Polish J. of Environ. Stud. Vol. 18, No. 2 (2009), 289-292

Letter to Editor

Water Retention Time in Intermittently Dosed Sand Filters

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Received: 22 March 2008
Accepted: 17 November 2008

Abstract

This paper presents a simple theoretical approach to calculating of the retention time of water and/or wastewater in intermittently dosed filters. It assumes that a single dose of water is completely mixed with the previously stored water in the filter and that the field capacity of the granular medium is achieved before the next wastewater application. Retention time is weighted by the water volume stored within the filter. It is presented in a discrete form. The model was successfully validated on the basis of empirical data gathered by Schudel and Boller.

Keywords: sand filter, retention time, water detention, intermittent dosing, wastewater treatment

Introduction

Sand filters are beds of medium-to-coarse sands, usually 60-100 cm deep, underlain with gravel containing collection drains. Primary or secondary-treated effluent is intermittently dosed on the bed and percolates through the sand to the bottom of the filter. The underdrains collect the leachate and convey it to the final treatment and/or discharge. Sand filters can be used for purification of storm water before its infiltration into the native soil or to receiving surface water bodies.

Sand filters are divided into buried, open (single pass) and recirculating filters. They are effective in organic carbon, SS and nutrient removal from domestic and agricultural wastewaters. Despite the long historical use of buried and open sand filters, their dosing frequencies and retention times have not been optimized.

Numerous investigations were carried out in the past on the performance of sand filters both in laboratories and full-scale plants. The technology was assessed as "a highly stable process, able to accept wide variations in organic and hydraulic loading with little deleterious effect on effluent quality" [1]. To obtain good effluent quality, sufficient time must be provided between doses to allow for reaeration of the pore space. The provision of unsaturated conditions also affects virus removal. For fine-to-medium sand sizes, two doses per day were found to be optimal. For filters with grain diameters greater than about 0.45 mm, that higher dosing frequency was more effective, e. g. 12-24 doses per day [2]. This was because the lower retention capacity of the coarser media limited dose volume. That multiple dosing concept has been successfully used in recirculating sand filters with a dosing frequency of once every 30 minutes (48 doses per day) [3].

There are several simplified methods of estimation of percolation time used in soil science. These methods are generally based on the assumption of a continuous application of water into the filter [4].

In the case of intermittent-dosing, Van Cuyk et al. [5] recommended calculating the time to 10% recovery of tracer (KBr) in wastewater soil absorption systems by using the following formula:

$$t_{10} = \frac{L \cdot n_e \cdot VUE}{100 \cdot q} \tag{1}$$

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...where:
L – soil (filter) length, cm;
n_e – effective porosity, or macroporosity, which is approximately equal to porosity minus volumetric soil water content at field capacity -;
VUE – volumetric utilization efficiency, %;
q – application rate over design infiltration area (hydraulic load), cm^3/cm^2h = cm/h.

VUE is defined as the fraction of filter/soil volume that the wastewater is in contact with. Equation (1) indicates that, more strictly, VUE should be interpreted as an effective pore volume in contact with the wastewater. According to Van Cuyk et al. [5], *VUE* value increases with the volume of effluent applied. This hypothesis was partially confirmed by their own experiments, showing an increase from 46-54% to 95-100% after ten weeks of operation and then – after 45 weeks – a decrease to 75-98%. The last decrease did not support the hypothesis that *VUE* value increases with time.

Eq. (1) estimates the travel time through the filter, assuming plug flow under unsaturated conditions. However, it seems that time t_{10} is too short and uncertain to characterize the retention time in a sand filter and other soil infiltration systems.

Materials and Methods

A soil column filled with uniform, granular material (sand) is considered. Our assumptions differ from those made by Van Cuyk et al. [5]; we assume that water storage within the soil is limited to field capacity (not effective porosity) and that the intermittently dosed sand filter represents a complete-mix reactor instead of a plug-flow reactor. The initial moisture of the soil is approximately equal to field capacity (Fig 1a). In a short time a water dose of volume $V_{D(n)}$ is applied to the filter (Fig. 1b). As shown in Fig. 1d, after the *n-th* dose application, one may expect in the filter effluent $p_1 V_{D(n)}$ of the observed dose (usually marked using a tracer) and $(1 - p_1)V_D$ of the earlier retained wastewater, where p_1 is the fraction of the first dose in the effluent after dosing, and V_D is dose volume.

