BIOSYSTEMS ENGINEERING 106 (2010) 521–526

Available at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Assessment of head loss equations developed with dimensional analysis for micro irrigation filters using effluents

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ARTICLE INFO

Article history:
Received 25 March 2010
Received in revised form
27 May 2010
Accepted 1 June 2010
Published online 2 July 2010

Several equations have been developed using dimensional analysis to determine the head loss in the filters commonly used in micro irrigation systems. The variables included in these existing equations were established using dimensional analysis and Buckingham's theorem. A filtration experiment using effluents with sand, screen and disc filters was carried out for up to 2000 h to obtain data to enable the developed equations to be correlated. A new equation that included head loss, filtration velocity, concentration of total suspended solids (TSS) in the filter influent, water density and viscosity, and inside diameter of the inlet and outlet pipes as variables showed similar and satisfactory predictions to as previously developed equations that required the use of more variables.

1. Introduction

Appropriate filtration is essential for the successful operation of irrigation systems because it helps prevent emitter clogging caused by organic and inorganic particulate matter (Ayars, Bucks, Lamm, & Nakayama, 2007). Filtration is particularly important when effluents are applied through micro irrigation systems because effluents result in increased clogging hazards due to their generally greater salt, nutrient, solids and biological concentrations (Trooien & Hills, 2007). The three common filter types used in micro irrigation systems are screen, disc and sand media filters. Sand media filters are often considered the standard for filtration protection of micro irrigation systems (Trooien & Hills, 2007). However, disc filters, if properly designed, can perform at levels similar to those of sand media filters (Capra & Scicolone, 2007).

Although filter performance in micro irrigation systems using effluents has been studied by a number of authors (Adin & Elimelech, 1989; Capra & Scicolone, 2007; Duran-Ros, Puig-Bargués, Arbat, Barragán, & Ramírez de Cartagena, 2009a, 2009b; Puig-Bargués, Barragán, & Ramírez de Cartagena, 2005a; Ravina et al., 1997; Ribeiro, Paterniani, Airoldi, & Silva, 2008; Tajrishy, Hills, & Tchobanoglous, 1994), equations to predict head loss in the filters commonly used in such systems are not widely available. The few that are those developed by Puig-Bargués, Barragán, and Ramírez de Cartagena (2005b) and Yurdem, Demir, and Degirmencioglu (2008, 2010) through dimensional analysis using Buckingham's pi-theorem.

Puig-Bargués et al. (2005b) found the following equation useful for disc, screen and sand filters working with effluents and adjusted it to provide satisfactory performance using experimental data:

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doi:10.1016/j.biosystemseng.2010.06.001

Nomenclature

a	empirical coefficient, dimensionless
A	total filtration surface, m^2
A_i	inflow area where the inlet pipe intersects with the body of the filter, m^2
b	empirical coefficient, dimensionless
c	empirical coefficient, dimensionless
C	concentration of total suspended solids (TSS) in the filter influent, kg m^{-3}
CV	variation coefficient, dimensionless
d_i	inside diameter of the filter disc, m
d_o	outside diameter of the filter disc, m
D_b	inside diameter of the filter body, m
D_p	inside diameter of the inlet and outlet pipe, m
e	empirical exponent, dimensionless
Eu	Euler number, dimensionless
L_f	effective length of the filter disc group, m
P_d	mean diameter of effluent particle size distribution, m
Q	flow rate across the filter, $m^3\ s^{-1}$
R^2	regression coefficient, dimensionless
Re	Reynolds number, dimensionless
$RMSE$	root mean square error, dimensionless
υ_f	filtration velocity, m s^{-1}
υ_i	water velocity at the inlet pipe, m s^{-1}
V	water volume across the filter, m^3
ΔH	total head loss, Pa
μ	water viscosity, Pa s
ρ	water density, kg m^{-3}
Φ_f	filtration level, m
υ	kinematic viscosity, $m^2\ s^{-1}$

$$\frac{\mu}{\Delta H^{\frac{1}{4}}\cdot Q^{\frac{1}{2}}\cdot C^{\frac{3}{4}}}=a\bullet\left(\frac{\Delta H^{\frac{3}{4}}\bullet V}{C^{\frac{3}{4}}\bullet Q^{\frac{3}{2}}}\right)^{e_1}\bullet\left(\frac{\Delta H^{\frac{1}{2}}\bullet A}{C^{\frac{1}{2}}\bullet Q}\right)^{e_2}\bullet\left(\frac{\Delta H^{\frac{1}{4}}\bullet \phi_f}{C^{\frac{1}{4}}\bullet Q^{\frac{1}{2}}}\right)^{e_3}\bullet\left(\frac{\Delta H^{\frac{1}{4}}\bullet P_d}{C^{\frac{1}{4}}\bullet Q^{\frac{1}{2}}}\right)^{e_4}\left(\frac{\rho}{C}\right)^{e_5} \tag{1}$$

