Spanish Journal of Agricultural Research (2005) 3(2), 182-191

Effluent particle removal by microirrigation system filters

J. Puig-Bargués[1]*, G. Arbat[1], J. Barragán[2] and F. Ramírez de Cartagena[1]

[1] *Department of Chemical and Agricultural Engineering and Technology. University of Girona. EPS. Campus Montilivi, s/n. 17071 Girona. Spain*

[2] *Department of Agricultural and Forestry Engineering. University of Lleida. ETSEA. Avda. Rovira Roure, 191. 25198 Lleida. Spain*

Abstract

The aim of this work was to determine whether the filters used in microirrigation systems can remove potentially emitter-clogging particles. The particle size and volume distributions of different effluents and their filtrates were established, and the efficiency of the removal of these particles and total suspended solids by screen, disc and sand filters determined. In most of the effluents and filtrates, the number of particles with a diameter > 20 µm was minimal. By analysing the particle volume distribution it was found that particles larger than the disc and screen filter pores appeared in the filtrates. However, the sand filter was able to retain particles larger than the pore size. The filtration efficiency depended more on the type of effluent than on the filter. It was also found that the particle size distribution followed a potential law. Analysis of the β exponents showed that the filters did not significantly modify the particle size distribution of the effluents.

Additional key words: clogging, drip irrigation, filtration, wastewater.

Resumen

Eliminación de partículas de efluentes en filtros de sistemas de riego localizado

La distribución del número y del volumen de partículas, y la eficiencia de eliminación de las partículas y los sólidos en suspensión de diferentes efluentes y sus filtrados, fueron analizadas para estudiar si los filtros más usuales en los sistemas de riego localizado eliminan las partículas que pueden obturar los goteros. En la mayoría de los efluentes y filtrados fue mínimo el número de partículas con diámetros superiores a 20 µm. Sin embargo, al analizar la distribución del volumen de las partículas, en los filtrados aparecieron partículas de dimensiones superiores a la luz de los filtros de anillas y malla, siendo el filtro de arena el que retuvo las partículas de mayor diámetro. La eficiencia de los filtros para retener partículas se debió más al tipo de efluente que al filtro. Se verificó también que la distribución del número de partículas sigue una relación de tipo potencial. Analizando el exponente β de la ley potencial, se halló que los filtros no modificaron significativamente la distribución del número de partículas de los efluentes.

Palabras clave adicionales: agua residual, filtración, obturación, riego localizado.

Introduction

Clogging is one of the main problems when using effluents in microirrigation systems; a small number of plugged emitters can affect distribution uniformity and reduce crop yields. Filtration to retain particles and reduce emitter clogging is therefore vital (Oron *et al*., 1979; McDonald *et al*., 1984).

The type of particles in wastewater depends on the treatment process (Adin and Elimelech, 1989; Adin *et al*., 1989; Tiehm *et al*., 1999). The properties that influence whether a particle is retained by a filter include size, shape, surface load, settling velocity and (probably) porosity. Since these properties vary from one type of particle to another, the particle size distribution, the variety of shapes and the density intervals must also be considered (Lawler, 1980, 1997). By determining the particle volume distribution, the volumes of each of the main particle sizes that are captured by a filter can be established (Adin, 1999).

Particle size and volume distribution curves have different shapes. While the particle size curve falls with particle diameter, particle volume produces a bell-shape since it is a third order power with regard to

* Corresponding author: jaume.puig@udg.es
Received: 09-07-04; Accepted: 15-02-05.

All authors are members of SEA.

particle diameter. Thus, the total volume of the particles of smaller size is less than that of the larger particles, even though the total number of larger sized particles is smaller (Adin *et al.*, 1989).

According to Lawler *et al.* (1980), particle size distributions in aqueous suspensions can be expressed as a potential law function:

$$\frac{dN}{dD_p} = \alpha \cdot D_p^{-\beta} \quad [1]$$

where N is the number of particles per volume unit, D_p is the particle diameter, and α and β are empirical constants. The empirical constant α is a coefficient related to the total concentration of particulate solids in the system. Exponent β results from the interaction between different physical processes such as coagulation and sedimentation (Lawler *et al.*, 1980). It also provides an estimate of particle diameter. If the value of β is low, then large diameter particles predominate in the effluent, if it is high, then small particles are in the majority (Lawler *et al.*, 1980; Adin and Elimelech, 1989). The potential law of equation [1] can be applied when the particles have a diameter > 1 µm (Adin, 1999) and a unimodal distribution (Adin and Elimelech, 1989).

Determining the particle size distribution helps in the assessment of the efficiency of filtration systems since it can detect problems that other methods cannot (Hatukai *et al.*, 1997; Kobler and Boller, 1997). However, Boller *et al.* (1997) indicate that particle size distribution analysis is not representative of particle transport due to the mixing and formation of preferential channels, although they accept its validity for assessing the differences between the retention of small and large particles.

The effect of filtration on effluent particle distribution has not been widely studied with the usual filters used in drip irrigation systems. Some studies with screen and sand filters do, however, stand out (Adin and Alon, 1986; Adin, 1987; Adin and Elimelech, 1989; Tajrishy *et al.*, 1994). The main conclusions of these studies are that sand filters are more efficient than screen filters at removing effluent particles that commonly plug emitters (10-80 µm in diameter), although the retention of solid particles never surpassed 20%, even in the best cases (Adin *et al.*, 1989). One of the main problems is that particles retained in the filter are gradually released, mainly due to the pressure increase during the filtration cycle. This means that aggregates of up to 20 µm could form in the filtrate (Adin, 1999).

