Hydrological and hydraulic behaviour of a surface flow constructed wetland treating agricultural drainage water in northern Italy

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Abstract: Surface flow constructed wetlands treating agricultural drainage water are not always impermeable, and therefore it can be difficult to perform the hydrological characterisation. The goal of this research was to investigate the hydrology and hydraulics, after more than a decade of operation, of such a system located near Bologna (Italy), through estimation of hydraulic properties and hydraulic retention time (HRT). Ponded infiltration measurements were conducted to estimate the saturated hydraulic conductivity, Ks, of the surface soil layer at the point scale. At the global scale, estimation of the infiltration rate, i, was computed to detect water leakages from the wetland. Tracer study was conducted to analyse the existence of preferential flow inside the system and to estimate its HRT. Infiltration experiments showed some clogging effects of the SFCW bed given that the mean Ks value near the inlet was 30 mm h-1, that was 7.13 times lower than the value at the outlet area. The estimated infiltration losses were found to be generally in the range 0.28 - 0.33 mm h-1, that were two order of magnitude lower than infiltration measured at the point scale. The results also confirmed the existence of a moderate amount of preferential flow paths and dead zones in the SFCW as the actual HRT (6.7 days) was shorter than the nominal one (8.1 days). Despite this, it can be concluded that the system after 17 years of operation is still in a good state.

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HYDROLOGICAL AND HYDRAULIC BEHAVIOUR OF A SURFACE FLOW CONSTRUCTED WETLAND TREATING AGRICULTURAL DRAINAGE WATER IN NORTHERN ITALY

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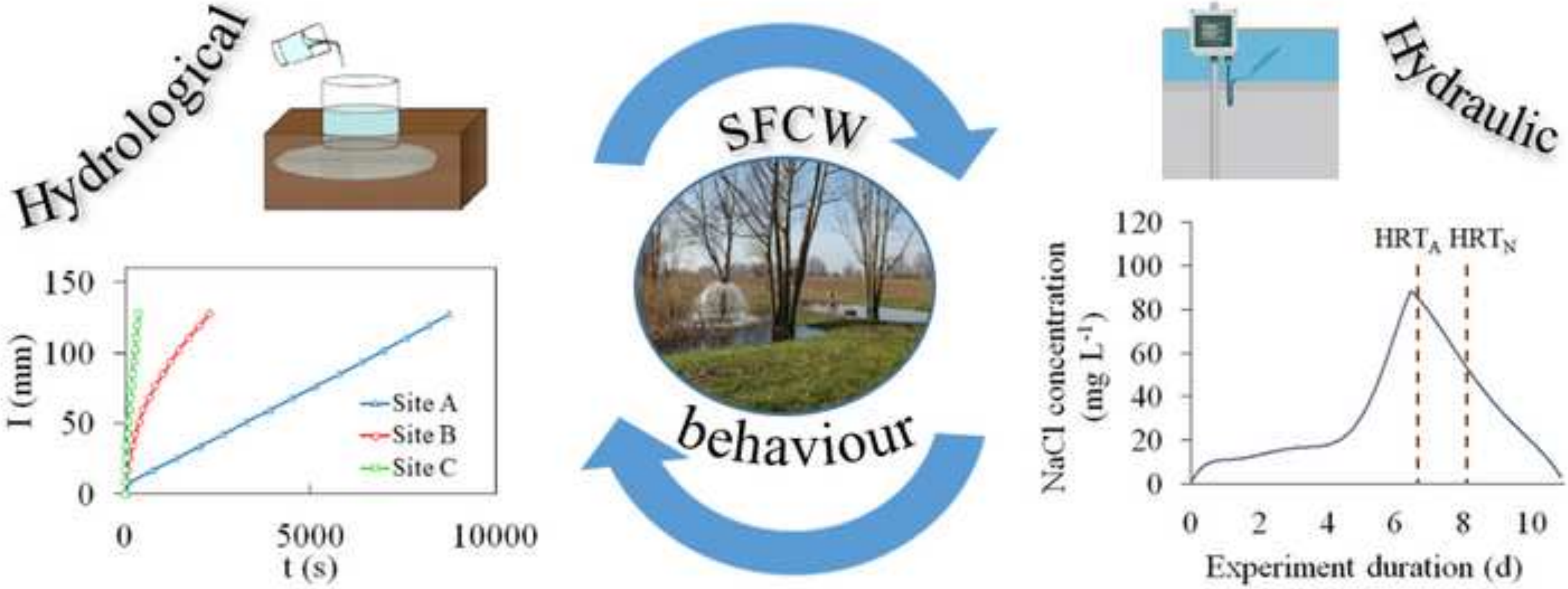
***Graphical Abstract**



Highlights:

- Surface flow constructed wetland (SFCW) treating agricultural drainage water was investigated
- Hydrological and hydraulic states of a SFCW after more than a decade of operation were assessed
- Tracer test was used to estimate hydraulic retention time
- Saturated hydraulic conductivity was estimated by infiltration tests
- Moderate amount of clogging of both bed layer and SFCW were detected

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K_s value near the inlet was 30 mm h^{-1}, that was 7.13 times lower than the value at the outlet area. The estimated infiltration losses were found to be generally in the range 0.28 - 0.33 mm h^{-1}, that were two order of magnitude lower than infiltration measured at the point scale. The results also confirmed the existence of a moderate amount of preferential flow paths and dead zones in the SFCW as the actual HRT (6.7 days) was shorter than the nominal one (8.1 days). Despite this, it can be concluded that the system after 17 years of operation is still in a good state.

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1. Introduction

Agriculture is one of the most important non-point sources of pollution and drainage water coming from arable land has a big impact on the existing ecosystems as documented by different authors and for different geographical areas (Blankenberg et al. 2008; Díaz et al. 2012; Lenhart et al. 2016; Mendes et al. 2018). For example, agricultural drainage water is a major transport pathway between fields and surface water bodies and, as such, contributes to the direct transport of NO_3-N to these ecosystems (Bruun et al. 2016).

