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

This is the submitted version (pre peer-review, preprint) of the following publication:

*Published Version:*

Lavrnjic S., Alagna V., Iovino M., Anconelli S., Solimando D., Toscano A. (2020). Hydrological and hydraulic behaviour of a surface flow constructed wetland treating agricultural drainage water in northern Italy. *SCIENCE OF THE TOTAL ENVIRONMENT*, 702(1 February 2020), 1-9 [10.1016/j.scitotenv.2019.134795].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/723431> since: 2024-02-05

*Published:*

DOI: <http://doi.org/10.1016/j.scitotenv.2019.134795>

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This is the manuscript draft of:

S. Lavrnić, V. Alagna, M. Iovino, S. Anconelli, D. Solimando, A. Toscano

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

*Science of The Total Environment*, Volume 702, 1 February 2020, 134795

The final published version is available online at:

<https://doi.org/10.1016/j.scitotenv.2019.134795>

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the Total Environment

Elsevier Editorial System(tm) for Science of

Manuscript Draft

Manuscript Number:

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

Article Type: Research Paper

Keywords: Hydraulic retention time; Infiltration; Saturated hydraulic conductivity; Surface flow constructed wetland

Corresponding Author: Professor Massimo Iovino, PhD

Corresponding Author's Institution: University of Palermo

First Author: Stevo Lavrnić, PhD

Order of Authors: Stevo Lavrnić, PhD; Vincenzo Alagna, PhD; Massimo Iovino, PhD; Stefano Anconelli; Domenico Solimando; Attilio Toscano, Professor

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). Pondered infiltration measurements were conducted to estimate the saturated hydraulic conductivity,  $K_s$ , 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  $K_s$  value near the inlet was  $30 \text{ mm h}^{-1}$ , 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  $0.28 - 0.33 \text{ mm h}^{-1}$ , 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.

Suggested Reviewers: Laurent Lassabatere

Ecologie des Hydrosystèmes Naturels et Anthropisés, University of Lyon

Laurent.LASSABATERE@entpe.fr

BEST procedure for soil hydraulic characterization; Soil hydrology; Soil water infiltration

Michal Dohnal

Faculty of Civil Engineering, Czech Technical University in Prague

Michal.Dohnal@cvut.cz

Soil water infiltration; Hydrologic modelling

Günter Langergraber  
University of Natural Resources and Life Sciences Vienna (BOKU)  
guenter.langergraber@boku.ac.at  
Constructed wetlands;  
Phytoremediation;  
Wastewater treatment and reuse

Antonina Torrens  
University of Barcelona  
antoninatorrens@ub.edu  
Constructed wetlands;  
Wastewater treatments

Miklas Scholz  
Lund University  
miklas.scholz@tvrl.lth.se  
Hydrodynamics, dye tracers, wastewater reuse

Opposed Reviewers:

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

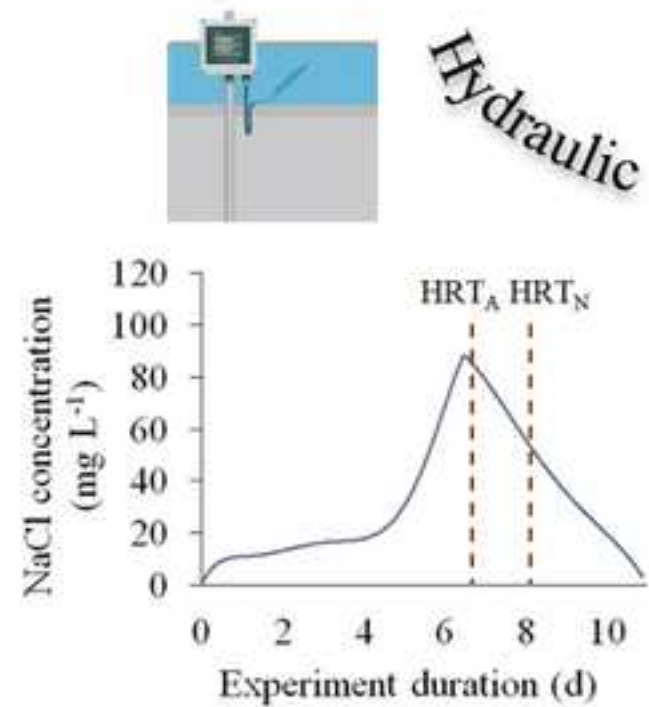
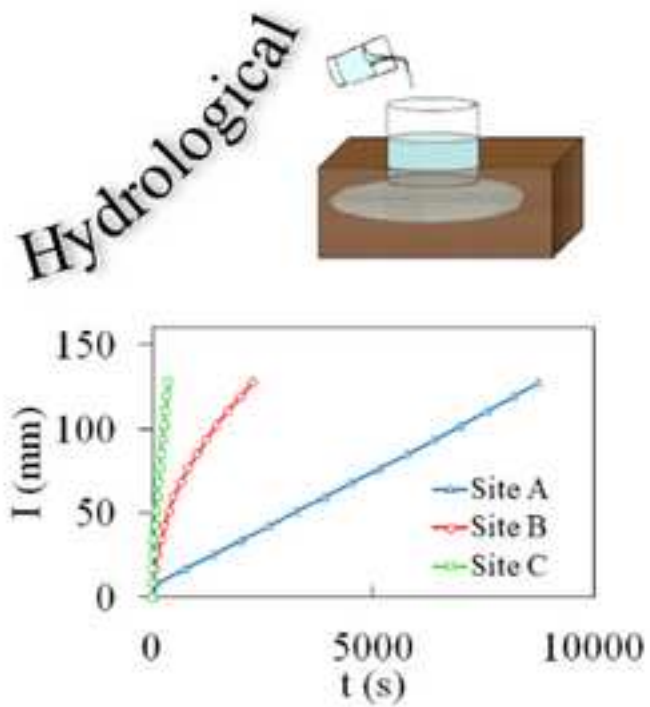
*S. Lavrnić<sup>a</sup>, V. Alagna<sup>a,b</sup>, M. Iovino<sup>b,\*</sup>, S. Anconelli<sup>c</sup>, D. Solimando<sup>c</sup>, A. Toscano<sup>a</sup>*