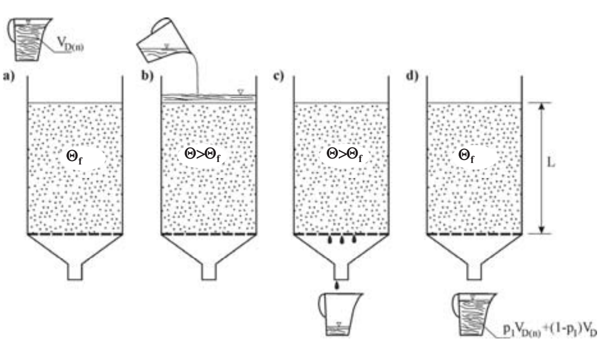

Fig. 1. Phases of water dosing.

The fraction of the first observed dose (recovery) after the second dose is:

$$p_2 V_{D(n+1)} = p_1(1 - p_1) V_{D(n)} \tag{2}$$

After the third dose of the same volume $V_{D(n+2)} = V_{D(n+1)} = V_{D(n)} = V_D$, it is:

$$p_3 = p_1(1 - p_1 - p_2) \tag{3}$$

...and, generally, after the n-th dose (for $n \geq 2$):

$$p_n = p_1(1 - \sum_{i=1}^{n-1} p_i) \tag{4}$$

Cumulative mass distribution function can be expressed as:

$$F(n) = \sum_{i=1}^{n} p_i \tag{5}$$

It is equal to the marked dose recovery after the *n-th* dose. For $n \to \infty$, $F(n) \to 1.0$.

Assuming that the first fracture $p_1 V_D$ leaves the filter relatively quickly (relative to the dosing frequency Δt) the mean retention time of one dose in the soil column can be expressed as:

$$t_m = p_2 \Delta t + p_3 2 \Delta t + ... + p_n (n-1) \Delta t = \Delta t \sum_{i=2}^{n} p_i (i-1) \tag{6}$$

The median retention time t_{50} corresponds to

$$t_{50} = \Delta t \sum_{i=1}^{k} p_i (i-1) \tag{7}$$

...where k is the number of doses at which one half of the observed dose is recovered.

Because of the discrete form of the relationship (7), in most cases the median retention time must be estimated using an interpolation technique.

The mean retention time t_m can also be calculated using:

$$t_m = \Delta t \frac{V_f}{V_D} \tag{8}$$

When $\Delta t \to 0$, the intermittent dosing is transformed into continuous dosing. A theoretical retention (residence) time distribution for a complete-mix reactor is exponential and its cumulative distribution function can be described by [6]:

$$F(t) = 1 - \exp\left(-\frac{t}{t_m}\right) = 1 - \exp\left(-\frac{t\,q}{V_f}\right) \tag{9}$$

...where: t – retention time, t_m – mean retention time, q – application rate, $V_f = A\,L\,\theta_f$ – water volume in the filter at its field capacity, A – cross-section of the filter of length L, θ_f – volumetric soil water content at field capacity.

The mean retention time t_m from Eq. (9) is:

$$t_m = 1.443\, t_{50} = \frac{V_f}{q} \tag{10}$$

...where: t_{50} – median of the retention time.

The inequality $t_m > t_{50}$ means that retention time distribution is not symmetrical and it has a positive skew.

Results and Discussion

A comparison between the theoretical relationships and experimental data published by Schudel and Boller [7] was made for a buried filter filled with a coarse sand (mean diameter d_{50} = 1.6 mm, effective size d_{10} = 0.4-0.8 mm) with water content at field capacity θ_f = 0.06 (i.e. 60 mm/m). The vertical length of the filter L = 100 cm consisted of two gravel layers and a sand layer of depth L_s = 80 cm. The filter was dosed four times per day, i.e. dosing frequency Δt = 6.0 h, at hydraulic loading rates of 10-20 mm per dose. The sand was not clean because of the application of septic tank effluent.

As a first approximation p_1 was taken as the ratio of the dose volume to the sum of the dose volume and the volume of water in the sand filter at its field capacity:

$$p_1 \approx \frac{V_D}{V_D + V_f} \tag{11}$$

Results of calculations using the above-presented relationships are shown in Table 1 and Figs. 2 and 3.

The presented model gives relatively good results when calculating mean and shorter water retention times. The observed discrepancy for longer times can be explained by an inadequacy of the proposed model and/or by diffusion of tracer into deeper parts of the liquid phase in the real filter and – as a consequence – an apparent loss in the marked dose recovery. Schudel and Boller stated that “30% of the applied tracer load is lost most probably by adsorption and exfiltration” [7].