Constructed wetlands (CWs), representing a simple but efficient technology for wastewater treatment and reuse (Toscano et al. 2013; Barbagallo et al. 2014; Russo et al. 2019a; Russo et al. 2019b), are extensively being applied also for preventing non-point source pollution (Dal Ferro et al. 2018). Some of their advantages in respect to the conventional wastewater treatment technologies are low operation cost, ability to provide ecosystem services and the fact that they do not need skilled operators (Lavrnić et al. 2018). Surface flow CWs (SFCWs) have been used for a past few decades and proved themselves successful in the treatment of agricultural drainage water (Bodin et al. 2012; Lavrnić et al. 2018). However, since CWs intended for this purpose are usually located at the farm fields and therefore occupy space that could be used for agricultural production, it is important to maintain their removal efficiencies at certain level (Liu et al. 2016).

Apart from water quality improvement, SFCWs can also serve to control flood peak and retain stormwater (Rizzo et al. 2018) and therefore water balance is an important component of their operation and management (Nicholls et al. 2016; Consoli et al. 2018). However, water balance assessment for CWs treating agricultural drainage water can be complicated given they are often not waterproofed. For operational reasons, the assumption of negligible infiltration of water from the wetland to the groundwater is often made (Ayub et al., 2010). Water leakages are mainly influenced by the hydraulic characteristics of the uppermost soil layer as well as the transmission properties of the deep soil layers that determine the bottom boundary conditions. The former are expected to change during system operation as a consequence of clogging due to sedimentation of suspended solids, biofilm formation and plant roots growth (Marzo et al. 2018; Licciardello et al. 2019). Despite an approximate evaluation of water leakage can be conducted from the global water balance, spatio-temporal assessment of CW clogging requires methods specifically developed to assess modification in pore distribution and hydraulic conductivity of the surface layer. The Beerkan Estimation of Soil Transfer (BEST) parameters procedure developed by Lassabatère et al. (2006), allowing for the simultaneous determination of both the soil water retention curve and the hydraulic conductivity function directly in the field with a minimum disturbance of the surface, has the potential for an accurate estimation of this phenomenon at the point scale and can be applied to the CWs.

Furthermore, hydraulic performance of a wetland is affected by different parameters such as the aspect ratio, the lay-out of inlet and outlet, bottom roughness, vegetation and irregular shape of wetland (Liu et al. 2016). A parameter that can change with wetland age is hydraulic retention time. The two most important processes for wastewater treatment in CWs are microorganisms-degradation and plant-adsorption, and they both depend on the retention time (Su et al. 2009). Nominal hydraulic residence time (HRT_N) does not usually give a precise measure of the time that water needs to pass through a system. Some of the reasons are that litter and stems occupy certain volume of SFCWs and the existence of stagnant pockets (Kadlec and Wallace, 2009). Those issues can be assessed by the actual hydraulic residence time (HRT_A) measurement. If it is longer than the HRT_N, it means that the water is stagnant and does not participate in the flow (Aiello et al. 2016). On the other hand, the HRT_A shorter than the HRT_N can imply existence of the short-circuits and preferential paths (Barbagallo et al. 2011). Since hydraulic conditions within the system can affect its performance in pollutant removal (Bodin et al. 2012; Bruun et al. 2016), it is important to improve the knowledge on wetland hydraulics by estimating the exact HRT_A, and make certain changes in the management and maintenance if the system efficiency is not satisfactory.

In the present study, the above aspects were investigated in a full-scale SFCW located in Northern Italy with the aim to detect modifications in its hydrologic and hydraulic behaviour after 17 years of constant operation. In particular, infiltration and evapotranspiration losses were estimated in order to close the water balance of the system, and to evaluate to what extent its operation was affected by accumulation of sediments and changes of water flow. Moreover, the actual hydraulic conditions of the same system were assessed by means of a tracer test and HRT_A estimation for a particular flow pattern (i.e. continuous flow).

2. Materials and methods

2.1. System description

The SFCW studied is located at the experimental agricultural farm of the land reclamation consortium Canale Emiliano Romagnolo (CER) in Italy. The farm has a total area of 12.5 ha and different crops are grown throughout the year. The wetland system treats the entire agricultural drainage water coming from the farm and it consists of four meanders that create a 470 m long water course with an overall surface of about 0.4 ha (Figure 1).

The length to width aspect ratio of the system (considering the water flow) was approximately 52:1 and therefore conditions similar to plug flow can be assumed. The total capacity of the SFCW is 1477 m^3 corresponding to an average depth of 0.40 m. Some of the plants that are present at the site are *Phragmites australis*, *Typha latifolia*, *Carex spp*. etc. The system is equipped with two mechanical flow meters that record influent and effluent volumes every hour and an automatic water level sensor located at the outlet. All the collected data are managed and recorded by a central control system. Rainfall is measured by a tipping-bucket rain gauge located 500 m far from the CW. More information about the system treatment capacity can be found in Lavrnić et al. (2018).

The SFCW is not waterproofed and its operation mainly depends on agricultural drainage discharges driven by rainfall and irrigation. Evapotranspiration and infiltration also influence its hydrology. During the dry periods (with minimal or no rain) only the first meander is wet, but it could also happen that no water at all is present inside the system. The system was constructed in 2000 and it is functioning since.

2.2. Estimation of soil characteristics and infiltration fluxes from the CW

The surface soil layer of the CW was sampled in July 2017 when the wetland was empty as no rainfall had occurred in the previous two months. Three locations were established close to the inlet (site A), at intermediate position (site B) and at the outlet (site C) (Figure 1). At each site, five BEST experiments were carried out to obtain a complete soil hydraulic characterization. Following a procedure commonly used for BEST experiments, undisturbed soil cores (5 cm in height by 5 cm in diameter) were collected at two depths in the uppermost horizon (0-5 cm and 5-10 cm) for determination of soil bulk density, ρ_b (g cm^{-3}) and volumetric water content, θ_0 (cm^3 cm^{-3}), at the time of sampling (Alagna et al. 2016). The saturated soil water content, θ_s, was assumed to coincide with soil porosity, ϕ. Disturbed soil samples were also collected at each location for determination of particle size distribution (PSD) by conventional methods (Gee and Bauder, 1986). Considering that the sampling areas were of few tens of squared metres, the soil was considered homogeneous at each site and a mean value of ρ_b, θ_0 and PSD was considered resulting from the arithmetic mean of all samples collected in that site. Beerkan infiltration tests were conducted using a cylinder having an inner diameter of 15 cm (Figure 1). The surface vegetation was removed over an area slightly larger than the cylinder diameter, while the roots remained in situ. The cylinder was positioned at the soil surface and inserted to a depth of 10 mm to prevent lateral losses of water. A fixed volume of water (175 mL corresponding to a water depth of 10 mm) was then poured into the cylinder at time zero, and the time required for infiltration was measured. As soon as the first volume had completely infiltrated, another equal volume of water was added to the cylinder and the time was recorded for this volume to infiltrate (cumulative time). The procedure was repeated 15 times. In this way, a cumulative infiltration, I (L), versus time, t (T) relationship, including 15 discrete points was determined.