The aims of the present work were to characterize the particle size and volume distributions of different effluents used in microirrigation, to determine the effect of different filters on the variation of their particle distributions, and to assess the quality of filtration on the basis of particle retention.

Material and Methods

Filtration experiments

The experimental material included five different effluents. Effluent 1, which received only preliminary treatment, was wastewater from a meat industry. Effluent 2 was the effluent produced after wastewater secondary treatment involving a sludge process at a wastewater treatment plant (WWTP) in Girona. Effluent 3 was the previous effluent filtered through a sand filter for microirrigation systems; its effective grain size (the mesh size that retains 90% of the sand mass) was 0.65 mm and its uniformity coefficient (the ratio between the mesh sizes that retain 40% and 90% of the sand) was 1.3. Effluent 4 was the effluent produced after wastewater secondary treatment involving a sludge process at Castell-Platja d'Aro WWTP. Finally, Effluent 5 was that produced after tertiary treatment at the same plant. This was obtained by filtering the secondary effluent through sand (effective grain size of 0.45 mm, uniformity coefficient 1.6) and disinfecting the product using ultraviolet light and chlorination treatments. Table 1 shows the means and standard deviations of some of the physical and chemical variables of the different effluents used.

Table 1. Means and standard deviations of some physical and chemical parameters of the different effluents at the filter inlets

Effluent	TSS (mg l^{-1})	Turbidity (NTU)	Particles ml^{-1}
1	176 ± 24.8	200 ± 29.0	64,048 ± 41,479
2	24.4 ± 14.7	11.3 ± 3.21	50,470 ± 26,320
3	8.61 ± 3.94	8.78 ± 6.05	52,900 ± 21,300
4	10.6 ± 3.42	4.51 ± 1.92	61,909 ± 32,516
5	4.93 ± 1.24	2.66 ± 1.30	37,372 ± 24,899

TSS: total suspended solids. NTU: nephelometric turbidity units. Effluents: 1, meat industry effluent; 2, Girona WWTP (wastewater treatment plant) secondary effluent; 3, Girona WWTP secondary treatment effluent filtered with sand; 4, Castell-Platja d'Aro WWTP secondary treatment effluent; 5, Castell-Platja d'Aro WWTP tertiary effluent.

The three most common filter types used in micro-irrigation systems —screen, disc and sand— were represented in different tests. The filters used with Effluents 1 and 2 were: a) three nylon screen filters 50.8 mm in diameter, with a total filtration surface of 946 cm^2 and pore sizes of 98 µm (S98), 115 µm (S115) and 178 µm (S178), b) three disc filters 50.8 mm in diameter with a filtration surface of 953 cm^2 and pore sizes of 115 µm (D115), 130 µm (D130) and 200 µm (D200), and c) a sand filter 508 mm in diameter with a filtration surface of 1,963 cm^2, and filled with 175 kg of sand as a single filtration layer. The effective diameter and the uniformity coefficient of the sand were 0.65 mm and 1.3 respectively. For Effluent 3, all the previous disc and screen filters were used, except the sand filter. For effluent 4, an inclined 130 µm nylon screen filter (S130) (50.8 mm in diameter with a filtration surface of 640 cm^2) and a 130 µm disc filter (D130) (50.8 mm in diameter with a filtration surface of 953 cm^2) were tested. For Effluent 5, only a screen filter with the same characteristics as that used with Effluent 4 (S130) was tested.

The aim of the experiments was to determine the head loss across the filters and the filtrate volume at regular time intervals until the head loss reached a value of 49 kPa. At this point the filters were cleaned. The screen and disc filters were cleaned manually using water under pressure. A backwashing system was used with the sand filter until the sand was clean. Table 2 shows the means and standard deviations of the surface filtration velocities. The average pressure at the disc and screen filter inlets was 124 kPa, 82 kPa, 61 kPa, 225 kPa and 242 kPa when using Effluents 1, 2, 3, 4 and 5 respectively. The sand filter operated under a mean pressure of 163 kPa with Effluent 1, and 80 kPa with Effluent 2.

In each experiment, samples of effluents were taken at the filter entry and exit points at different times. For Effluents 1, 4 and 5, seven samples were taken at the entry and exit points; ten samples were taken for Effluents 2 and 3.

Particle analysis

The particle size and volume distributions, and the number of particles at each sample point, were determined using a Galai Cis1 laser analyser (Galai Production Inc., Israel). The volume distributions were obtained at the 95% confidence level. The particle diameter determination intervals were 5-600 µm for Effluents 1, 2 and 3, and 2-300 µm for Effluents 4 and 5. These intervals were fixed for each effluent in preliminary trials.

In the particle analyser, a 5 ml cuvette was used in most cases to hold the effluent sample. A magnetic stirrer in this cell provided continuous agitation to avoid settling. Due to the high turbidity of Effluent 1, samples were diluted with distilled water in a proportion of 1:6.5. The particle size distributions of the diluted and original samples were very similar, probably because the dilution factor used was low. A continuous cuvette was used with this effluent; the fluid therefore circulated continuously to guarantee a constant and homogeneous suspension over time.

