. During the cold months (March, October) the GWF represents more than 90 % of WF. Contrary, during the warm summer months (June, August), the BWF represents about 90% of WF (**Table 5** and **Fig. 2**).

Table 3. Grey Water Footprint – Profiles: (1) inflow to the WWTP, (2) outflow from subsurface flow filter beds (inflow to the WSP) and (3) outflow from the WSP

Profile	**Date**	**GWF** [m^3.day^{-1}]	GWF_{BOD5} [m^3.day^{-1}]	GWF_{COD} [m^3.day^{-1}]	GWF_{SS} [m^3.day^{-1}]
1	30.03.2017	2951.1	2951.1	1844.5	1136.6
1	09.06.2017	1141.1	1141.1	663.2	433.5
1	14.08.2017	1375.2	1375.2	1034.0	290.6
1	10.10.2017	6757.5	6757.5	3736.5	3871.7
2	30.03.2017	761.3	761.3	480.8	249.8
2	09.06.2017	14.9	11.2	14.9	8.3
2	14.08.2017	17.0	12.8	17.0	10.7
2	10.10.2017	176.9	176.9	173.3	77.3
3	30.03.2017	468.0	468.0	299.6	31.2
3	09.06.2017	5.5	5.2	5.5	1.8
3	14.08.2017	5.8	5.8	5.0	1.1
3	10.10.2017	349.7	349.7	205.7	30.2



Profile 1 Profile 2 Profile 3

Fig. 2. *WF values in individual profiles of Lutopecny WWTP*

Table 4. Blue Water Footprint

Profile	**Date**	**Evaporation** [mm.day^{-1}]	**BWF** [m^3.day^{-1}]	**BWF$_{\text{reduced}}$** [m^3.day^{-1}]
subsurface flow filter beds	30.03.2017		24.7	
subsurface flow filter beds	09.06.2017		68.2	
subsurface flow filter beds	14.08.2017		43.2	
subsurface flow filter beds	10.10.2017		7.3	
waste stabilization pond	30.03.2017	1.0	4.1	
waste stabilization pond	09.06.2017	3.5	8.4	4.2
waste stabilization pond	14.08.2017	4.5	10.7	5.4
waste stabilization pond	10.10.2017	1.5	3.5	

Table 5. Water Footprint with and without WWTP

Profile	**Date**	**GWF** [m^3.day^{-1}]	**BWF** [m^3.day^{-1}]	**WF** [m^3.day^{-1}]	**GWF**	**BWF**
WWTP	30.03.2017	468.0	27.1	495.1	95%	5%
WWTP	09.06.2017	5.5	72.4	77.9	7%	93%
WWTP	14.08.2017	5.8	48.6	54.4	11%	89%
WWTP	10.10.2017	349.7	10.9	360.6	97%	3%
Without WWTP	30.03.2017	2951.1		2951.1	100%	0%
Without WWTP	09.06.2017	1141.1		1141.1	100%	0%
Without WWTP	14.08.2017	1375.2		1375.2	100%	0%
Without WWTP	10.10.2017	6757.5		6757.5	100%	0%