BEST considers certain analytic relationships for hydraulic characteristic curves (i.e. the relationships between soil water pressure head, h, volumetric water content, θ, and hydraulic conductivity, K) and estimates their shape parameters, which are texture dependent, from PSD by physical-empirical pedotransfer functions (Lassabatere et al. 2006). Structure dependent scale parameters are estimated by the Beerkan infiltration experiment using the two-term transient infiltration equation by Haverkamp et al. (1994). In particular, three different algorithms were used to estimate soil sorptivity, S (mm h$^{-0.5}$) and saturated hydraulic conductivity, K_s (mm h^{-1}) from infiltration tests, namely the BEST-slope (Lassabatere et al.

2006), the BEST-intercept (Yilmaz et al. 2010) and BEST-steady (Bagarello et al. 2014) procedures. Knowledge of S, K_s and shape parameters allowed estimation of the scale parameter for water retention, h_g (mm), that is related to the characteristic microscopic pore radius (Angulo-Jaramillo et al. 2016). The workbook by Di Prima (2013) was applied to automatically analyze the infiltration data collected for this investigation.

Estimates of water leakages from the wetland were obtained from the water balance:

$$Q_{in} + (P \times A) - Q_{out} - I - (ET \times A) = \frac{\mathrm{dV}}{\mathrm{dt}} \tag{1}$$

where Q_{in} and Q_{out} (m^3d^{-1}) are, respectively the inflow and outflow rates, P ($m\ d^{-1}$) is rainfall, I ($m^3\ d^{-1}$) is infiltration from the wetland into the groundwater, ET (m^3d^{-1}) is evapotranspiration, A (m^2) is wetland area, V (m^3) is wetland volume and t (d) is time. Eq. (1) was applied to several inter-rainfall periods between October and December 2017, in which ET could be considered negligible due to the low air temperatures (mean T = 11.3 °C, minimum T = –4 °C, maximum T = 15.4 °C) and quiescent phenological phase of vegetation. Duration of inter-rainfall periods ranged from four to 16 days during which the water level, z (m), ranged from 0.20 to 0.33 m. As the weir hedge at the outlet is positioned at 0.40 m, no outflow occurred as confirmed by measurements conducted at the outlet flow meter. Total variation of the wetland volume during each inter-rainfall period, $\Delta V/\Delta t$, was estimated from water level measurements provided a calibrated relationship between V and z was available for the wetland. Thus, infiltration, I, was estimated as:

$$I = Q_{in} - \frac{\Delta V}{\Delta t} \tag{2}$$

2.3. Evaluation of the hydraulic retention time

HRT_A was estimated by a test that used NaCl as a tracer, since it was reported to be a conservative tracer (Aiello et al. 2016). The solution was prepared by mixing 100 kg of NaCl in 450 L of water directly collected from the CW, and then it was pumped at the system inlet in order to ensure good mixing with inflow water. The pumping process itself lasted for approximately 5 minutes, and thus can be considered instantaneous when compared to the HRT_N.

Portable electrodes connected to the data logger were used to measure and record electrical conductivity, EC (mS cm^{-1}), values at the different points of the system (Figure 1). All the electrodes were set to register value every 15 minutes. The background EC value was subtracted from outflow EC values in order to assess the increase caused by NaCl addition. The differences were then transformed to the NaCl concentration (mg L^{-1}) by multiplying with a factor of 0.67 that was experimentally estimated by measuring EC of CW water solutions with known NaCl concentrations.

The trial lasted for 11 days (27th September - 8th October) and evapotranspiration and infiltration losses were considered negligible during this period. A flow rate of 6.8 m^3 h^{-1} was chosen in order to represent the worst case scenario (i.e., the conditions when the system is full and there is a constant inflow and outflow). Such a choice was made in order to estimate the shortest possible HRT, since this parameter is one of the most important ones for an effective pollutant removal in SFCWs. So, for the entire duration of the experiment, the system was continuously supplied with water to maintain maximum water level and constant inflow and outflow.

In addition, a certain part of the SFCW volume is occupied by vegetation and plant litter that was never removed from the system for 17 years of the operation. In order to subtract vegetation from the total system volume (Bodin et al. 2012), vegetation volume was visually estimated to be approximately 0.1 of the total CW volume and the system porosity was set to 0.9, close to the value of 0.95 that Kadlec and Wallace (2009) reported as a usual value for

SFCWs. Inflow and outflow rates were recorded by the central control unit and were used for calculation of the HRT_A and HRT_N as:

$$HRT_N = 0.9 * \frac{V}{Q} \quad (3)$$

$$Q = \frac{Q_{in} + Q_{out}}{2} \quad (4)$$

$$HRT_A = \frac{\int_0^\infty tCdt}{\int_0^\infty Cdt} \quad (5)$$

where V is the volume of the system (m^3), Q flow rate ($m^3\ h^{-1}$), t time (h) and C effluent NaCl concentration (mg L^{-1}) (Kadlec and Wallace, 2009; Marzo et al. 2018). The tracer mass recovery was later calculated by multiplication of outflow volume and NaCl concentration in that moment, and summing all the values during the experiment duration. Acceptable values of the tracer mass recovery are in the range 80-120%. In the case when it is less than 100% the possible reasons are that the tracer was adsorbed or degraded (Kadlec and Wallace, 2009). Hydraulic efficiency (λ) was calculated in order to determine how effectively the total CW volume is used. It is the ratio between the time when tracer concentration reached its highest value (t_p) and the HRT_N (Guo et al. 2017). Depending on the λ value, a CW hydraulic efficiency can be classified as poor ($\lambda \leq 0.5$), satisfactory ($0.5 < \lambda \leq 0.75$) and good ($\lambda > 0.75$). Good hydraulic efficiency means that large part of wastewater is included in the flow and therefore the total volume is better used (Aiello et al. 2016). Also, the effective volume ratio that is the ratio between HRT_A and HRT_N, was determined in order to find out how effective was system volume (V_{eff}) (Bodin et al. 2012).