<sup>a</sup> Alma Mater Studiorum - University of Bologna, Department of Agricultural and Food Sciences,  
Viale Giuseppe Fanin 50, Bologna 40127, Italy (stevo.lavrnica@unibo.it; v.alagna@unibo.it;  
attilio.toscano@unibo.it).

<sup>b</sup> Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze,  
90128 Palermo, Italy ([massimo.iovino@unipa.it](mailto:massimo.iovino@unipa.it)).

<sup>c</sup> Consorzio di Bonifica Canale Emiliano Romagnolo, Via Ernesto Masi 8, Bologna 40137, Italy  
(anconelli@consorzioicer.it; solimando@consorzioicer.it)

\*Corresponding author: [massimo.iovino@unipa.it](mailto:massimo.iovino@unipa.it)



**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

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

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6 *S. Lavrnić<sup>a</sup>, V. Alagna<sup>a,b</sup>, M. Iovino<sup>b,\*</sup>, S. Anconelli<sup>c</sup>, D. Solimando<sup>c</sup>, A. Toscano<sup>a</sup>*

7  
8 <sup>a</sup> Alma Mater Studiorum - University of Bologna, Department of Agricultural and Food  
9 Sciences, Viale Giuseppe Fanin 50, Bologna 40127, Italy (stevo.lavrnic@unibo.it;  
10 v.alagna@unibo.it; attilio.toscano@unibo.it).

11 <sup>b</sup> Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle  
12 Scienze, 90128 Palermo, Italy ([massimo.iovino@unipa.it](mailto:massimo.iovino@unipa.it)).

13 <sup>c</sup> Consorzio di Bonifica Canale Emiliano Romagnolo, Via Ernesto Masi 8, Bologna 40137,  
14 Italy (anconelli@consorziocer.it; solimando@consorziocer.it)

15 \*Corresponding author: [massimo.iovino@unipa.it](mailto:massimo.iovino@unipa.it)

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36

## 37 **1. Introduction**

38 Agriculture is one of the most important non-point sources of pollution and drainage water  
39 coming from arable land has a big impact on the existing ecosystems as documented by  
40 different authors and for different geographical areas (Blankenberg et al. 2008; Díaz et al.  
41 2012; Lenhart et al. 2016; Mendes et al. 2018). For example, agricultural drainage water is a  
42 major transport pathway between fields and surface water bodies and, as such, contributes to  
43 the direct transport of  $\text{NO}_3\text{-N}$  to these ecosystems (Bruun et al. 2016).

44 Constructed wetlands (CWs), representing a simple but efficient technology for wastewater  
45 treatment and reuse (Toscano et al. 2013; Barbagallo et al. 2014; Russo et al. 2019a; Russo et  
46 al. 2019b), are extensively being applied also for preventing non-point source pollution (Dal  
47 Ferro et al. 2018). Some of their advantages in respect to the conventional wastewater  
48 treatment technologies are low operation cost, ability to provide ecosystem services and the  
49 fact that they do not need skilled operators (Lavrnić et al. 2018). Surface flow CWs (SFCWs)  
50 have been used for a past few decades and proved themselves successful in the treatment of  
51 agricultural drainage water (Bodin et al. 2012; Lavrnić et al. 2018). However, since CWs

52 intended for this purpose are usually located at the farm fields and therefore occupy space that  
53 could be used for agricultural production, it is important to maintain their removal efficiencies  
54 at certain level (Liu et al. 2016).

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

74 Furthermore, hydraulic performance of a wetland is affected by different parameters such as  
75 the aspect ratio, the lay-out of inlet and outlet, bottom roughness, vegetation and irregular  
76 shape of wetland (Liu et al. 2016). A parameter that can change with wetland age is hydraulic

77 retention time. The two most important processes for wastewater treatment in CWs are  
78 microorganisms-degradation and plant-adsorption, and they both depend on the retention time  
79 (Su et al. 2009). Nominal hydraulic residence time ( $HRT_N$ ) does not usually give a precise  
80 measure of the time that water needs to pass through a system. Some of the reasons are that  
81 litter and stems occupy certain volume of SFCWs and the existence of stagnant pockets  
82 (Kadlec and Wallace, 2009). Those issues can be assessed by the actual hydraulic residence  
83 time ( $HRT_A$ ) measurement. If it is longer than the  $HRT_N$ , it means that the water is stagnant  
84 and does not participate in the flow (Aiello et al. 2016). On the other hand, the  $HRT_A$  shorter  
85 than the  $HRT_N$  can imply existence of the short-circuits and preferential paths (Barbagallo et  
86 al. 2011). Since hydraulic conditions within the system can affect its performance in pollutant  
87 removal (Bodin et al. 2012; Bruun et al. 2016), it is important to improve the knowledge on  
88 wetland hydraulics by estimating the exact  $HRT_A$ , and make certain changes in the  
89 management and maintenance if the system efficiency is not satisfactory.