In Table 1 it can be seen that theoretically a twofold increase in hydraulic load (from 40 mm/day to 80 mm/day) brought about a 62% decrease in median retention time (from 21 h to 8 h) and a 50% decrease in mean retention time (from 36 to 18 h). The analogous decreases for the continuous dosing were 52% and 50%, correspondingly. The data in Table 1 show that the dosing mode does not impact the mean retention time, but it influences the median retention time in a granular filter. The latter is shorter in intermittently dosed filters than that in continuously dosed filters; when dose volume V_D is equal to or greater than the filter field capacity, then the median retention time is close to zero.

In Figs. 2 and 3 it can be seen that the assumption about the continuous flow cannot be accepted when considering intermittent dosing with frequencies of 4 doses per day or fewer.

Table 1. Comparison of median and mean retention times for conditions described by Schudel and Boller [7].

Hydraulic load	t_{50} in hours acc. to		t_m in hours acc. to	
mm/day	Eq. (7)	Eq. (10)	Eq. (6) & (8)	Eq. (10)
40	21	25	36	36
80	8	12	18	18
Dosing frequency	6 h	continuous	6 h	continuous

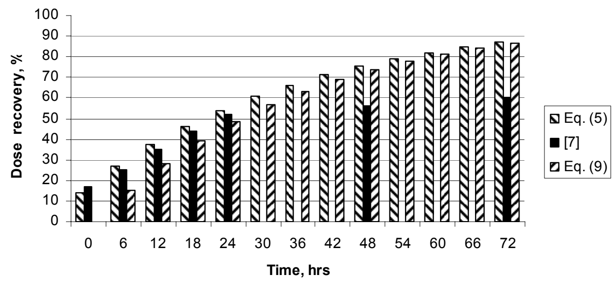

Fig. 2. Comparison of retention times calculated by Eq. (5) at hydraulic load q = 10 mm per dose and Eq. (9) at q = 40/24 = 1.67 mm/h, with those measured by Schudel and Boller [7].

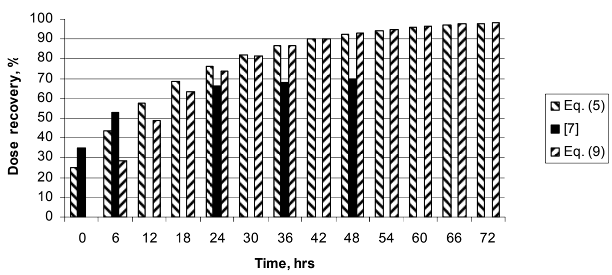

Fig. 3. Comparison of retention times calculated by Eq. (5) at hydraulic load q = 20 mm per dose and Eq. (9) at q = 80/24 = 3.33 mm/h, with those measured by Schudel and Boller [7].

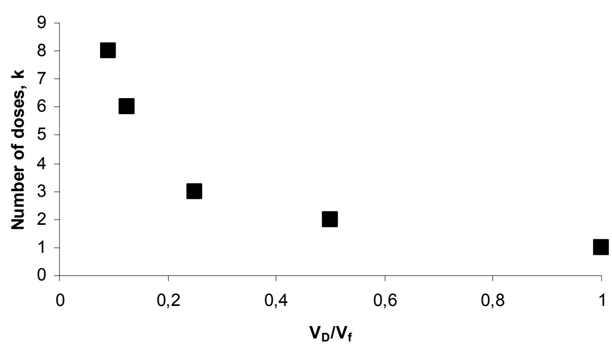

Fig. 4. Numbers of doses needed to obtain 50% recovery of a marked dose volume in the effluent (k) as a function of relative dose volume.

Fig. 4 shows the numbers of doses needed to get 50% recovery of a marked dose in the effluent of the filter, calculated using Eq. (5) for $n \approx k$ and $F(k) \approx 0.5$. It can be seen that the greater dose in relation to the filter field capacity the quicker dose recovery. From the practical point of view it is often not advantageous to have a quick recovery with poor effluent quality. Thus, the number of doses should be optimized concerning quality requirements.

More exact modeling is available using mathematical (numerical) models based on Richards' equations such as HYDRUS [8, 9].

Conclusions

- The presented complete-mix reactor model gives relatively good results when calculating mean and shorter water retention times. It can be applied for relatively permeable media (medium and coarse sands).
- Dosing mode does not impact mean retention time, but it influences the median retention time in a granular filter. The latter is shorter in intermittently dosed filters than that in continuously dosed filters.
- The greater the dose in relation to filter field capacity, the quicker the dose recovery.
- More exact modeling is available using mathematical models based on Richards' equations such as HYDRUS.
- There is a need to investigate the influence of biomass inside a sand biofilter (especially in the surface clogging layer) on the field capacity of the filter.

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