# Assessment of clogging in constructed wetlands by saturated hydraulic conductivity measurements

F. Licciardello, R. Aiello, V. Alagna, M. Iovino, D. Ventura and G. L. Cirelli

## ABSTRACT

This study aims at defining a methodology to evaluate $K_s$ reductions of gravel material constituting constructed wetland (CW) bed matrices. Several schemes and equations for the Lefranc's test were compared by using different gravel sizes and at multiple spatial scales. The falling-head test method was implemented by using two steel permeameters: one impervious (IMP) and one pervious (P) on one side. At laboratory scale, mean $K$ values for a small size gravel ($8–15 \times 10^{-2}$ m) measured by the IMP and the P permeameters were equal to 19,466 m/d and 30,662 m/d, respectively. Mean $K_s$ values for a big size gravel ($10–25 \times 10^{-2}$ m) measured by the IMP and the P permeameters were equal to 12,135 m/d and 20,866 m/d, respectively. Comparison of $K_s$ values obtained by the two permeameters at laboratory scale as well as a sensitivity analysis and a calibration, lead to the modification of the standpipe equation, to evaluate also the temporal variation of the horizontal $K_s$. In particular, both permeameters allow the evaluation of the $K_s$ decreasing after 4 years-operation and 1–1.5 years' operation of the plants at full scale (filled with the small size gravel) and at pilot scale (filled with the big size gravel), respectively.

**Key words** | horizontal flow, $K_s$ measurements, permeameter cell

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## INTRODUCTION

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

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application of chemicals to the gravel bed; and most recently, the application of earthworms to the system (Nivala *et al.* 2012).

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

Clogging assessment techniques include hydrodynamic visualisations by means of tracer tests (Bowmer 1987; Knowles *et al.* 2010), the analysis of accumulated solids in filter media (Caselles-Osorio & Garcia 2007; Pedescoll *et al.* 2009), and determination of the hydraulic gradients between points in the filter media (from which the mean hydraulic conductivity can be estimated) (Sandford *et al.* 1995; Rodgers & Mulqueen 2006; Suliman *et al.* 2006). The clogging process is very much affected by the size of filtration material and consequently by its saturated hydraulic conductivity ($K_s$). Common laboratory methods in CW is not advisable, to measure $K_s$ in CW due to the difficulties to take undisturbed media samples. For this reason, the measurement of $K_s$ in CWs have been mostly carried out by means of *in situ* methods (Knowles *et al.* 2011).

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

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

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

## MATERIAL AND METHODS

### Experimental schemes implemented at laboratory scale

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

Depending on the length of the cavity at the bottom of the piezometric tube, the measured $K_s$ can represent the horizontal, three-dimensional or vertical saturated hydraulic conductivity within the measurement zone (Amoozegar 2002). If the cavity cannot be maintained during measurements due to soil collapse, a well screen can be attached at the bottom of the piezometric tube. According to the geometry of the cavity (that is the ratio between radius, R, and length, L) different schemes can be considered (NAVFAC 1986). Three of them were tested in the present paper and were reported in Figure 1 (schemes 1 to 3), together with the corresponding equations to calculate $K_s$ and their applicability conditions. In particular, scheme 1 and scheme 3 implied the use of an impervious permeameter cell (IMP) with and without gravel inside, respectively; scheme 2 implied the use of a pervious permeameter cell (P) without gravel inside. The scheme 1, also called the standpipe test, did not require a borehole to be drilled as the pipe was merely inserted directly into the substrate, which can save much time compared with schemes 2 and 3. Also, excavation of a borehole could be a disturbance to porous medium. As a disadvantage, this method did not allow to evaluate horizontal $K_s$. This could be not a problem for isotropic gravel (clean or not clogged gravels) but, given that the clogging process is likely not to be isotropic, vertical $K_s$ values obtained by this method could be different from horizontal ones. On the other hand, to our knowledge, a scheme for predicting also horizontal $K_s$ using a P permeameter and that does not require a borehole to be drilled was not proposed. Thus, scheme 4, which implies the use of P permeameter with gravel inside was also implemented. An arrangement similar to scheme 4 was already used in literature by Pedescoll *et al.* (2009), but these authors calculated $K_s$ by Equation (2) that properly corresponds to scheme 2 (Figure 1). In the present paper, besides checking this combination (scheme 4 – Equation (2)), scheme 4 was applied using, as a first stage, the original Equation (1) and then a calibrated version of Equation (1), as described below.