Efficiency of particle and solid removal

Using the data on particle size distribution and total suspended solids (TSS) at the filter entry and exit

Table 2. Means and standard deviations for the surface filtration velocities of the different filters and effluents

Filter	Mean surface filtration velocity (l m^{-2} s^{-1})				
	Effluent 1	Effluent 2	Effluent 3	Effluent 4	Effluent 5
D115	11.53 ± 6.08	4.73 ± 2.43	1.40 ± 0.03	—	—
D130	7.75 ± 5.57	5.11 ± 3.02	1.34 ± 0.10	3.01 ± 0.14	—
D200	7.23 ± 5.55	6.42 ± 0.22	1.29 ± 0.07	—	—
S98	16.17 ± 5.09	2.67 ± 0.96	0.96 ± 0.02	—	—
S115	11.23 ± 8.54	3.13 ± 3.00	0.91 ± 0.08	—	—
S130	—	—	—	4.46 ± 0.34	5.09 ± 0.08
S178	6.76 ± 4.04	5.41 ± 2.38	0.92 ± 0.01	—	—
Sand	3.88 ± 2.47	2.88 ± 0.25	—	—	—

D115: 115 µm disc filter. D130: 130 µm disc filter. D200: 200 µm disc filter. S98: 98 µm screen filter. S115: 115 µm screen filter; S130: 130 µm screen filter. S178: 178 µm screen filter. Effluents defined in Table 1.

points, the efficiency (E) of the different filters at removing both was calculated by employing the equation:

$$E = \frac{N_o - N}{N_o} \quad [2]$$

where N_o and N are the values of the variables in the unfiltered and filtered effluents respectively.

Statistical analysis

The data obtained in the filtration experiments were fitted to equation [1] using the REG procedure of the SAS statistical package (SAS, 1999). This allowed the α and β exponents of equation [1] to be determined for each effluent and filtrate. Duncan's test was used to compare the means of α and β as well as the particle and TSS removal efficiencies. Significance was set at $P < 0.05$.

Results

Particle size distribution

Figure 1 shows the mean particle size distribution of Effluent 2 before and after filtration. It was similar to that of the other effluents: unimodal and with small particles clearly predominating over large particles. Particles with a diameter of < 14 µm made up about 86% of Effluent 1

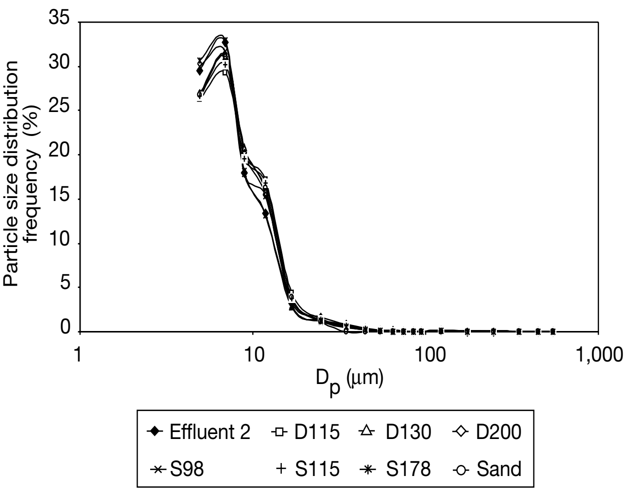

Figure 1. Mean particle size distributions of the secondary effluent from the Girona wastewater treatment plant (Effluent 2) before and after filtration with 115 µm (D115), 130 µm (D130) and 200 µm (D200) disc filters, 98 µm (S98), 115 µm (S115) and 178 µm (S178) screen filters, and a sand filter with a 0.65 mm effective grain size.

particles, 94% of Effluent 2 and 3 particles, and 98% of Effluent 4 and 5 particles. No important differences were seen in terms of the particle size distribution of the effluents either before or after filtering.

Table 3 shows the fit of the particle size distributions for the different effluents and filtrates to the potential law of equation [1]. Despite the variability of the regression coefficients, all fits were statistically significant ($P < 0.05$). No significant differences were seen in the α coefficients or β exponents of the effluents and their filtrates (except that the α coefficient of the filtrate produced by the 130 µm disc filter was significantly greater than that of the sand filter when Effluent 1 was tested).

Particle and solid removal efficiencies of filters

Since the comparison of the mean particle size distributions allowed no testing of the ability of the filters to retain particles, the total particle and TSS removal efficiencies were determined using equation [2] (Table 4). Negative efficiencies indicate an increase in particle number and TSS at the filter outlet. The results were very variable probably due to the differences in the composition of the effluents; indeed, the results obtained with same filter differed depending on the test effluent. In some cases, the agreement between particle and TSS removal efficiencies was low.

With Effluent 1 (the poorest quality effluent), only the sand filter achieved significant reductions in the number of particles and TSS. With Effluent 2, the TSS removal efficiencies of the sand, disc and screen filters were the same, although the particle removal efficiency of the 115 µm disc filter and the 98 µm screen filter was significantly higher than that achieved with the sand filter. When Effluents 3, 4 and 5 were used, the disc and screen filters showed no significant differences in terms of reducing the TSS or number of particles. However, the 115 µm disc filter achieved greater reductions in the number of particles than did the 130 or 200 µm disc filters when testing with Effluent 3.