$$e = \frac{HRT_A}{HRT_N} = \frac{V_{eff}}{V} \quad (6)$$

Wetland systems are usually described by either plug flow or continuously stirred tank reactor model. However, various studies have failed to confirm that one of these two theories fits to the actual conditions. Instead, tank in series model and its description of non-ideal flow conditions is considered more appropriate. This model is based on the assumption that a system is divided into a N number of tanks of equal size (Bodin et al. 2012) that can be calculated according to the following relationship:

$$N = \frac{\mathrm{HRT}_A^2}{\int_0^{\infty} (\mathrm{HRT}_A - t)^2 f(t)\,dt} \tag{7}$$

2.4. Data analysis

The normality of the statistical distribution of soil sorptivity, *S*, saturated hydraulic conductivity, K_s, and water retention scale parameter, h_g, was tested by the probability plot correlation coefficient test at P = 0.05 (Helsel and Hirsch, 1992). Only the normal and the log-normal distributions were considered because *S*, K_s and h_g were often found to be adequately described by these distributions (Warrick, 1998). Soil bulk density and volumetric water content were assumed to be normally distributed. Comparisons between two mean values were conducted by a t-test ($P = 0.05$), either homoscedastic or not according to a F-test ($P = 0.05$). Comparison among three means were conducted according to a Tukey Honestly Significant Difference test ($P = 0.05$).

3. Results and discussion

3.1. Soil physical characteristics

According to USDA classification (Gee and Bauder, 1986), texture of the CW soil was not uniform and a relatively higher percentage of clay particles was detected at the inlet (site A) (Table 1). The middle and the outlet sites showed similar textural composition. No appreciable differences could be detected between samples collected in the upper surface layer (UP layer 0-5 cm depth) and in the subsurface layer (DW layer, 5-10 cm depth). Similarly, no difference was observed between mean ρ_b and θ_0 values in the UP and DW layers of the different sampling sites (Table 1). It can be concluded that PSD, bulk density and water content at the sampling time were vertically uniform in the soil profile explored by the Beerkan infiltration tests (i.e., 0-10 cm) thus supporting the assumption to use, at each site, a unique value of ρ_b, θ_0 and PSD for application of BEST procedure. Accordingly, for the subsequent statistical analyses the ρ_b and θ_0 data collected at a given site were pooled together.

The Tukey HSD test confirmed that the surface bulk density of the wetland soil was uniform and differences among sites were not significant (Table 1). A lower water content was detected at the outlet of the wetland (site C) compared to the other two sampling sites.

3.2. Soil hydraulic properties

Duration of the Beerkan infiltration test was relatively longer and more variable in site A (mean test duration, μ = 8769 s, standard duration, σ = 4480 s) than in sites B (μ = 2433 s, σ = 3351 s) and C (μ = 373 s, σ = 255 s). Cumulative infiltration vs. time curves exhibit a common shape, with a concave part corresponding to the transient phase of infiltration and a linear part showing that a steady state stage was achieved (Figure 2).

Steady-state stage was better defined for site A where from 7 to 13 points could be considered. For the other sites, most of the steady states were detected by only 3 points (Figure 2). Inaccurate definition of the steady-state phase probably resulted in violation of the constraints assumed for the BEST-slope and BEST-intercept algorithms that, consequently, resulted in an unrealistic estimate of either S or K_s (i.e., negative values of one of the two parameters were obtained). In particular, BEST-slope failed in 10 out of 15 experiments, whereas the rate of failure was lower for BEST-intercept (three out of 15 experiments). However, even when successful, these two algorithms yielded relative errors between the measured and modelled transient infiltration data greater than 5.5%, which is considered the maximum acceptable error (Lassabatère et al. 2006). BEST-steady always allowed to successfully estimate S and K_s. Therefore, for the aim of comparison of the hydraulic properties among the different sampling sites, only the results obtained by BEST-steady were considered.

The log-normal distribution was never rejected for S, K_s and h_g values whereas for K_s data the hypothesis of normality was rejected in one case (site B). Therefore, mean and associated coefficient of variation (CV) were calculated according to the statistical distribution better describing the experimental data (Lee et al. 1985).

The lowest mean value of K_s was 30 mm h^{-1} and it was measured at the inlet (site A). Mean K_s increased by a factor 1.4 from site A to site B and by a factor of 7.13 from site B to site C (Table 2). Statistically significant differences were found between site A and the other sites that can be attributed to pore sealing processes occurring at the inlet. Despite not significant, a clear increasing trend was detected from the inlet to the outlet of the wetland as consequence of different occurrence of sealing due to selective settling of suspended soil particles. The lower variability of K_s, the higher mean bulk density value and increased clay content (Table 1) observed at the inlet of the wetland are additional concurrent signs that settling of fine particle resulted in a more homogeneous and compacted soil surface layer that affected hydraulic conductivity and infiltration. This finding is similar to the one reported by Caselles-Osorio and García (2006), who found that clogging in an experimental horizontal flow CW reduced inlet hydraulic conductivity to 64% of outlet hydraulic conductivity.

Soil sorptivity also increased along the wetland with mean S value for site A that was statistically lower than at the other sites (Table 2). Sorptivity represents the soil capability to absorb water without gravity (Angulo-Jaramillo et al. 2016) and it increases as the soil moisture decreases. As initial soil water content decreased from the inlet to the outlet of the wetland (Table 1), the observed trend in soil sorptivity is clearly explained by the different wetness of the surface soil at the time of sampling. However, site B was characterized by a 5-fold higher sorptivity than site A despite initial soil water content between the two sites was not statistically different. For a given initial saturation degree, fine textured soils show lower values of soil sorptivity (Touma et al. 2007). The observed result is therefore in line with literature findings and further confirms the occurrence of soil clogging at the inlet of the wetland.

