Particle size analysis as a tool for performance measurements in high rate effluent filtration

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Abstract In the Netherlands almost all wastewater treatment plants have been redesigned and adapted in order to remove nitrogen, phosphorus and suspended solids to a very low level. The improved effluent quality leads to a growing interest in the reuse of effluent of the modernised wastewater treatment plants. This again results in investigations on filtration techniques as deep bed filtration and membrane filtration. At the wastewater treatment plant Ede research was done on deep bed filtration in order to develop relations between particle removal and filter performance and to explore ways of optimization.

The results of the experiments are rather typical for effluent of modern Dutch wastewater treatment plants. The very low concentrations of suspended solids and precipitable substances result in poor flocculating properties.

From turbidity measurements it may be concluded that the best results were obtained with a dosage of flocculant. However, the particle size measurements indicated the opposite. Suspended solids calculations, based on the particle volume distributions, showed a better removal without a dosage of flocculant. From this it is concluded that a dosage of coagulant (Fe^{3+} or Al^{3+}) has an adverse effect on the removal efficiencies even at low dosages (1 mg/l).

Keywords Deep bed filtration; flocculating filtration; high filtration rates; particle removal; particle size distribution; suspended solids removal

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Introduction

In the Netherlands wastewater treatment is entering a new phase. Almost all plants have been redesigned and adapted in order to remove nitrogen and phosphorus. Influenced by many other developments such as sustainability, integrated water management and the abatement of exsiccation the interest in reuse of effluent of the modernised wastewater treatment plants is growing. This again results in investigations on filtration techniques as deep bed filtration and membrane filtration.

Earlier experiments showed promising results for deep bed filtration (Van der Graaf, 1998); filtration rates up to 30 m/h were applicable. Therefore, further investigations were planned on a larger scale (5–10 m^3/h) at the wastewater treatment plant of Ede. This wastewater treatment plant produces a high quality effluent by the low-loaded activated sludge process with alternating cycles (Biodenipho), including nitrogen removal and biological phosphorus removal (see Table 1). This effluent water may be used as so called household water in a living area which will be developed near to the treatment plant. The usage of household water (for cloth washing machines, toilet flushing and gardening) leads to new requirements with respect to particles, hygienic quality, ammonia and heavy metals. Some schemes for the treatment of effluent have been investigated including deep bed filtration, membrane filtration, disinfection and natural treatment by ponds and bank filtration. A dominant role in these schemes is taken by the deep bed filtration process. But, until now, practical experiences with this technique are not available for this type of effluent. Especially the relatively low concentration of suspended solids (less than 5 mg/l) seems to be an important factor in the performance of the filter. However, the analytical determination of suspended solids in the low concentration region is very troublesome. Therefore,

Table 1 Effluent data (1998) of the wastewater treatment plant of Ede

flow	**35,000 m^3/d**				
COD	40 mg O_2/l	Kjeldahl-N	3.1 mg N/l	pH	7.7
BOD	2.9 mg O_2/l	NO_3-N	3.0 mg N/l	chloride	98 mg/l
total-P	0.6 mg P/l	Suspended solids	4.0 mg/l	sulphate	51 mg/l

use of a particle size measurement technique was chosen as a tool for observing the filtration process. The main objectives of the research were to investigate the filtration process under different circumstances, to develop relations between particle removal and filter performance and to explore ways of optimization.

Methods and materials

In long term filtration experiments secondary effluent from the wastewater treatment plant of Ede was filtered in a pilot unit, mainly consisting of a feed pump, a three layer deep bed filter, a flocculant dosing system, a filtrate storage tank and an air/water backwash system (see Table 2). The total depth of the filter bed was 1.47 metres and the supernatant level was controlled at approximately 155 cm. The flocculant was dosed just before a static mixer (mixing time <1 s, G=500–1000 s^{-1}) in the feed line. For optimal flocculation a mixer was installed in the supernatant above the filter bed (De Koning *et al.*, 1999).