In order to test the four proposed schemes, two different steel tubes were used (internal diameter 0.10 m and length

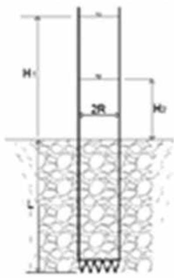
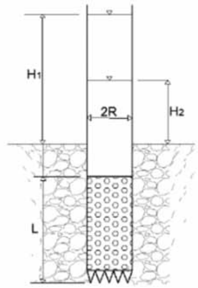
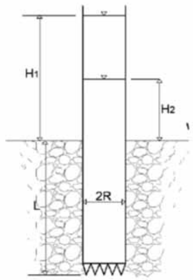
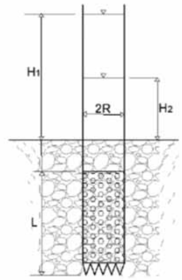
| Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|---|---|---|---|
| Impervious permeameter cell with material inside (Standpipe) | Pervious permeameter cell without material inside (Cased hole with uncased extension) | Impervious permeameter cell without materials inside (Cased hole) | Pervious permeameter cell with material inside |
|  |  |  |  |
| $K_s = \frac{2\pi R + 11L}{11(t_2 - t_1)}\ln\left(\frac{H_1}{H_2}\right)$ (1) | $K_s = \frac{R^2}{2L(t_2 - t_1)}$ (2) | $K_s = \frac{2\pi R}{11(t_2 - t_1)}\ln\left(\frac{H_1}{H_2}\right)$ (3) | $K_s$ was calculated by<br>Uncalibrated eq. 1<br>Uncalibrated eq. 2 (Pedescoll et al., 2009)<br>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 |

**Figure 1** | Schemes and equations tested for $K_s$ measurements by falling-head method adapted from NAVFAC 1986). R is 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 (meters, m) in the permeameter cell corresponding to time $t_1$ and $t_2$ (s).

1.5 m), one being impervious (IMP permeameter) and one being pervious on one side (P permeameter) for a total area of $3.11 \times 10^{-4}$ m$^2$, distributed along 0.25 m from the bottom of the permeameter. The P permeameter was implemented in order to also evaluate the temporal variation of horizontal $K_s$ by repeated measurements in the time. The permeameters were inserted, using a mallet, into the medium to a depth of about 0.32 m, after the creation of a small hole in the granular medium to reach the water table. To instantaneously add water to the permeameter (in a single-pulse mode) a plastic water reservoir (6.6 L volume) was assembled to the measurement units by means of a bulb valve (Figure 2).

Variation of the water level, H, within the permeameter was measured by a pressure probe (STS – Sensor Technik Sirnach, AG), connected to a laptop by means of a CR200-R (Campbell Scientific) data logger. The pressure probe was positioned inside the steel permeameter through a driver