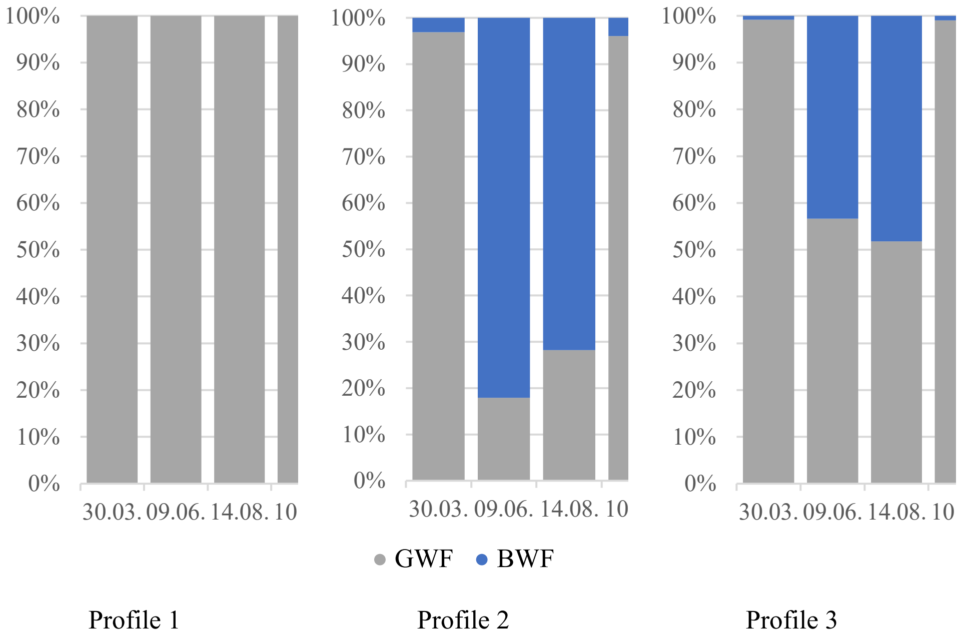


Fig. 3. *Comparison of GWF and BWF in individual profiles of Lutopecny WWTP*

5 Discussion

This study quantified for the first time the impact of CWs on the overall water balance in the basin through WF. Evaporation from CWs significantly affects the overall water balance of the basin. BWF is lower than reduction of GWF. However, wastewater losses through evaporation are about 15 to 30 % in cold months and up to 98 % in warm months. Water that was withdrawn higher in the watershed, used by consumers, and would have been discharged back into the watershed if a conventional WWTP were used, is lost from the watershed during the warm months when CWs are used. This can represent a significant impact on ecosystem services in the lower parts of the catchment. In areas suffering from water scarcity and high temperatures, consideration should therefore be given to whether a conventional biological treatment plant is a more appropriate way of treating wastewater.

It is typical for stabilization ponds, including the ponds for final purification that the diversity and total cell volume of the phytoplankton are changing during a year with regard to actual weather conditions [e.g. 12,13,18]. Development of the phytoplankton community in WSPs leads to higher turbidity occurrence. The algae cells increase the total suspended solids concentration at the outflow profile. This is connected with a certain increase in BOD and COD values. The situation is typical for parts of vegetation periods (April-May, late summer) under the climate conditions of the Czech Republic and it was observed in early autumn (Sept-first part of Oct) based on actual weather conditions [19]. Therefore, a similar situation could cause the increase of GWF of BOD_5 and COD in the profile 3 of the presented WSP in October. However, there are insufficient data to confirm this claim.

The results of the preliminary study are limited by its scope. Data from only 4 days in 2017, provided by the mayor of Lutopecny village, was used for the calculations. The validity of this data was not examined due to a lack of supporting documentation. A detailed investigation is planned for 2022, when we plan to equip the site with measuring instruments.

Nevertheless, we do not anticipate that the results could be dramatically skewed and we consider the basic conclusions, i.e. the significance of evaporation (blue water footprints) in warm months, to be proven.

6 Conclusion

The current work presents the preliminary assessment of the blue and grey water footprints of constructed wetland in Lutopecny village. The constructed wetland is used as a wastewater treatment plant. Although only a limited dataset was used, it can be assumed that the findings are valid in general. Statistically more robust numerical quantification would need to be derived from a larger dataset and for more CWs. Only one type of CW was included in the study, and similar studies on other types of CWs would need to be performed in future work to generalize the results to all types of CWs used as WWTPs. Meteorological data were not available for the solution to calculate the evaporation from the stabilization pond. Therefore, data derived from satellite data was used, which increases the uncertainty in the determination of this value. During cold months, the grey water footprint represents the main part of the total water footprint. During warm months, the situation is reversed and the blue footprint is dominant. The increase in the blue water footprint due to evaporation from the subsurface flow filter beds (CWs) and waste stabilization pond is many times less than the reduction of the grey water footprint in the wastewater treatment plant. On the other hand, water balance in the catchment could be importantly affected by water losses caused by evapotranspiration from nature-based solutions for wastewater treatment.

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