where μ is the water viscosity in Pa s, ΔH is the total head loss across the filter in Pa, Q is the flow rate across the filter in $m^3\ s^{-1}$, C is the concentration of total suspended solids (TSS) in the filter influent in kg m^{-3}, V is the water volume across the filter in m^3, A is the total filtration surface in m^2, Φ_f is the filtration level or filter pore in m, P_d is the mean diameter of effluent particle size distribution in m, ρ is the water density in kg m^{-3}, a is an empirical coefficient and e_1, e_2, e_3, e_4 and e_5 are empirical exponents that take different values for each filter type.

Yurdem et al. (2008), on the other hand, developed the following equation to compute head loss in disc filters with different geometries working with freshwater:

$$\frac{\Delta H}{\rho\bullet\upsilon_i^2}=28.7872\bullet\left(\frac{\upsilon_i\bullet D_p}{\upsilon}\right)^{-0.3196}\bullet\left(\frac{d_o}{d_i}\right)^{9.3784}\bullet\left(\frac{A_i}{D_b\bullet L_f}\right)^{-1.1584}\bullet\left(\frac{D_b}{d_o}\right)^{0.6699}\bullet\left(\frac{D_p}{L_f}\right)^{3.2139}\cdot\left(\frac{L_f}{D_b}\right)^{2.2383} \tag{2}$$

where υ_i is the water velocity at the inlet pipe in m s^{-1}, D_p is the inside diameter of the inlet and outlet pipe in m, υ is the kinematic viscosity in $m^2\ s^{-1}$, d_0 is the outside diameter of the filter disc in m, d_i is the inside diameter of the filter disc in m, A_i is the inflow area where the inlet pipe intersects with the body of the filter in m^2, D_b is the inside diameter of the filter body in *m* and L_f is the effective length of the filter disc group in *m*.

The difference between the above two equations is that Puig-Bargués et al. (2005b) introduced effluent quality parameters to filter head loss, while Yurdem et al. (2008) focused on filter geometry because they worked with freshwater.

As there is no agreement about which variables are relevant, and should be used to develop equations, the objective of this study was to assess the validity of the equations developed by Puig-Bargués et al. (2005b) and Yurdem et al. (2008) with new data, and to develop and analyse the feasibility of generating further equations also using dimensional analysis.

2. Materials and methods

2.1. Experimental set-up

A filtration bank (Fig. 1) with three filtration systems was used to carry out the experiments with the effluents from the wastewater treatment plant (WWTP) of Celrà (Girona, Spain), which treats urban and industrial wastewater using a sludge process. The first filtration system consisted of one screen filter (Arkal Filtration Systems, Jordan Valley, Israel) with a 50.8 mm inlet diameter, a 110 000 mm^2 filtration surface and a 120 μm filtration level. The second system was formed by two disc filters (Arkal Filtration Systems, Jordan Valley, Israel) operated in parallel, both with 50.8 mm inlet diameters, a filtration surface of 94 000 mm^2 and a filtration level of 130 μm. The third filtration system was formed by two sand filters (Regaber, Parets del Vallès, Spain) in parallel, with a 50.8 mm inlet diameter and 196 300 mm^2 of filtration surface. The filters operated at two different inlet pressures: 300 kPa and 500 kPa.

For the experiments at 300 kPa, the sand filters were each filled with 175 kg of sand with an effective sand media size