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

97

## 98 **2. Materials and methods**

### 99 2.1. System description

100 The SFCW studied is located at the experimental agricultural farm of the land reclamation  
101 consortium Canale Emiliano Romagnolo (CER) in Italy. The farm has a total area of 12.5 ha

102 and different crops are grown throughout the year. The wetland system treats the entire  
103 agricultural drainage water coming from the farm and it consists of four meanders that create  
104 a 470 m long water course with an overall surface of about 0.4 ha (Figure 1).

105 The length to width aspect ratio of the system (considering the water flow) was approximately  
106 52:1 and therefore conditions similar to plug flow can be assumed. The total capacity of the  
107 SFCW is 1477 m<sup>3</sup> corresponding to an average depth of 0.40 m. Some of the plants that are  
108 present at the site are *Phragmites australis*, *Typha latifolia*, *Carex spp.* etc. The system is  
109 equipped with two mechanical flow meters that record influent and effluent volumes every  
110 hour and an automatic water level sensor located at the outlet. All the collected data are  
111 managed and recorded by a central control system. Rainfall is measured by a tipping-bucket  
112 rain gauge located 500 m far from the CW. More information about the system treatment  
113 capacity can be found in Lavrnić et al. (2018).

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

119

## 120 2.2. Estimation of soil characteristics and infiltration fluxes from the CW

121 The surface soil layer of the CW was sampled in July 2017 when the wetland was empty as  
122 no rainfall had occurred in the previous two months. Three locations were established close to  
123 the inlet (site A), at intermediate position (site B) and at the outlet (site C) (Figure 1). At each  
124 site, five BEST experiments were carried out to obtain a complete soil hydraulic  
125 characterization. Following a procedure commonly used for BEST experiments, undisturbed  
126 soil cores (5 cm in height by 5 cm in diameter) were collected at two depths in the uppermost

127 horizon (0-5 cm and 5-10 cm) for determination of soil bulk density,  $\rho_b$  ( $\text{g cm}^{-3}$ ) and  
128 volumetric water content,  $\theta_0$  ( $\text{cm}^3 \text{cm}^{-3}$ ), at the time of sampling (Alagna et al. 2016). The  
129 saturated soil water content,  $\theta_s$ , was assumed to coincide with soil porosity,  $\phi$ . Disturbed soil  
130 samples were also collected at each location for determination of particle size distribution  
131 (PSD) by conventional methods (Gee and Bauder, 1986). Considering that the sampling areas  
132 were of few tens of squared metres, the soil was considered homogeneous at each site and a  
133 mean value of  $\rho_b$ ,  $\theta_0$  and PSD was considered resulting from the arithmetic mean of all  
134 samples collected in that site. Beerkan infiltration tests were conducted using a cylinder  
135 having an inner diameter of 15 cm (Figure 1). The surface vegetation was removed over an  
136 area slightly larger than the cylinder diameter, while the roots remained in situ. The cylinder  
137 was positioned at the soil surface and inserted to a depth of 10 mm to prevent lateral losses of  
138 water. A fixed volume of water (175 mL corresponding to a water depth of 10 mm) was then  
139 poured into the cylinder at time zero, and the time required for infiltration was measured. As  
140 soon as the first volume had completely infiltrated, another equal volume of water was added  
141 to the cylinder and the time was recorded for this volume to infiltrate (cumulative time). The  
142 procedure was repeated 15 times. In this way, a cumulative infiltration,  $I$  (L), versus time,  $t$   
143 (T) relationship, including 15 discrete points was determined.

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

152 2006), the BEST-intercept (Yilmaz et al. 2010) and BEST-steady (Bagarello et al. 2014)  
153 procedures. Knowledge of  $S$ ,  $K_s$  and shape parameters allowed estimation of the scale  
154 parameter for water retention,  $h_g$  (mm), that is related to the characteristic microscopic pore  
155 radius (Angulo-Jaramillo et al. 2016). The workbook by Di Prima (2013) was applied to  
156 automatically analyze the infiltration data collected for this investigation.

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

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

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

$$I = Q_{in} - \frac{\Delta V}{\Delta t} \quad (2)$$

170

### 171 2.3. Evaluation of the hydraulic retention time

172  $HRT_A$  was estimated by a test that used NaCl as a tracer, since it was reported to be a  
173 conservative tracer (Aiello et al. 2016). The solution was prepared by mixing 100 kg of NaCl

174 in 450 L of water directly collected from the CW, and then it was pumped at the system inlet  
175 in order to ensure good mixing with inflow water. The pumping process itself lasted for  
176 approximately 5 minutes, and thus can be considered instantaneous when compared to the  
177  $HRT_N$ .

