Universitat de Lleida

COMPARISON BETWEEN SURFACE AND SUBSURFACE DRIP IRRIGATION SYSTEMS USING EFFLUENTS

Maha Abdelhameed Elbana

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Ph.D. Dissertation

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Ph.D. dissertation presented to the department of agroforestry engineering, School of Agricultural and Forestry Engineering, University of Lleida, Spain in partial fulfilment of the requirements of the Doctor of Philosophy degree under the direction of Dr. Jaume Puig i Bargués and Dr. Francisco Ramírez de Cartagena Bisbe

Signature of the candidate

Signatures of the thesis supervisors

Dr. Jaume Puig i Bargués **Dr. Francisco Ramírez de Cartagena Bisbe**

Signatures of the thesis advisor

Dr. Joaquin Monserrat Viscarri

If..

If you can keep your head when all about you
are losing theirs and blaming it on you;
If you can trust yourself when all men doubt you,
but make allowance for their doubting too:
If you can wait and not be tired by waiting,
or, being lied about, don't deal in lies,
or being hated don't give way to hating,
and yet don't look too good, nor talk too wise;
If you can dream---and not make dreams your master;
If you can think---and not make thoughts your aim,
If you can meet with Triumph and Disaster
and treat those two impostors just the same:
If you can bear to hear the truth you've spoken
twisted by knaves to make a trap for fools,
or watch the things you gave your life to, broken,
and stoop and build'em up with worn-out tools;
If you can make one heap of all your winnings
and risk it on one turn of pitch-and-toss,
and lose, and start again at your beginnings,
and never breathe a word about your loss:
If you can force your heart and nerve and sinew
to serve your turn long after they are gone,
and so hold on when there is nothing in you
except the Will which says to them: "Hold on!"
If you can talk with crowds and keep your virtue,
or walk with Kings---nor lose the common touch,
If neither foes nor loving friends can hurt you,
If all men count with you, but none too much:
If you can fill the unforgiving minute
With sixty seconds' worth of distance run,
Yours is the Earth and everything that's in it,
and---which is more---you'll be a Man, my son!

By Rudyard Kipling

For you Tamer, and to all my lovely family

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Maha Elbana

Resum

Els sistemes de reg per degoteig es consideren com un mètode apropiat per a la reutilització d'aigües regenerades, ja que disminueixen els riscos sanitaris. No obstant això, el problema més important en l'aplicació dels efluents en els sistemes de reg localitzat és l'obturació dels filtres i degoters, el que disminueix la uniformitat de distribució del aigua. L'objectiu principal d'aquesta tesi doctoral va ser comparar el comportament hidràulic d'un sistema de reg per degoteig superficial (DI) i un d'enterrat (SDI) aplicant un efluent terciari amb tres freqüències de rentat dels laterals (sense rentat, un rentat al final de cada temporada de reg i un rentat mensual) amb dos tipus d'emissors (autocompensant i no autocompensant). Altres objectius han estat investigar la influència de la qualitat de l'efluent en el procés de filtració i calcular la pèrdua de càrrega i la durada dels cicles de filtració en el filtre de sorra mitjançant l'anàlisi dimensional.

Els resultats van demostrar que la durada del cicle de filtració va dependre principalment de la qualitat de l'efluent aplicat i del diàmetre efectiu de la sorra utilitzada. També es va constatar que l'eficàcia del procés de filtració va ser deguda al diàmetre efectiu de la sorra del filtre i que quan menor va ser el diàmetre efectiu de la sorra utilitzada, més eficaç va ser la filtració. L'anàlisi dimensional va ajudar a desenvolupar un model matemàtic per a descriure la pèrdua de càrrega en el filtre amb un alt coeficient de determinació ajustat i una bona distribució del residus. A més, es va trobar que el cabal del lateral va dependre significativament del tipus de degoter, sistema de reg, la temporada de reg i la freqüència de neteja. En el sistema de DI, el cabal de l'emissor no autocompensant es va incrementar significativament durant l'experiment a causa d'un desgast de l'emissor i es va disminuir significativament en el sistema de SDI degut a l'obturació del degoters. El cabal del degoter autocompensant va augmentar durant l'experiment en els sistemes de DI i SDI. També es va observar que la causa principal de l'obturació de l'emissor en el sistema de DI va ser el desenvolupament de biofilm, mentre que en el SDI es va correspondre a una combinació de factors biològics i físics. Finalment, es va trobar que rentar els laterals una sola vegada al final de cada temporada de reg va ser la millor opció de maneig per assolir la major eficiència de distribució de l'aigua després de 1620 h de reg, tant en DI com SDI.

Resumen

Los sistemas de riego por goteo se consideran como un método apropiado para la reutilización de aguas regeneradas, ya que disminuyen los riesgos sanitarios. Sin embargo, el problema más importante en la aplicación de los efluentes en sistemas de riego localizado es la obturación tanto de filtros como de goteros, lo que disminuye la uniformidad de distribución del agua. El objetivo principal de esta tesis doctoral es comparar el comportamiento de un sistema de riego por goteo superficial (DI) y otro enterrado (SDI) aplicando un efluente terciario con tres frecuencias de lavado de los laterales (sin lavado, un lavado al final de cada temporada de riego y otro mensual) con dos tipos de emisores (autocompensante y no autocompensante). Otros objetivos fueron investigar la influencia de la calidad del efluente en el proceso de filtración y calcular la pérdida de carga y la duración de los ciclos de filtración en filtro de arena mediante el análisis dimensional.

Los resultados demostraron que la duración del ciclo de filtración dependió principalmente de la calidad del efluente aplicado y del diámetro efectivo de la arena utilizada. También se constató que la eficacia del proceso de filtración fue debida al diámetro efectivo de la arena del filtro, pues cuanto menor era el diámetro efectivo de la arena utilizada, más eficaz fue la filtración. El análisis dimensional ayudó a desarrollar un modelo matemático para describir la pérdida de carga en el filtro con un alto coeficiente de determinación ajustado y una buena distribución de los residuos. Además, se encontró que el caudal del lateral dependió significativamente del tipo del gotero, sistema de riego, temporada de riego y la frecuencia del lavado. En el sistema de DI, el caudal del emisor no autocompensante se incrementó significativamente durante el experimento debido a un deterioro del gotero y se disminuyó significativamente por culpa de la elevada porcentaje de los emisores obturados. El caudal del gotero autocompensante aumentó durante el experimento en los sistemas de DI y SDI. También se observó que la causa principal de la obturación del emisor en el sistema de DI fue el desarrollo de un biofilm, mientras que el de SDI se correspondió a una combinación de factores biológicos y físicos. Sin embargo, se encontró que lavar los laterales una sola vez al final de cada temporada de riego fue la mejor opción de manejo para lograr la mayor eficiencia de distribución del agua después de 1620 h de riego tanto en el sistema de riego por goteo superficial como en el enterrado.

Summary

Microirrigation is considered as an appropriate method for reclaimed wastewater reuse because it diminishes the health risks. However, the most important problem when applying reclaimed effluents in microirrigation systems is emitter and filter clogging, which lead to low system distribution uniformity. The main target of this PhD dissertation is to compare the performance of a surface (DI) and a subsurface (SDI) drip irrigation systems when applying a tertiary treated effluent under three flushing frequency (no flushing, seasonal flushing and monthly flushing) using two emitter types (pressure and non-pressure compensating). In addition, the study aimed to investigate the influence of effluent quality on the sand filtration process. Another purpose was to compute head loss across the sand media filter and time between backwashing in a sand filter media through dimensional analysis.

The results revealed that sand filtration cycle duration depended mainly on the applied effluent quality and sand filter effective diameter. It was also found that the effectiveness of filtration process was significantly due to sand effective diameter, being the smaller the effective diameter the more effective the filtration process. The dimensional analysis helped to develop a mathematical model to calculate head loss across sand filter with a high adjusted coefficient of determination and a good distribution of residuals. Besides, it was found that lateral flow rates depended significantly on emitter type, irrigation system, irrigation season and flushing frequency. In DI system, lateral flow of the non-pressure compensating emitter was significantly increased throughout the experimental time due to emitter failure and significantly decreased in SDI one due to the elevated percentage of clogged emitters. The pressure compensating emitter lateral flow was increased during the experiment for DI and SDI systems. The study, as well, showed that emitter clogging in DI system was primarily due to biological factors and in the SDI one was due to a combination of biological and physical factors. However, it was found that the seasonal flushing frequency was the best management practice for achieving the highest system distribution uniformity after 1620 h of irrigation for both DI and SDI systems.

مُلخص

يُعتبر نظام الرى بالتنقيط هو الأسلوب الأمثل لإعادة إستخدام مياه الصرف الصحى المعالجه نظراً لتقليله من المخاطر الصحيه التى قد تنتج عن إستخدامها. على الرغم من ذلك، تُعَد إنسداد مرشحات المياه والنقاطات المشكله الرئيسيه التى يواجهها مستخدمى هذا النوع من المياه نظراً لأنه يؤدى فى النهايه إلى إنخفاض التوزيع المتجانس للمياه فى نظام الرى.

الهدف الرئيسى من تلك الأُطروحه هو المقارنه بين أداء نظامى رى بالتنقيط أحدهما سطحى والأخر تحت سطحى عند تطبيق مياه الصرف المعالجه مع ثلاث معاملات مختلفه لغسيل خراطيم الرى (عدم الغسيل، غسيل مره واحده فى نهاية كل موسم، غسيل شهرى) مع إستخدام نوعين مختلفين من النقاطات أحدهما يُعادل الضغط بداخله أما الأخر فلا. بالإضافه إلى ذلك، تهدف هذه الدراسه إلى بحث تأثير مدى جودة مياه الصرف المعالجه على كفاءة أداء المرشحات الرمليه وعمل نموذج رياضى لحساب فرق الضغط داخل المرشح الرملى وأخر لحساب الوقت اللازم لدورة الترشيح قبل بد عملية الغسيل العكسى للمُرشِح.

طبقاً للنتائج المُتَحَصَّل عليها، فقد وُجِدَ أن الوقت اللازم لدورة الترشيح يتوقف على خصائص جودة مياه الصرف الصحى المستخدمه وعلى القُطر الفعَّال لحبيبات الرمل داخل المُرشِح. وأتضح أيضاً أن كفاءة عملية الترشيح تتوقف على القُطر الفعَّال لحبيبات الرمل فكلما صغُر القُطر الفعال كلما إزدادت كفاءة عملية الترشيح. هذا وقد تم الحصول على نموذج رياضى لحساب فرق الضغط داخل المرشح الرملى بدقه عاليه ومعامل إنحدار مرتفع.

ولقد وُجِدَ كذلك طبقا للنتائج المُتحصل عليها أن معدل تدفق المياه فى خراطيم الرى إعتمد بشكل أساسى على نوع النقاط المستخدم ونظام الرى وموسم الرى ومعدل غسيل خراطيم الرى. ففى نظام الرى بالتنقيط السطحى، وُجِدَ أن مُعدل التدفق فى النقاطات غير المُعَدِله للضغط يزداد بمرور زمن التجربه نتيجه للتدهور الملحوظ فى حالة النقاط بينما إنخفض بشكل معنوى فى نظام الرى تحت السطحى لإرتفاع نسبة إنسداد النقاطات. أما عن النقاطات المُعَدِله للضغط، فقد وُجِدَ أن مُعَدل التدفق فيها يزداد مع الوقت فى كلا نظامى الرى بالتنقيط السطحى وتحت السطحى.

وعلى صعيدٍ أخر فقد كشَّفت النتائج بالإضافه إلى ما سبق عن أسباب إنسداد النقاطات حيث وُجِدَ أنه فى نظام الرى بالتنقيط السطحى كان ذلك راجعاً لعوامل حيويه تعود لتكون طبقات من البيوفيلم داخل النقاطات بينما فى نظام الرى بالتنقيط تحت السطحى فقد عاد إنسداد النقاطات إلى إتحاد العوامل الحيويه مع العوامل الفيزيائيه عن طريق إلتصاق حبيبات التربه بالبيوفيلم المتكون داخل النقاط. لقد تم التوصل أيضاً من خلال النتائج إلى أن غسيل خراطيم الرى مره واحده فى نهاية الموسم أى كل 540 ساعه رى هى أفضل معامله للحصول على أفضل توزيع متجانس لمياه الرى خلال 1620 ساعه هى طوال زمن التجربه وذلك فى كلا نظامى الرى محل الدراسه.