The filter was equipped with sampling probes along the height of the filter bed (every 100 mm), with which samples could be taken for measurement of turbidity and particle counting. A similar set of probes was used for head loss measurements.

The turbidity was measured by a colorimeter (Hach RATE 0-XR). Particles were counted applying a Met One PCX particle counter in the 2–750 μm range, based on laser light blocking. The data were produced in a particle number frequency function with intervals of 0.5 μm.

Several conditions were tested, varying the filtration rate, the type and concentration of flocculants (ferric chloride, $FeCl_3$ and aluminium chloride, $AlCl_3$); see Table 3.

Every experiment starts with a clean filter (thoroughly backwashed) and runs for at least several days; after 24 hours or earlier if needed due to a too high head loss, backwashing was applied. During the filtration cycle the particle counting measurements took place with regular intervals; the main results refer to the measurements after one hour.

Table 2 Specifications of the pilot plant

Type	Deep bed filter	upper layer	770 mm anthracite (2.0–4.0 mm, 1,400 kg/m^3)
Diameter	800 mm	middle layer	400 mm quartz sand (1.7–2.5 mm, 2,600 kg/m^3)
Hydraulic capacity	2.5–15.1 m^3/h	bottom layer	300 m garnet (0.7–1.25 mm, 3,500 kg/m^3)
Filtration rate	5–30 m/h	backwash rate	air (max 100 m/h), water (50 m/h)

Table 3 Experimental programme (November 1998–February 1999)

Exp	**filtration rate (m/h)**	**flocculant**	**dosage (mg/l)**	**exp**	**filtration rate (m/h)**	**flocculant**	**dosage (mg/l)**
1	10	–	–	6	10	$AlCl_3$	1 (Al^{3+})
2	15	–	–	7	15	$AlCl_3$	1 (Al^{3+})
3	20	–	–	8	20	$AlCl_3$	1 (Al^{3+})
4	10	$FeCl_3$	1 (Fe^{3+})	9	10	$AlCl_3$	2 (Al^{3+})
5	10	$FeCl_3$	2 (Fe^{3+})				

Calculations on particle size distribution

The measurement of the particle size provides a histogram for numbers versus size (Figure 1). This distribution function is transformed into a particle volume distribution function assuming the particles having an ideal spheric shape. This function covers the range from 2–100 µm.

With the particle volume distribution function several other calculations can be done:

- cumulative particle volume distribution (in m^3/m^3) versus particle size
- relative cumulative particle volume distribution (in %) versus particle size.

The horizontal axis can be either linear or logarithmic.

A cumulative particle size distribution ($N(d_p)$) would always be increasing as the particle size increased, until some maximum is reached. The slope of such a cumulative distribution ($dN(d_p)/dd_p$) is known as the particle size distribution function ($n(d_p)$). The latter can be calculated with the power law function:

$$n(d_p) = Ad_p^{-\beta} \quad \text{or} \quad \log n(d_p) = \log A - \beta \log d_p$$

d_p is the nominal particle size and A and β are constants. The power coefficient β is a specific characteristic for the particle size distribution of the investigated water (Lawler, 1997; Neis *et al.*, 1997).

Results and discussion

General observations

The various experiments produced different filtrates. Also changes in filtration characteristics were observed. Some data on general observations are presented in Table 4. From this table it may be concluded that the best results were reached with the dosing of coagulants; the particle counting measurements the results of which are presented below however indicated different conclusions.