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

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

193 In addition, a certain part of the SFCW volume is occupied by vegetation and plant litter that  
194 was never removed from the system for 17 years of the operation. In order to subtract  
195 vegetation from the total system volume (Bodin et al. 2012), vegetation volume was visually  
196 estimated to be approximately 0.1 of the total CW volume and the system porosity was set to  
197 0.9, close to the value of 0.95 that Kadlec and Wallace (2009) reported as a usual value for

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

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

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

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

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

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

214 Wetland systems are usually described by either plug flow or continuously stirred tank reactor  
215 model. However, various studies have failed to confirm that one of these two theories fits to  
216 the actual conditions. Instead, tank in series model and its description of non-ideal flow



217 conditions is considered more appropriate. This model is based on the assumption that a  
218 system is divided into a N number of tanks of equal size (Bodin et al. 2012) that can be  
219 calculated according to the following relationship:

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

220

#### 221 2.4. Data analysis

222 The normality of the statistical distribution of soil sorptivity,  $S$ , saturated hydraulic  
223 conductivity,  $K_s$ , and water retention scale parameter,  $h_g$ , was tested by the probability plot  
224 correlation coefficient test at  $P = 0.05$  (Helsel and Hirsch, 1992). Only the normal and the log-  
225 normal distributions were considered because  $S$ ,  $K_s$  and  $h_g$  were often found to be adequately  
226 described by these distributions (Warrick, 1998). Soil bulk density and volumetric water  
227 content were assumed to be normally distributed. Comparisons between two mean values  
228 were conducted by a t-test ( $P = 0.05$ ), either homoscedastic or not according to a F-test ( $P =$   
229  $0.05$ ). Comparison among three means were conducted according to a Tukey Honestly  
230 Significant Difference test ( $P = 0.05$ ).

231

### 232 **3. Results and discussion**

#### 233 3.1. Soil physical characteristics

234 According to USDA classification (Gee and Bauder, 1986), texture of the CW soil was not  
235 uniform and a relatively higher percentage of clay particles was detected at the inlet (site A)  
236 (Table 1). The middle and the outlet sites showed similar textural composition. No  
237 appreciable differences could be detected between samples collected in the upper surface  
238 layer (UP layer 0-5 cm depth) and in the subsurface layer (DW layer, 5-10 cm depth).  
239 Similarly, no difference was observed between mean  $\rho_b$  and  $\theta_0$  values in the UP and DW

240 layers of the different sampling sites (Table 1). It can be concluded that PSD, bulk density and  
241 water content at the sampling time were vertically uniform in the soil profile explored by the  
242 Beerkan infiltration tests (i.e., 0-10 cm) thus supporting the assumption to use, at each site, a  
243 unique value of  $\rho_b$ ,  $\theta_0$  and PSD for application of BEST procedure. Accordingly, for the  
244 subsequent statistical analyses the  $\rho_b$  and  $\theta_0$  data collected at a given site were pooled  
245 together.

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

249

### 250 3.2. Soil hydraulic properties

251 Duration of the Beerkan infiltration test was relatively longer and more variable in site A  
252 (mean test duration,  $\mu = 8769$  s, standard duration,  $\sigma = 4480$  s) than in sites B ( $\mu = 2433$  s,  $\sigma$   
253  $= 3351$  s) and C ( $\mu = 373$  s,  $\sigma = 255$  s). Cumulative infiltration vs. time curves exhibit a  
254 common shape, with a concave part corresponding to the transient phase of infiltration and a  
255 linear part showing that a steady state stage was achieved (Figure 2).

256 Steady-state stage was better defined for site A where from 7 to 13 points could be  
257 considered. For the other sites, most of the steady states were detected by only 3 points  
258 (Figure 2). Inaccurate definition of the steady-state phase probably resulted in violation of the  
259 constraints assumed for the BEST-slope and BEST-intercept algorithms that, consequently,  
260 resulted in an unrealistic estimate of either  $S$  or  $K_s$  (i.e., negative values of one of the two  
261 parameters were obtained). In particular, BEST-slope failed in 10 out of 15 experiments,  
262 whereas the rate of failure was lower for BEST-intercept (three out of 15 experiments).  
263 However, even when successful, these two algorithms yielded relative errors between the  
264 measured and modelled transient infiltration data greater than 5.5%, which is considered the

265 maximum acceptable error (Lassabatère et al. 2006). BEST-steady always allowed to  
266 successfully estimate  $S$  and  $K_s$ . Therefore, for the aim of comparison of the hydraulic  
267 properties among the different sampling sites, only the results obtained by BEST-steady were  
268 considered.

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

273 The lowest mean value of  $K_s$  was  $30 \text{ mm h}^{-1}$  and it was measured at the inlet (site A). Mean  $K_s$   
274 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  
275 (Table 2). Statistically significant differences were found between site A and the other sites  
276 that can be attributed to pore sealing processes occurring at the inlet. Despite not significant, a  
277 clear increasing trend was detected from the inlet to the outlet of the wetland as consequence  
278 of different occurrence of sealing due to selective settling of suspended soil particles. The  
279 lower variability of  $K_s$ , the higher mean bulk density value and increased clay content (Table  
280 1) observed at the inlet of the wetland are additional concurrent signs that settling of fine  
281 particle resulted in a more homogeneous and compacted soil surface layer that affected  
282 hydraulic conductivity and infiltration. This finding is similar to the one reported by Caselles-  
283 Osorio and García (2006), who found that clogging in an experimental horizontal flow CW  
284 reduced inlet hydraulic conductivity to 64% of outlet hydraulic conductivity.

