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Assessment of clogging in constructed wetlands by saturated hydraulic conductivity measurements

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11   **Abstract:** This study aims at defining a methodology to evaluate K_s reductions of gravel material constituting CW bed
12 matrices. Several schemes and equations for the Lefranc's test were compared by using different gravel sizes and at
13 multiple spatial scales. The falling-head test method was implemented by using two steel permeameters one impervious
14 (IMP) and one pervious (P) on one side. At laboratory scale, mean K values for a small size gravel (8-15 x 10^{-2} m)
15 measured by the IMP and the P permeameters were equal to 19466 m/d and 30662 m/d, respectively. Mean K_s values for a
16 big size gravel (10-25 x 10^{-2} m) measured by the IMP and the P permeameters were equal to 12135 m/d and 20866 m/d,
17 respectively. Comparison of K_s values obtained by the two permeameters at lab scale as well as a sensitivity analysis and a
18 calibration, lead to the modification of the standpipe equation, to evaluate also the temporal variation of the horizontal K_s.
19 In particular, both permeameters allow the evaluation of the K_s decreasing after 4 years-operation and 1-1.5 years-operation
20 of the plants at full scale (filled with the small size gravel) and at pilot scale (filled with the big size gravel) respectively.

21 **Keywords:** Horizontal flow; K_s measurements; permeameter cell

22 ## Introduction

23 The process of clogging is inevitable in horizontal subsurface flow (HSSF) constructed wetlands (CWs)
24 due to the slow flowing of treated wastewater through the porous medium. The development of
25 clogging can be detected by the appearance of water on the surface of the granular medium. The
26 phenomenon is very variable in space, being generally most severe within the first few meters
27 (Vymazal 2018) of the CW but sometimes, also occurring close to the outlet area. Due to its
28 complexity, the development and impact of clogging on system design and operation must be taken
29 into account (Knowles *et al.* 2011). Main causes of clogging can be organized in three categories. In
30 particular, some factors are related to influent characteristics (pre-treatment, BOD_5 and TSS
31 concentrations and flow); others are related to the system design (shape, size, operation mode,
32 distribution and collection systems, pipes, media, plants); others are related with bed activities
33 (rhizosphere, biofilm, chemical processes, accumulated matter composition). The factors related to the
34 first two categories can influence the third making the phenomena not currently known in detail
35 (Correia 2016). In some cases, clogged HSSF-CWs can operate with overland flow and still meet
36 treatment objectives (Griffin *et al.* 2008). If the surface loading rates are characterized by BOD_5 <10 g
37 m^{-2} d^{-1}, COD <20 g m^{-2} d^{-1}, <10 g TSS m^{-2} d^{-1}, partial clogging may occur only after about 15 years
38 of operation (Vymazal 2019). Partial ponding has no significant effect on the quality of discharged
39 water, as well as the replacement of partially clogged inflow zone filtration material does not give any
40 significant improvement (Vymazal 2018). However, reduced treatment performance or the risk of
41 human contact with untreated or partially treated sewage sometimes attracts the attention of regulatory
42 agencies and stakeholders. Preventative strategies, such as best management practices, inlet and
43 loading adjustments, and changes to hydraulic operating conditions (including intermittent operation,
44 backwashing and/or reversing the direction of flow) can be carried out to delay or minimize the

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1   negative effects associated with clogging. Advanced clogging may eventually require restorative
2   strategies such as: excavation of dirty gravel and its replacement with new or washed one, and use of
3   gravel; direct application of chemicals to the gravel bed; and most recently, the application of
4   earthworms to the system (Nivala *et al.* 2012).

5   Due to the fact that clogging is a widespread operational problem in HSSF-CWs, as demonstrated by
6   frequent reporting over the past two decades, it has become increasingly important to identify practical
7   methods for its measurement.

8   Clogging assessment techniques include hydrodynamic visualisations by means of tracer tests
9   (Bowmer 1987; Knowles *et al.* 2010), the analysis of accumulated solids in filter media (Caselles-
10 Osorio *et al.* 2007; Pedescoll *et al.* 2009), and determination of the hydraulic gradients between points
11 in the filter media (from which the mean hydraulic conductivity can be estimated) (Sandford *et al*.
12 1995; Rodgers and Mulqueen 2006; Suliman *et al.* 2006). The clogging process is very much affected
13 by the size of filtration material and consequently by its saturated hydraulic conductivity (K_s).

14 Common laboratory methods in CW is not advisable, to measure K_s in CW due to the difficulties to
15 take undisturbed media samples. For this reason the measurement of K_s in CWs have been mostly
16 carried out by means of *in situ* methods (Knowles *et al.* 2011).