The average removal efficiencies for each particle diameter interval were also analysed. Figure 2 shows the efficiency of the 130 µm disc filter in relation to the different effluents. Negative efficiencies were seen for some particle diameters in all the effluents tested; this means that the number of particles in the filtrate was higher than in the influent. Twenty percent of the

Table 3. Means and standard deviation of α and β, plus the range of the adjusted regression coefficient (R^2) ($P < 0.05$) for the particle size distributions in equation [1] for different effluents and sample points (filter inlet and outlet)

Effluent	Sample point	α	β	R^2 adjusted range
1	Inlet	$2.3 \cdot 10^6 \pm 0.7 \cdot 10^{6\ ab}$	2.37 ± 0.08	0.690-0.940
	D115	$3.2 \cdot 10^6 \pm .7 \cdot 10^{6\ ab}$	2.44 ± 0.15	0.641-0.942
	D130	$6.4 \cdot 10^6 \pm 3.6 \cdot 10^{6\ a}$	2.30 ± 0.23	0.663-0.928
	D200	$2.1 \cdot 10^6 \pm 0.4 \cdot 10^{6\ ab}$	2.44 ± 0.05	0.872-0.932
	S98	$2.6 \cdot 10^6 \pm 0.5 \cdot 10^{6\ ab}$	2.57 ± 0.06	0.880-0.964
	S115	$3.9 \cdot 10^6 \pm 1.1 \cdot 10^{6\ ab}$	2.54 ± 0.10	0.893-0.920
	S178	$2.6 \cdot 10^6 \pm 0.5 \cdot 10^{6\ ab}$	2.56 ± 0.07	0.645-0.915
	Sand	$3.6 \cdot 10^5 \pm 0.2 \cdot 10^{6\ b}$	2.45 ± 0.04	0.580-0.811
2	Inlet	$1.5 \cdot 10^6 \pm 0.3 \cdot 10^6$	2.26 ± 0.05	0.756-0.973
	D115	$8.4 \cdot 10^5 \pm 0.7 \cdot 10^6$	2.17 ± 0.15	0.809-0.900
	D130	$3.3 \cdot 10^5 \pm 0.2 \cdot 10^6$	2.06 ± 0.11	0.761-0.941
	D200	$9.4 \cdot 10^5 \pm 0.4 \cdot 10^6$	2.18 ± 0.11	0.765-0.966
	S98	$5.3 \cdot 10^5 \pm 0.2 \cdot 10^6$	2.35 ± 0.11	0.829-0.952
	S115	$7.1 \cdot 10^5 \pm 0.2 \cdot 10^6$	2.12 ± 0.10	0.798-0.919
	S178	$1.6 \cdot 10^6 \pm 0.5 \cdot 10^6$	2.25 ± 0.11	0.859-0.960
	Sand	$3.2 \cdot 10^6 \pm 2.3 \cdot 10^6$	2.21 ± 0.11	0.552-0.963
3	Inlet	$3.2 \cdot 10^6 \pm 2.3 \cdot 10^6$	2.21 ± 0.11	0.552-0.963
	D115	$2.9 \cdot 10^6 \pm 0.1 \cdot 10^6$	2.28 ± 0.23	0.567-0.933
	D130	$8.2 \cdot 10^6 \pm 0.4 \cdot 10^6$	2.47 ± 0.29	0.696-0.939
	D200	$6.4 \cdot 10^6 \pm 0.4 \cdot 10^6$	2.16 ± 0.31	0.564-0.966
	S98	$3.1 \cdot 10^6 \pm 1.7 \cdot 10^6$	2.58 ± 0.17	0.606-0.894
	S115	$1.6 \cdot 10^7 \pm 1.3 \cdot 10^6$	2.59 ± 0.26	0.618-0.921
	S178	$6.9 \cdot 10^5 \pm 0.3 \cdot 10^6$	2.12 ± 0.15	0.523-0.967
4	Inlet	$1.5 \cdot 10^7 \pm 1.4 \cdot 10^7$	3.55 ± 0.47	0.866-0.980
	D130	$1.6 \cdot 10^7 \pm 1.3 \cdot 10^7$	4.23 ± 0.47	0.745-0.986
	S130	$4.1 \cdot 10^6 \pm 1.4 \cdot 10^6$	3.89 ± 0.38	0.703-0.999
5	Inlet	$6.7 \cdot 10^6 \pm 4.0 \cdot 10^6$	4.13 ± 0.26	0.799-0.956
	S130	$1.6 \cdot 10^6 \pm 0.6 \cdot 10^6$	3.51 ± 0.16	0.787-0.952

Effluents and filters defined in Tables 1 and 2. Within each effluent section, different letters show significant differences ($P < 0.05$).

particles with a diameter of 130 µm were retained, while 80% of the 175 µm particles were removed when Effluent 1 was filtered through the 130 µm disc filter. This filter achieved the complete removal of particles larger than 85 µm from Effluent 3, and achieved the same for particles over 35 µm in Effluent 4. Nevertheless, with Effluent 2, particles below 14 µm and over 65 µm were not retained. Thus, negative efficiencies of 100% were reached for the 175 µm particle diameter. The release of particles that later formed aggregates with a larger diameter was observed with all disc filters and with the 115 µm and 178 µm screen filters operating with the Effluent 2. Figure 3 shows the filtration efficiencies achieved with the 115 µm screen filter. The 98 µm screen showed the worst behaviour when using Effluent 3, due to a degradation of the screen.

The sand filter was the most efficient with both Effluents 1 and 2 (Fig. 4). With Effluent 1, sand filtering removed particles of all diameters, and achieved the total retention of particles with a diameter of > 45 µm. However, with Effluent 2, the efficiency of this filter was only positive with particle diameters > 25 µm; efficiency was nearly 100% when the particle size was > 125 µm. This difference in the removal of particles of different diameters explains why the sand filter had a filtration efficiency of 68.9% (with respect to total particles) with Effluent 1, but only 2.70% with Effluent 2 (Table 4).