285 Soil sorptivity also increased along the wetland with mean  $S$  value for site A that was  
286 statistically lower than at the other sites (Table 2). Sorptivity represents the soil capability to  
287 absorb water without gravity (Angulo-Jaramillo et al. 2016) and it increases as the soil  
288 moisture decreases. As initial soil water content decreased from the inlet to the outlet of the  
289 wetland (Table 1), the observed trend in soil sorptivity is clearly explained by the different

290 wetness of the surface soil at the time of sampling. However, site B was characterized by a 5-  
291 fold higher sorptivity than site A despite initial soil water content between the two sites was  
292 not statistically different. For a given initial saturation degree, fine textured soils show lower  
293 values of soil sorptivity (Touma et al. 2007). The observed result is therefore in line with  
294 literature findings and further confirms the occurrence of soil clogging at the inlet of the  
295 wetland.

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

312 Figure 3 shows the water level vs. time relationship during the period from 18 October to 13  
313 December with indication of the inter-rainfall periods considered for application of eq. (2). It  
314 can be seen that the rate of the water level decline,  $dz/dt$ , is almost constant within each inter-

315 rainfall period with average values ranging from 3 to 5 mm/d (Table 3). The knowledge of the  
316 wetland geometry allowed to calculate the infiltration surface,  $A$  ( $m^2$ ), as function of the water  
317 level and, then, the infiltration rate,  $i$  (mm/h) (Table 3). For the considered period, the  
318 estimated infiltration rate ranged from 0.28 to 0.33 mm/h. Application of the water balance to  
319 a different period of the year (28 March to 30 April) confirmed these results (Table 3). In this  
320 case, the relatively higher infiltration rate ( $i = 0.48$  mm/h) as compared to fall measurements  
321 could be attributed to the higher average water level,  $z$ , as well as to the neglected  
322 contribution of evapotranspiration due to the beginning of the spring vegetative activity.

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

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

340

341 3.3. Hydraulic residence time estimation

342 The calculated tracer mass recovery was 71% and outside of the acceptable range of 80-120%  
343 (Kadlec and Wallace, 2009), but several other studies done at SFCWs reported comparable  
344 recovery values (Dierberg and DeBusk, 2005; Bodin et al. 2012; Guo et al. 2017). Since the  
345 density of the tracer solution was higher than the density of water, low tracer mass recovery  
346 could be due to the settling and water velocity that was insufficient to prevent it (Bodin et al.  
347 2012). As previously said, tracer injection could be considered instantaneous (section 2), and  
348 a longer injection period could have increased tracer mass recovery by preventing a possible  
349 settling to the bottom (Dierberg and DeBusk, 2005).

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

361 Although mass recovery of the tracer can be considered insufficient, some conclusions can  
362 still be drawn. The total duration of the experiment was 10.8 days, and the  $HRT_A$  was  
363 calculated to be 6.7 days. Tournebize et al. (2017) suggested that 50%  $NO_3-N$  removal can be  
364 reached with HRT of minimum 2 days, while for the same percentage of pesticide removal at

365 least 10 days are needed. In addition, the SFCW area to catchment ratio is in the range of 0.1-  
366 5%, which is recommended for efficient nutrient removal (Kadlec and Wallace, 2009). Since  
367 the minimum HRT of the studied SFCW is 6.7 days, it can be concluded that even during  
368 extreme rain events it should be enough to achieve reduction of more than 50% of the inflow  
369  $\text{NO}_3\text{-N}$  load. However, since average HRT of the system should be much longer, higher  
370 removals are expected and that hypothesis will be tested in the research that is currently  
371 ongoing.

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

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

390

#### 391 **4. Conclusions**

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

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

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

414



415

416 **Acknowledgements**

417 This work was supported by the Ministero dell'Istruzione, dell'Università e della Ricerca of  
418 Italy [PRIN 2015 - GREEN4WATER CUP B72F16000550005]

419

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533

**Table 1**[Click here to download Table: Table 1.docx](#)

Table 1. Soil texture and classification (USDA), bulk density,  $\rho_b$ , and volumetric water content at the time of sampling,  $\theta_0$ , for the different sites and depths

| Site       | sampling depth | sand (%) | silt (%) | clay (%) | USDA  | $\rho_b$<br>(g cm <sup>-3</sup> ) | $\theta_0$<br>(cm <sup>3</sup> cm <sup>-3</sup> ) |
|------------|----------------|----------|----------|----------|-------|-----------------------------------|---|
|            | UP 0-5 cm      | 15.9     | 42.9     | 41.3     | clay  | 1.154a                            | 0.407a  |
| A - inlet  | 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  |
|            | UP 0-5 cm      | 13.4     | 53.6     | 33.0     | silty | 1.167a                            | 0.388a  |
| B - middle | 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  |
|            | UP 0-5 cm      | 14.8     | 57.7     | 27.5     | silty | 1.142a                            | 0.315a  |
| C - outlet | 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**[Click here to download Table: Table 2.docx](#)