17 K_s measurements can be conducted by falling and constant head tests specifically developed to detect
18 the potentially high hydraulic conductivity of wetland gravels. Ideally, these methods are able to
19 measure a wide range of hydraulic conductivities of porous media, as determined by media properties
20 and the stage of clogging (i.e., K_s values lower than 500 m/day that might be typical of the transition
21 between clean and completely clogged media).The repeatability and accuracy of the methods used
22 have been previously described in Knowles and Davies (2009) and Pedescoll *et al.* (2011). However,
23 these methods need further validation tests, as development and application within this scope is
24 relatively recent (Knowles *et al.* 2011; Aiello *et al*. 2016).

25 In particular, the falling head permeameter, based on Lefranc's test, has been used to measure K_s of
26 CWs (Nivala *et al*. 2012) applying different schemes and equations suggested in literature (NAVFAC
27 1986).

28   This study aims at defining a methodology sufficiently accurate and relatively easy to implement, to
29 estimate K_s reductions of gravel material constituting CW bed matrices due to clogging phenomena. In
30 order to meet this aim, different schemes and equations for the Lefranc's test were compared by using
31 different gravel sizes and at multiple spatial scales (lab, pilot and full plant) employing also a new type
32 of *in situ* permeameter cell specifically developed for falling head tests.

Material and Methods

Experimental schemes implemented at lab scale

35 Different schemes can be applied to determine saturated hydraulic conductivity from falling-head tests
36 conducted in a CW by *in situ* permeameter cell condisting of an open ended tube that may eventually
37 encase the sample to be tested (Morris and Knowles 2011).

38 Depending on the length of the cavity at the bottom of the piezometric tube, the measured K_s can
39 represent the horizontal, three-dimensional or vertical saturated hydraulic conductivity within the
40 measurement zone (Amoozegar 2002). If the cavity cannot be maintained during measurements due to
41 soil collapse, a well screen can be attached at the bottom of the piezometric tube. According to the
42 geometry of the cavity (that is the ratio between radius, R, and length, L) different schemes can be
43 considered (NAVFAC 1986). Three of them were tested in the present paper and were reported in
44 Figure 1 (schemes 1 to 3), together with the corresponding equations to calculate K_s and their

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1   applicability conditions. In particular, scheme 1 and scheme 3 implied the use of an impervious
2   permeameter cell (IMP) with and without gravel inside, respectively; scheme 2 implied the use of a
3   pervious permeameter cell (P) without gravel inside. The scheme 1, also called standpipe test, did not
4   require a borehole to be drilled as the pipe was merely inserted directly into the substrate, which can
5   save much time compared with schemes 2 and 3. Also, excavation of a borehole could be a disturbance
6   to porous medium. As a disadvantage, this method did not allow to evaluate horizontal K_s. This could
7   be not a problem for isotropic gravel (clean or not clogged gravels) but, given that the clogging process
8   is likely not to be isotropic, vertical K_s values obtained by this method could be different from
9   horizontal ones. On the other hand, to our knowledge a scheme for predicting also horizontal K_s using
10   a P permeameter and that does not require a borehole to be drilled was not proposed. Thus, scheme 4,
11   which implies the use of P permeameter with gravel inside was also implemented. An arrangement
12   similar to scheme 4 was already used in literature by Pedescoll et al. (2009), but these authors
13   calculated K_s by equation 2 that properly corresponds to scheme 2 (Figure 1). In the present paper,
14   besides checking this combination (scheme 4-equation 2), scheme 4 was applied using, as a first stage,
15   original equation 1 and then a calibrated version of equation 1, as described below.

16   In order to test the four proposed schemes, two different steel tubes were used (internal diameter
17   0.10 m and length 1.5 m), being one impervious (IMP permeameter) and one pervious on one side (P
18   permeameter) for a total area of 3.11×10^{-4} m^2, distributed along 0.25 m from the bottom of the
19   permeameter. The P permeameter was implemented in order to evaluate also the temporal variation of
20   horizontal K_s by repeated measurements in the time. The permeameters were inserted, using a mallet,
21   into the medium to a depth of about 0.32 m, after the creation of a small hole in the granular medium
22   to reach the water table. To instantaneously add water to the permeameter (in a single-pulse mode) a
23   plastic water reservoir (6.6 L volume) was assembled to the measurement units by means a bulb valve
24   (Figure 2).

25   Variation of the water level, H, within the permeameter was measured by a pressure probe (STS -
26   Sensor Technik Sirnach, AG), connected to a laptop by means of a CR200-R (Campbell Scientific)
27   data logger. The pressure probe was positioned inside the steel permeameter through a driver added to
28   the device. The pressure value at atmospheric pressure was checked before each measurement started.
29   Four water level data per second were recorded for a duration of 30 seconds. The decrease of water
30   height inside the permeameter was monitored until the water reached the water table.