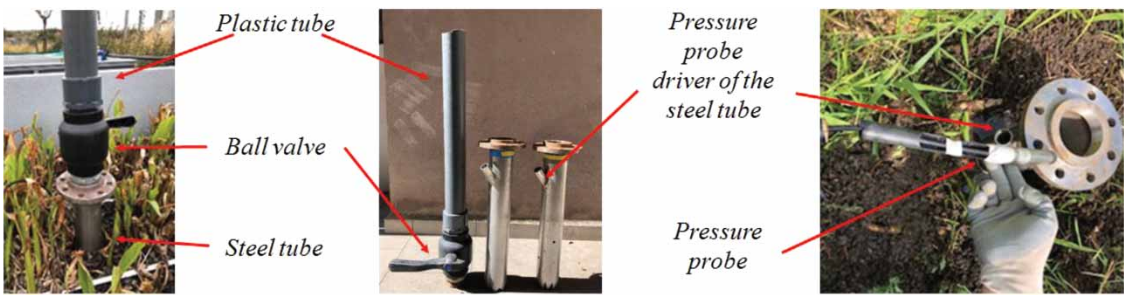



**Figure 2** | Permeameter unit for falling head tests.

added to the device. The pressure value at atmospheric pressure was checked before each measurement started. Four water level data per second were recorded for a duration of 30 seconds. The decrease of water height inside the permeameter was monitored until the water reached the water table.

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

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

where $H_{obs}$ is the height of the water table level measured inside the permeameter at time t during the test (m); $H_{sim}$ is the corresponding modelled data calculated by the different Equations (1)–(4) depending on the used scheme.

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

## Standpipe scheme calibration at laboratory scale by using both IMP and P permeameters

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

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

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

The hybrid CW system working as secondary wastewater treatment system of the Ikea® located in the industrial district of Catania, Eastern Sicily, Italy (37°26′54.2″N 15°02′05.2″E, 11 m a.s.l.) was considered as plant test at full scale. The plant is located in a semi-arid climate area, characterized by an average annual precipitation of about 500 mm, and values of air temperature in summer reaching 40 °C. The CW system was added to the pre-existing treatment system (including a sequential batch reactor system and a screening unit) in 2014, in order to respond to the high hydraulic and nitrogen load variability during the year. The sequential batch reactor system (SBR) was designed to treat a maximum flow rate of 30 $m^3\ day^{-1}$ (two batch phases every 12 h) and total nitrogen (TN) concentration of 135 $mg\ L^{-1}$. Anyway, during holidays or pre-holidays, wastewater flow rate could be 2–4 times greater than that during a normal working day, and $NH_4$ can be higher than 200 $mg\ L^{-1}$. The hybrid CW

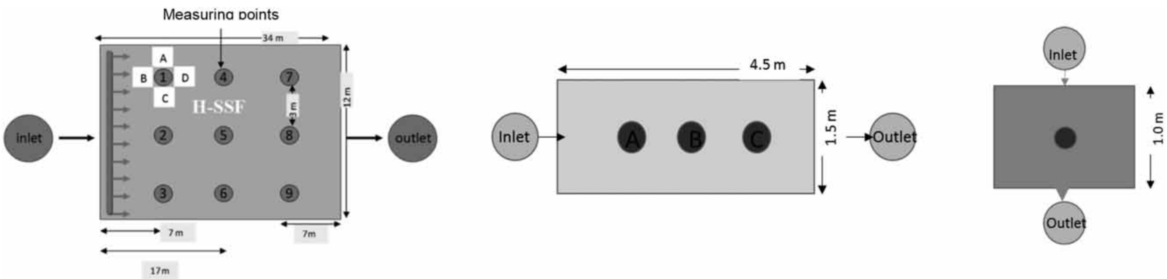



**Figure 3** | Measuring points inside the full scale, the pilot and the laboratory tank used to measure $K_s$. A, B, C and D inside the full scale plant indicate repeated infiltration tests conducted around each fix installed piezometer.

system includes three in series beds: a horizontal subsurface treatment wetland allowing a reduction of organic matter and suspended solids concentrations followed by two vertical subsurface flow treatment wetlands. The $K_s$ measurements were carried out only in the horizontal subsurface treatment wetland filled with 'small size' gravel. This bed covered a surface area of about 400 $m^2$ ($12 \times 34$ m) with a depth of 0.60 m, and it was planted (with a density of 3 plants $m^{-2}$) in July 2014, with two different aquatic species *Phragmites australis* (for $\approx 80\%$ of the horizontal flow (HF) surface area), and *Iris pseudacorus* close to the HF outlet. The bed was designed to be fed discontinuously, receiving 30 $m^3$ daily effluent from SBR (two discharges of 15 $m^3$ each one) and 20 $m^3$ effluent from the screening unit, that bypass the SBR when the wastewater production exceeds the designed flow rate. The hydraulic loading rate of the bed varied between 75 and 125 L $m^{-2}$ $d^{-1}$. For more details about the full scale hybrid CW system, see Marzo *et al.* (2018).