Table 2. Minimum (Min), maximum (Max), geometric mean (GM), and coefficient of variation (CV, in %) of the saturated soil hydraulic conductivity,  $K_s$  ( $\text{mm h}^{-1}$ ), soil sorptivity,  $S$  ( $\text{mm h}^{-0.5}$ ), 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 |
|---------------------------------|-----------|--------|--------|--------|
| $S$<br>( $\text{mm h}^{-0.5}$ ) | Min       | 3.1    | 18.2   | 79.9   |
|                                 | Max       | 26.0   | 120.6  | 62.8   |
|                                 | GM        | 8.2a   | 52.9b  | 120.5b |
|                                 | CV        | 122.3  | 93.5   | 35.6   |
| $K_s$<br>( $\text{mm h}^{-1}$ ) | Min       | 13.7   | 3.3    | 112.7  |
|                                 | Max       | 61.4   | 257.7  | 548.7  |
|                                 | GM        | 30.5a  | 41.1b  | 293.0b |
|                                 | CV        | 60.3   | 537.4  | 92.6   |
| $ h_g $<br>(mm)                 | Min       | 1.0    | 148.3  | 84.8   |
|                                 | 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**[Click here to download Table: Table 3.docx](#)

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

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



# Figure 1

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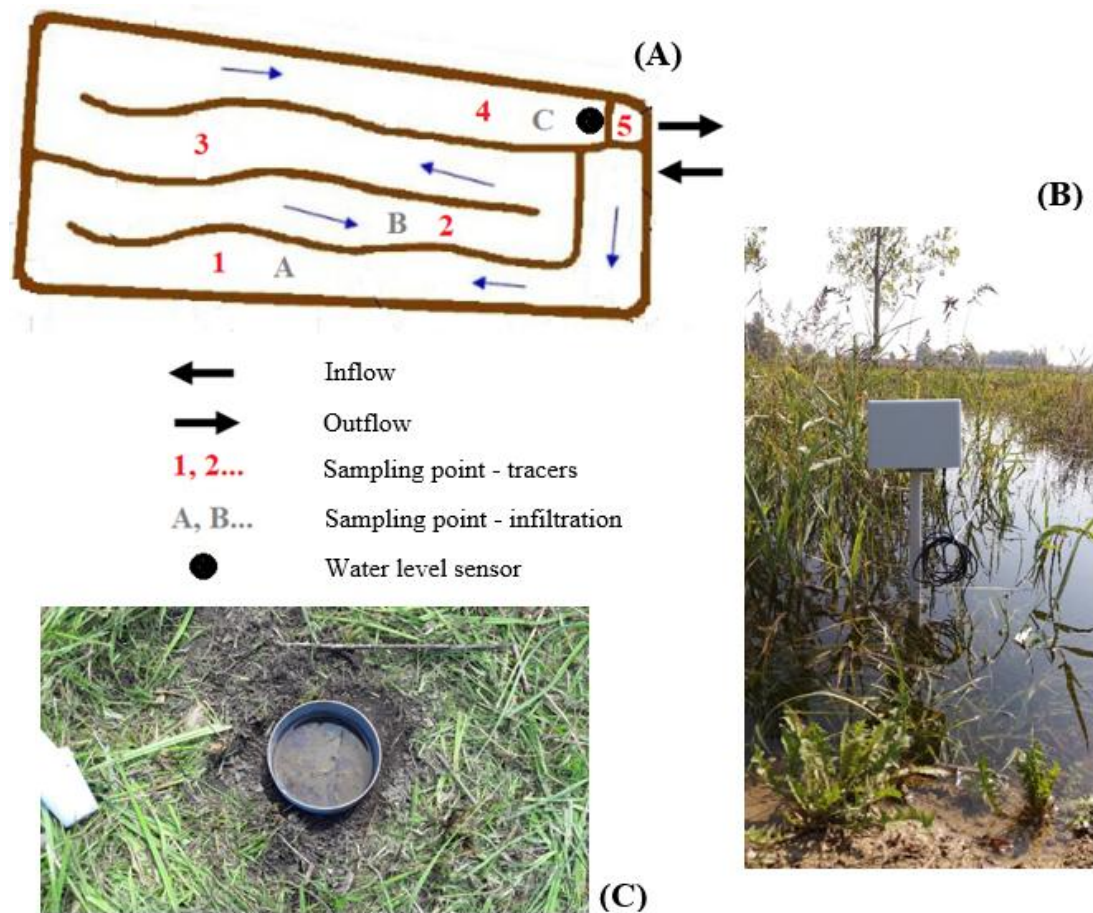


Figure 1. Schematic plan of the SFCW with different measuring points (A), data logger and electrode (B) and Beerkan ring infiltrometer tests (C) at the study site.