The absolute value of the water pressure head scale parameter, h_g, can be used to obtain an estimate of the characteristic microscopic pore radius that is the mean characteristic dimension of the hydraulically functioning pores (Angulo-Jaramillo et al. 2016). In particular, the lower is the h_g value the greater is the effect of gravity compared to capillarity as infiltration driven force. Table 2 shows a significant lower mean value of h_g for site A that would indicate a prevalence of gravity flux which contradicts the lower saturated hydraulic conductivity observed at this site. However, a closer examination of h_g data for site A shows that this parameter exhibited a two-order magnitude variation (Table 2) with spots in which infiltration is probably driven by few large conducting pores and other spots in which capillarity prevails. Castellini et al. (2016) concluded that h_g values estimated by BEST procedure were able to signal modifications in soil structure due to land use changes. In our case, the sealing effects probably affected the pore space in a very uneven way that did not allow a clear interpretation of the measured h_g values. However, the very high variability of the hydraulically functioning mean pore sizes determined by the BEST procedure for site A, as compared to the other sites, can be considered another sign of soil structural modifications due to sealing phenomena

Figure 3 shows the water level vs. time relationship during the period from 18 October to 13 December with indication of the inter-rainfall periods considered for application of eq. (2). It can be seen that the rate of the water level decline, dz/dt, is almost constant within each inter-rainfall period with average values ranging from 3 to 5 mm/d (Table 3). The knowledge of the wetland geometry allowed to calculate the infiltration surface, A (m^2), as function of the water level and, then, the infiltration rate, i (mm/h) (Table 3). For the considered period, the estimated infiltration rate ranged from 0.28 to 0.33 mm/h. Application of the water balance to a different period of the year (28 March to 30 April) confirmed these results (Table 3). In this case, the relatively higher infiltration rate (i = 0.48 mm/h) as compared to fall measurements could be attributed to the higher average water level, z, as well as to the neglected contribution of evapotranspiration due to the beginning of the spring vegetative activity.

Estimated infiltration rate are at least two order of magnitude lower than the measured saturated hydraulic conductivity at the wetland surface. Also keeping into account that ET is neglected in the water balance analysis, comparison show that global scale estimation and point measurements are not in agreement. Several reason could be invoked to explain this large discrepancy: i) different explored soil volume with the two methods; ii) continuity and connection of macropores that probably pertain to the upper soil layer and not the lower more compacted soil layers; iii) influence of the relatively high water table that negatively affected the full scale infiltration rate.

The conclusion is that point scale techniques based on ponded infiltration experiments, like BEST, are probably suitable methods for measuring the spatial and temporal variability of surface hydraulic conductivity as a consequence of wetland operation. Surface sealing due to particle settling, compaction of surface layer as a consequence of roots development, evidence of preferential flow due to biotic and abiotic phenomena are some examples of processes that can be adequately monitored in space and time with the BEST procedure. However, the relatively limited depth of the explored layer made this technique not suitable for a total assessment of the wetland leakage that probably needs other more cumbersome full-scale measurements.

3.3. Hydraulic residence time estimation

The calculated tracer mass recovery was 71% and outside of the acceptable range of 80-120% (Kadlec and Wallace, 2009), but several other studies done at SFCWs reported comparable recovery values (Dierberg and DeBusk, 2005; Bodin et al. 2012; Guo et al. 2017). Since the density of the tracer solution was higher than the density of water, low tracer mass recovery could be due to the settling and water velocity that was insufficient to prevent it (Bodin et al. 2012). As previously said, tracer injection could be considered instantaneous (section 2), and a longer injection period could have increased tracer mass recovery by preventing a possible settling to the bottom (Dierberg and DeBusk, 2005).

The portable electrodes enabled tracking of the tracer through the system (Figure 4). The points where water EC was measured were approximately at the same distance from one another (Figure 1), but it can be seen that the peak time of tracer concentration did not follow the same pattern. The reasons are twofold: i) although the system has four meanders of approximately similar dimensions, there are differences in slope, bottom topography or width at specific cross-sections, ii) different parts of the SFCW do not have comparable vegetation densities or plant species. For example, deeper initial part of the system or especially dense vegetation that is present in the third meander could have increased time needed for the tracer to reach points 1 or 3. On the other hand, due to the fact that during warm or dry periods of the year water is not present in the fourth meander, vegetation density there is smaller than in the first meander and therefore difference of only 0.3 days between peak time at point 3 and 4.

Although mass recovery of the tracer can be considered insufficient, some conclusions can still be drawn. The total duration of the experiment was 10.8 days, and the HRT_A was calculated to be 6.7 days. Tournebize et al. (2017) suggested that 50% NO_3-N removal can be reached with HRT of minimum 2 days, while for the same percentage of pesticide removal at least 10 days are needed. In addition, the SFCW area to catchment ratio is in the range of 0.1-5%, which is recommended for efficient nutrient removal (Kadlec and Wallace, 2009). Since the minimum HRT of the studied SFCW is 6.7 days, it can be concluded that even during extreme rain events it should be enough to achieve reduction of more than 50% of the inflow NO_3-N load. However, since average HRT of the system should be much longer, higher removals are expected and that hypothesis will be tested in the research that is currently ongoing.

The results showed that the HRT_A was shorter than the calculated HRT_N of 8.1 days (Figure 5). That indicates a possible existence of preferential paths inside the system. Similarly, hydraulic efficiency (λ = 0.79) and effective volume ratio (e = 0.71) indicate that a quarter of wetland volume does not participate in the flow and consequently in the different reactions that remove pollutants. However, these values do not present a big problem since systems that have an effective volume ratio in the range 0.5-0.75 have moderate amount of dead zones, while small amount of dead zones is present in the systems whose effective volume ratio is in the range 0.75-1 (Bodin et al. 2012). It can be argued that the physical division of wetland cell in four meanders and consequently high aspect ratio contributed to a small amount of dead zones since such a structure favours a more channelled flow. This is in accordance with Su et al. (2009) who recommended an aspect ratio to be higher than 5, and at least 1.88 in order to maintain the uniform flow.

Number of tanks in series that can represent the system studied is 3.78, very close to the number of meanders in the wetland (4). That value is in the range 0.3-10.7 and it is very close to a mean value of 4.1 that were established for the SFCWs (Kadlec and Wallace, 2009). Since N=1 indicates a completely mixed system (Guo et al. 2017), it can be concluded that different parts of the SFCW are not mixed in the same way, as also confirmed by peak times of the tracer concentration at different points of the system (Figure 4).