Particle volume distribution

Figure 5 shows the particle volume distributions for some of the effluents and their filtrates. In the filtrates

Table 4. Means and standard deviations of the filtration efficiency for TSS, and the number of particles by filter and effluent

Effluent	Filter	TSS	Particles ml^{-1}
1	D115	17.7 ± 10.9^{b}	17.6 ± 46.2^{b}
	D130	18.5 ± 18.5^{b}	13.3 ± 57.7^{b}
	D200	13.7 ± 6.02^{b}	16.7 ± 34.3^{b}
	S98	31.6 ± 15.5^{b}	20.6 ± 30.8^{b}
	S115	20.7 ± 23.0^{b}	7.56 ± 11.1^{b}
	S178	23.1 ± 22.2^{b}	20.2 ± 7.59^{b}
	Sand	61.9 ± 11.3^{a}	68.9 ± 8.52^{a}
2	D115	53.7 ± 15.3	38.7 ± 31.6^{ab}
	D130	50.9 ± 15.5	35.4 ± 29.6^{abc}
	D200	45.5 ± 14.6	8.59 ± 9.83^{bcd}
	S98	49.6 ± 20.0	48.4 ± 32.9^{a}
	S115	31.8 ± 19.2	19.4 ± 7.70^{abcd}
	S178	31.9 ± 17.0	-6.20 ± 21.8^{d}
	Sand	49.6 ± 30.0	2.70 ± 42.8^{cd}
3	D115	-7.93 ± 31.7	34.5 ± 26.2^{a}
	D130	-4.72 ± 31.7	7.73 ± 22.8^{b}
	D200	0.01 ± 2.06	1.49 ± 14.7^{b}
	S98	-4.69 ± 10.7	25.5 ± 34.2^{ab}
	S115	-1.78 ± 10.2	26.5 ± 27.3^{ab}
	S178	-7.48 ± 5.54	25.5 ± 22.5^{ab}
4	D130	24.4 ± 15.5	19.8 ± 28.9
	S130	27.9 ± 15.6	15.4 ± 29.7
5	S130	-12.4 ± 10.1	12.1 ± 10.4

Effluents and filters defined in Tables 1 and 2. Within each effluent section, different letters show significant differences ($P < 0.05$).

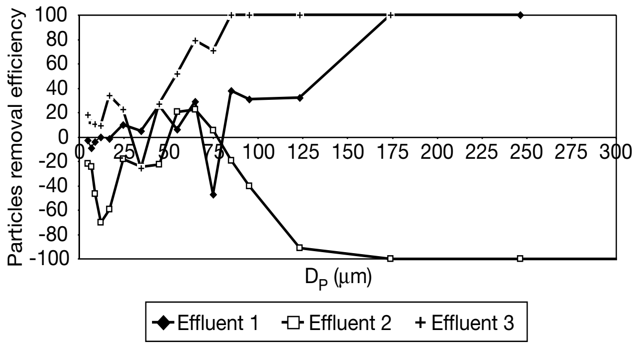

Figure 3. Efficiency of a 115 µm screen filter (S115) at removing different particle sizes (Dp) from effluents.

produced by the disc and screen filters working with Effluent 1 and, in particular, Effluent 2, volumes of particles with diameters larger than the filter pores were seen. When the sand filter was used, no such result was seen: particles with a diameter of > 45 µm were not seen in the filtrate of Effluent 1, nor were particles > 450 µm seen in that of Effluent 2.

The screen and disc filters only very slightly attenuated the particle volume distribution of Effluent 3 (which was obtained by filtering Effluent 2 with sand; effective grain size 0.65 mm). Only the filtrate produced by the 98 µm screen filter showed a larger volume of particles in the 100-200 µm diameter interval than that found in the initial effluent. This was also observed when the filtration efficiency was studied with respect to the particle size distribution.

The 130 µm disc filter and 130 µm screen filter retained particle volumes from a diameter of 30 µm when Effluent 4 was filtered. This effluent had few particles with larger dimensions; the filters were therefore more effective at filtering this effluent than the others.

Finally, the 130 µm screen only released a larger volume of particles in the 15-20 µm diameter interval than that seen in the original Effluent 5 (data not shown). For the other particle diameters, the volume of filtrate

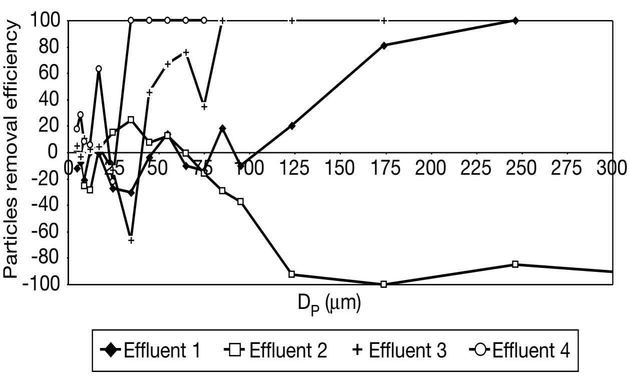

Figure 2. Efficiency of a 130 µm disc filter (D130) at removing different particle sizes (Dp) from effluents.