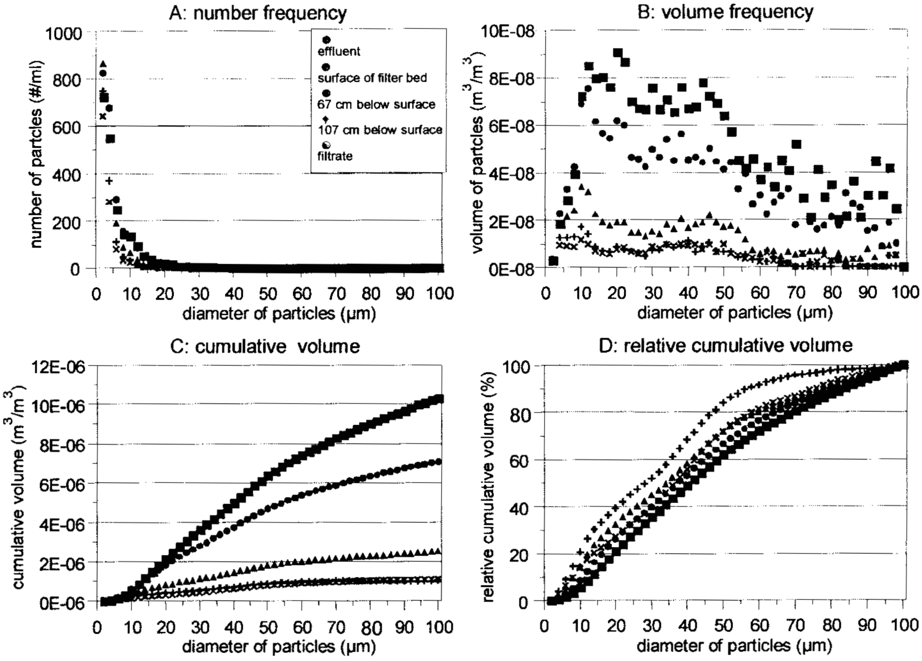

Figure 1 Particle distribution curves, examples (filtration rate: 15 m/h, no dosage of flocculant). A. number frequency, B. volume frequency, C. cumulative volume, D. relative cumulative volume

Table 4 General data for the filtration experiments

Experiment	1	2	3	4	5	6	7	8	9
Turbidity (NTU)									
• effluent	2.2	2.7	2.7	1.3	0.9	1.4	1.1	1.2	0.9
• just above filter	2.0	2.4	2.4	1.3	1.1	1.5	1.2	1.3	0.8
• filtrate	0.9	1.0	0.9	0.6	0.5	0.6	0.7	0.7	0.3
Head loss over the total filter bed (in cm)									
• after 1 hr	40.2	57.1	76.6	30.0	39.0	35.9	45.4	69.2	40.7
• after 6 hrs	42.3	60.2	80.1	31.6	41.5	43.9	68.5		43.6

Progress of the filtration process

The measurements of the various parameters during the filtration process produced an indicative impression of the progress of the process. In this case the degree of removal of particles seems to be constant after a short start-up period of not more than 15 minutes up to the end of the filter run which mostly was after more than 24 hours; this long filtration time was mainly caused by the very low suspended solids concentration of the effluent. Some examples are presented in Figure 2. Due to these observations the comparison of different operation conditions was made mainly for the measurements after 1 hour of operation.

Comparison of the results at different filtration rates (10, 15 and 20 m/h) showed only very small differences in performance (see Figure 3). This coincides with the observation that the removal of suspended solids is almost independent of the filtration rate (Kaminski *et al.*, 1997). Of course the rate of fouling of the filter increased with increasing filter rates leading to shorter filter run lengths. However, with a filtration rate of 20 m/h the head loss after 6 hours still was quite acceptable.