**Figure 2**  
[Click here to download Figure: Figure 2.docx](#)

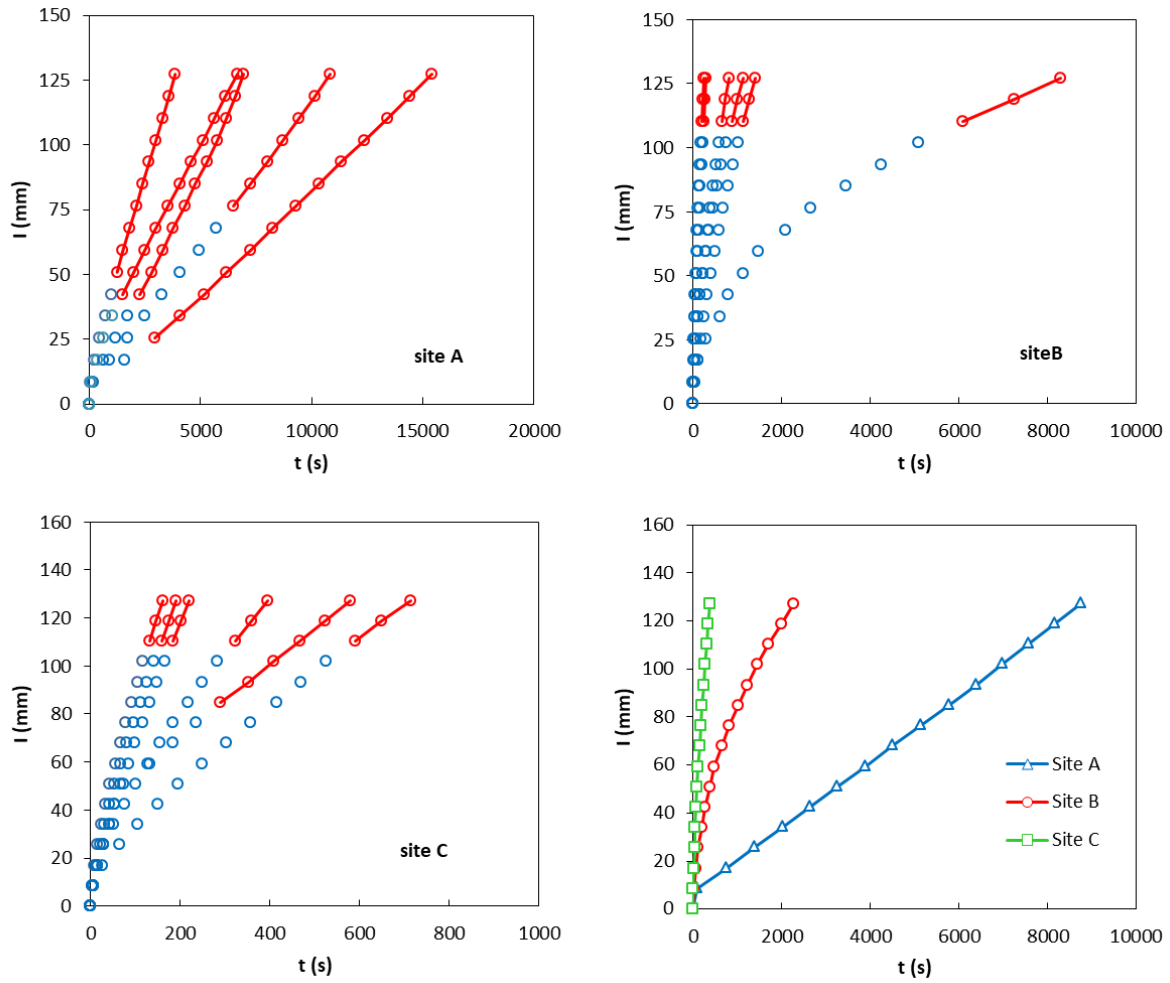


Figure 2. Cumulative infiltration ( $I$ ) versus time ( $t$ ) data for the Beerkan experiments and average infiltration curves for the three selected sites.

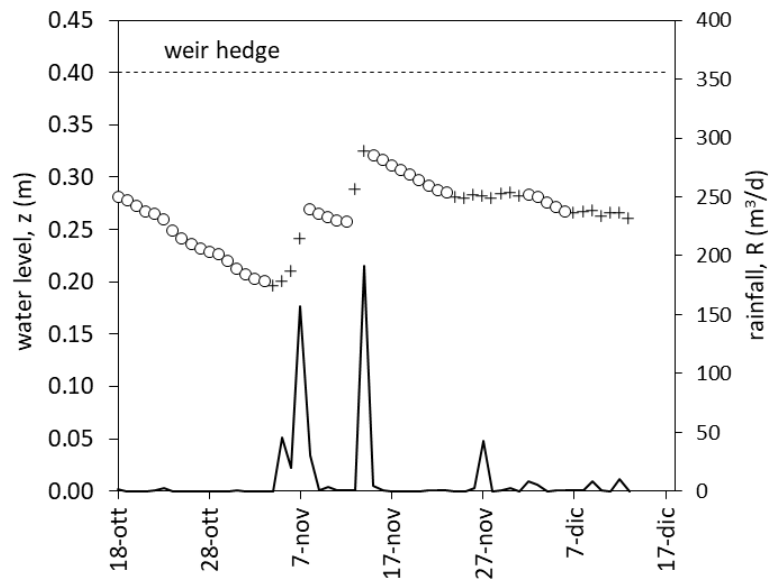


Figure 3. Water levels recorded in the wetland in the spell from 18 October to 13 December 2017. Rainfalls in this period are also showed.