4. Conclusions

The goal of this study was to assess hydraulic and hydrological properties of a mature full-scale SFCWs that is in use since 2000. Given the amount of time that has passed, it was understandable that some short-circuits, preferential flow paths and clogging were detected in the system. For example, clogging of the SFCW bottom, a consequence of the sediment accumulation, can be connected to the particular operation of the system which mainly depends on agricultural drainage discharges. Since water does not always reach the outlet and remains near the entrance, clogging of the bed layer also followed that pattern and it was found to be much higher in the inlet zone compared to other parts that were closer to the outlet. Indeed, BEST infiltration experiments confirmed this statement given that the K_s mean value in the inlet zone was 7.13 times lower than in the outlet area. Moreover, not all the system volume participated in the water flow sine HRT_A was shorter than HRT_N, but both hydraulic efficiency ($\lambda = 0.79$) and effective volume ratio ($e = 0.71$) were found to be in an acceptable range.

Other very important aspects of this kind of assessment are water losses of the studied SFCW that was not waterproofed. The estimated infiltration rate, computed on the basis of the water balance, was two order of magnitude lower than the measured K_s by BEST technique at the wetland top layer. Therefore, global scale infiltration estimation and point scale measurements based on ponded infiltration experiments, like BEST, are not in agreement making the latter one not suitable for a total assessment of the wetland leakage.

Overall, it can be said that the system is still in a good state, and that negative effects of more than a decade of operation were limited and even brought certain advantages (e.g. clogging of the SFCW bed reduced infiltration and consequently water losses from the system).

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Table 1. Soil texture and classification (USDA), bulk density, ρ_b, and volumetric water content at the time of sampling, θ_0, for the different sites and depths

Site	sampling depth	sand (%)	silt (%)	clay (%)	USDA	ρ_b (g cm^{-3})	θ_0 (cm^{3}cm^{-3})
A - inlet	UP 0-5 cm	15.9	42.9	41.3	clay	1.154a	0.407a
	DW 5-10 cm	12.5	46.3	41.3	clay	1.580a	0.383a
	mean	14.2	44.6	41.3		1.326A	0.403A
B - middle	UP 0-5 cm	13.4	53.6	33.0	silty	1.167a	0.388a
	DW 5-10 cm	10.8	56.2	33.0	silty	1.364a	0.384a
	mean	12.1	54.9	33.0		1.228A	0.387A
C - outlet	UP 0-5 cm	14.8	57.7	27.5	silty	1.142a	0.315a
	DW 5-10 cm	9.5	57.5	33.0	silty	1.454a	0.346a
	mean	12.2	57.6	30.3		1.252A	0.327B

For a given site, the values in a column (i.e., UP and DW) followed by the same lower case letter are not significantly different according to a two tailed t test ($P = 0.05$). The values followed by the same upper case letter are not significantly different according to a Tukey HSD ($P = 0.05$).

Table 2. Minimum (Min), maximum (Max), geometric mean (GM), and coefficient of variation (CV, in %) of the saturated soil hydraulic conductivity, K_s (mm h^{-1}), soil sorptivity, S (mm h$^{-0.5}$), and the water pressure head scale parameter, h_g (mm), values obtained applying BEST-Steady algorithm for the infiltration experiments carried at the three selected sites (sample size $N = 5$).

Variable	Statistic	Site A	Site B	Site C
S	Min	3.1	18.2	79.9
(mm h$^{-0.5}$)	Max	26.0	120.6	62.8
	GM	8.2a	52.9b	120.5b
	CV	122.3	93.5	35.6
K_s	Min	13.7	3.3	112.7
(mm h^{-1})	Max	61.4	257.7	548.7
	GM	30.5a	41.1b	293.0b
	CV	60.3	537.4	92.6
$\lvert h_g \rvert$	Min	1.0	148.3	84.8
(mm)	Max	131.9	293.1	148.5
	GM	10.0a	201.4b	111.7b
	CV	1408.5	26.7	22.0

Values in a row followed by the same letter are not statistically different according to a Tukey HSD test ($P = 0.05$).

Table 3**.** Application of the water balance equation to different inter-rainfall periods.

Period	n. days	dz/d*t* (m/d)	$Q_{in} + P$ (m^3)	ΔV (m^3)	$\bar{z}$ (m)	A (m^2)	i (mm/h)
18/10 - 3/11	16	5.04x10^{-3}	5.5	-353.9	0.240	2979.5	0.31
8/11 - 12/11	4	3.13x10^{-3}	36.2	-54.9	0.263	2994.6	0.32
15/11 - 23/11	9	4.37x10^{-3}	7.6	-153.3	0.302	3021.0	0.28
2/12 - 6/12	5	3.90x10^{-3}	26.0	-68.5	0.276	3003.2	0.33
28/3 - 30/4	33	4.60x10^{-3}	502.4	-665.9	0.344	3048.5	0.48