31   For each scheme – equation combination tested in the paper, in order to obtain the best fit between
32   simulated and measured water levels, the sum of squared differences between the theoretical curve and
33   that obtained in the field was minimized, to estimate the value of K_s by means of an iterative, non
34   linear, procedure that make use of Excel solver (Frontline Systems, Incline Village, NV):

35
$$\sum_{t=0}^{n} = [H_{obs}(t) - H_{sim}(t)]^2 \tag{4}$$

36   where H_{obs} is the height of the water table level measured inside the permeameter at time t during the
37   test (m); H_{sim} is the corresponding modelled data calculated by the different equations 1,2,3 and 4
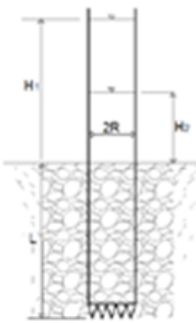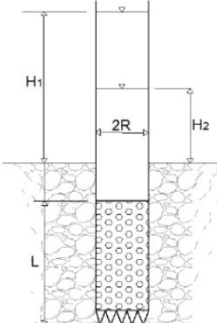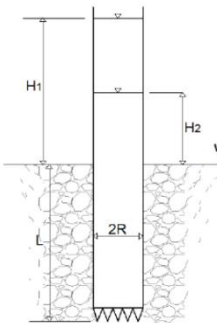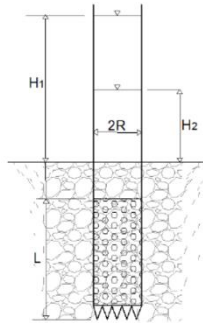38   depending on the used scheme.

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Scheme 1	Scheme 2	Scheme 3	Scheme 4
Impervious permeameter cell with material inside (Standpipe)	Pervious permeameter cell without material inside (Cased hole with uncased extension)	Impervious permeameter cell without materials inside (Cased hole)	Pervious permeameter cell with material inside
$K_s = \dfrac{2\pi R + 11L}{11(t_2 - t_1)} \ln\left(\dfrac{H_1}{H_2}\right)$ (1)	$K_s = \dfrac{R^2}{2L(t_2 - t_1)}$ (2)	$K_s = \dfrac{2\pi R}{11(t_2 - t_1)} \ln\left(\dfrac{H_1}{H_2}\right)$ (3)	K_s was calculated by Uncalibrated eq. 1 Uncalibrated eq. 2 (Pedescoll et al., 2009) Calibrated eq. 1
K_s represents vertical hydraulic conductivity of the soil	If $4 \leq L/R \leq 8$ K_s primarily represents the horizontal hydraulic conductivity of the soil; if $L \approx R$, the measured K_s becomes three-dimensional.	Used for K_s determination at shallow depths below the water table.	K_s represents both the horizontal and vertical hydraulic conductivity of the soil

1   Figure 1. Schemes and equations tested for K_s measurements by falling-head method adapted from NAVFAC 1986). R is
2   the radius of the tube (m), L is the submerged length of the tube (m), t is time (s) and H1 and H2 are the water levels
3   (meters, m) in the permeameter cell corresponding to time t_1 and t_2 (s).

4   Ten falling head infiltration tests were performed at lab scale in a central point of a tank of 1m x 1 m
5   (Figure 3). Two different sizes of clean gravel medium, 8-15 x 10^{-2} m ('small') and 10-25 x 10^{-2} m
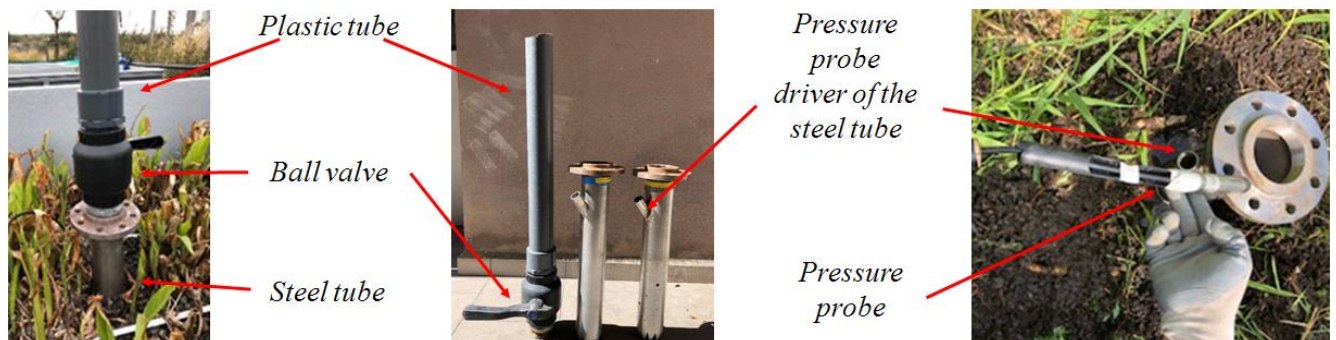6   ('large') were tested with the same procedure. The effective porosity, n,of both media was 0.4.