**Figure 4**  
[Click here to download Figure: Figure 4.docx](#)

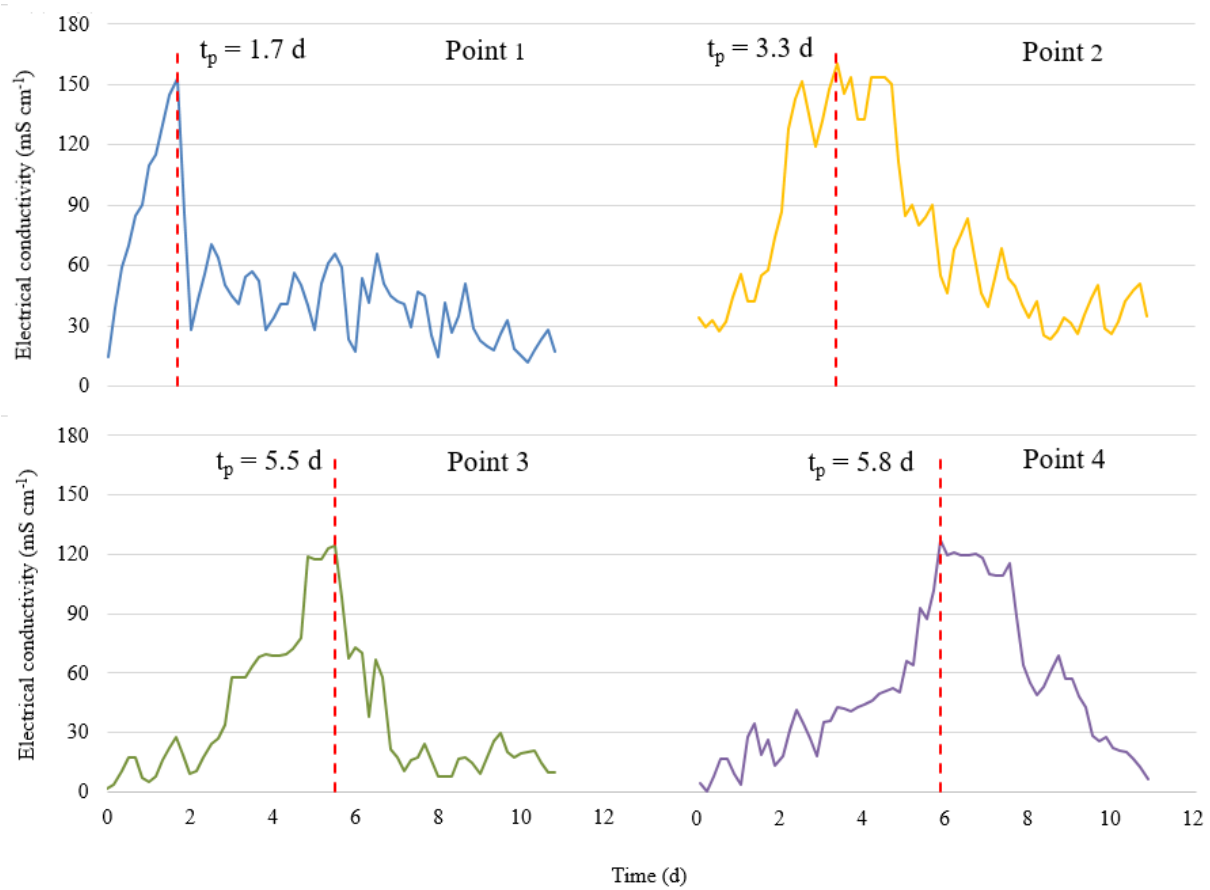


Figure 4. Movement of tracer through the system.

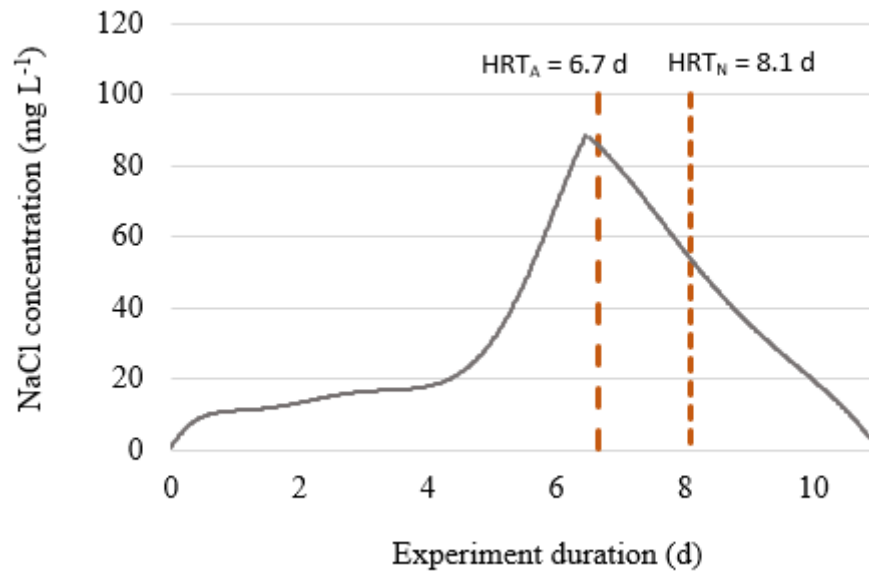


Figure 5. Concentration of the tracer at the outflow of the SFCW.