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

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

## RESULTS

### $K_s$ values obtained at laboratory, pilot and full scale by using NAVFAC (1986) schemes and equations

Table 1 reports mean $K_s$ values ($N = 10$) for both sizes of clean gravel obtained by using P and IMP permeameters at laboratory scale, as well as, the ratio between P – $K_s$ and IMP – $K_{s\ s}$ mean values. Unexpectedly, the $K_s$ was lower for the 'big' gravel than the 'small 'one, probably due to a lower uniformity and to a prevalent angular shape of bed matrix. As expected, P permeameter gave higher values of $K_s$ than IMP permeameter for both size of gravels; the ratio between P – $K_s$ and IMP – $K_s$ values was 1.6 and 1.7, respectively, for 'small' and 'big' size gravels. The highest standard deviation (3,903 m/d) was observed in correspondence to the highest mean $K_s$ values (P permeameter filled with 'small' size material).

Table 2 reports mean $K_s$ values ($N = 4$ repetitions $\times$ 9 piezometers $= 36$) measured around the nine measuring points at the full scale plant by using P and IMP permeameters and the corresponding standard deviations. All $K_s$ values obtained with the IMP permeameter were lower than the values observed for the clean gravel at laboratory scale (Table 1), with reductions up to about 90% in the area close to the inlet and up to about 55–65% in the middle and in the outlet areas. The behaviour was the same when the P permeameter was used. The reductions were higher than the variability of measurements, being maximum standard deviation value equal to 2,022 m/d for

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

| Small size ($8–15 \times 10^{-2}$ m) | $K_s$ (m/d) | SD | Big size ($10–25 \times 10^{-2}$ m) | $K_s$ (m/d) | SD |
|---|---|---|---|---|---|
| IMP permeameter | 19,466 | 1,553 | IMP permeameter | 12,135 | 1,591 |
| P permeameter | 30,662 | 3,903 | P permeameter | 20,866 | 1,628 |
| P/IMP | 1.6 | – | P/IMP | 1.7 | – |

**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 | 3,999 | 1,300 | 5,045 | 1,130 | 3,072 | 614 |
| 17 | 4 | 6,896 | 2,022 | 8,629 | 298 | 6,500 | 1,677 |
| 27 | 7 | 8,629 | 1,769 | 11,819 | 945 | 7,311 | 585 |
| 7 | 2 | 4,023 | 1,044 | 6,520 | 1,482 | 4,546 | 961 |
| 17 | 5 | 8,123 | 1,329 | 10,217 | 2,937 | 10,217 | 2,937 |
| 27 | 8 | 5,810 | 1,182 | 9,014 | 796 | 5,301 | 716 |
| 7 | 3 | 2,604 | 1,374 | 2,554 | 512 | 2,046 | 575 |
| 17 | 6 | 9,061 | 1,646 | 13,659 | 1,283 | 8,449 | 793 |
| 27 | 9 | 6,661 | 1,458 | 10,843 | 1,183 | 6,310 | 471 |

the IMP permeameter and 2,937 m/d for the P permeameter. Mean $K_s$ values ($N = 4$ repetitions x 3 piezometers $= 12$) obtained by averaging the measurements at each transect from the inlet are reported in Figure 4. Mean $K_s$ values close to the inlet were 5.5 and 4.1 times lower than those measured for the clean gravel by IMP and P permeameters, respectively. In the middle and in the outlet areas of the full scale CW both permeameters gave mean $K_s$ values 2.2 times lower than those measured for the clean gravel.