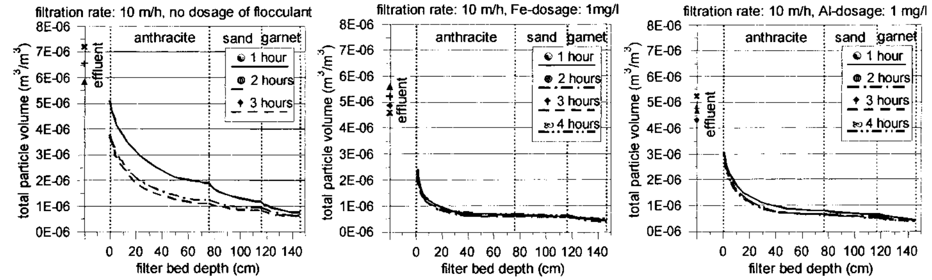

Figure 2 Progress of the filtration process for 10 m/h; development of total particle volume in the water at several points of time (1, 2, 3, 4 hours)

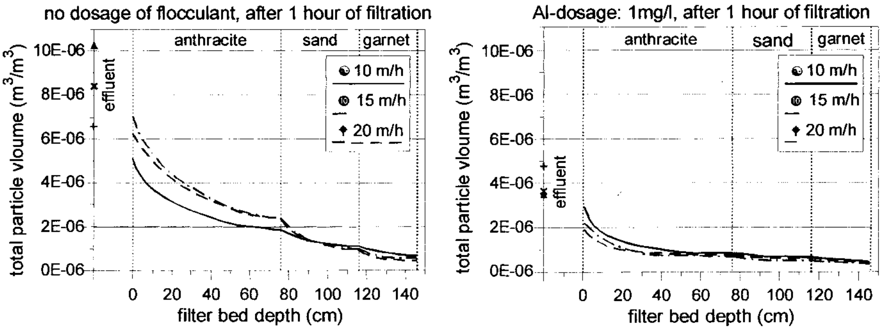

Figure 3 Influence of the filtration rate; development of total particle volume in the water for several filtration rates (10, 15 and 20 m/h)

Coagulants

Furthermore it became clear that with a dosage of flocculants (Fe^{3+}, Al^{3+}) only very small quantities were needed. A maximum dosage of 2 mg/l resulted in a decrease of turbidity; higher dosages lead to a high turbidity in the filtrate indicating unsuccessful flocculation. Here it must be stressed that 1 mg flocculant/l produces theoretically 2–3 mg/l of precipitating particles which is of the same order of magnitude as the original suspended solids (4 mg/l). Also the low phosphorus concentration (0.15 mg total P/l) may only require a very low dosage of coagulants. Figure 4 shows that the influence of the differences in flocculant dosage is small.

Density

Using all measurements, the density of the particles could be calculated. For the secondary effluent an average volume of the particles of 5.90×10^{-6} m^3/m^3 and a suspended solids concentration of 4 mg/l indicate a density of the particles in the effluent of 680 kg/m^3. From many observations it became clear that fluctuations in the suspended solids concentration could be determined much better indirectly by particle counting followed by volumetrical calculations and further by mass calculation than by direct analytical mass measurements (Gregory, 1997).

Removal efficiency of different layers

From Table 5 it can be seen that the removal efficiency varies for the different layers. The efficiency is calculated from the total volume of particles after a layer compared to that of the entrance of the filter bed, so after the flocculation zone.

The differences between the results of the experiments are significant. Without a dosage of coagulants (exp. 1, 2 and 3) the filter really acts as a deep bed filter, removing approximately 60–65% in the anthracite layer, another 15–20% in the sand layer and the last 5–10% in the garnet layer, resulting in a total removal of approximately 90%. The differences for varying filtration rates are small. With a dosage of coagulants the results change drastically. The main removal (70–75%) takes place in the anthracite layer and in particular in the first part of it; however the second and third layer only give a slight improvement of the removal efficiency, finally resulting in a total removal of approximately 85%.