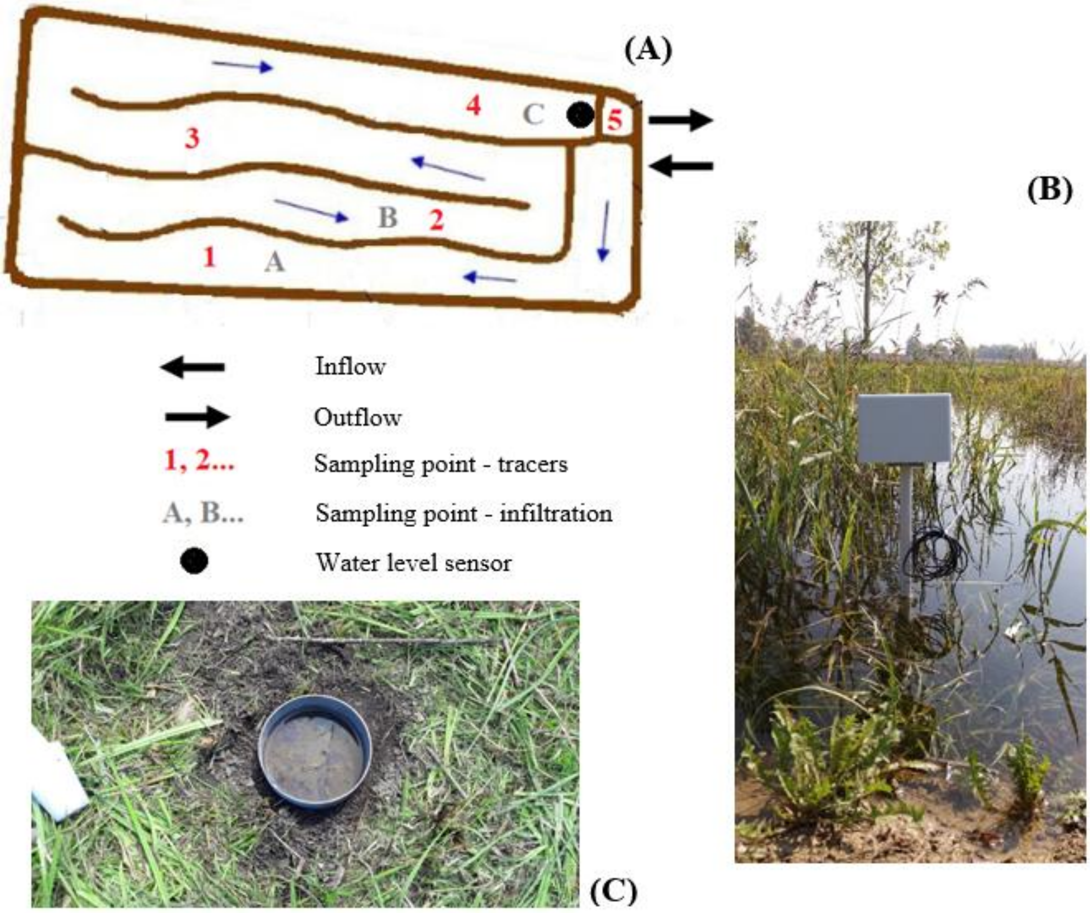

Figure 1. Schematic plan of the SFCW with different measuring points (A), data logger and electrode (B) and Beerkan ring infiltrometer tests (C) at the study site.

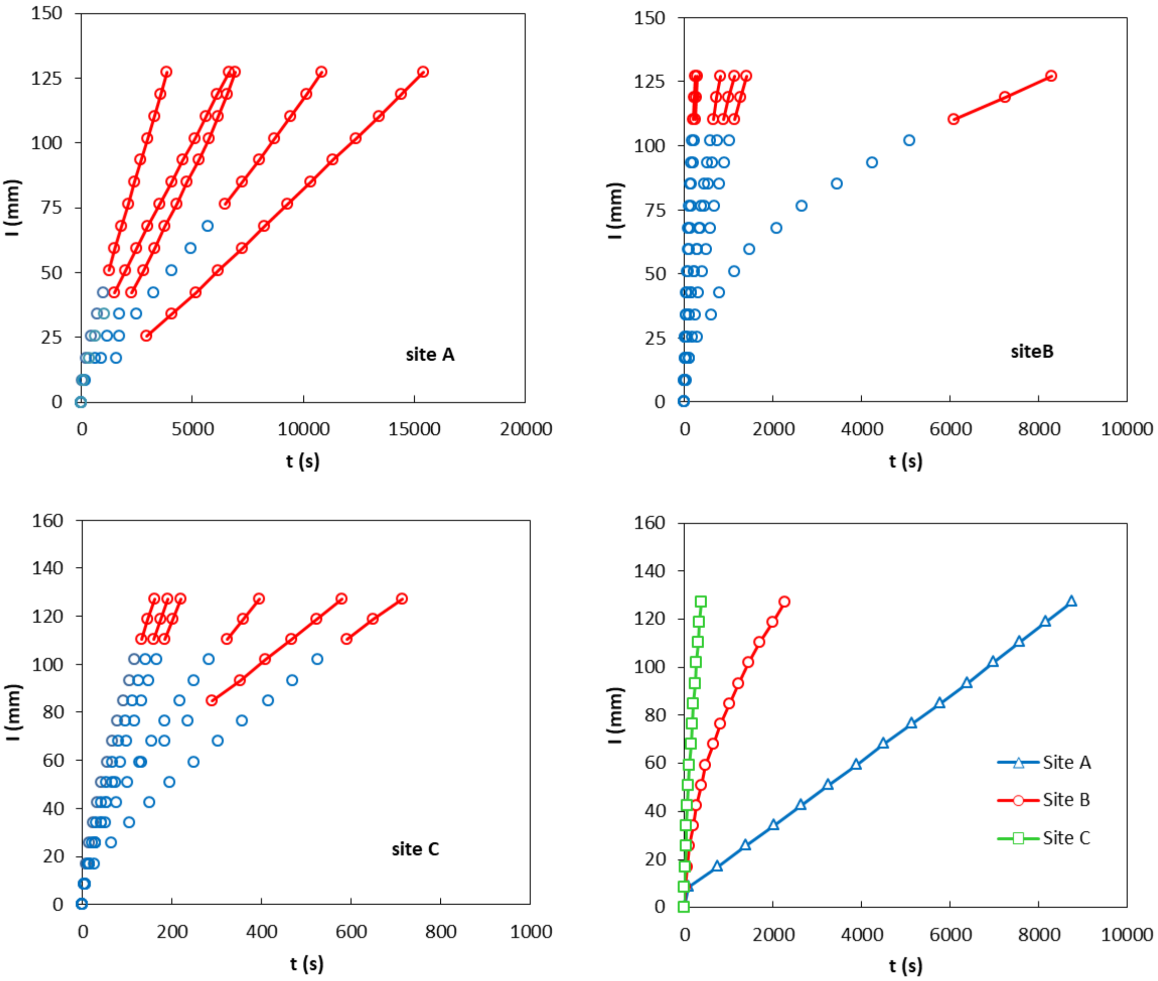

Figure 2. Cumulative infiltration (*I*) versus time (*t*) data for the Beerkan experiments and average infiltration curves for the three selected sites.