7

8   Figure 2. Permeameter unit for falling head tests

9   *Standpipe scheme calibration at lab scale by using both IMP and P permeameters*

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1   To make the original equation 1 suitable for scheme 4, a calibration procedure was carried out. The
2   values of K_s obtained by the combination of scheme 4 – original equation 1 (P- K_s) and those obtained
3   by the combination of scheme 1 – original equation 1 (IMP- K_s) were used to modify the original
4   equation 1. In particular, for the P- K_s values the R and L parameters of equation 1 were reduced in
5   order to obtain results closer to IMP- K_s values. To be more specific, R (equal to 5.0 cm) was fixed to
6   4.9 cm to account for a reduction of the cross permeameter area corresponding to the total area of the
7   small lateral holes (3.11×10^{-4} m^2). Then, it was assumed that P permeameter allowed water to flow
8   out of the P permeameter at a smaller depth (from the level of the ground) than the IMP permeameter.
9   Thus L was reduced to give P- K_s values closer to those measured with the IMP permeameter. The
10   calibration procedure of the original equation 1 was applied to 'small' and 'large' size of clean gravel
11   medium.

12   *Stand pipe scheme application at pilot and full scale by using both IMP and P permeameters*

13   The combinations mentioned above (schemes 1 and 4 with original equation 1) were also tested at
14   full and pilot scale in two experimental plants.

15   The hybrid CW system working as secondary wastewater treatment system of the Ikea®, located in
16   the industrial district of Catania, Eastern Sicily, Italy (37°26'54.2"N 15°02'05.2"E, 11 m a.s.l.) was
17   considered as plant test at full scale. The plant is located in a semi-arid climate area, characterized by
18   an average annual precipitation of about 500 mm, and values of air temperature in summer reaching 40
19   °C. The CW system was added to the pre-existing treatment system (including a sequential batch
20   reactor system and a screening unit) in 2014, in order to respond to the high hydraulic and nitrogen
21   load variability during the year. The sequential batch reactor system (SBR) was designed to treat a
22   maximum flow rate of 30 m^3 day^{-1} (2 batch phases every 12 hours) and Total Nitrogen (TN)
23   concentration of 135 mg L^{-1}. Anyway, during holidays or pre-holidays, wastewater flow rate could be
24   2-4 times greater than that during a normal working day, and NH$_4$ can be higher than 200 mg L^{-1}. The
25   hybrid CW system includes three in series beds: a horizontal subsurface treatment wetland allowing a
26   reduction of organic matter and suspended solids concentrations followed by two vertical subsurface
27   flow treatment wetlands. The K_s measurements were carried out only in the horizontal subsurface
28   treatment wetland filled with "small size" gravel. This bed covered a surface area of about 400 m^2 (12
29   × 34 m) with a depth of 0.60 m, and it was planted (with a density of 3 plants m^{-2}) in July 2014, with
30   two different aquatic species *Phragmites australis* (for ≈ 80% of the HF surface area), and *Iris*
31   *pseudacorus* close to the HF outlet. The bed was designed to be fed discontinuously, receiving 30 m^3
32   daily effluent from SBR (two discharges of 15 m^3 each one) and 20 m^3 effluent from the screening
33   unit, that by-pass the SBR when the wastewater production exceeds the designed flow rate. The
34   hydraulic loading rate of the bed varied between 75 and 125 L m^{-2} d^{-1}. For more details about the full
35   scale hybrid CW system, see Marzo *et al*. (2018).

36   The hybrid pilot scale CW, also located within the parking area of the retail store Ikea®, consists of
37   a fiberglass retention pond (flow rate of 2 m^3/d), followed by two identical parallel lines (flow rate 1
38   m^3/d), each one including in series a HSSF bed and a free water surface (FWS) unit. The system,
39   operating since the end of 2016 with a hydraulic retention time of 96 hours per line, alternatively
40   treated storm water of a parking area and the sequential batch reactor WW produced from the retail
41   store (toilets, kitchens and bar). The K_s measurements were carried out in both HSSF beds (H1 and
42   H2) filled with the "large size" gravel. Both HSSF beds, characterized by a width of 1.5 m, a length of
43   4.5 m and having a depth of 1.1 m, were planted with *Canna Indica*. The falling head tests were
44   carried out at a distance of 1 m (A), 2 m (B) and 3 m (C) from the inlet (Figure 3). For more details
45   about the pilot scale hybrid CW system see Ventura *et al*. (2018).