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Notation

a	Constant value	$L^0\ M^0\ \theta^0$	-
A	Total filtration surface	$L^2\ M^0\ \theta^0$	m^2
cfu	Colony-forming unit	$L^0\ M^0\ \theta^0$	-
Ct	Number of totally clogged emitters	$L^0\ M^0\ \theta^0$	-
C	Suspended solids concentration	$L^{-3}\ M^1\ \theta^0$	$kg\ m^{-3}$
$\mathbf{C_{inf}}$	Percentage of total inefficient backwashing cycles	$L^0\ M^0\ \theta^0$	%
CV	Manufacturer variation coefficient	$L^0\ M^0\ \theta^0$	-
C/N	Ratio of the mass of carbon to the mass of nitrogen in a substance	$L^0\ M^0\ \theta^0$	-
$\mathbf{d_e}$	Sand effective diameter	$L^1\ M^0\ \theta^0$	m
$\mathbf{d_f}$	Internal sand filter diameter	$L^1\ M^0\ \theta^0$	m
DO	Dissolved oxygen	$L^{-1}\ M^1\ \theta^0$	$g\ m^{-3}$
$\mathbf{d_p}$	Inside diameter of the inlet and outlet pipe	$L^1\ M^0\ \theta^0$	m
$\mathbf{D_p}$	Mean diameter of particle size distribution	$L^1\ M^0\ \theta^0$	m
DU	Distribution uniformity	$L^0\ M^0\ \theta^0$	-
$\mathbf{DU_{lq\Delta P}}$	System pressure distribution uniformity	$L^0\ M^0\ \theta^0$	-
$\mathbf{DU_{lq\ flow}}$	System flow distribution uniformity	$L^0\ M^0\ \theta^0$	-
EC	Electrical conductivity	$L^{-3}\ M^{-1}\ \theta^3 A$	$\mu s\ cm^{-1}$
EU	Emission uniformity	$L^0\ M^0\ \theta^0$	%
Eu	Euler number	$L^0\ M^0\ \theta^0$	-
FNU	Formazin nephelometric unit	$L^0\ M^0\ \theta^0$	-
Fr	Froude number	$L^0\ M^0\ \theta^0$	-
g	Acceleration of gravity	$L^1\ M^0\ \theta^{-2}$	$m\ s^{-2}$
$\mathbf{H_i}$	Inlet filter pressure	$L^{-1}\ M^1\ \theta^{-2}$	Pa

H_o	Outlet filter pressure	$L^{-1} M^1 \theta^{-2}$	Pa
m	Number of independent parameters	$L^0 M^0 \theta^0$	-
M_{ms}	Total sand sample mass	$L^0 M^1 \theta^0$	g
m_s	Sand mass inside the filter	$L^0 M^1 \theta^0$	kg
n	Total number of observations	$L^0 M^0 \theta^0$	-
n°	Number of all observed emitters	$L^0 M^0 \theta^0$	-
n_c	Number of totally clogged emitters	$L^0 M^0 \theta^0$	-
$n_{C\ inf}$	Number of inefficient backwashing cycles	$L^0 M^0 \theta^0$	-
$n_{C\ tot}$	Total number of backwashing cycles	$L^0 M^0 \theta^0$	-
n_{tc}	Percentage of totally clogged emitters	$L^0 M^0 \theta^0$	%
O	Weight of aluminium weighing dishes with glass-fiber filter discs before filtration process	$L^0 M^1 \theta^0$	g
P	Working pressure head at the emitter	$L^{-1} M^1 \theta^{-2}$	Pa
P_{25}	Average pressure of 25% of emitters that provide the lower pressure	$L^{-1} M^1 \theta^{-2}$	Pa
P_{field}	pressure measured in field	$L^{-1} M^1 \theta^{-2}$	Pa
P_{nom}	Nominal pressure	$L^{-1} M^1 \theta^{-2}$	Pa
$\overline{P}$	The overall average pressure	$L^{-1} M^1 \theta^{-2}$	Pa
q	Emitter discharge	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
$\overline{q}$	Average emitter discharge rate	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
q_{25}	Average flow of 25% of emitters that provide the lower flow	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
Q	Filtered liquid flow rate	$L^3 M^0 \theta^{-1}$	$m^3\ s^{-1}$
$Q_{P\ field}$	Flow emitted to the pressure measured in field	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
$Q_{P\ nom}$	Flow emitted at the nominal pressure	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
r	The phenomenon dimensional matrix	$L^0 M^0 \theta^0$	-

$\mathbf{R_{adj}^2}$	Adjusted coefficient of determination	$L^0 M^0 \theta^0$	%
Re	Reynolds number	$L^0 M^0 \theta^0$	-
$\mathbf{RE_y}$	Removal efficiency for a parameter y	$L^0 M^0 \theta^0$	%
$\mathbf{R_m}$	Retained sand mass on the screen	$L^0 M^1 \theta^0$	g
$\mathbf{S_h}$	Pressure standard deviation	$L^0 M^0 \theta^0$	-
$\mathbf{S_q}$	Standard deviation for emitter discharge	$L^0 M^1 \theta^{-1}$	$l\ h^{-1}$
St.dv	Standard deviation	-	-
t	Time duration for every filtration cycle	$L^0 M^0 \theta^1$	s
T	Effluent temperature	$L^0 M^0 \theta^1 Q^{-1}$	^0C
TSS	Total suspended solids	$L^{-1} M^1 \theta^0$	$g\ m^{-3}$
$\mathbf{UC_s}$	Sand uniformity coefficient	$L^0 M^0 \theta^0$	%
$\mathbf{U_{hs}}$	Statistical pressure uniformity	$L^0 M^0 \theta^0$	%
$\mathbf{U_{pf}}$	Statistical uniformity of emitter performance	$L^0 M^0 \theta^0$	%
$\mathbf{U_{qp}}$	Statistical uniformity for emitter discharge including clogging factor	$L^0 M^0 \theta^0$	%
$\mathbf{U_s}$	Statistical uniformity	$L^0 M^0 \theta^0$	%
v	Filtration velocity	$L^1 M^0 \theta^{-1}$	$m\ s^{-1}$
V	Filtered liquid volume	$L^3 M^0 \theta^0$	m^3
$\mathbf{V_{BW}}$	Percentage of filtered water consumed by backwashing process	$L^0 M^0 \theta^0$	%
$\mathbf{V_f}$	Total volume of filtered effluent	$L^3 M^0 \theta^0$	m^3
$\mathbf{V_{hs}}$	Hydraulic design of coefficient of variation	$L^0 M^0 \theta^0$	-
$\mathbf{V_{pf}}$	Emitter performance coefficient of variation	$L^0 M^0 \theta^0$	-
$\mathbf{V_{qh}}$	Emitter discharge coefficient of variation	$L^0 M^0 \theta^0$	-
$\mathbf{V_{qp}}$	Emitter discharge coefficient including clogging factor	$L^0 M^0 \theta^0$	-
$\mathbf{V_{qs}}$	Coefficient of variation for the submain unit	$L^0 M^0 \theta^0$	-

V_s	Sample volume	$L^1 M^0 \theta^0$	ml
V_u	Volume of filtered water consumed by filter backwashing process	$L^3 M^0 \theta^0$	m^3
x	Emitter flow exponent	$L^0 M^0 \theta^0$	-
X	Weight of aluminium weighing dishes with glass-fiber filter discs after filtration process	$L^0 M^1 \theta^0$	g
$\hat{x}_i$	Calculated sample phenomena	$L^0 M^0 \theta^0$	-
x_i	Observed phenomena value	$L^0 M^0 \theta^0$	-
y_i	Physical parameter value before being filtered	-	-
y_o	Physical parameter value after being filtered	-	-
α	Significance level	$L^0 M^0 \theta^0$	-
ΔH	head loss across the filter	$L^{-1} M^1 \theta^{-2}$	Pa
μ	Water viscosity	$L^{-1} M^1 \theta^{-1}$	Pa s
π	Dimensionless independent parameter	$L^0 M^0 \theta^0$	-
ρ	Water density	$L^{-3} M^1 \theta^0$	kg m^{-3}
$Ø_f$	Filtration media height	$L^1 M^0 \theta^0$	m
$\%M_A$	Percentage of total accumulated sand mass sifted by each screen	$L^0 M^0 \theta^0$	%
$\%R_m$	Percentage of retained sand mass in each screen	$L^0 M^0 \theta^0$	%

Abbreviations

ASAE	*American Society of Agricultural Engineers*
DI	*Drip irrigation system*
E1	*Pressure compensating emitter Ram 17012*
E2	*Non-pressure compensating emitter Tiran 16010*
FAO	*Food and Agriculture Organization*
FPOM	*Fine particulate organic matter*
ITRC	*Irrigation Training and Research Center, California Polytechnic State University*
PE	*Polyethylene*
PLC	*Programmable logic controller*
PVC	*Polyvinyl chloride*
RMSE	*Root mean square error*
SCADA	*Supervisory control and data acquisition*
SDI	*Subsurface drip irrigation system*
T1	*No lateral flushing frequency treatment*
T2	*Seasonal lateral flushing frequency each 540 h experiment*
T3	*Monthly lateral flushing frequency*
USEPA	*United States Environmental Protection Agency*
WHO	*World Health Organization*
WWTP	*Wastewater treatment plant*

I. Introduction

I.1. Water availability

More than 97% of the water of the Earth planet is seawater, 2% is locked in icecaps and glaciers, and a large proportion of the remaining 1% lies too far underground to exploit it (Postel, 1992). Fortunately, a tiny fraction of the planet's water (less than 0.3%) is renewed and made fresh by nature's solar-powered water cycle (Jackson et al., 2001).

One of the clearest signs of water scarcity is the increasing number of countries in which population has surpassed the level that can be sustained comfortably by the water available (Postel, 1992). Growing water scarcity, rapid increase in population, rapid urbanization and megacity development, increasing competition among water users, and growing concerns for health and environmental protection are important examples in water security and availability issues (Lazarova and Asano, 2005).

Despite improvements in the efficiency of water use in many developed countries, the demand for freshwater has continued to climb as the world's population and economic activity have expanded (Lazarova and Asano, 2005). In 1995 about 2.3 billion people (41% of the world's population at the time) resided in river basins considered to be water stressed (< 1700 m^3 of water $person^{-1}$ yr^{-1}) and this value has been predicted to increase to 3.5 billion by 2025 (48% of the projected population). Of these, 2.4 billion will live under high water stress conditions (World Resources Institute, 2000).

On the other hand, water for agriculture is critical for food security. Agriculture remains the largest water user, with about 70% of the world's freshwater consumption (Lazarova and Asano, 2005).

The challenge to satisfy the irrigation water demand under conditions of increasing water scarcity in both developed and emerging countries is to conserve water and improve the efficiency of water use through better water management and policy reforms (Lazarova and Asano, 2005). Therefore, many strategies will need to be implemented during the coming decades to deal with water stress, and wastewater irrigation will undoubtedly be one of the most important strategies. Wastewaters of municipal and industrial origin are used to irrigate a wide variety of crops and landscapes across the world (Hamilton et al., 2007).

I.2. Irrigation with recycled effluent: benefits and constraints

The most accepted goal for wastewater reclamation and reuse projects is to produce water of sufficient quality to be used for all the potential uses that do not require drinking water quality standards, such as agricultural and landscape irrigation, industrial uses and non potable urban uses (Sala and Serra, 2004). Many potential advantages exist for irrigating crops with effluent instead of fresh water, regardless of the irrigation system type, such as:

- Conserve potable water resources by providing another alternative water resource for irrigation (Lazarova, 2005; Lazarova and Asano, 2005; Trooien and Hills, 2007; Kiziloglu et al. 2008).
- Reduce wastewater discharge to the environment, particularly to sensitive coastal, lacustrine and riverine systems (Anderson, 2003; Hamilton et al., 2006; Aronino et al., 2009).
- Decrease the use of fertilizers thanks to the nutrients present in the applied effluents (Haruvy, 1998; Meli et al., 2002; Ramirez-Fuentes et al., 2002; Trooien and Hills, 2007).
- Increase the productivity and yield of some crops (e.g. celery, eggplant, lettuce, maize and sorghum) due to the effluent content of fertilizers (Kaddous and Stubbs, 1983; Chakrabarti, 1995; Al-Nakshabandi et al., 1997; Marecos Do Monte, 1998; Sheikh et al., 1998).
- The metabolism activity of soil microorganisms increases when sewage effluents were used for irrigation (Gonçalves et al., 2007).
- Cost/benefit ratio is favourable in some situations (Lazarova and Asano, 2005).

- A possibility of decreasing the purification level and the derived treatment costs, thanks to the role of soil and crops in acting as a bio-filter (Haruvy, 1998).

However, as well as using treated wastewater for irrigation has great benefits, it is also may have some constraints in some cases just as:

- The over concentration of nutrients in wastewater leads to reduce crop size and quality, delay maturation of sunflower (Marecos Do Monte, 1998) and affect the plant ability to resist diseases (Wright, 1993).
- Environmental problems, such as, water eutrophication may occur in consequence of using effluent for irrigation (Sala and Mujeriego, 2001).
- In case of high C/N ratio, soil microfauna would be increased which leads to pores-clogging problems in the soil matrix due to a significant decrease of the soil hydraulic conductivity (Magesan et al., 2000).
- Leaching nutrients and other solutes poses one of the greatest threats to groundwater health (Bond, 1998; Haruta et al., 2008).
- Possible contamination with heavy metals. However, in the treated wastewater effluents, the concentration of heavy metals is smaller (Sheikh et al., 1998; Hamilton et al., 2007).
- Irrigation with wastewater effluents could raise the sanitary problems, such as risk of viral and bacterial infections for both of farmers and crops (Blumenthal et al., 2000; Pereira et al., 2002). Nevertheless, when effluent is treated following the allowed standards provided by the international organizations, e.g. WHO, health risks will be reduced.