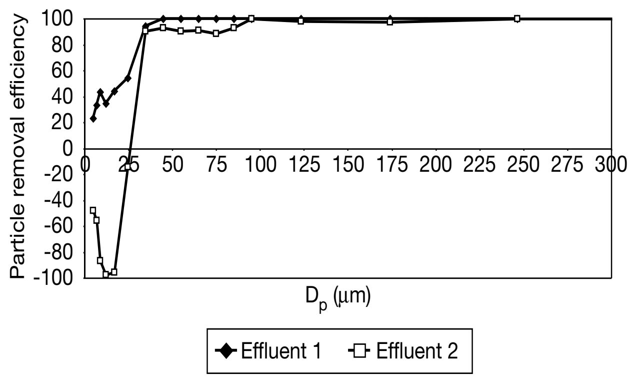

Figure 4. Efficiency of sand filter at removing different particle sizes (Dp) from Effluents 1 and 2.

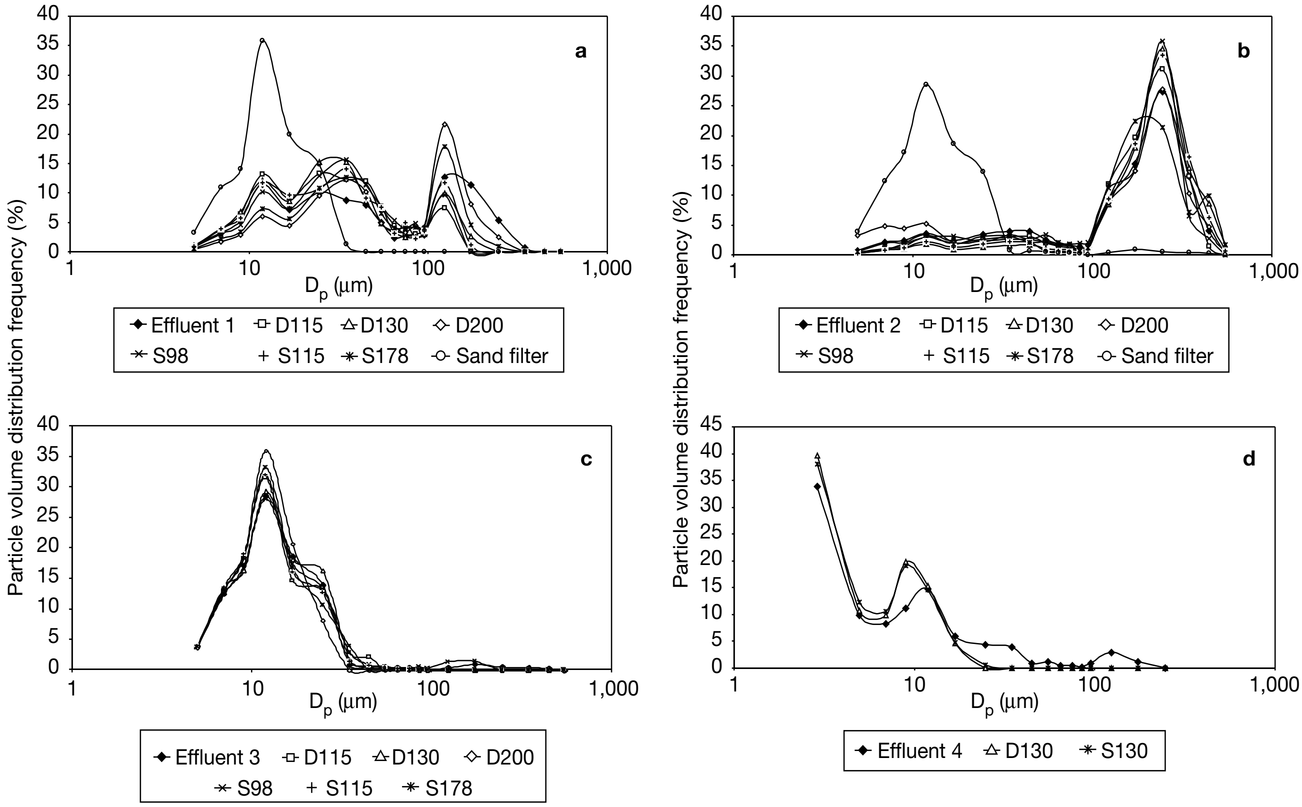

Figure 5. Mean particle volume distributions of Effluent 1 (a), 2 (b), 3 (c) and 4 (d) before and after filtration with a 115 µm (D115), 130 µm (D130) and 200 µm (D200) disc filter, 98 µm (S98), 115 µm (S115) and 178 µm (S178) screen filter, and a sand filter with an effective grain size of 0.65 mm.

particles was slightly smaller than those obtained with the other effluents.

Discussion

The mean particle size distribution results obtained agree with those reported by Ravina *et al.* (1995), who found that, in irrigation effluents, 98% of the suspended solids was composed of particles with a diameter of < 100 µm. Adin and Elimelech (1989) found that more than the 90% of the particles of reservoir effluents had a diameter < 10 µm.

The superposition observed in the mean particle size distributions was due to particles with a diameter of < 10 µm not usually being retained by the filters (Adin and Elimelech, 1989). In fact, in all the analysed filtrates there were large numbers of particles of this size.

In all effluents, most of the particles were smaller than the filter pores, but the filters still became clogged; this was also observed by Adin and Alon (1986). The particle size distribution only shows the number of particles present, it does not take into account the volume of particles that can clog a filter or emitter.