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1   The K_s measuring points at lab, pilot and full scale plants are represented in Figure 3. Four falling
2   head infiltration tests were performed for each of the 9 measuring points located in the full scale plant.
3   Mean K_s were then calculated by averaging 4 x 3 K_s data obtained at each transect at the same distance
4   from the inlet (i.e. 1-2-3, 4-5-6, 7-8-9) (Figure 3). Three falling head infiltration tests were performed
5   for each of the 3 measuring points located in the pilot scale plant; in this case, given that the two beds
6   work in parallel, the tests were repeated in both beds. The falling head tests at full scale were carried
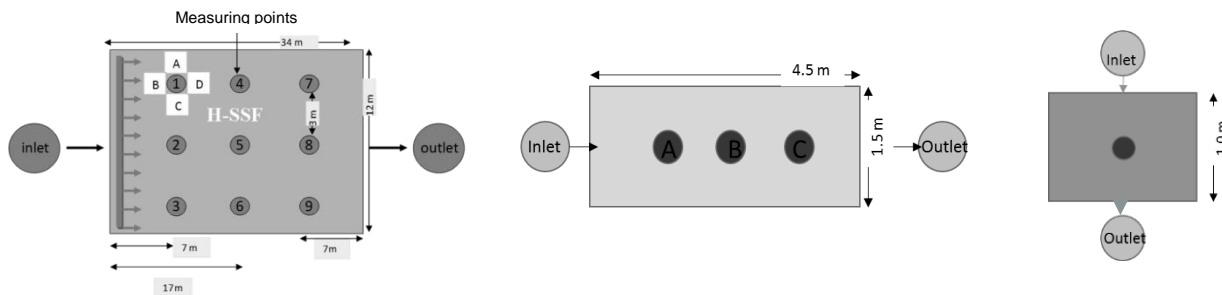7   out in April 2018 whereas at pilot scale in February and June 2018.

8

Figure 3 Measuring points inside the full scale, the pilot and the lab tank used to measure K_s. A, B, C and D inside the full scale plant indicate repeated infiltration tests conducted around each fix installed piezometer.

Results

9   *K_s values obtained at lab, pilot and full scale by using NAVFAC (1986) schemes and equations*

10   Table 1 reports mean K_s values (N =10) for both sizes of clean gravel obtained by using P and IMP
11   permeameters at lab scale, as well as, the ratio between P- K_s and IMP- K_s s mean values.
12   Unexpectedly, the K_s was lower for the 'big' gravel than the 'small 'one, probably due to a lower
13   uniformity and to a prevalent angular shape of bed matrix. As expected, P permeameter gave higher
14   values of K_s than IMP permeameter for both size of gravels; the ratio between P- K_s and IMP- K_s
15   values was 1.6 and 1.7 respectively for 'small' and 'big' size gravels. The highest standard deviation
16   (3903 m/d) was observed in correspondence to the highest mean K_s values (P permeameter filled with
17   'small' size material).

18   Table 2 reports mean K_s values (N= 4 repetitions x 9 piezometers = 36) measured around the 9
19   measuring points at the full scale plant by using P and IMP permeameters and the corresponding
20   standard deviations. All K_s values obtained with the IMP permeameter were lower than the values
21   observed for the clean gravel at lab scale (table 1), with reductions up to about 90% in the area close to
22   the inlet and up to about 55-65% in the middle and in the outlet areas. The behaviour was the same
23   when the P permeameter was used. The reductions were higher than the variability of measurements,
24   being maximum standard deviation value equal to 2022 m/d for the IMP permeameter and 2937 m/d
25   for the P permeameter. Mean K_s values (N= 4 repetitions x 3 piezometers = 12) obtained by averaging
26   the measurements at each transect from the inlet are reported in Figure 4. Mean K_s values close to the
27   inlet were 5.5 and 4.1 times lower than those measured for the clean gravel by IMP and P
28   permeameters, respectively. In the middle and in the outlet areas of the full scale CW both
29   permeameters gave mean K_s values 2.2 times lower than those measured for the clean gravel.