I.3. Wastewater treatment and recycling

Wastewater derived from municipal treatment facilities is becoming an important source of water for irrigation, being in some localities the only available source of water. Nevertheless, as irrigation with effluents raises health problems (Pereira et al., 2002), some restrictions have been placed on its use, especially for the irrigation of edible crops

(Trooien and Hills, 2007). In Spain, the Royal Decree 1620/2007 (BOE, 2007) establishes the legal framework for the reuse of treated water. Microirrigation is particularly suitable for wastewater reuse because it minimises the health risks to farmers and product consumers (Oron et al., 1992a). However, in microirrigation systems, the most important problems that face the irrigators with reclaimed effluents are emitter and filter clogging that lead to low system distribution uniformity. For the importance of clogging problems and system distribution uniformity in the microirrigation systems regarding to the scope of the present study, they will be discussed in details later.

Most engineers agree that the choice of water treatment process depends on water supply source, required finished water quality, capital and operating costs, process footprint versus ion availability, residuals disposal and applicability to multiple-barrier approach (AWWA, 2003). Nevertheless, the choice of wastewater treatment schemes depends on water quality requirement, type of irrigated crops, irrigation method, public access and potential adverse impacts on soils and crops (Lazarova, 2005). Before implementing any irrigation program with effluent, its characteristics must be analyzed.

There are many types of water treatment methods that are regularly used to improve water quality, remove microorganisms and reduce the level of toxic substances. These methods fall into the following general categories (AWWA, 2003):

- Air stripping and aeration. This method is used to remove dissolved gases, taste-and-odor compounds, volatile organic compounds and to oxidize iron and manganese.
- Coagulation process that is used to aggregate small particles, such as clay, turbidity and organic matter into larger particles that can be removed using gravity processes.
- Ion exchange. This method is used to exchange unwanted ions for another ion.
- Chemical precipitation that uses chemical compounds to coagulate and flocculate the suspended material in the water.
- Membrane processes. These methods include microfiltration for removal of particles, ultrafiltration for removal of large molecular weight organics,

nanofiltration for the removal of divalent ions, and the reverse osmosis for the demineralization process.

- Disinfection. This method is used to disinfect water and remove harmful microorganisms.
- Adsorption. This method uses powdered or granular activated carbon for the removal of dissolved organics, colour and taste-and-odor causing compounds.

Usually, wastewater treatment is classified into three types (Trooien and Hills, 2007). The first type is the primary treatment that is generally a screening or settling process that removes organic and inorganic solids from the effluent. The second type is the secondary treatment that is a biological process that uses bacteria to remove complex material from the effluent. The third and last type is the tertiary treatment that includes membrane filtration and disinfection methods to produce water with a very high quality.

In general, effluents that passed by the primary treatment may be used for microirrigation systems, but additional treatment may be required prior to effluent use. However, the secondary treatment is more adequate for agricultural microirrigation systems (Trooien and Hills, 2007). However, in Spain, the type of treatment depends on the cultivated crop and the irrigation method according to the present regulation (BOE, 2007).

I.4. Microirrigation systems

Microirrigation systems are usually defined in terms of installation method, emitter discharge rate, wetted soil surface area or mode of operation (Ayars et al., 2007). According to ASAE (2001), microirrigation is the slow application of water on, above, or below the soil by surface drip, subsurface drip, bubbler, and microsprinkler systems. Water is applied as discrete or continuous drips tiny streams, or miniature spray through emitters or applicators placed along a water delivery line adjacent to the plant row.

During the last three decades, microirrigation systems made major advances in technology development and the uptake of the technology increased from 3 Mha in 2000 to more than 6 Mha in the world in 2006 (Reinders, 2006).

I.4.1. Advantages and disadvantages of microirrigation systems

Microirrigation, if properly managed, offers several potential advantages over other methods of irrigation (Pitts et al., 1990; Trooien et al., 2000; Ayars et al., 2007; Maestre-Valero and Martínez-Álvarez, 2010):

- Greater water application uniformity and water use efficiency (improved crop yield and quality and reduced non beneficial use and deep percolation).
- Improve cultural practice and weed control.
- Decrease energy requirement.
- Safe use of biological effluent and treated wastewater as a valuable resource of water and in some cases nutrients and also, capability of using saline water.
- Reduced bacteria, fungi, disease, and other pests that require a moist environment.
- Efficient delivery of fertilizer (fertigation) and other chemicals (chemigation) through the irrigation system.
- Ability to irrigate land too steep for irrigation by other means.
- Increase irrigation water dissolved oxygen concentration.

Finally, other additional advantages for applying effluents with subsurface drip irrigation (SDI) systems include (Hills et al., 1989; Oron et al., 1992b; Gushiken, 1995; Trooien et al., 2000; Lamm, 2002; Oron et al., 2001):

- Minimizes effluent odor and reduce human contact with it.
- Reduces significantly soil evaporation and salt concentration, which helps to diminish chemical clogging.
- Separation (setback) distance is decreased.

- Dripline temperatures in subsurface drip irrigation (SDI) systems are lower, which may help to reduce biological and chemical clogging hazards.

Despite the observed advantages of microirrigation systems, using effluents for microirrigation systems faces a serious problem that is emitter clogging (Bucks et al., 1979; Adin and Sacks, 1987; Ravina et al., 1992). System (especially emitter) clogging or root intrusion in SDI system could cause nonuniformity or system failure (Ayars et al., 2007). Moreover, other problems and disadvantages were observed by Ayars et al (2007) such as:

- Salt accumulation near plants.
- Restricted root development that has the potential to decrease plant growth and yields.

On the other hand, some potential disadvantages of applying biological effluent also exist, regardless of microirrigation system type, just as (Trooien and Hills, 2007):

- Land area requirements, maintenance requirements and installation costs could be increased.
- System performance monitoring requirements may be increased.
- Soil degradation could interfere with system operation or plant growth.
- Management may require more expertise. Limited experience could result in improper system design or management criteria.

Despite problems have occurred with wastewater that has been improperly treated (Anderson, 2003; Hamilton et al., 2006), those that have undergone adequate tertiary treatment generally have been successfully used in microirrigation (Nakayama et al., 2007). A greater understanding of the conditions that cause clogging may lead to improvement in operation and design for optimal treatment efficiency and improved system reliability (Leverenz et al., 2009).

The main design goal for a microirrigation system is to insure that an acceptable uniformity of water application is obtained throughout the field by controlling emitter clogging to assure a suitable economic life for the microirrigation system (Ayars et al., 2007). Basically, a microirrigation system consists of a filtration unit for improving effluent characteristics and driplines and emitters for maintaining a good distribution of the effluent in the field.

I.4.2. Description of DI and SDI irrigation systems

In the present PhD study, surface drip and subsurface drip irrigation systems have been used. In the surface drip irrigation system (DI), emitters and lateral lines were laid on the soil surface. On the other hand, in subsurface drip irrigation (SDI), water is applied slowly below the soil surface through buried emitters.

A continuous monitoring and control of system performance was provided to achieve the maximum efficiency of the irrigation operation (Clark and Phene, 1992). The continuous monitoring helps to avoid any disruption to the irrigation schedule during the experiment. Moreover, the systematic inspection of the microirrigation system was required to spot the malfunctioning emitters, pipelines, leaks and accessory equipment failures (Abbott, 1985).

I.4.3. Filtration

There is a universal agreement that prevention rather than cleaning is the best method of reducing or overcoming emitter clogging. Cleaning refers to the flushing process of filters and laterals in the microirrigation systems. Filtration is a key aspect in microirrigation systems that use wastewater (Oron et al., 1979; McDonald et al., 1984). Effluent filtration prevents immediate clogging by large particles (Adin and Sacks, 1991), but not completely (Tajarishy et al., 1994). Adequate water filtration is a primary requirement for reliable emitter operation. Filtration systems must be able to handle local peak loads in suspended particulates from the source water (Nakayama et al., 1978). In general, particles present in water range in size from the submicron virus to the larger sand-size fractions as listed in Table I-1.

Table I-1. Classification of suspended particle size in water (Nakayama et al., 2007).

Particle diameter, µm	Particle designation
> 1000	Coarse sand
250 – 500	Medium sand
50 – 250	Very fine sand
2 – 50	Silt
< 2	Clay
0. 4 – 2	Bacteria
< 0.4	Virus

In practice, the suspended solids concentration in surface irrigation water is much greater than 10 g m^{-3}, which is a tremendous amount of solids that pass through driplines and especially emitters. When the suspended materials are left in the driplines, they can eventually become cemented together by microbial by products and chemical reactions to form larger particles. As a consequence, significant changes can occur in the flow and pressure characteristics of the supply lines and emitters (Nakayama et al., 2007). Thus, a good filtration system to remove suspended material is an essential component of a microirrigation system (Abbott, 1985). Nevertheless, the complete removal of suspended materials from water used for microirrigation is impractical, being the removal of finer particles cost prohibitive.

Therefore, water treatment aim primarily at removing the larger particle size and allowing the final suspended load to be in the range that emitters and delivery systems can tolerate for long operational period (Nakayama et al., 2007).

Purchas and Sutherland (2002) defined the filter medium as any material that, under operation conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components. The principle role of the medium is to separate particulates from the liquid with the minimum consumption of energy. To achieve this selection of correct medium takes into account factors such as the permeability of the clean medium, its particle retention capability and the permeability loss of the medium during use (Wakeman, 2007). Filters must be matched to handle the flow rate of the irrigation system to insure proper filtration (Neufeld et al., 1997). There are three common types of filters that used in microirrigation system: screen, disc and sand media filters (Abbott, 1985).

I.4.3.1. Screen filters

Screen filters are the most widely used filters in microirrigation systems. The screens which may be made of steel, plastic or synthetic cloth are enclosed in a pressurized housing and are popular because of their easily operation (Abbott, 1985). The method of operation varies with the manufacturer's design and relates to the way that water entry, circulation, and exit are handled. When properly sized and maintained, screen filters do an adequate job for removing suspended particles from the water. Self-cleaning screens provide a rotating mechanism inside the filter that can "scrub" the contaminants off the surface of the screen when it starts to accumulate debris (Nakayama et al., 2007).

I.4.3.2. Disc filters

Disc filters use a series of grooved discs to form a filtering device when clamped together (Abbott, 1985). The filtration element in disc filters consists of a number of plastic or plastic-coated metal discs that are placed side-by-side on a telescopic circular shaft inside the housing. When these discs are stacked tightly together, they form a cylindrical filtering body, which resembles a deep tubular screen (Nakayama et al., 2007). These filters have more surface area than screen filters of similar sizes and like screen filters must be cleaned periodically (Burt et al., 1998).

I.4.3.3. Media filters

Media filters are usually consisting on sand and/or gravel of selected sizes placed in a pressurized tank (Abbott, 1985). Nevertheless, many materials in diverse forms are used as filter media. These include solid fabrications (e.g. wire wound tubes), metal sheets (e.g. perforated), rigid porous media (e.g. ceramics), cartridges, plastic sheets (e.g. fibrillated film) and membranes (Wakeman, 2007).

Sand filters could remove particles down to around 10 µm. However, when used in conjunction with good flocculation, it is possible to consistently remove solids down to micron and sub-micron levels. This performance can only be maintained if there is zero channelling of water through the filter bed (Dryden, 2007). Pressure-type, high-flow sand or mix-bed media filters are the more popular ones used to clarify irrigation water for microirrigation systems. Almost the full depth of the sand is used in the pressurized filters compared with gravity filters, where surface action is the primary filtration mechanisms. These filters are cleaned by reversing flow water throughout the media to cause the separation and suspension of sand material into individual particles (Nakayama et al., 2007).

On the other hand, sand filters have additional advantages like the capability of removing viruses in the size range of 200 nm (Aronino et al., 2009). They are as well suited for removal of inorganic particles beside the organic contaminants due to their three dimensional nature that increases the ability to entrap large amounts of pollutants (Adin and Elimelech, 1989; Adin and Sacks, 1991; Haman et al. 1994; Phillips, 1995; Ravina et al., 1997; Sawa and Frenken, 2002). Therefore, sand media filtration is often considered the standard for filtration protection of microirrigation systems (Trooien and Hills, 2007).

I.4.3.4. Choosing among filter types

The choice between filters types depends on the origin and quantity of contamination anticipated in the system as well as the size of the irrigation system (Haman et al., 1994). Generally speaking, surface water requires a greater degree of filtration than groundwater. Relatively clean water may get by with a screen or disc filter, while dirtier water may require media filters (Neufeld et al., 1997).

Screen filters are a primary choice when water is pumped from a well where the only filtration requirement is to remove mineral particulate matter while media (sand) filters are recommended when large amounts of algae (Naghavi and Malone, 1986) or other organic contaminants are present (Haman et al., 1994) because screen filters cannot remove them without reducing the flow and thus requiring frequent flushing (Chauhan, 1995). Other studies found also that disc and screen filters resulted in lower levels of turbidity and total suspended solids (TSS) removal than sand filters (Adin and Alon, 1986).

In general, disc filters are a good choice for small flow rates because they have larger filtration capacity than screen filters, and because media filters are more expensive for low flow rates (Nakayama et al., 2007) and have a bigger dirt-holding capacity than screen ones (Burt and Styles, 2000). This besides that, media filters are not typically available for small flows (Burt and Styles, 2000). Even though, disc filters, on condition that are of good quality, are cheaper and simpler to manage, and assured performance levels similar to those of the gravel media filters (Capra and Scicolone, 2004).