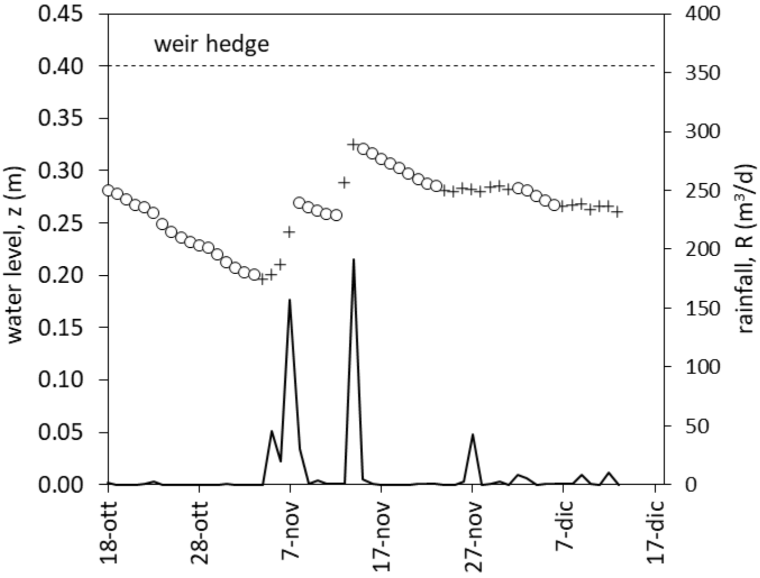

Figure 3. Water levels recorded in the wetland in the spell from 18 October to 13 December 2017. Rainfalls in this period are also showed.

Figure 4

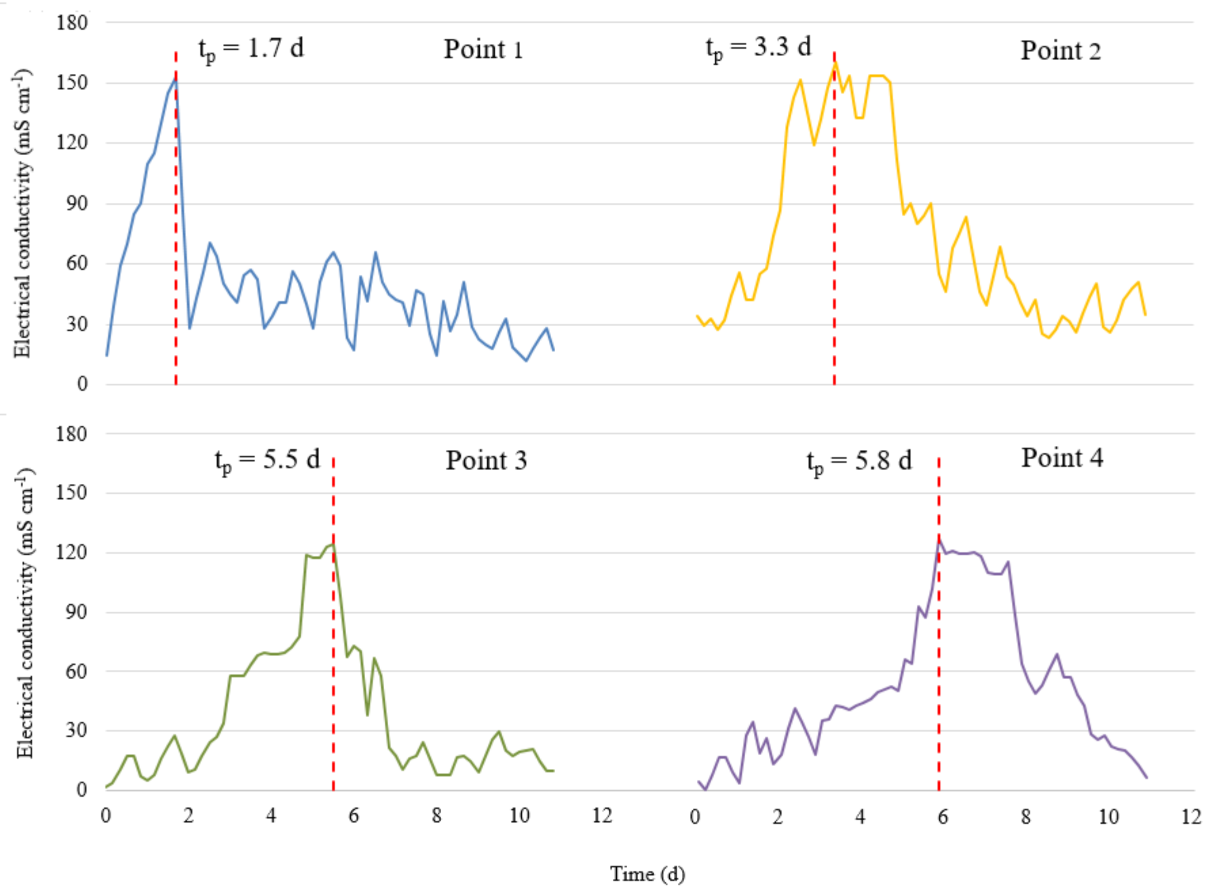

Figure 4. Movement of tracer through the system.

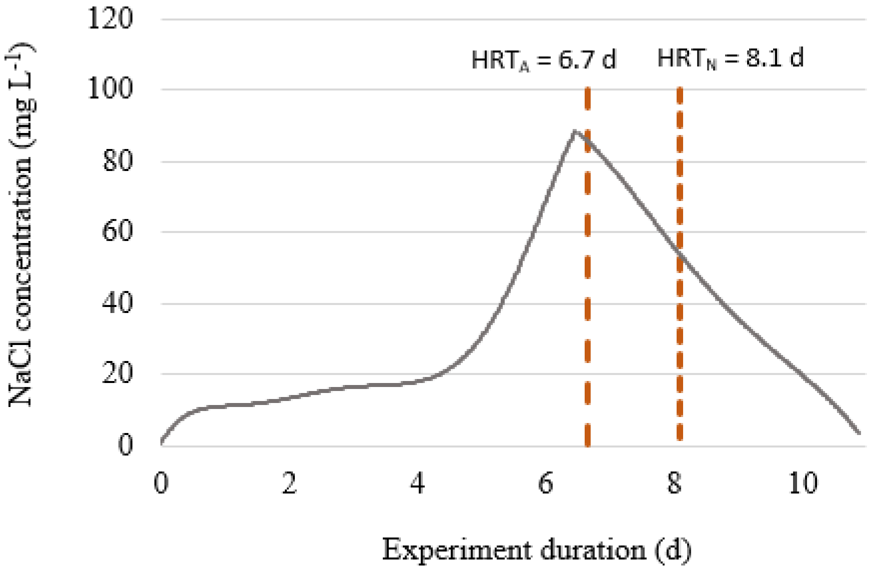

Figure 5. Concentration of the tracer at the outflow of the SFCW.