30   Table 3 reports K_s mean values (N8 = 3 repetitions x 3 piezometers x 2 beds =18) measured in both
31   pilot beds (H1 and H2), filled with "big size" material, at different distance from the inlet in February
32   and June 2018 by using IMP and P permeameters. At both sampling dates, K_s values were lower than
33   the value measured for the clean gravel (table 1) just in the area close to the inlet in both beds and in

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1 the H2 bed also in the area close to the outlet. Anyway, K_s values measured in February and in June
2 were very similar for all sampling points and for both beds, therefore only the K_s reductions with
3 respect to clean gravel will be discussed. The K_s reductions measured with the IMP permeameter were
4 higher than the maximum standard deviation of the repetitions in the same place and time equal to
5 about 1500 m/d. Mean K_s values measured in the middle areas and close to the outlet, were sometimes
6 even higher than the values observed for the clean gravel (i.e. point H1-A and H2-C when IMP
7 permeameter was used and H1-C for P permeameter). This behaviour could be due to the high
8 variability of K_s values, being those values in the range of the measured variability of the parameter.
9 The behaviour of K_s values observed with the P permeameter was similar to that obtained for IMP
10 permeameter. Anyway, K_s reductions after the operation period measured by P permeameter were
11 lower than those observed by using the IMP permeameter and standard deviation of the repetitions in
12 the same place and time reached about 2646 m/d. Again, the highest variation of the measurements
13 was associated to a very high mean K_s value (Table 3). Figure 5 reports the behaviour of K_s values
14 averaged between both pilot beds (N= 3 repetitions x 1 piezometer x 2 beds = 6) after 1 and 1,5 years-
15 operation. Again, it was clear that there was not a significant K_s reduction from February to June 2018.
16 Mean K_s values close to the inlet were 83 % and 97% of the K_s values measured for the clean gravel by
17 IMP and P permeameters, respectively.

18 The saturated hydraulic conductivity values obtained by using the scheme 2 and the respective
19 equation were lower than those obtained by using scheme 1 and equation 1 of about one order-of-
20 magnitude. However, the K_s values obtained by using the scheme 3 and the respective equation were
21 not reliable due to the fast lowering of the water level inside the permeameter. Anyway, schemes 2 and
22 3 were too time consuming and difficult to apply especially at real scale plants.

23

24 *K_s values obtained by scheme 4 and calibrated equation 1*

25 As expected, K_s values obtained at each spatial scale, by uncalibrated equation 1 and scheme 4 were
26 overestimated. To assess the degree of overestimation, the ratio between K_s values obtained for clean
27 gravel and after the operation in both full (N=12) and pilot scale (N=6) plants was calculated for P and
28 IMP permeameters.

29 The ratio for clean gravels was very similar for 'small' and 'big' size materials being 1.6 and 1.7,
30 respectively. After the operation period, the ratio P/IMP of the mean K_s values was different along
31 both plants (considering inlet, middle and outlet areas). In particular, the ratio varied in the range 1.3-
32 1.5 for the 'small' size material and 1.7-2.0 for the 'big' size material (Figures 4 and 5). The variation
33 could be due to a non uniform spatial and temporal evolution of the clogging process. In particular, in
34 the middle area of the pilot plant, where there was almost no clogging, and K_s values measured after
35 the 1.5 years-operation period were the same of those obtained for the clean gravel, the ratio value of
36 1.7 was confirmed. This result can help in the reliability of the proposed methodology.

37 Results of the sensitivity analysis carried out by using clean gravels at lab scale, showed that K_s
38 values were not very sensitive to the reduction of R up to 10%. On the other hand, the K_s values were
39 very sensible to the variation of L that was changed from 10 to 50% from the initial value of 32 cm.
40 The values that allowed us to obtain P- K_s values closest to IMP- K_s values, and so to calibrated
41 equation 1, were L = 18 cm for the 'large' size material and L = 20 cm for the 'small' size material.

42 Calibrated equation 1 was applied to K_s values measured at full (Table 2) and pilot (Table 3) scale
43 CWs. The standard deviations among repetitions in the same place or close to each other were of the

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1 same order-of-magnitude of those obtained for P permeameter. The variation of K_s values averaged
2 among those obtained at the same distance from the inlet after the operation period of beds and that
3 take into account also the accumulation of clogging in the horizontal direction is also showed in
4 Figures 4 and 5 for full and pilot scale CW beds.

5 **Discussion**

6 The decrease of K_s after the CW operation period was higher in the full scale plant than in the pilot
7 scale plant, probably due to the longer operation life and a higher organic load (data not shown). As
8 widely reported in literature (Vymazal 2018; Pedescoll *et al.* 2012; Knowles *et al.* 2009), the clogging
9 phenomena were more severe in the area close to the inlet of both plants. However, the observed K_s
10 reduction in the area close to the outlet of the H2 were also documented in literature (Correia 2016).