The greater reduction in the number of particles and TSS achieved by the sand filter (compared to the disc and screen filters) when using Effluent 1 agreed with that reported by Tajrishy *et al.* (1994). In most of cases, the reductions achieved in TSS with the different effluents were not great with the screen and disc filters; this agrees with the results of other authors (Adin and Elimelech, 1989; Ravina *et al*., 1997). Nevertheless, it is surprising that the efficiency of the screen filters (compared to the disc filters) in reducing both the TSS and the number of particles was slightly higher with Effluent 1. Theoretically, disc filters should, of course, retain more solids than screen filters. The thicker filtration cake formed in the screen filters may have played an important role in this. The better performance of screen filters with some effluents can reduce emitter clogging (Puig-Bargués *et al.*, 2003) .

An increase was seen in suspended solids but not in the number of particles at the outlet of most of the disc and screen filters when using Effluent 3. The greater quantities of solids at the filter exits, shown by their negative efficiency, were probably due to their detachment from the filter cake, as observed by Adin and Alon (1986). When biological particles are retained in the filter and the pressure increases, these particles can become deformed and pass through.

Poor agreement was observed between the TSS and particle removal efficiencies. The explanation might be that all the particles were counted to determine their number, but to determine TSS a 2 µm filter was used to retain the suspended solids. Thus, the small particles —the most numerous— were not taken into account in the TSS analysis.

Although the particle removal efficiencies describes what happens with all the particles together, it is important to know whether filters can retain particles of all diameters. The particle removal efficiencies varied for each particle diameter and effluent. Thus, there was no diameter of particle that was specifically retained by the same filter when different effluents were used. Once hydraulic problems in the filters are discarded, the negative filter efficiencies seen with Effluent 2 can only be explained by the presence of a weak particle aggregate. If this aggregate were retained on a disc or screen filter, a soft filtration cake would be formed, unlike that produced by Effluent 1. As head losses in the filters became higher during the filtration cycle, the filter inlet pressure would increase and the filtration cake would break into small particles that could pass through the filter and later regroup, as indicated by Adin and Alon (1986). Neis and Tiehm (1997) indicate that there are some effluents with particles that are less resistant to deformation than others, so aggregate breaking may occur often. Tiehm *et al.* (1999) found that the particle diameter was smaller in secondary effluents than in primary effluents, which might explain the poor filtering performance with Effluent 2. Nevertheless, no such problem was seen with the other secondary or tertiary effluents (Effluents 3, 4 and 5).

The poor performance of the disc and screen filters with Effluent 2 was determined by analysing their efficiency in removing different sized particle, not by studying their efficiency in removing all particles. Since the filters retained some of the small particles (the most numerous), the particle removal efficiency was positive and no information was provided on particle release.

The results of this study do not agree with those of Arnó (1990), who reported that the screen filter to provide the best performance for filtering sand particles with a diameter of between 200 and 300 µm was the 130 µm filter. For sand particles with a diameter of between 80 and 200 µm, the best were the 80 µm and 100 µm screen filters. The results of the present paper were obtained in field conditions and working with effluents that had inorganic and organic particles; these might have more irregular shapes than sand particles, making their retention more difficult.

All the fits of the particle size distributions to equation [1] (Table 3) were significant and showed high regression coefficients. This confirms the validity of the model when unimodal particle size distributions are used; similar findings have been reported by other authors (Lawler *et al.*, 1980; Adin and Elimelech, 1989; Alon and Adin, 1994; Kaminski *et al.*, 1997; Van der Graaf *et al.*, 2001).

Kaminski *et al.* (1997) showed a better fit for the filtrate than the filter influent with respect to the potential law since the ratio between the entry and exit particle distribution changed during filtration. However, the results of Table 3 show no better adjustments for the filtrate particle size distribution.

The α coefficients of the effluents and filtrates were similar; in fact only the filtrates produced with the 130 µm disc filter and the sand filters had different values when Effluent 1 was used. This means that the number of particles in the sand filter filtrate was smaller than in the 130 µm disc filtrate, as shown by the particle removal efficiency. For this effluent, no differences were seen between the filtrate produced by the sand filter and that of the other disc and screen filtrates.

The exponent β values for Effluents 1, 2 and 3 were between 2.2 and 2.6, clearly lower than those for Effluents 4 and 5 (3.6 and 4.1 respectively). These β values are similar to those reported by Lawler *et al.* (1980) who worked with secondary effluents obtained from a sludge process (between 2.2 and 4.7), and Van der Graaf *et al.* (2001) ($\beta = 2.75$, also with secondary effluents). Neis and Tiehm (1997), however, reported values equal to or lower than 1. The higher β values for Effluents 4 and 5 indicate a smaller presence of particles with larger diameters.

The fact that the β exponents of the filtrates were not significantly different from those of the effluents indicates that the filters do not retain the particles. Despite the strong variation, there was only a tendency for β to decrease with all filters when Effluent 2 was used. This shows that there were particles with large diameters present in the filtrate as a result of the aggregation of particles of smaller size (Kaminski *et al.*, 1997; van der Graaf *et al.*, 2001), as mentioned above for Effluent 2. Nevertheless, the β value increased for most of the filtrates of Effluents 1, 3 and 4, showing that the filters retained the larger diameter particles.

The particle volume distributions showed whether the particles larger than the filter pores were present in the filtrates of Effluents 1, 2 and 3. This gives more useful information about the performance of the filters than does the particle size distribution alone.