I.4.4. Filter backwashing

Filters' serious loss of permeability may follow plugging or blinding of the filter medium and can determine its lifetime if an uneconomic filtration rate results. Permeability and particle retention are dependent on interactions between the medium structure and the shape and size distribution of the particles in the feed suspension (Wakeman, 2007). Suspended materials trapped by the filter eventually decrease filtration efficiency and the filter must be cleaned. Cake formation or cementation on top of filters' surface during the initial stages of filtration causes a significant pressure drop that eventually results in shorter filtration cycles (Aronino et al., 2009) and can result in complete clogging of the bed, or alternately, the formation of large, continuous pores called "rat holes" that decrease filter performance (Nakayama et al., 2007).

Most manufacturers of microirrigation systems recommend high filtration levels. Consequently, in many cases of low quality waters, the main problems in the operation of drip irrigation systems have been with clogged filters rather than emitters clogging (Ravina et al., 1997). Therefore, filters should be backwashed frequently (Pitts et al., 1990).

The backwashing process consists on cleaning the filters by reversing the direction of water flow through the filtration media lifting it up to allow the dirty water to flow outside the filter (Abbott, 1985). Fig. I-1 illustrates the backwashing process in a disc filter.

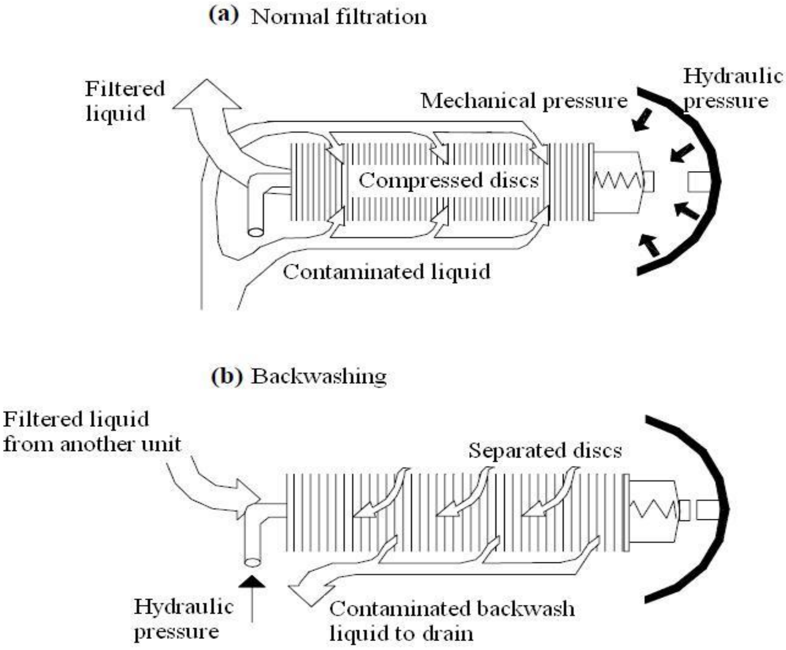


Fig. I-1. Backwashing process in disc filters (Burt and Styles, 2000).

Backwashing can be manual or automatic, on a set time interval or at a specific pressure drop. Either manual or automatic backwashing operations are available for media, screen or disc filters to improve filter function and efficiency. Excessive pressure loss across the filter is typically used to control automatic backwashing (Ayars and Phene, 2007). Burt and Styles (2000) recommended clean the filter when head loss across it reaches 35 – 55 kPa for sand filters and 41.4 – 48.3 kPa for disc ones. Ravina et al. (1992) recommended as well initiating the backwashing process when head loss across the filter reaches 50 kPa. Haman et al. (1994) recommended a range of 20 – 55 kPa for clean media filters depending on the size of the media and flow rate used. Yet, this is in the range set by Sawa and Frenken (2002) of 70 kPa for sand filters.

The benefit of the automatic filter backwashing systems is that it eliminates sudden changes in water quality which can create problems if a filter is washed only at regular intervals (Haman et al., 1994) and avoids the contact between the effluent and the irrigator (Capra and Scicolone, 2004).

Media filters are not easily blocked by algae or bacterial slimes, and can remove large amounts of suspended solids before backwashing is required. Yet, they can provide conditions favourable for increased bacterial growth (Abbott, 1985). Nevertheless, filtration systems that have only one filter are impossible to be properly backwashed, as there will be no clean water from one filter to backwash the other (Sawa and Frenken, 2002).

The period of degraded effluent water quality passing through a filter immediately after being backwashed is called filter ripening. Even the ripening period has been deeply studied, scientists were focused primarily on effluent turbidity as a principal indicator to filter ripening determination (Pittsburgh Filtration Commission, 1899; Amirtharajah and Wetstein, 1980; Amirtharajah, 1988; USEPA, 1998; Amburgey and Amirtharajah, 2005; Satterfield, 2005) and on particle size distribution (Darby and Lawler, 1989, 1990). Amirtharajah (1988) showed that more than 90% of particles passing through a well-operated filter did so during the ripening period. Different estimations for filter ripening were pointed out. The USEPA (1998) pointed out that filtered effluent turbidity return to its normal value within 15 min of restart the backwashing. However, Satterfield (2005) indicated that effluent turbidity deterioration would occur anywhere from a few minutes to 40 or more minutes after returning to filter operation mode.

I.4.5. Emitters

The key component of a microirrigation system is the lateral which is placed in the crop root zone and delivers water to the crop. Water is conveyed through the lateral and into the soil profile through emitters which are located within the lateral (Neufeld et al., 1997). Microirrigation emitters are the small water-dispensing devices that are designed to dissipate pressure and constantly discharge a small and uniform flow of water (Clark et al., 2007). Ideally, an emitter permits a small uniform flow of water at a constant discharge rate that does not vary significantly throughout the field or subunit (Ayars et al., 2007). Emitters have a several designs such as short-path, long-path, short-orifice, vortex, pressure compensating, self flushing, perforated single- and double chamber tubings, as well as the aerosol emitters, foggers, misters, or the miniature sprays and sprinklers used in microsprinkler irrigation. Many different emitters have been devised and manufactured with the concept that the emitters should be inexpensive, reliable (not clog), and compact as well as provide a uniform water discharge (Ayars et al., 2007).

In general, emitter discharge depends on the flow exponent value determined by the manufacturer as shown in equation I-1.

$$\mathbf{q = a \cdot P^{x}} \qquad \text{(I-1)}$$

were q is emitter discharge, l h^{-1}, a is constant value, P is working pressure head at the emitter, kPa and x is flow exponent.

The sensitivity of an emitter discharge to the pressure head depends mainly on the value of x. Laminar flow would give a straight line corresponds to x = 1; while a totally pressure compensating emitter would have a value of x = 0, which corresponds to another horizontal line. Between these two extreme values (0 and 1), exists a range of intermediate values, where the smaller the value of x the smaller the impact of inlet water pressure variation-induced changes in discharge rate and uniformity (Medina, 1988). When x is equal to 0.5, then orifice or turbulent flow is occurring. This is similar to the discharge from many standard sprinklers. As the value of x decreases below 0.5, pressure compensating flow starts to occur (Clark et al., 2007). An example for emitter discharge relationship with emitter pressure head for three different emitter types is illustrated in Fig. I-2.

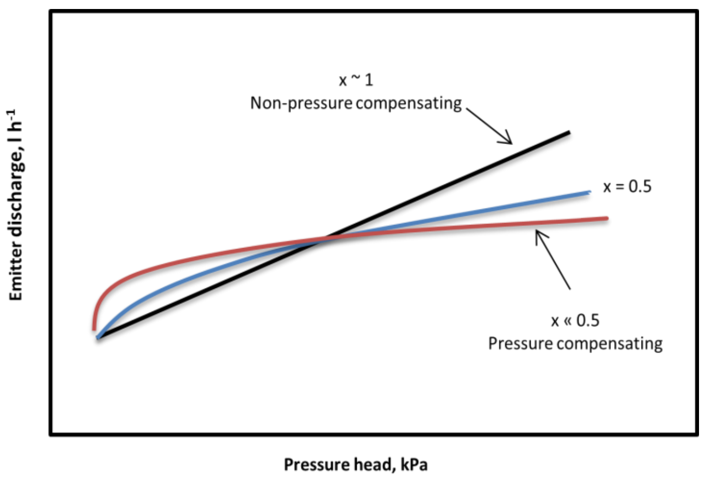


Fig. I-2. Example of emitter discharge relationship for non-pressure compensating flow (x = 1), orifice flow (x = 0.5) and pressure compensating flow (x « 0.5) (Clark et al., 2007).

The pressure compensating emitters are generally more expensive than the non-pressure compensating ones, and their performance may be affected by material fatigue caused by temperature, extended chlorination, microbial activity and acid injection in flushing process (Ravina et al., 1992). Therefore, only under proper microirrigation system design and with sufficient financial support, the pressure compensating emitters types are firstly recommended for drip irrigation with treated sewage effluents (Liu and Huang, 2009).

Even though, the short path drippers are subject to the clogging by big particles that often occur at the beginning of water path and long path drippers are subject to the siltation by very tiny particles which deposit on the walls of the water path if the flow is not turbulent enough (Abbott, 1985).

I.4.6. Clogging problems

One of the most serious problems that face the use of microirrigation systems is emitter clogging problem. Emitter clogging can be derived from physical, biological or chemical causes (Bucks et al., 1979).

I.4.6.1. Physical clogging

Physical clogging is caused when different particles of sand and suspended debris that are too large to pass through the opening of emitters precipitate around it (Pitts et al., 1990; Adin and Sacks, 1991). Furthermore, sometimes the physical clogging problem may occur when clay particles flocculate and form aggregates even the unflocculated clay and silt-sized particles are normally too small to plug emitters (Pitts et al., 1990). Physical clogging of emitters takes two forms (Abbott, 1985):

- Clogging by big particles often at the beginning of the water path. The change of emitter discharge in this situation is instantaneous.
- Siltation by very tiny particles deposited on the walls of the water paths if the flow is not turbulent enough. The change of emitter discharge in this case is very slow.

I.4.6.2. Biological clogging

At some stages, most microirrigation systems suffer from emitter clogging due to biological activity and associated by-products. The organic material produced appears as slimy deposits in laterals and drippers and if allowed to build up, adversely affects the performance of the system. Suspended particles in the water also tend to stock to the biofilm and agglomerate (Abbott, 1985). The microirrigation system can provide a favourable environment for bacterial growth, resulting in biofilm buildup (Pitts et al., 1990) forming sediment in the emitter flow path (Dazhuang et al., 2009; Yan et al., 2010).

This biofilm can combine with mineral particles in the water and form aggregates large enough to plug emitters (Li et al., 2010; Yan et al., 2010; Li et al., 2011). Furthermore, certain bacteria can cause enough precipitation of manganese, sulphur and iron compounds to cause emitter clogging, too. In addition, algae can be transported into the irrigation system from the water source and create conditions that may promote the formation of aggregates (Pitts et al., 1990).

I.4.6.3. Chemical clogging

Chemical clogging is usually the result of the precipitation of one or more of the following minerals (Abbott, 1985; Pitts et al., 1990): calcium, magnesium, iron, or manganese. The minerals precipitate from solution and form encrustations that may partially or completely block the flow of water through the emitter. There are three different forms of chemical clogging (Abbott, 1985):

- Clogging by evaporation at the end of the emitter path.
- Clogging inside the dripper water path. This is frequently observed when fertilizers are used without sufficient care.
- Clogging of emitters at the beginning of the water path by scales of carbonates which break off deposits which have formed on the walls of the plastic tubing.

I.4.6.4. Other causes of clogging

Moreover, other minor factors that cause emitter clogging such as ants, insect eggs and webbing have been reported (Abbott, 1985). These factors may be considered as physical clogging if the eggs are died or they may be considered as biological clogging if they are alive. Frequently, clogging is caused by a combination of more than one of the physical, chemical and biological factors (Pitts et al., 1990). These factors are closely interrelated, and controlling one factor may also alleviate problems caused by the others (Nakayama et al., 2007). For example, by reducing biofilm, the tendency of suspended solids particles to stick, agglomerate, and build up in microirrigation driplines and emitters are also reduced. In addition, small aquatic organisms such as snail eggs and larva, which are not readily observed and analyzed, can develop into large colonies in the lateral tubings and results in a combined physical and biological problem (Nakayama et al., 2007).

A summary for the principal physical, chemical and biological clogging factors in microirrigation system is provided in Table I-2.

Table I-2. Principal physical chemical and biological contributors to clogging of trickle systems according to Bucks et al. (1979).

Physical (suspended solids)	Chemicals (precipitation)	Biological (bacteria and algae)
Inorganic particles:	Calcium or magnesium carbonate	Filaments
Sand	Calcium sulphate	Slimes
Silt	Heavy metal hydroxides, carbonates,	Microbial depositions
Clay	silicates and sulfides	Sulfur
Plastic	Oil or other lubricants	Iron
Organic particles:	Fertilizers:	Manganese
Aquatic plants (phytoplankton/algae)	Phosphate	
Aquatic animals (zooplankton)	Aqueous ammonia	
Bacteria	Iron, copper, zinc and manganese	

In general, the clogging problem increases when microirrigation systems utilize treated effluent stored in surface reservoirs (Ravina et al., 1997). Surface water resources from rivers and unlined storages often give problems with suspended solids particularly, silts and clays while the water that comes from wells and bores often contains sand particles.

Furthermore, chemical clogging problems are frequently reported from systems that use groundwater which often contains significant quantities of dissolved salts (Abbott, 1985).