11 The saturated hydraulic conductivity determined with the implemented IMP permeameter and
12 modelled with equation 1 gave values comparable to those reported in literature for clean gravels with
13 similar sizes and porosity. In particular, Reed et al. (1995) for media with $8<D_{10}<16$ mm and
14 $30<n<38\%$ reported K_s values ranging from 500 to 10,000 m/d, whereas for media with $16<D_{10}<32$
15 mm and $36<n<40\%$ the K_s values ranging from 10,000 to 50,000 m/d. In other studies, K_s observed
16 with different method (i.e. surveys) are of the same-order-of-magnitude in the area close to the outlet
17 (Knowles *et al.* 2009; Nivala *et al.* 2012). Contrarily, in some studies (Caselles-Osorio *et al.* 2007;
18 Pedescoll *et al.* 2009) lower K_s values are reported (maximum values at the outlet area 810 m/d).
19 However these studies, applied the scheme 4 with equation 2, thus this combination was also verified
20 in the present paper. The results showed that in this case mean K_s values were lower than those
21 obtained with other schemes up to a factor of 25, however they were of the same order-of-magnitude
22 compared to those of the cited studies.

23 Therefore, results showed that scheme 1 used with equation 1 was the most suitable to measure K_s in
24 clean gravels or unclogged media where the isotropic conditions are still valid and vertical and
25 horizontal K_s are the same. During the operation period of CWs at both pilot and full scales, the
26 clogging phenomenon made the medium non-isotropic, so, vertical K_s alone was not representative
27 anymore. Calibrated equation 1 (by using L and R optimized values) allowed us to use P permeameter
28 to evaluate K_s variation during the operation period of CWs taking into account also the influence of
29 clogging in the horizontal direction and also saving time. High standard deviations among repetitions
30 carried out in the same place (for pilot scale plant) or close to each other (for full scale plant) and at the
31 same sampling data were often associated at higher K_s values, generally, they were higher for P- K_s
32 values. This phenomenon should be reduced during CW operation period, namely when the use of P
33 permeameter will become more useful, due to the increasing of clogging and the consequent
34 decreasing of K_s. It seems that as soon as the clogging increase, the ratio P/IMP moves away from the
35 value obtained for clean gravels; this behaviour can confirm the reliability of the procedure.

36

37 **Table 1** Mean and standard deviation of saturated hydraulic conductivity K_s (N=10) at lab scale for both small and big
38 sizes of clean gravel

Small size ($8\text{-}15 \times 10^{-2}$ m)			Big size ($10\text{-}25 \times 10^{-2}$ m)		
	K_s (m/d)	SD		K_s (m/d)	SD
IMP permeameter	19466	1553	IMP permeameter	12135	1591
P permeameter	30662	3903	P permeameter	20866	1628
P/IMP	1.6	-	P/IMP	1.7	-

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Table 2 Mean values of saturated hydraulic conductivity K_s (N=4) measured in the nine points inside the full scale plant and their standard deviation (SD) after 4-years operation

Distance from the inlet (m)	Piezometer	IMP		P – EQ1		P – CAL EQ1	
		K_s (m/d)	SD	K_s (m/d)	SD	K_s (m/d)	SD
7	1	3999	1300	5045	1130	3072	614
17	4	6896	2022	8629	298	6500	1677
27	7	8629	1769	11819	945	7311	585
7	2	4023	1044	6520	1482	4546	961
17	5	8123	1329	10217	2937	10217	2937
27	8	5810	1182	9014	796	5301	716
7	3	2604	1374	2554	512	2046	575
17	6	9061	1646	13659	1283	8449	793
27	9	6661	1458	10843	1183	6310	471

6

Table 3 Mean values of Saturated hydraulic conductivity K_s (N=4) measured along H1 and H2 pilot beds and their standard deviation (SD)

		February 2018					
Distance from the inlet (m)	Position	IMP		P – EQ1		P – CAL EQ1	
		K_s (m/d)	SD	K_s (m/d)	SD	K_s (m/d)	SD
1	H1 A	10066	1024	19988	1820	11280	980
2	H1 B	13807	1380	21132	1902	11925	1400
3	H1 C	12175	1100	20762	1154	11717	1150
1	H2 A	10222	922	20368	1042	10783	1010
2	H2 B	11564	1453	21348	2170	12047	1340
3	H2 C	8384	1072	19550	2215	11032	1040

		June 2018					
Distance from the inlet (m)	Position	IMP		P – EQ1		P – CAL EQ1	
		K_s (m/d)	SD	K_s (m/d)	SD	K_s (m/d)	SD
1	H1 A	10484	489	19544	2001	10341	1059
2	H1 B	11733	1496	19991	2646	10818	1400
3	H1 C	12125	961	21164	1260	11522	1200
1	H2 A	9387	1085	18839	942	9969	498
2	H2 B	11007	1486	20482	1985	10838	1050