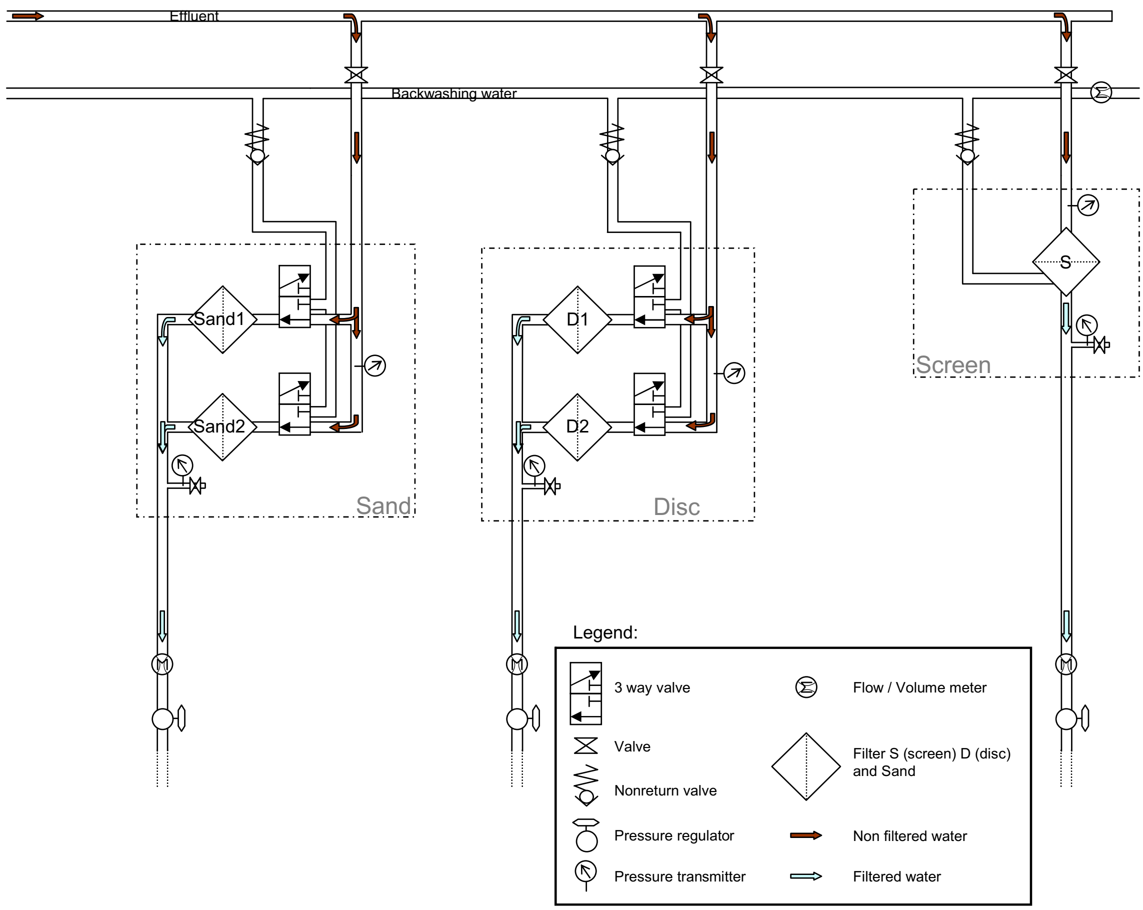

Fig. 1 – Hydraulic scheme of the filtration bank and location of monitoring and control equipment.

(the size opening that will pass 10% by dry weight of a representative sample of the filter material (AWWA, 2001)) of 0.40 mm, and a sand uniformity coefficient (the ratio of the size opening that will pass 60% of the sand to the size opening that will pass 10% (AWWA, 2001)) of 2.41. After 1000 h of operation when the experiments at this pressure ended, the sand media was replaced according to the filter manufacturer's instructions. The new sand that was supplied had an effective size of 0.27 mm and a uniformity coefficient of 2.89.

Filters were controlled by two different filter backwashing programmers. A Filtron 246 2 DC (Talgil, Kiryat Motzkin, Israel) was used for screen filters, while a Reg 8 Plus (Regaber, Parets del Vallès, Spain) with a Cas 155 (Danfoss, Nordborg, Denmark) differential pressure switch was used for the disc and sand filters.

An MBS 4010 (Danfoss, Nordborg, Denmark) pressure transmitter with flush diaphragm (±0.3% accuracy) measured the pressure at the inlet and outlet of each filtration system. The flow at the filter outlets was measured by an MP-400-CB (Comaquinsa, Llinars del Vallès, Spain) electromagnetic flowmeter (±1% accuracy). The location of these sensors is shown in Fig. 1. These devices were connected to a supervisory control and data acquisition (SCADA) system, which allowed for filter scheduling and also filter data performance to be collected every minute (Duran-Ros, Puig-Bargués, Arbat, Barragán, & Ramírez de Cartagena, 2008).