Bucks et al. (1979) classified the effect of water resource according to its main physical, chemical and biological characteristics to slight, moderate and severe clogging hazard. These classification criteria of clogging potential of microirrigation water sources are shown in Table I-3. Bucks et al's classification is commonly used worldwide. Capra and Scicolone (1998) proposed a new clogging hazard noting, increasing the threshold values for suspended solids, electrical conductivity, iron and manganese removing parameters like pH, hydraulic sulfide and bacterial population and introducing new parameters like calcium and magnesium. Liu and Huang (2009) pointed out that Bucks et al. (1979) criteria are better than those of Capra and Scicolone (1998) for assessing emitter clogging caused by chemical precipitation when using a treated effluent.

Table I-3. Criteria for plugging potential of microirrigation water sources according to Bucks et al. (1979).

	Plugging hazard based on concentration		
Factor	**Slight**	**Moderate**	**Severe**
Physical			
Suspended solids, g m^{-3}	< 50	50 - 100	> 100
Chemical			
pH	≤ 7	7.0 – 8.0	≥ 8
Dissolved oxygen, g m^{-3}	< 500	500 – 2000	> 2000
Manganese, g m^{-3}	< 0.1	0.1 - 1.5	> 1.5
Iron, g m^{-3}	< 0.1	0.1 - 1.5	> 1.5
Hydrogen sulfide, g m^{-3}	< 0.2	0.2 - 2.0	> 2.0
Biological			
Bacteria population cfu ml^{-1}	< 10000	10000 – 50000	> 50000

I.4.7. Lateral flushing

Prevention of emitter clogging is important for the successful operation of a microirrigation system (Ayars et al., 2007). Flushing of the microirrigation system is needed to remove particles that accumulate in the lines before they build up to sizes and amounts that cause clogging problems (Smajstrla and Boman, 1998). Filtration systems do not remove all suspended materials from the water because of the high cost of removing very small particles. Agricultural filters are usually designed to remove only particles larger than about 10% of the emitter orifice diameter. Therefore, filters do not normally remove clay and silt size particles. Although these particles are small enough to be discharged through the emitters, they can cause clogging problems when large quantities are present (Nakayama et al., 2007).

Flushing of irrigation system pipelines is an essential part of the maintenance program required for long-term success with microirrigation. Flushing will prevent accumulation of small particles and their buildup to size that can plug emitters (Smajstrla and Boman, 1998).

Irrigation laterals are flushed by opening the ends of the lines during operation and allowing water to freely discharge, carrying particulate matter along. The goal of flushing is to discharge water at sufficient velocity so that any particulate matter will be suspended and removed from the system with the flush water (Smajstrla and Boman, 1998). Flushing operation should continue until the collected water appears sufficiently clean or until no improvement in clarity is observed.

The duration of flushing depends on many factors, especially the water quality and system design. Before a system is installed, it is difficult to accurately estimate the time required to adequately flush a pipeline (Smajstrla and Boman, 1998). This observation normally only requires a short time and usually only a minute or two is sufficient (Nakayama et al., 2007) because the debris mainly accumulate at the end of the pipeline near the flush valve (Smajstrla and Boman, 1998).

To achieve the best effectiveness of a microirrigation system, it should be designed so that it can be flushed properly. Flushing must be done at a suitable velocity to dislodge and transport the accumulated sediments (Pitts et al., 1990; Adin and Sacks, 1991; Ravina et al, 1992; Nakayama et al., 2007). A minimum flow velocity of 0.3 m s^{-1} is needed for flushing of lateral lines as recommended by ASAE Standards (1985). However, Hills and Brenes (2001) recommended a flushing velocity within the dripline not smaller than 0.5 m s^{-1} to assure that all particles are removed.

I.4.8. Distribution uniformity

The distribution uniformity is considered an important measurement for showing the efficiency degree of a microirrigation system. The uniformity is a measurement of the nonuniform pattern of emitter flow of a microirrigation system (Wu et al., 2007). Water application uniformity can be affected by the hydraulic design, topography, operating pressure, pipe size, emitter spacing and emitter discharge variability.

I.4.8.1. Determination of distribution uniformity

Several methods have been developed to determine system uniformity such as FAO method (Vermeiren and Jobling, 1986), ASAE method (ASAE Standards, 1998) and the ITRC of California Polytechnic State University method (Burt, 2004). Each one of these methods is based on different concepts. For example, the early work on describing uniformity of drip irrigation systems like Vermeiren and Jobling (1986) used the “emission uniformity” term (EU) but Burt (2004) utilized the distribution uniformity term (DU) term even both are computed with the same formula. Burt (2004) explained the main reasons to use the term DU as following:

- The term EU refers only to uniformity of emitters on a single new lateral and accounted for, no more, the manufacturing and pressure variations. On the other hand, EU does not account for factors such as unequal drainage and uneven spacing that DU takes into consideration.
- EU was reserved only for drip/microirrigation system. However, the same uniformity definition should be applicable for furrow, drip and sprinkler systems.

Therefore, the ITRC of California Polytechnic State University method considered in its calculation program the pressure differences between emitters, uneven spacing, unequal drainage and other factors that would cause flow rate differences among emitters (Burt, 2004). The unequal drainage would be caused when a drip/microsystem is shut off and some emitters continue to drain while the other emitters have stopped discharging water.

On the other hand, the ASAE method use the statistical uniformity term (U_s) for describing system uniformity (ASAE Standards, 1998). This method takes into consideration the actual emitter discharge coefficient of variation (V_{qs}) that may be affected due to the overlapping nature of the variance. For this situation the V_{qs} shall be adjusted by dividing it by the square root of the number of emitters per plant to obtain the corrected emitter discharge coefficient of variation and the corrected statistical uniformity (U_s) (ASAE Standards, 1998).

I.4.8.2. Acceptability degree of distribution uniformity

A lot of researches were made to classify the distribution uniformity degree (Rodríguez, 1990; ASAE Standards, 1998). The acceptability degree of system distribution uniformity that was classified by Rodríguez (1990) is presented in Table I-4. Moreover, the classification of the uniformity degree elaborated by ASAE EP458 (ASAE Standards, 1998) and Burt (2004) are pointed out in Table I-5.

Table I-4. Acceptability degree for applied microirrigation systems' uniformity (Rodríguez, 1990).

Rating	$DU_{lq\ flow}$, %
Excellent	> 94
Good	86 - 94
Acceptable	80 – 86
Unacceptable	< 80

Table I-5. Classification of statistical uniformity (U_s) (ASAE Standards, 1998) and distribution uniformity ($DU_{lq\ flow}$) (Burt, 2004).

Rating	U_s, %	$DU_{lq\ flow}$, %
Excellent	> 95	> 94
Very Good	90 - 94	87 – 93
Good	80 - 89	75 – 86
Fair	70 - 79	62 – 74
Poor	60 - 69	50 – 61
Unacceptable	< 60	< 50

Observing a low quality flow distribution indicates the inefficiency of the microirrigation system. Understanding the actual reasons and causes that let to this failure would help in solving the problem and improving the distribution uniformity degree. Rodríguez (1990) elaborated a diagram (Fig. I-3) for helping to recognize and determine the main reasons and causes when observing low quality flow distribution that took into consideration the system distribution of pressure uniformity ($DU_{Iq\Delta P}$). Both distribution and pressure uniformities will be deeper explained in Chapter V.

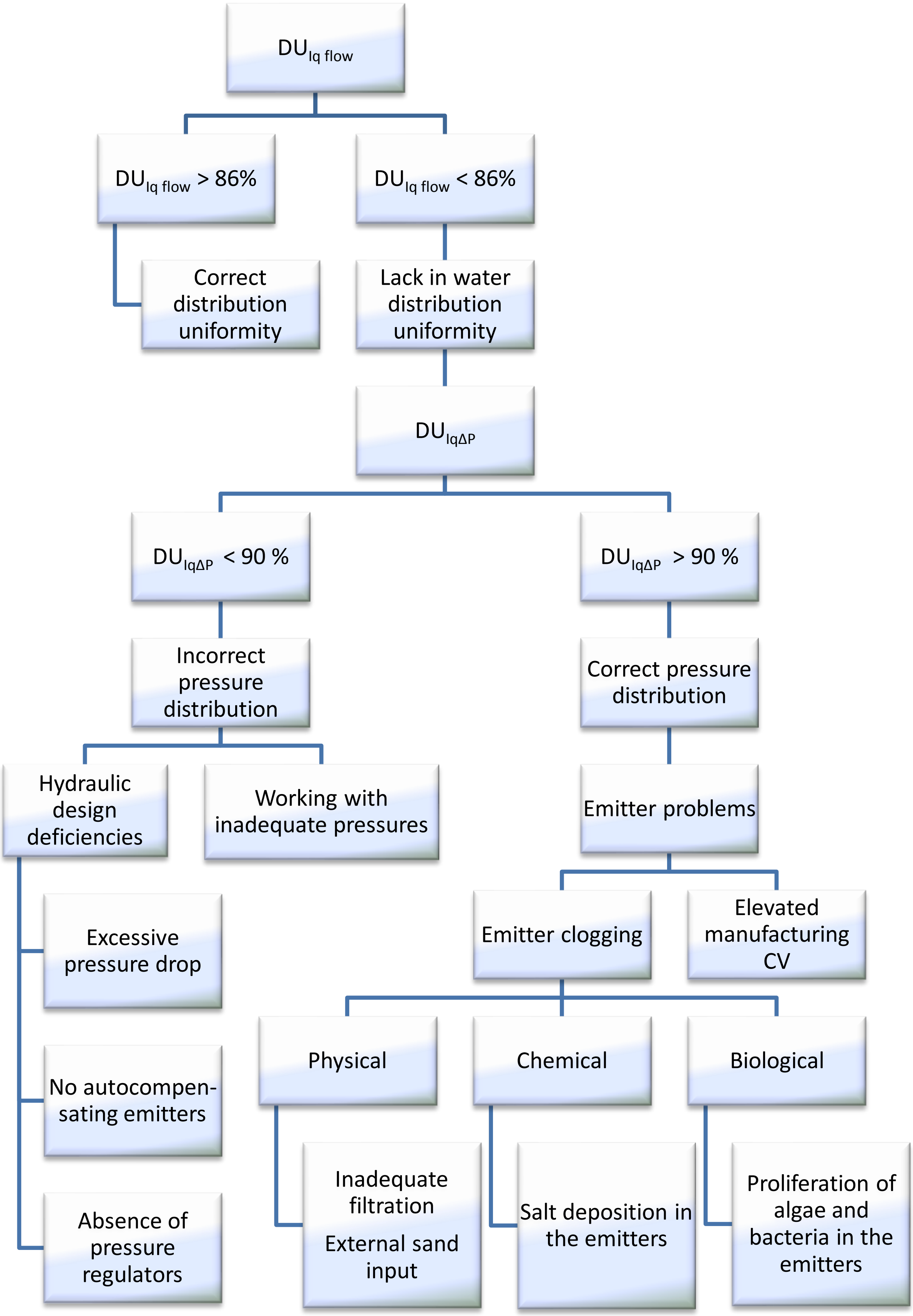


Fig. I-3. Diagnostic diagram for irrigation system on base of uniformity coefficient (Rodríguez, 1990).

II. General and specific objectives

II.1. General objective

Since microirrigation systems are considered as one of the most effective systems in applying effluent for irrigation, the foremost objective of this PhD dissertation is to compare hydraulically two microirrigation systems (surface (DI) and subsurface (SDI) drip irrigation) when applying a tertiary treated effluent filtered in a sand filter.

II.2. Specific objectives

To reach the main objective, the following specific objectives must be achieved:

- Identify the influence of the applied effluent quality on filtration process and sand media filter characteristics (Chapter III).
- Analyse and predict head loss and filtration cycle duration in a sand filter unit applying dimensional analysis (Chapter IV).
- Determine the effect of flushing frequency, emitter type, emitter location and clogging on DI and SDI system performance (Chapter V).

III. Influence of effluent quality on sand filter operation and characteristics in microirrigation systems

III.1. Introduction

Filtration is an important process in microirrigation systems. It depends primarily on a combination of complex physical and chemical mechanisms, the most important being adsorption (AWWA, 2003). Sand media filters are one of the popular filter types in microirrigation, especially when irrigating with effluents (Burt and Styles, 2000). The media grain size has effects on the efficiency of filtration and on backwashing requirements. The coarse media may not effectively remove effluent turbidity, which is related to the presence of suspended matter. Very fine sand media will resist the flow of water and require frequent backwashing or migrate to the laterals during the backwashing causing emitter clogging problems (AWWA, 2003).

Sand uniformity coefficient (UC_s) and sand effective diameter (d_e) are two indicators of sand media homogeneity and sand particle size. Sand effective diameter is defined as the size of the screen opening which will pass 10% of the total sand sample mass (Haman et al., 1994). The UC_s is the ratio between the screen pores that let pass 60 and 10% of sand through them. When UC_s equals one, this indicates that all sand particles have the same size. A uniform sand media has a low UC_s value while a good graded media is characterized by a high UC_s value (Burt and Styles, 2000). A UC_s of 1.5 is recommended by Haman et al. (1994), but Phillips (1995) suggested working with lower UC_s.