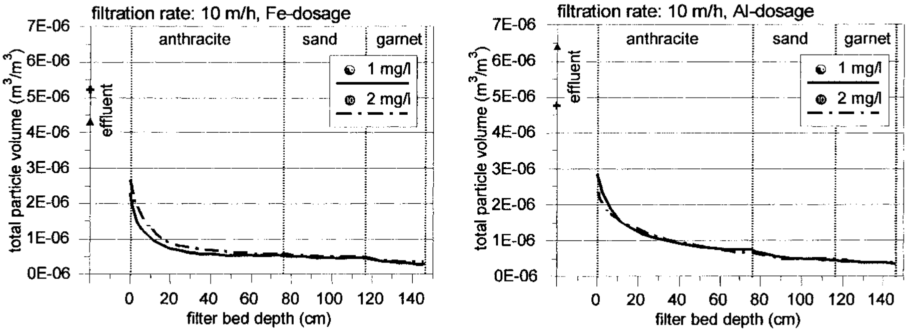

Figure 4 Influence of flocculant; total particle volume in the water for different dosages of flocculant

Table 5 Volume removal efficiency (%) in the three layers (cumulative)

Experiment	1	2	3	4	5	6	7	8	9
anthracite	64	65	61	76	76	75	69	56	69
sand	78	84	85	79	80	81	78	68	79
garnet	86	91	91	85	83	88	85	80	84

This means that many parameters that are related to the solids concentration such as heavy metals, some organic micro pollutants, and bacteria will be removed to a higher degree without the dosage of coagulants. This result probably may be contributed to the very low concentration of suspended solids.

Pre-treatment

Before the actual filtration through the three layers the secondary effluent undergoes some steps that really influence the particle characteristics. After pumping by the feed pump the effluent passes a static mixer where the coagulants can be dosed; then it flows through a highly turbulent inlet box into the water layer of approximately 155 cm above the filter bed. By measurement of the particle size distribution before the filter feed pump and just before entering the filter bed an impression of changes can be derived. In Table 6 the total particle volumes are presented for the various experiments, as well as the suspended solids concentration; the suspended solids in the effluent are calculated from the total particle volume (with use of a density of 680 kg/m^3); when dosing chemicals the addition of 1 mg Fe and 1 mg Al produces 1.9 mg and 3.0 mg of solids respectively.

From these data it can be seen that the addition of coagulants results in a logical increase of solids but a drastic decrease of the total particle volume. This results in an increase in density up to approximately 2770 kg/m^3. This indicates that the flocs shrink in volume, an effect comparable with dewatering of sludge caused by the decrease in water binding capacity of the flocs due to neutralisation of the negatively charged surface layers. In Figure 5 the particle number distribution functions illustrate that the total numbers also decrease; this is in contradiction with other experiments (Kobler *et al.*, 1997) which demonstrated an increase of (especially smaller) particles by flocculation however using higher dosages and effluents with higher suspended solids contents and higher phosphorus concentrations.

Power factor β

Table 7 gives the results of the calculations of β. In this table it can be seen that for the secondary effluent the average value of β is 2.75 and that the variation in the value of β is low. After flocculation (exp. 4–9) the value of β increases to an average of 3.04 indicating a shift into the smaller particle sizes. Also without flocculation (exp. 1–3) the particle size distribution is shifted into smaller sizes although not as far as with flocculation. Probably, the feed pump breaks larger flocs into smaller ones. This is confirmed by the particle counts; the total number of particles entering the filter bed increases compared to the total number of particles in the effluent.

The increased value of β in the filtrate indicates that only the larger particles are removed in the filter; the smallest particles partially pass the filter bed (Kaminski *et al.*, 1997).

Table 6 Comparison of measurements on the original effluent and at the entrance of the filter bed

Experiment	1	2	3	4	5	6	7	8	9
total particle volume in 10^{-6}m^3/m^3									
effluent	6.55	10.28	8.40	5.22	4.33	4.76	3.51	3.63	6.41
at entrance of the filter bed	5.11	7.06	6.26	2.31	2.70	2.86	2.16	1.81	2.40
filtrate	0.72	0.60	0.54	0.35	0.46	0.34	0.33	0.37	0.38
suspended solids (calculated) in mg SS/l									
effluent	4.4	7.0	5.7	3.5	2.9	3.2	2.4	2.5	4.3
at entrance of the filter bed	4.4	7.0	5.7	5.4	6.7	6.2	5.4	5.5	10.3
filtrate	0.5	0.4	0.4	1.0	1.3	0.9	0.9	1.0	1.1