2.2. *Operational procedure*

Two experiments were carried out, both lasting 1000 h. In the first experiment, the inlet filter pressure was 300 kPa while in the second it was 500 kPa. During the first experiment each filtration system operated during two 6 h periods per day while in the second they worked 7 h per day during the working week (Monday to Friday) and for two 6 h periods over the weekend (Saturday and Sunday) and holidays. Before the start of the second experiment, all screens and discs were cleaned with pressurised freshwater and submerged for 8 h in a solution of 5% NaOCl, while, as previously mentioned, the sand of the media filters was replaced. In both experiments the working time was scheduled so that each filtration system operated at different times of the day. Thus, any hourly variation in effluent parameters did not always affect the same filtration unit.

Filters were cleaned automatically by backwashing when the head loss across the filter exceeded 50 kPa (Ravina et al., 1997) for more than 2 min.

Effluent samples were taken twelve times in the first experiment and ten times in the second at each filter inlet to determine the physical parameters required by head loss equations. Samples were taken during the 15 min after filter backwashing took place. TSS were determined in the laboratory by weighing the solids retained in a glass fibre filter in line with the Spanish Standard UNE-EN 872 (AENOR, 1996). The number of particles was analysed using a Galai Cis 1 (Galai, Migdal Haemek, Israel) laser particle analyser. The range of the main experimental variables is shown in Table 1.

2.3. Obtaining new equations by dimensional analysis

The first step was to decide which variables need to be included in the equations. Because Puig-Bargués et al. (2005b) and Yurdem et al. (2008) used a number of different variables, eight were chosen as a first step and were related as follows:

$$f(\Delta H,\ \phi_f,\ A,\ C,\ \mu,\ \rho,\ \upsilon_f,\ D_p) = 0 \tag{3}$$

Three of the variables (head loss, viscosity and density) appeared in both Puig-Bargués et al. (2005b) and Yurdem et al. (2008) models, three (filtration level, filtration surface and concentration of TSS in the filter influent) only in Puig-Bargués et al. (2005b) and two (filtration velocity and internal diameter of the inlet and outlet pipes) only in Yurdem et al. (2008).

As the dimensional matrix had a range of 3, according to Buckingham's method, five different dimensionless π terms were obtained:

$$\pi_1 = \frac{\Delta H}{\rho \cdot \upsilon_f^2} = Eu \tag{4}$$

$$\pi_2 = \frac{\rho \cdot \upsilon_f \cdot D_p}{\mu} = \mathrm{Re} \tag{5}$$

$$\pi_3 = \frac{\phi_f}{D_p} \tag{6}$$

$$\pi_4 = \frac{A}{D_p^2} \tag{7}$$

$$\pi_5 = \frac{C}{\rho} \tag{8}$$

Two of these π terms should be highlighted. π_1 is the Euler number (Eu), which relates inertial forces with pressure forces, and π_2 is the Reynolds number (Re), which relates inertial and viscous forces.

Using this group of dimensional numbers the following equation developed was:

$$\frac{\Delta H}{\rho \cdot \upsilon_f^2} = b\left(\frac{\rho \cdot \upsilon_f \cdot D_p}{\mu}\right)^{e_6} \cdot \left(\frac{\phi_f}{D_p}\right)^{e_7} \cdot \left(\frac{A}{D_p^2}\right)^{e_8} \cdot \left(\frac{C}{\rho}\right)^{e_9} \tag{9}$$

where b is an empirical coefficient and e_6, e_7, e_8, and e_9, are empirical exponents.

The following new relationship appeared when two variables (filtration level (Φ_f) and filtration surface (A)) were removed in Eq. (3):

$$f(\Delta H,\ C,\ \mu,\ \rho,\ \upsilon_f,\ D_p) = 0 \tag{10}$$

Again using Buckingham's method, the following π terms were found:

$$\pi_6 = \frac{\rho}{C} \tag{11}$$

$$\pi_7 = \frac{\upsilon_f \cdot C^{\frac{1}{2}}}{\Delta H^{\frac{1}{2}}} \tag{12}$$

$$\pi_8 = \frac{\mu}{\Delta H^{\frac{1}{2}} \cdot C^{\frac{1}{2}} \cdot D_p} \tag{13}$$

With this group of dimensionless numbers a potential relation was obtained:

$$\frac{\upsilon_f \cdot C^{\frac{1}{2}}}{\Delta H^{\frac{1}{2}}} = c \cdot \left(\frac{\rho}{C}\right)^{e_{10}} \cdot \left(\frac{\mu}{\Delta H^{\frac{1}{2}} \cdot C^{\frac{1}{2}} \cdot D_p}\right)^{e_{11}} \tag{14}$$

where c is an empirical coefficient and e_{10} and e_{11} are empirical exponents.