The particle volume distribution was multimodal for most of the effluents. As reported by Tajrishy *et al.* (1994), in this multimodal distribution there were two particle diameters with the highest particle volume frequencies. Tajrishy *et al.* (1994) verified that in a granular filtration medium of 0.45 mm effective grain size, particles of around 40 µm were removed, causing an increase in the 1 µm and 35 µm diameter particles in the particle size distribution. Although the particle diameter interval considered in the present study was wider, the results obtained with the sand filter confirmed this tendency; with a particle diameter from 40 µm upwards, the particle diameter volume decreased with respect to the initial effluent. The validity of this observation is corroborated by Adin (1999), who affirms that, independent of the effective sand grain size, there is practically no difference in the removal of particles with a diameter 10-60 µm. The removal of particles with these diameter intervals is of health interest since it could include helminth eggs (diameter 20- 80 µm) (Landa *et al.*, 1997).

Acknowledgements

The authors would like to acknowledge the Spanish Ministry of Science and Technology for the financial support of this work (REN2000-0642/HID and REN2002-00690/HID), and the *Consorci de la Costa Brava*, Dargisa, Girona WWTP and the Castell-Platja d'Aro WWTP for their assistance.

References

ADIN A., 1987. Clogging in irrigation systems reusing pond effluents and its prevention. Water Sci Technol 19(12), 323-328.

ADIN A., 1999. Particle characteristics: a key factor in effluent treatment and reuse. Water Sci Technol 40(4-5), 67-74.

ADIN A., ALON G., 1986. Mechanisms and process parameters of filter screens. J Irrig Drain E-ASCE 112(4), 293-304.

ADIN A., ELIMELECH M., 1989. Particle filtration for wastewater irrigation. J Irrig Drain E-ASCE 115(3), 474-487.

ADIN A., RUBINSTEIN L., ZILBERMAN A., 1989. Particle characterization in wastewater effluents in relation to filtration and irrigation. Filtr Separat 26, 284-287.

ALON G., ADIN A., 1994. Mathematical modeling of particle size distribution in secondary effluent filtration. Water Environ Res 66(6), 836-841.

ARNÓ J., 1990. Obturación física en filtros de malla. Comportamiento hidrodinámico y aplicación a la tecnología del riego localizado. Master's Thesis. Universitat Politècnica de Catalunya, Lleida, 164 pp.

BOLLER M., KOBLER D., KOCH G., 1997. Particle separation, solids budgets and headloss development in different biofilters. Water Sci Technol 36(4), 239-247.

HATUKAI S., BEN-TZUR Y., REBHUN M., 1997. Particle counts and size distribution in system design for removal of turbidity by granular deep bed filtration. Water Sci Technol 36(4), 225-230.

KAMINSKI I., VESCAN N., ADIN A., 1997. Particle size distribution and wastewater filter performance. Water Sci Technol 36(4), 217-224.

KOBLER D., BOLLER M., 1997. Particle removal in different filtration systems for tertiary wastewater treatment - a comparison. Water Sci Technol 36(4), 259-267.

LANDA H., CAPELLA A., JIMÉNEZ B., 1997. Particle size distribution in an effluent from an advanced primary treatment and its removal during filtration. Water Sci Technol 36(4), 159-165.

LAWLER D.F., 1997. Particle size distribution in treatment processes: theory and practice. Water Sci Technol 36(4), 15-23.

LAWLER D.F., O'MELIA C.R., TOBIASON J.E., 1980. Integral water treatment plant design from particle size to plant performance. In: Particulates in water (Kavanaugh M.C., Leckie J.O., eds). American Chemical Society, Washington DC. pp. 353-388.

McDONALD D.R., LAU L.S., WU I.P., GEE H.K., YOUNG S.C.H., 1984. Improved emitter and network system design for wastewater reuse in drip irrigation. Technical Report No. 163. Water Resources Research Center, Honolulu, Hawaii, 87 pp.

NEIS U., TIEHM A., 1997. Particle size analysis in primary and secondary waste water effluents. Water Sci Technol 36(4), 151-158.

ORON G., SHELEF G., TRUZYNSKI B., 1979. Trickle irrigation using treated wastewaters. J Irrig Drain Div 105(IR2), 175-126.

PUIG-BARGUÉS J., ARBAT G., BARRAGÁN J., RAMÍREZ DE CARTAGENA F.. 2003. Hydraulic performance of drip irrigation subunits using WWTP effluents. Proc. VI Inter-Regional Conference on Environment-Water, Albacete, Spain. September 3-5. pp. 97-98.

RAVINA I., PAZ E., SAGI G., SCHISCHA A., MARCU A., YECHIELY Z., SOFU Z., LEV Y., 1995. Performance evaluation of filters and emitters with secondary effluent. Proc. V Intnl Microirrigation Congress, Orlando, Florida, April 2-6. pp. 244-249.

RAVINA I., PAZ E., SOFER Z., MARCU A., SCHISCHA A., SAGI G., YECHIALY Z., LEV Y., 1997. Control of clogging in drip irrigation with stored treated municipal effluent. Agric Water Manage 33(2-3), 127-137.

SAS, 1999. SAS/STAT User's Guide, Version 8. Volumes 1, 2 and 3. SAS Institute Inc., Cary, NC, USA, 3848 pp.

TAJRISHY M.A., HILLS D.J., TCHOBANOGLOUS G., 1994. Pretreatment of secondary effluent for drip irrigation. J Irrig Drain E-ASCE 120(4), 716-731.

TIEHM A., HERWIG V., NEIS U., 1999. Particle size analysis for improved sedimentation and filtration in waste water treatment. Water Sci Technol 39(8), 99-106.

VAN DER GRAAF J.H.J.M., DE KONING J., TANG J., 2001. Particle size analysis as a tool for performance measurements in high rate effluent filtration. Water Sci Technol 43(10), 303-310.