Total suspended solids (TSS) and dissolved oxygen (DO) are two important indicators to the filtration process efficiency. TSS is the measure of larger undissolved particles in the effluent and is primarily organic matter. Removal of TSS is critical and is most often accomplished by microirrigation filters prior to pumping the effluent into the microirrigation system. If TSS not adequately removed, the suspended solids can readily clog emitters and other components in the systems. In practice, only larger suspended particles are removed by the filters. The smaller particles that pass through the filter are able to pass through all system components including emitters. Therefore, system performance must be monitored to assure that these small solids do not coagulate within the system and clog emitters or other components (Trooien and Hills, 2007).

Moreover, dissolved oxygen content is an important irrigation water quality parameter that can be a limiting factor in some intensive agriculture systems (Raviv et al., 2004; Bhattarai et al., 2005; Marfà et al., 2005). A low dissolved oxygen concentration in the irrigation water may have critical consequences, as it causes root oxygen deficiency which in turn can lead to agronomic problems such as crop stress, slow plant growth, or low yields (Bhattarai et al., 2008). Moreover, oxygen deficiency in the root zone of plants can lead to poor root and plant performance and an increase in disease (Chérif et al., 1997).

III.2. Objectives

The foremost objective of this chapter is studying the influence of water quality on filtration process and the performance of sand filters for the improvement of effluent characteristics. This objective could be accomplished when reaching the following specific objectives:

- Determine the effect of the applied effluent quality on filtered flow rate and duration of operation of sand filters.
- Characterize the evolution of sand granulometry as a function of the filtration process using sand filters during the experiment.
- Identify the effect of filtration and backwashing processes on applied effluent quality.

III.3. Material and methods

III.3.1. Experimental setup

An experimental microirrigation system was installed in a 0.35 ha field (approximately 38 m wide and 94 m long with an average slope of 0.85%) located at the Wastewater Treatment Plant (WWTP) of the municipality of Celrà (Province of Girona, Catalonia, Spain).

The satellite picture for the WWTP of Celrà municipality and the experimental plot is shown in Fig. III-1. This WWTP treats the urban and industrial wastewater of the municipality through a biological treatment for removing nitrogen and phosphorus (ACA, 2010). The effluent was obtained by filtration from a sludge process through a disc filter with a 130 μm filtration level and treatment by ultraviolet radiation, which achieved an average reduction of mesophilic aerobic bacteria from $1.30 \cdot 10^5$ cfu ml^{-1} to $1.50 \cdot 10^4$ cfu ml^{-1}.

Fig. III-1. Satellite picture of the experimental plot (marked in yellow) and filtration bank (marked in red) set in the WWTP of Celrà municipality (ICC, 2010).

The experimental microirrigation system was divided in surface and subsurface drip irrigation systems that operated during three irrigation seasons each of 540 h. The start and end date of each irrigation season during the experiment are pointed out in Table III-1.

Table III-1. Start and end date of each irrigation season during the experiment.

Irrigation season	Start date	End date
First	August 3, 2007	December 7, 2007
Second	March 11, 2008	May 26, 2008
Third	June 26, 2008	September 7, 2008

Both irrigation systems were connected to a sand filtration unit (Fig. III-2). The sand unit consisted of two sand filters in parallel (Regaber, Parets del Vallès, Spain) to increase the filtering capacity and clean them through the backwashing process (Haman et al., 1994; Sawa and Frenken, 2002).

Each sand filter had an internal diameter (d_f) of 0.508 m, a filtration surface (A) of 1963 cm^2 and a media height ($Ø_f$) of 0.50 m. Both sand filters were filled with 175 kg of sand as a single filtration layer. Sand was changed only once during the experiment at the end of the second irrigation season as recommended by the manufacturer to change the sand media after 1000 h of filtration. Filters were backwashed various times at the beginning of the experiment and after changing sand media to get rid of finer particles that could cause clogging problems later.

Fig. III-2. Filtration unit consisting of two sand filters in parallel.

III.3.2. Data control and automation

A previously developed supervisory control and data acquisition (SCADA) system (Duran-Ros et al., 2008) was modified and used to monitor and control the experimental microirrigation system.

This SCADA system consisted of a computer unit, a programmable logic controller (PLC) connected to different equipments, and a communication system between the computer and the PLC. The system was also prepared for remote access to the computer from any other computer connected to the Internet. The communication diagram of the SCADA system used in the experiment is shown in Fig. III-3.

From the computer it was possible to access a main screen from where it was allowed to schedule the irrigation events, monitor the filter backwashing parameters and check the supervised data in real time. The system created a weekly working register file for an easier exporting to the pre-registered data that had been collected every minute.

The SCADA system allowed a continuous monitoring and controlling for effluent's most important physical and chemical parameters every minute. These parameters were the filtrated liquid flow rate (Q), inlet filter pressure (H_i), outlet filter pressure (H_o), inlet and outlet dissolved oxygen (DO), inlet and outlet turbidity, inlet electrical conductivity (EC), inlet pH, inlet temperature, number of sand filter backwashings, lateral flow rate and irrigation scheduling. Periodically, flow meters were manually read to compare them with the corresponding values from the SCADA system.

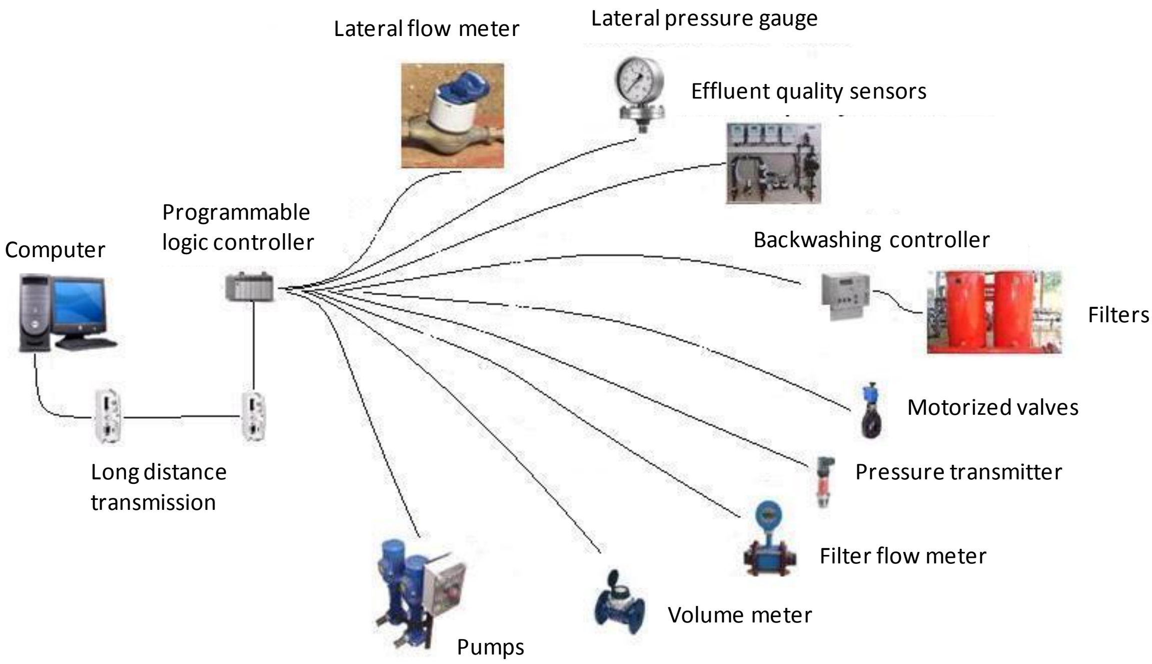


Fig. III-3. Communication diagram of the SCADA system used in the experiment.

III.3.3. Experimental filtration cycles

Filter operation time varied between 6 to 12 h per day, with a minor interruption of a few days duration primarily due to operation problems and system maintenance. Filters were backwashed automatically on base of the pressure head loss across the filter. When head loss across the filters reached 50 kPa, the system started the backwashing process as recommended by Ravina et al. (1992) without interrupting the irrigation for 90 s. The backflushing water was discharged and did not enter the irrigation system. Manual backwashings were run as well 15 min before sampling for the total suspended solids determination and when necessary. It was used the filtered effluent from one filter to backwash the other.

The average inlet filter pressure during the irrigation cycle (H_i) was 477 kPa decreasing during backwashing process to 436 kPa for the first irrigation season. It was 396 kPa decreasing to 360 kPa and 471 kPa decreasing to 430 kPa during backwashing process for the second and third irrigation seasons, respectively.

The evolution of hydraulic parameters and effluent characteristics of each filtration cycle, i.e. operation time between two backwashings, was collected through the SCADA system. The total amount of filtration cycles was 928 cycles during the experiment that lasted for 1620 h. Sometimes, at the beginning or at the end of filtration cycles occurred some disturbance in water flow because the backwashing process caused anormal irrigation conditions such as low flow rates (minor than 7 m^3 h^{-1}) that coincided with extremely high head loss. These data were removed from the analysis. Therefore, data for studying filter performance were taken from only 878 filtration cycles.

III.3.4. Applied effluent characteristics

III.3.4.1. Online measurement of effluent characteristics

Online measurement of pH, temperature, DO, turbidity and EC at filter inlet was achieved using Endress + Hauser (Nesselwang, Germany) sensors (Orbisint CPS11D, OxyMax W COS61, TurbiMax W CUS 31 and ConduMax W CLS 21, respectively) and transmitters (CPM253, COM253, CUM253 and CLM253, respectively). At the filter outlet, only DO and turbidity were monitored, using the same type of sensors and transmitters installed at the filter inlet. The control panel localizing the digital monitors and different sensors that measure effluent parameters before and after being filtered is illustrated in Fig. III-4. Only turbidity sensor needed to be washed periodically with potable water. This operation could be activated with the SCADA system or manually. When, in some cases, this automatic washing was not able to remove some particles from the sensor, the turbidity meter was washed manually with distilled water.

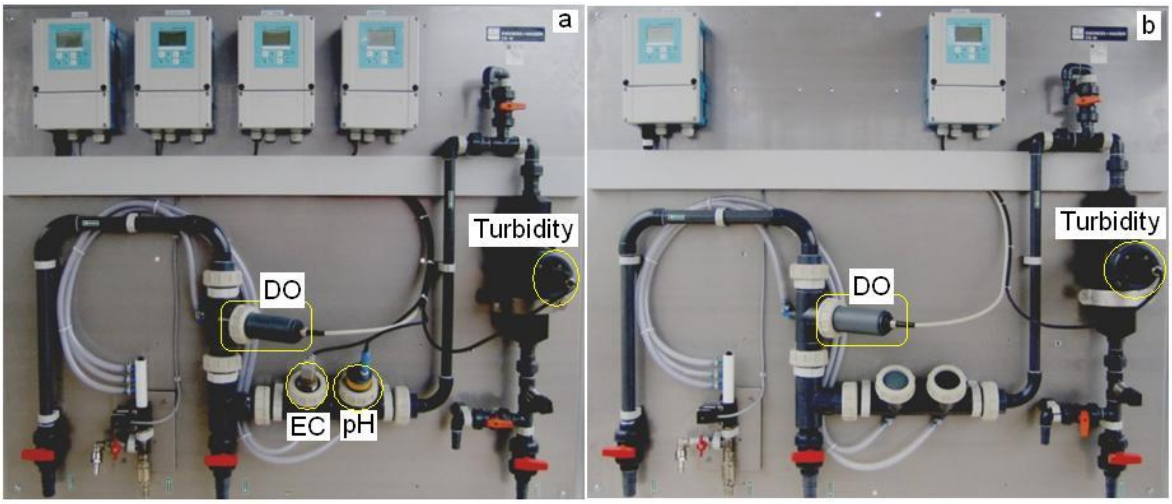


Fig. III-4. Control panel with the digital monitors and sensors for (a) inlet effluent parameters and (b) filtered effluent.

Some incidents while the process of registering data occurred causing missed data for some periods of time. At the first irrigation season (around 220 - 240 h) the control panel that measured effluent inlet physical parameters (Fig. III-4 a) did not register data for being shut down by a thunderstorm incident. Also, at the third irrigation season (around 1270 h), a problem occurred in the sensor that measured DO for filtered effluent. This period was coincident with the last weeks of the experiment and it was not possible to repair the sensor. In consequence, DO values for filtered effluent during this period were missed.

III.3.4.2. Field measurement of effluent characteristics

Periodically, samples of the applied effluent were obtained and analyzed to verify that the sensors were measuring correctly. The pH and DO were determined at the experimental site with a Multi 340i (WTW, Weilheim, Germany) handheld multiparameter instrument, while turbidity was measured with a HI 93703 handheld turbidity meter (Hanna Instruments, Woonsocket, Rhode Island, USA).

III.3.4.3. Laboratory measurement of total suspended solids

Twelve samples were taken for determining total suspended solids (TSS) concentration in the applied effluent and its relationship with effluent turbidity. Samples were taken 15 min after the backwashing process to be sure that the experimental conditions returned to its normal state and distribution of sand inside the filters became stable. At the same moment of sampling process, other physical parameters (DO, turbidity, EC, pH and temperature) were observed and written down from the digital monitors of SCADA control panel.

The total suspended solids dried at 103-105°C method (Clesceri et al., 1998) was used for determining the average of suspended solids concentration in the applied effluent before and after being filtered as following.