2.4. Statistical analyses

Data from the filtration experiments were recorded each minute by the SCADA system. However, only data from filtration cycles that came after efficient backwashing, which were those that produced an initial head loss acceptable for a clean filter and allowed a normal filtration cycle, as described by Duran-Ros et al. (2009b), were considered in this study. The duration of the experiments and the high number of efficient backwashings, meant there were 130, 215 and 462 filtration cycles for the screen, disc and sand filters, respectively, giving 37 440, 52 625 and 64 925 experimental points to be recorded for the same filters.

Data from the physical parameters of the water were used to calculate the different dimensionless groups found by Puig-Bargués et al. (2005b), Yurdem et al. (2008) (obtained only for disc filters) and the new ones obtained in this paper. These groups were statistically correlated with Eqs. (1), (2), (9) and (14) using the regression procedure (REG) of the SAS statistical package (SAS Institute, Cary, NC, USA).

Table 1 – Range (minimum and maximum values) of the main variables during the experiment.

Variable	Sand filter	Disc filter	Screen filter
Flow Q ($m^3\ s^{-1}$)	0.0021–0.0025	0.0020–0.0026	0.0020–0.0026
TSS C ($kg\ m^{-3}$)	0.0044–0.0180	0.0032–0.0180	0.0032–0.0180
Filtered volume V (m^3)	0.13–102.84	0.11–141.00	0.12–210.28
Mean diameter of effluent particle P_d (μm)	2.54–3.64	2.62–8.02	2.62–3.89
Filtration velocity υ_f ($m\ s^{-1}$)	0.0054–0.0064	0.0108–0.0136	0.0184–0.0233
Water velocity υ_i ($m\ s^{-1}$)	–	1.0032–1.2568	–
Reynolds number	275–324	548–687	933–1179
Euler number	421 174–1 750 933	93 499–349 636	19 121–153 321

Table 2 – Regression coefficients, significance levels, variation coefficients CV (%) and RMSE for the correlations of different equations for each filter.

Filter type	Equation	R^2	CV (%)	RMSE
Sand	(1)	0.998***	0.439	0.012
	(2)	–	–	–
	(9)	0.245***	1.486	0.206
	(14)	0.996***	0.133	0.017
Disc	(1)	0.988***	1.255	0.036
	(2)	0.008***	7.698	0.250
	(9)	0.193***	1.830	0.225
	(14)	0.987***	0.293	0.035
Screen	(1)	0.979***	1.461	0.039
	(2)	–	–	–
	(9)	0.056***	3.631	0.400
	(14)	0.984***	0.349	0.040

*** Probability $P < 0.001$.

3. Results and discussion

The results of the correlations with experimental data using Eqs. (1) (Puig-Bargués et al., 2005b) and (2) (Yurdem et al., 2008) and the newly developed Eqs. (9) and (14), are presented in Table 2. Equations (1) and (14) had the highest regression coefficients ($R^2 > 0.979$) and the smallest variation coefficients (CV) (<1.46%) and the lowest root mean square error (RMSE) (<0.040). The differences between Eqs. (1) and (14) for these goodness of fit indicators were minimal. Moreover the correlations did not show any obvious pattern in the residual plots.

Table 3 shows the empirical values of Eq. (1) obtained by Puig-Bargués et al. (2005b) and the correlated values under the experimental conditions of this paper. Regression coefficients for Eq. (1) adjusted with data obtained in this experiment were slightly greater, with increases of 0.155, 0.061 and 0.127 for sand, disc and screen filters, respectively. CV were between 5.26 and 29.86% smaller.

The lost of significance of some of the π terms from Eq. (1) is also shown in Table 3. There was greater variability in the Puig-Bargués et al. (2005b) experiment because they correlated their equation using different effluents and different filtration levels. Exponent e_3 obtained in disc and screen filters was 0 because only one filtration level had been tested, so this π term was constant in the assay. If π terms with exponents e_1, e_3 and e_4 are excluded, the fitting goodness is almost the same with maximum reductions of R^2 of 0.001 and maximum increases of CV of 0.157 and RMSE of 0.005. On the other hand, flows registered during the experiments were higher (2 l s^{-1}) than flows registered by Puig-Bargués et al. (2005b) (0.25–1.1 l s^{-1}). This could explain some of the differences observed.