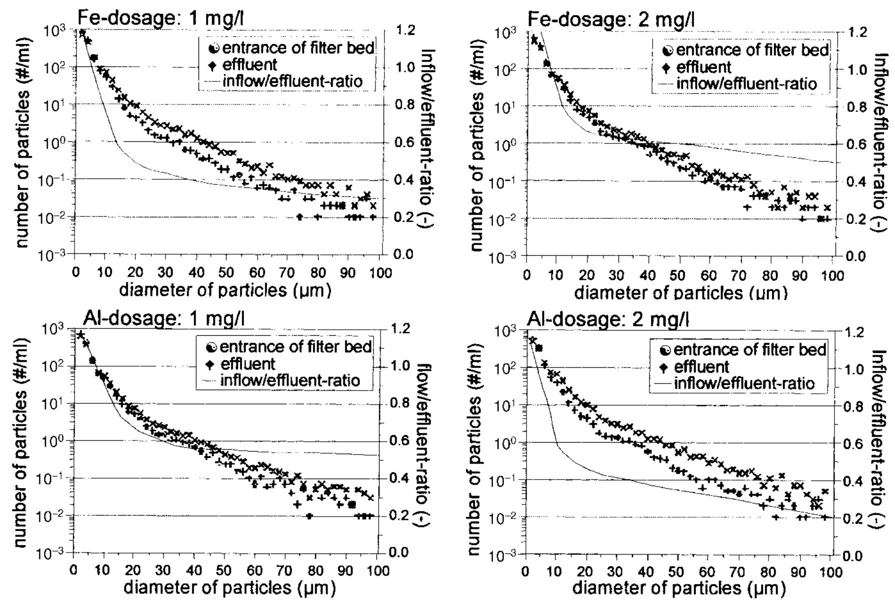

Figure 5 Particle number distribution and inflow/effluent-ratio (= [number of particles with diameter d_p in inflow of filter bed]/[number of particles with diameter d_p in effluent]) for a filtration rate of 10 m/h and several dosages of flocculant

Table 7 Comparison of β-values of effluent, before entrance of the filter, in the filter bed, and of filtrate

Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Effluent									
	2.83	2.69	2.78	2.82	2.79	2.74	2.80	2.73	2.60
at entrance of the filter bed									
	2.96	2.93	2.98	3.22	3.06	3.02	3.01	2.94	3.00
in the filter bed (cm below filter bed surface)									
7	2.98	3.00	3.02	3.43	3.21	3.09	3.02	2.96	2.99
67	3.07	3.25	3.21	3.36	3.37	3.14	3.02	2.95	3.02
107	3.31	3.24	3.22	3.04	3.23	3.03	3.17	2.96	3.07
Filtrate									
	3.60	3.62	3.50	2.96	3.48	3.22	3.15	2.80	3.18

Conclusions

The experiments showed various results which are rather typical for this type of wastewater treatment plant effluent. The very low concentration of suspended solids and precipitable substances results in poor flocculating properties. Compared to other experiences great differences in filtration properties are found.

In following the filtration process the applied particle counter is a very useful instrument; with this method the solids concentration can be calculated for the low region values (< 5 mg/l).

Good removal results (up to 90%) were reached for three layer filtration at filtration rates up to 20 m/h; no differences between various filtration rates or during a filtration period were observed.

Flocculant (as Fe^{3+} and Al^{3+}) has an adverse effect on the removal efficiency even at low dosages (1 mg/l); however, the final turbidity showed better results. This can be explained by the destabilisation of the floc particles decreasing its water binding properties and causing smaller but more dense flocs.

The calculated values of β indicate that after flocculation and filtration the particle size distributions were shifted to the smaller sizes.

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