Apparatus

- Desiccator, provided with a desiccant containing a colour indicator of moisture concentration or an instrumental indicator (Nalgene, Rochester, New York, USA).
- A Digitheat 190 L (Selecta, Abrera, Spain) drying oven, for operation at 105°C.
- An AND GX-4000 (Sartorius, Gottingen, Germany) analytical balance, with an accuracy of 0.1 mg.
- Graduated cylinder.
- Low-form beaker.
- Glass-fiber filter discs (Ahlstrom, Helsinki, Finland) of 4.7 cm diameter and 1.2 µm pore.
- A magnetic filter funnel (Pall Corporation, East Hills, New York, USA) filtration apparatus, associated with a vacuum pump SV 1004 B (Busch, Maulburg, Germany).
- Suction flask, of sufficient capacity for sample size selected.
- Aluminium weighing dishes.
- Reagent-grade water.

Procedure

- Put the glass-fiber filters discs on the aluminium weighing dishes.
- Mark each filter disc and aluminium dish with the same mark.
- Dry glass-fiber filters discs putting the aluminium weighing dishes in the drying oven all night long at 105°C.
- Take the aluminium weighing dishes of the oven and put them in the desiccators for 2 h to reach room temperature.
- Weight glass-fiber filters discs with the aluminium dishes using the analytical balance.
- Put the glass-fiber filters discs in the filtration apparatus.
- Measure 300 ml sample by the graduated cylinder and add them on the glass fiber filters discs.
- Apply vacuum and wash filter discs with reagent-grad water.
- Continue suction to remove all traces of water and turn the vacuum off to discard washings.
- Remove filter from filtration apparatus and transfer each into its previous aluminium weighing dish.
- Put aluminium weighing dishes in the drying oven at 105°C for 2 h.
- Take off the aluminium weighing dishes of the drying oven and put them again in the desiccators for 2 h to reach room temperature.
- Re-weight glass-fiber filters discs with the aluminium weighing dishes using the analytical balance.
- TSS were computed as follows:

$$\mathbf{TSS} = \frac{[\mathbf{X-O}]}{\mathbf{V_s}} \cdot \mathbf{10^6} \qquad \text{(III-1)}$$

where TSS are total suspended solids in g m^{-3}, X is the weight of aluminium weighing dishes with glass-fiber filter discs after filtration process in g, O is the weight of aluminium weighing dishes with glass-fiber filter discs before filtration process in g, V_s is the sample volume, ml and 10^6 is a constant value for transferring the TSS from g ml^{-1} into g m^{-3}.

III.3.5. Sand filter characteristics

Filters' used sand granulometry was determined through a homogeneous and representative sand samples that taken four times (before the first, after the second, before the third and after the third irrigation seasons). Samples before the first and after the third irrigation seasons were taken before applying the initial backwashing process. It was difficult to take homogenous samples after starting the experiment to determine its granulometry. Characterization of sand granulometry was determined according to the following steps.

Apparatus

- A Digitheat 190 L (Selecta, Abrera, Spain) drying oven for operation at 105°C.
- Twelve stainless steel screens of 0.060, 0.120, 0.150, 0.177, 0.200, 0.250, 0.400, 0.630, 0.750, 0.810, 1.000 and 1.200 mm pores.
- Analytical balance AND GX-4000 (Sartorius, Gottingen, Germany) with an accuracy of 0.1 mg.
- A Microcomputer Screener machine (Vibration Filter, Badalona, Spain).

Procedure

- Weight four replicates of 250 g of a homogeneous and representative sand sample.
- Dry samples in drying oven at 105°C for all night long.
- Take the samples off from the drying oven and let them in room temperature to calm the heat down for 24 h.
- Weight each stainless steel screen then put them in an ascendant order.
- Put the sand sample in the upper screen which have the highest pore diameter and cover it well to prevent sample loss while vibration then put it on the Microcomputer Screener machine.
- Shake and sieve the sample for 5 min, with a power amplifier at the 9th position and vibration frequency of 2 s.

- After finishing the sieving process re-weight every screen again. Difference between screens' weight after and before the sieving process is the sand mass in grams.
- Weight accumulated for each fraction, in %, versus sieve opening size, in mm, defines the granulometric curve.
- The percentage of retained sand mass (% R_m) in each screen was calculated as following:

$$\%\mathbf{R_m} = \frac{\mathbf{R_m}}{\mathbf{M_{ms}}} \cdot \mathbf{100} \qquad \text{(III-2)}$$

where R_m is the retained sand mass on the screen in g after the sifting process and M_{ms} is the total sand sample mass, in g.

- Calculate the percentage of the total accumulated sand mass sifted by each screen (%M_A) as following:

$$\%\mathbf{M_A} = \mathbf{100} - \frac{\sum_o^j \mathbf{R_m}}{\mathbf{M}} \cdot \mathbf{100} \qquad \text{(III-3)}$$

where o and j represent sand mass rang in g that o is the smallest sand mass value and j is the highest sand mass value.

The relationship between the stainless steel screens pores and the percentage of the total accumulated sand mass sifted by each screen was determined in order to elaborate the granulometric curve. Sand effective diameter (d_e) and uniformity coefficient (UC_s) can be determined from the granulometric curve.

III.3.6. Analysis of backwashing cycles

As mentioned before in section III.3.1, backwashing processes were run automatically when head loss (ΔH) across the filtration unit reached 50 kPa. The backwashing process was classified in function of filter head loss recovery after the backwashing into:

- Efficient backwashing process: when after this automatic backwashing, the head loss across the filter was between 20 and 40 kPa.
- Inefficient backwashing process: when the head loss across the filter after the backwashing was greater than 40 kPa.

Percentage of the total inefficient backwashing cycles for each irrigation season (C_{inf}) was computed using the formula:

$$\mathbf{C_{inf} = \frac{n_{C\,inf}}{n_{C\,tot}} \cdot 100} \qquad \text{(III-4)}$$

where $n_{C\,inf}$ is number of inefficient backwashing cycles for each irrigation season and $n_{C\,tot}$ is the total number of backwashing cycles during the irrigation season.

The percentage of filtered water consumed by filter backwashing process (V_{BW}) was determined as following:

$$\mathbf{V_{BW} = \frac{V_u}{V_f + V_u} \cdot 100} \qquad \text{(III-5)}$$

where V_u is volume of filtered water consumed by filter backwashing process per season in m^3 and V_f is total volume of filtered effluent for each irrigation season in m^3.

III.3.7. Statistical analyses

Statistical analysis was applied using the SPSS statistical program (SPSS Inc., Chicago, Illinois, USA) and results were checked at 0.05 significance level.

III.3.7.1. SCADA system and handheld instruments relationship

A regression analysis was applied to determine the significant degree and adjusted coefficient of determination for the relationship between obtained data by the SCADA system and by the handheld instruments. An analysis was set to check the efficiency of the SCADA system.

III.3.7.2. Analysis of effluent physico-chemical parameters

In addition, the differences in effluent examined parameters among the three irrigation seasons were studied statistically applying a multivariate general linear model. Duncan test as well was run to determine which parameter means were differ. Further, a regression analysis was set for determining the relationship between effluent TSS and turbidity.

III.3.7.3. Analysis of filter flow rate

After determining the applied effluent quality and whether it was stable during the three irrigation seasons, a relationship was set applying regression analysis to define the influence of this quality (presented in turbidity values) on flow rate and duration of operation of the filters.

III.3.7.4. Analysis of filtration efficiency

A paired samples T test was applied to study whether the two determined physical parameters after filtration (turbidity and DO) were significantly different before and after filtration or not per each irrigation season. The test aimed to indicate the efficiency of sand filters as a filtration unit.

A multivariate general linear model was set to examine whether the removal efficiencies of DO and turbidity were influenced with sand effective diameter (d_e) during the experiment or not. The effectiveness of a filter (removal efficiency) is a measure of its ability to remove particles of a certain size (Haman et al., 1994). Removal efficiency for both DO and turbidity physical parameters was determined as it is in equation (III-6).

$$\mathbf{RE_y = \frac{y_i - y_o}{y_i} \cdot 100} \qquad \text{(III-6)}$$

where RE_y is removal efficiency for the physical parameter y, y_i is the physical parameter value before being filtered and y_o is its value after filtration. Duncan test was chosen to determine which phenomena means were differ.

Since there were some missed data for DO of filtered effluent after 1270 h that coincided with the 0.63 mm sand effective diameter at the end of third irrigation season, the removal efficiency for DO physical parameter was only examined with the determined d_e only at the start of the experiment, after the second and before the third irrigation seasons.

An average of filtered effluent $RE_{Turbidity}$ and RE_{DO} for 10 min before and 10, 15, 30, 45, 60 and 120 min after filter backwashing process was computed in order to study the duration of filter ripening and the behaviour of $RE_{Turbidity}$ and RE_{DO} during the studied periods applying a multivariate general linear model. Only 67 filtration cycles, which were longer than 4 h were used to avoid repetitions and data overlapping.

In addition, average DO and turbidity removal efficiencies of 0 - 10% of filtration cycle duration before backwashing and 10 - 20, 30 – 40, 50 – 60, 70 – 80 and 90 – 100% after it were analysed applying a multivariate general linear model. This analysis aimed to determine the efficiency of filtration unit to removing organic contaminants and total suspended matter during filter ripening and during the normal filter run cycle. Moreover, the analysis strived to examine whether the filtration efficiency differ significantly before and after the backwashing or not. A total of 176 filtration cycles were used. Filtration cycles that were shorter than 20 min were not considered while analysing data.

III.4. Results and discussion

III.4.1. Inlet effluent characteristics

The average registered sand filter surface flow rates during irrigation season varied between 13.81 and 15.44 l s^{-1} m^{-2} of filter surface area. These rates were within the range 10.17 – 16.94 l s^{-1} m^{-2} recommended by Pitts et al., (1990), Haman et al. (1994) and Phillips (1995) and smaller to the average of 17 l s^{-1} m^{-2} (Abbott, 1985) to avoid channelling formation in sand media bed or the hydraulic movement of contaminants through it.

There were good relationships between physical parameters values measured by the sensors connected to the SCADA system and by portable meters. The relationships were statistically significant ($P \leq 0.003$) and had an adjusted coefficient of determination higher than 0.913 even two parameters (EC and pH) were measured only in three samples. Therefore, more confidence in the sensor measurements was given and it was decided to measure the effluent physical parameters using only the sensors and the SCADA system during the rest of the experiment. The registered physical parameters by SCADA system are pointed out in Table III-2.

Table III-2. Average and standard deviation of the effluent physical parameters for each irrigation season at both filter inlet and outlet registered by the SCADA system.

	1st irrigation season		2nd irrigation season		3rd irrigation season	
Parameter	**Inlet**	**Outlet**	**Inlet**	**Outlet**	**Inlet**	**Outlet**
Flow rate, l s^{-1}	3.03 ± 0.20		2.73 ± 0.13		2.71 ± 0.22	
DO, g m^{-3}	3.96 ± 0.80	4.16 ± 0.83	3.54 ± 0.92	3.57 ± 0.98	3.74 ± 1.22	3.40 ± 0.95
Turbidity, FNU	10.33 ± 10.50	3.40 ± 2.83	9.08 ± 9.88	2.87 ±3.66	8.06 ± 8.51	2.02 ± 1.92
EC, dS m^{-1}	5.57 ± 1.04		4.94 ± 0.80		4.59 ± 0.56	
pH	7.33 ± 0.09		7.97 ± 0.25		-	
Temperature, ^{o}C	21 ± 3		19 ± 1		27 ± 1	

Standard deviation values for effluent turbidity were high (Table III-2), which indicates the high irregularity of the effluent characteristics during the experiment.

In addition, EC values classified the applied effluent as moderately saline water (Rhoades et al., 1992). Even though, since the experiment did not have the plant factor into consideration, effluent salinity did not affect the decision of using this effluent type while planning the experiment. On the other hand, effluent pH values were at the range recommended for irrigation (6.5 - 8.4) by Ayers and Westcot (1985) for the first and second irrigation seasons. In the third irrigation season, the pH sensor experienced technical problems and, as data values were not always logical, these values were removed. However, pH analyses conducted by the WWTP showed a pH range similar to the two previous irrigation periods. The development of registered physical parameters by SCADA within time during experiment is shown in Fig. III-5. The inlet and outlet effluents presented a slight to moderate chemical clogging hazard during the experiment based on the concentration of pH values according to Bucks et al. (1979) (Table I-3).