Table 3 – Comparison between coefficient and exponents of Eq. (1) for disc, screen and sand filters obtained by Puig-Bargués et al. (2005b) and those obtained in this work.

Filter type	Coefficient a	Exponents Puig-Bargués et al. (2005b)				
		e_1	e_2	e_3	e_4	e_5
Disc	4.81×10^{-6}	−0.2103	0.6696	0.6492	−0.1157	0.6718
Screen	1.10×10^{-6}	−0.1745	0.7378	0.7217	−0.1879	0.6122
Sand	8.61×10^{-8}	−0.1402	0.8112	0.6895	−0.1848	0.5248
Filter type	Coefficient a	New exponents obtained				
Disc	1.99×10^{-4}	−0.0054	−0.4386	0.0000	−0.0047	0.9371
Screen	4.35×10^{-4}	−0.0008	−0.4797	0.0000	0.0327	0.9019
Sand	3.60×10^{-4}	−0.0051	−0.4598	0.0775	0.0215	0.9591

Table 4 – Empirical coefficient and exponents of Eq. (14) for disc, screen and sand filters.

Filter type	Coefficient	Exponents	
	c	e_{10}	e_{11}
Disc	212.18	−0.9433	0.9334
Screen	386.25	−0.9154	0.9929
Sand	270.58	−0.9870	1.0053

Equations (2) and (9) did not present an acceptable improvement and there was a structural pattern in the residual plots. The reason for the poor performance of Eq. (2) could be that this equation was developed with many geometrical variables, while our experiment was carried out with only one type of disc filter which did not contribute to variability. This meant that the dimensionless numbers in Eq. (2) were constant during the whole experiment and this led to zero being made the exponents of this equation. Yurdem et al. (2008) worked with a greater range of flow (1.25–20.39 l s^{-1}) than the almost constant flow of 2 l s^{-1} under which the present experiment was conducted. It should be pointed out that Yurdem et al. (2008) adjusted their equation using experimental data with freshwater, not with effluents. According to the results, it would seem necessary to consider the parameters of filtered water such as TSS, if they contribute to filter head loss, as effluent and irrigation water with an important particle load (Adin & Elimelech, 1989). When freshwater is used, other equations such as that of Yurdem et al.(2008) can be used for disc filters with reasonable accuracy as these parameters have little effect on filter head loss.

Equation (9) was developed because it includes both Eu and Re; they are similarly used in Yurdem's equation. When disc filters were used, Eu varied between 93 499 and 349 636 (Table 1). These values are within the range (19 005–361 310) studied by Yurdem et al. (2008). However, Re values in the experiment (548–687) were clearly higher than those in the experiment conducted by Yurdem et al. (2008) with only with disc filters (20–360), but both studies were carried out in laminar flow. However, the introduction of the Eu and Re did not achieve improved correlations for the equation tested in this paper or for other equations explored previously (Duran-Ros, 2008). Thus, Eu and Re were not considered when Eq. (14) was developed further. Table 4 shows the empirical coefficient and exponents that are necessary to use Eq. (14) for each type of filter.

According to the results, both Eqs. (1) and (14) can be used for computing head losses in disc, screen and sand filters when using effluents because they have similar goodness of fit values. The choice between equations depends on the available information about effluent characteristics. Thus, Eq. (1) requires the TSS and mean effluent particle to be determined, while Eq. (2) only needs the value of TSS.

4. Conclusions

A new equation (Eq. (14)) for computing head loss in sand, screen and disc filters for micro irrigation systems was developed using dimensional analysis. The variables involved in this equation are filtration velocity, concentration of TSS in the filter influent, total head loss, water density, water viscosity and inside diameter of the inlet and outlet pipes. Using experimental data this equation had very similar regression coefficients to the equation previously developed by Puig-Bargués et al. (2005b), which required three more variables more than the new developed equation. The results show that some physical parameters, such as concentration of TSS, need to be incorporated in the equations for describing head loss when water with particulate load or effluents are being used because they have an important effect on head loss.

Despite the good correlations obtained with some equations and the large amount of data used in to develop them, it is important to monitor water quality continuously because it is difficult to identify the typical variability of effluent characteristics.

Acknowledgements

The authors would like to express their gratitude to the Spanish Ministry of Education and Science for their financial support of this study through grants REN2002-00690/HID and CGL2005-02201/HID. The authors would also like to thank Regaber and the Municipality of Celrà for their help in carrying out this experiment.

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