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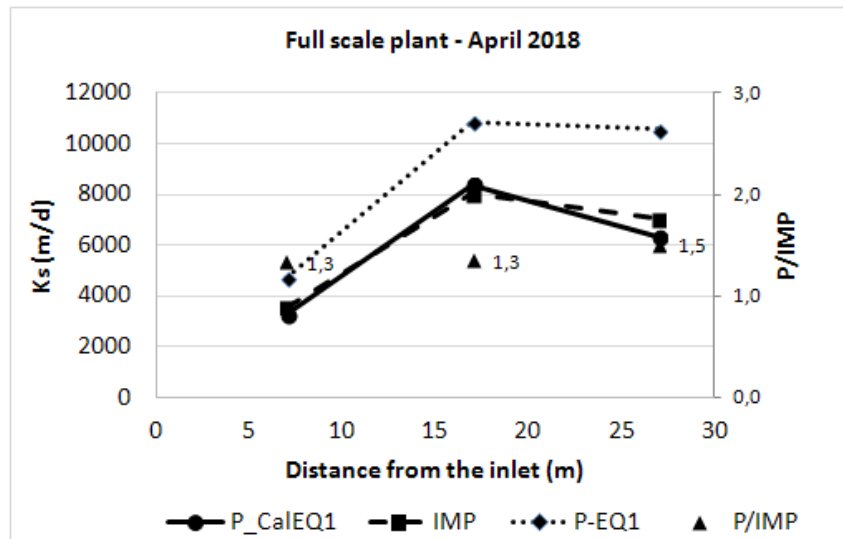
| 3 | H2 C | 9614 | 1075 | 17745 | 2545 | 9390 | 1347 |

1

2

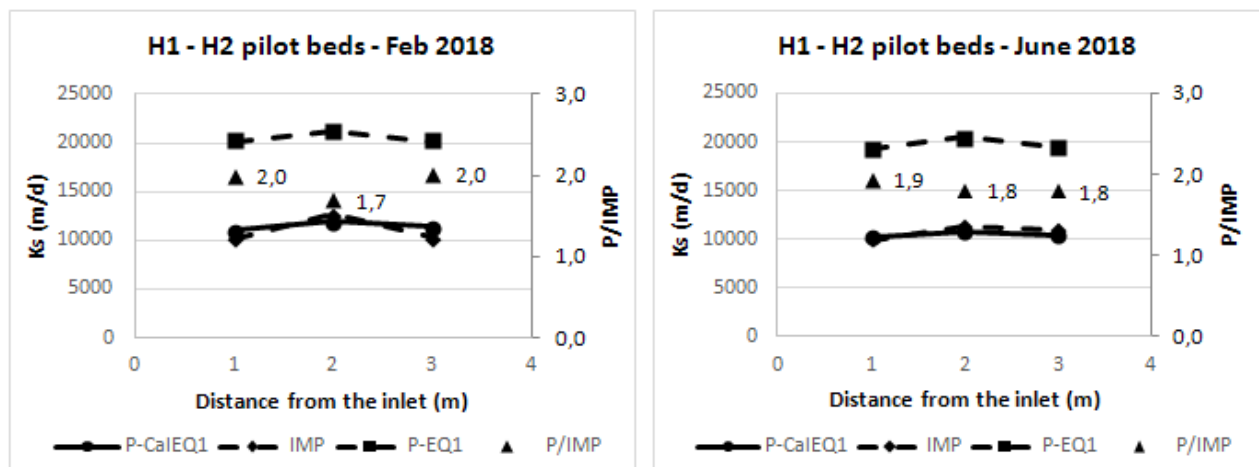**Figure 4** Variation of K_s measured by pervious (P) and impervious (IMP) permeameters, and their ratio (P/IMP), along the full scale plant after 4 years-operation

3

Figure 5 Variation of K_s values measured by pervious (P) and impervious (IMP) permeameters, and their ratio (P/IMP), along the two beds (H1 and H2) at pilot scale plant

Conclusions

4   The falling head method for saturated hydraulic conductivity measurements was suitable to assess
5 clogging in CWs at different locations in full scale and pilot scale CWs filled with different size of
6 gravels and after different operation periods (from 1 to 4 years). In particular, the IMP implemented
7 permeameter used with the original equation was the most suitable method to measure K_s in clean
8 gravels (i.e. unclogged) media where the isotropic conditions are still valid and vertical and horizontal
9 K_s are the same. After the starting of the clogging process, vertical K_s alone was not representative
10 anymore. An implemented P permeameter used with a calibrated equation allowed us to evaluate K_s
11 variations taking into account also the influence of clogging in the horizontal direction and also saving
12 time. The decrease of K_s during the CWs operation period was higher in the full scale plant than in the

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1 pilot scale plant, probably due to the longer operation life and a higher organic load. As widely
2 reported in literature, the clogging process was more severe in the area close to the inlet of both plants.

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