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

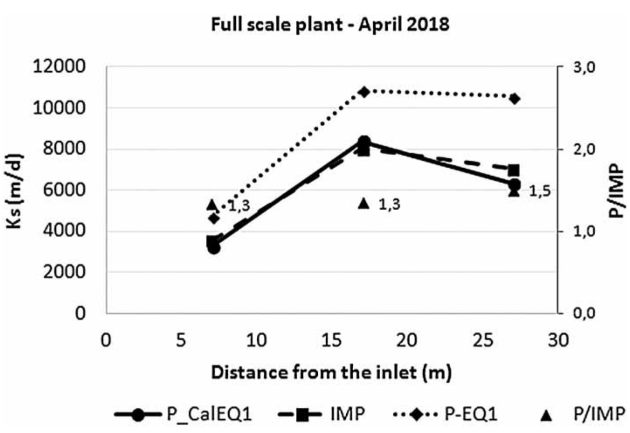



**Figure 4** | Variation of $K_s$ measured by pervious (P) and impervious (IMP) permeameters, and their ratio (P/IMP), along the full scale plant after 4 years' operation.

outlet. Anyway, $K_s$ values measured in February and in June were very similar for all sampling points and for both beds, therefore only the $K_s$ reductions with respect to clean gravel will be discussed. The $K_s$ reductions measured with the IMP permeameter were higher than the maximum standard deviation of the repetitions in the same place and time equal to about 1,500 m/d. Mean $K_s$ values measured in the middle areas and close to the outlet were sometimes even higher than the values observed for the clean gravel (i.e. point H1-A and H2-C when IMP permeameter was used and H1-C for P permeameter). This behaviour could be due to the high variability of $K_s$ values, being those values in the range of the measured variability of the parameter. The behaviour of $K_s$ values observed with the P permeameter was similar to that obtained for IMP permeameter. Anyway, $K_s$ reductions after the operation period measured by P permeameter were lower than those observed by using the IMP permeameter and standard deviation of the repetitions in the same place and time reached about 2,646 m/d. Again, the highest variation of the measurements was associated to a very high mean $K_s$ value (Table 3). Figure 5 reports the behaviour of $K_s$ values averaged between both pilot beds ($N = 3$ repetitions × 1 piezometer × 2 beds = 6) after 1 and 1.5 years' operation. Again, it was clear that there was not a significant $K_s$ reduction from February to June 2018. Mean $K_s$ values close to the inlet were 83% and 97% of the $K_s$ values measured for the clean gravel by IMP and P permeameters, respectively.

The saturated hydraulic conductivity values obtained by using the scheme 2 and the respective equation were lower than those obtained by using scheme 1 and Equation (1) of about one order-of-magnitude. However, the $K_s$ values obtained by using the scheme 3 and the respective equation

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

| 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 |
| February 2018 | | | | | | | |
| 1 | H1 A | 10,066 | 1,024 | 19,988 | 1,820 | 11,280 | 980 |
| 2 | H1 B | 13,807 | 1,380 | 21,132 | 1,902 | 11,925 | 1,400 |
| 3 | H1 C | 12,175 | 1,100 | 20,762 | 1,154 | 11,717 | 1,150 |
| 1 | H2 A | 10,222 | 922 | 20,368 | 1,042 | 10,783 | 1,010 |
| 2 | H2 B | 11,564 | 1,453 | 21,348 | 2,170 | 12,047 | 1,340 |
| 3 | H2 C | 8,384 | 1,072 | 19,550 | 2,215 | 11,032 | 1,040 |
| June 2018 | | | | | | | |
| 1 | H1 A | 10,484 | 489 | 19,544 | 2,001 | 10,341 | 1,059 |
| 2 | H1 B | 11,733 | 1,496 | 19,991 | 2,646 | 10,818 | 1,400 |
| 3 | H1 C | 12,125 | 961 | 21,164 | 1,260 | 11,522 | 1,200 |
| 1 | H2 A | 9,387 | 1,085 | 18,839 | 942 | 9,969 | 498 |
| 2 | H2 B | 11,007 | 1,486 | 20,482 | 1,985 | 10,838 | 1,050 |
| 3 | H2 C | 9,614 | 1,075 | 17,745 | 2,545 | 9,390 | 1,347 |

were not reliable due to the fast lowering of the water level inside the permeameter. Anyway, schemes 2 and 3 were too time consuming and difficult to apply, especially at real scale plants.

## $K_S$ values obtained by scheme 4 and calibrated *Equation (1)*

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

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

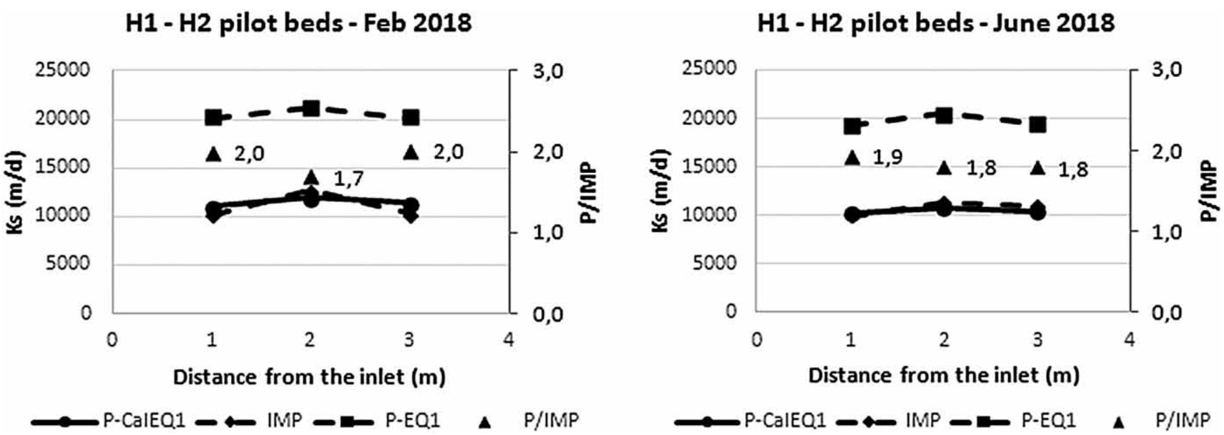



**Figure 5** | Variation of $K_s$ values measured by pervious (P) and impervious (IMP) permeameters, and their ratio (P/IMP), along the two beds (H1 and H2) at pilot scale plant.

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

Calibrated Equation (1) was applied to $K_s$ values measured at full (Table 2) and pilot (Table 3) scale CWs. The standard deviations among repetitions in the same place or close to each other were of the same order-of-magnitude of those obtained for P permeameter. The variation of $K_s$ values averaged among those obtained at the same distance from the inlet after the operation period of beds and that take into account also the accumulation of clogging in the horizontal direction is also showed in Figures 4 and 5 for full and pilot scale CW beds.

## DISCUSSION

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

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

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

## CONCLUSIONS

The falling head method for saturated hydraulic conductivity measurements was suitable to assess clogging in CWs at different locations in full scale and pilot scale CWs filled with different size of gravels and after different operation periods (from 1 to 4 years). In particular, the IMP implemented permeameter used with the original equation was the most suitable method to measure $K_s$ in clean gravels (i.e. unclogged) media where the isotropic conditions are still valid, and vertical and horizontal $K_s$ are the same. After the starting of the clogging process, vertical $K_s$ alone was not representative anymore. An implemented P permeameter used with a calibrated equation allowed us to evaluate $K_s$ variations taking into account also the influence of clogging in the horizontal direction and also saving time. The decrease of $K_s$ during the CWs operation period was higher in the full scale plant than in the pilot scale plant, probably due to the longer operation life and a higher organic load. As widely reported in literature, the clogging process was more severe in the area close to the inlet of both plants.

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