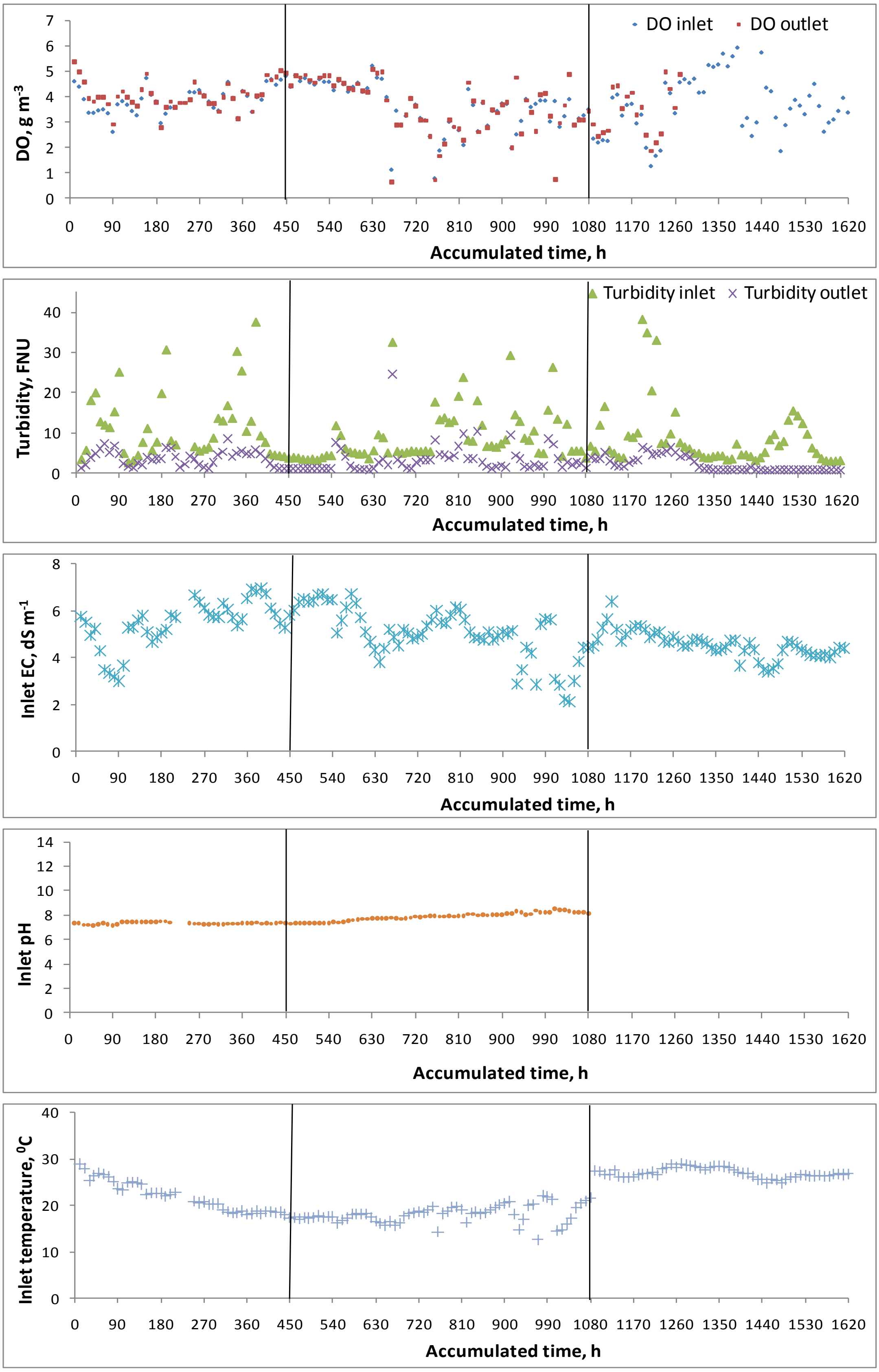


Fig. III-5. Evolution of each 10 h average values of the inlet effluent parameters through three irrigation seasons each of 540 h.

DO values for filtered effluent were higher than what they were before filtration (Table III-2), which indicated that the sand filter removed organic contaminants from the effluent and had a good performance.

On the other hand, there was a big drop in turbidity values after filtration as it could be seen in Table III-2 and Fig. III-5 that reflects the high performance of the sand filter in reducing effluent suspended materials. These results were in agreement with those obtained by Duran-Ros et al. (2009), who used a sand filtration unit for filtering a secondary and tertiary effluent in a microirrigation system.

As it could be seen in Fig. III-5, there was a difference of pH and temperature of the inlet effluent among the three irrigation seasons. The pH values were increasing and reached their maximum at the end of the second irrigation season. On the other hand, temperature decreased during the first and second irrigation periods and then increased during the third one. The temperature evolution was due to the variability in annual seasons when the experiment was carried out. As it could be seen in Table III-1, the first irrigation period started in summer season (August, 2007) to finish in autumn (December, 2007). Then, the second irrigation season lasted from March to May, 2008, being the spring temperatures smaller than in the previous autumn. On the other hand, the third irrigation season begun in June, 2008 and lasted until September, 2008 that coincided with the summer season. These temperature differences were studied statistically to determine which means were different from an irrigation season to another. Fig. III-6 shows the statistical significant differences ($P \leq 0.003$) resulted from Duncan test between effluent DO, EC, pH and temperature among different irrigation seasons.

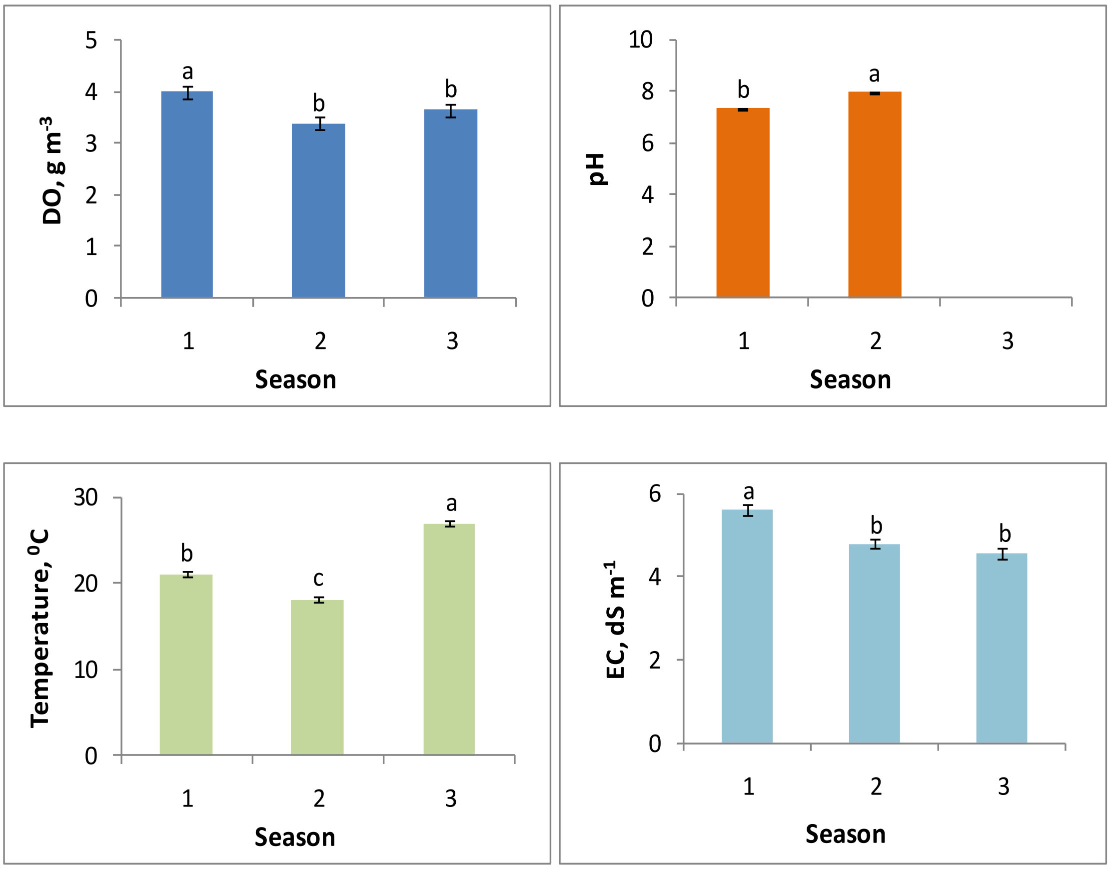


Fig. III-6. Average and standard error of the different effluent characteristics among the three irrigation seasons. Different letters mean significant differences ($P \leq 0.003$).

There were significant differences ($P \leq 0.003$) between inlet effluent DO, EC, pH and temperature among the different irrigation seasons but not for turbidity ($P = 0.558$). DO and EC mean values for the first irrigation season were significantly higher than in the second and third ones (Fig. III-6), which were not statistically different. On the other hand and as it is shown in Fig. III-6, the increasings in pH and temperature values previously shown in Table III-2 and Fig. III-5 were statistically significant.

III.4.2. Relationship between effluent turbidity and total suspended solids

After determining total suspended solids (TSS) applying equation (III-1), the relationship between effluent turbidity and TSS was significant ($P \leq 0.001$), had an $R_{adj}^2 = 0.910$ and is presented in equation (III-7).

$$\mathbf{TSS = 1.681 \cdot Turbidity} \quad \text{(III-7)}$$

being TSS the total suspended solids in g m^{-3} and the turbidity in FNU

The graphical presentation of this relationship is shown in Fig. III-7. There were no obvious patterns in the residual plot that defines the relationship between the observed TSS and residuals of equation (III-7) (Fig. III-7). This means that the assumptions of the regression were met (Wisniak and Polishuk, 1999).

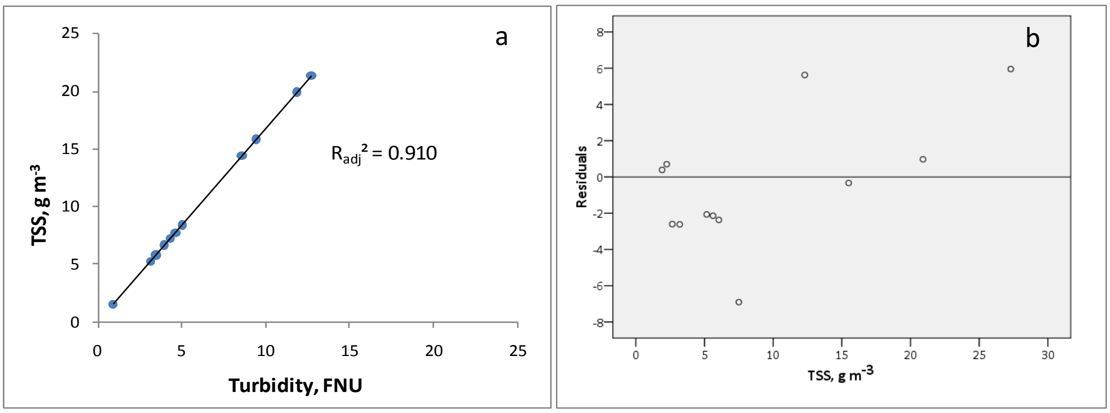


Fig. III-7. (a) Significant relationship (P < 0.001) between effluent concentrations of total suspended solids (TSS) in g m^{-3} and its turbidity in FNU applying equation (III-7) and (b) the residual plot for the same model.

Other studies also were set in order to determine the TSS as a function of turbidity in a river water (Christensen et al., 2001), stormwater retention/detention ponds (Packman et al., 1999) and in secondary and tertiary reclaimed effluents (Duran-Ros, 2008). All these different models had different constant values. This is because of that the relationship between the total suspended solids and turbidity is not constant (Packman et al., 1999). Gippel (1995) found that mineral particles can cause lower turbidity levels for a solution of the same overall concentration with higher percentage of fine particulate organic matter (FPOM). On contrary, Gilvear and Petts (1985) found the opposite; this is lower turbidity readings from FPOM versus the same concentration of fines. Moreover, turbidity depends also on the particle shape, size and amount of surface area which can cause variation in reflection, refraction and absorption of light (Packman et al., 1999) that lead at the end to different relationships in different solutions.

Applying equation (III-7), the TSS of the applied effluent was computed and pointed out in Table III-3 for the three different irrigation seasons.

Table III-3. Average TSS and standard deviation computed with equation (III-7) values for the filter inlet and outlet effluent during the experiment.

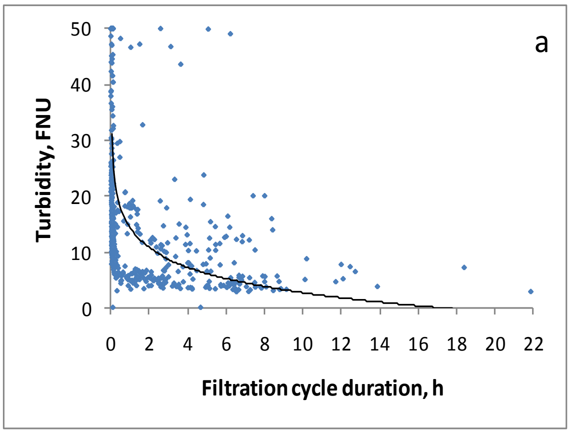
	1st irrigation season		2nd irrigation season		3rd irrigation season	
Parameter	**Inlet**	**Outlet**	**Inlet**	**Outlet**	**Inlet**	**Outlet**
TSS, g m^{-3}	14.16 ± 14.40	4.66 ± 3.88	12.45 ± 13.54	3.94 ± 5.01	11.05 ± 11.67	2.77 ± 2.64

The inlet effluent TSS concentration reduced from an average of 13 g m^{-3} to 4 g m^{-3} in effluent outlet. Rowan et al. (2004) experienced a reduction of TSS from 55 to 3 g m^{-3} when a sand bioreactor was used as effluent treatment. According to the classification proposed by Bucks et al. (1979), the inlet and outlet effluent would constitute a slight physical clogging.

III.4.3. Effect of effluent quality on flow rate and filter operating time

The operating time of the filters (period between cleaning operations) is clearly dependent on both water quality and filter type (Capra and Scicolone, 2004). So, the relationships between inlet effluent turbidity and both filtration cycle duration and flow rate were analysed (Fig. III-8).

As it could be seen in Fig. III-8 there was a significant ($P < 0.001$) reverse relationship between effluent turbidity and filtration cycle duration. However, the adjusted coefficient of determination of this relationship was low ($R_{adj}^2 = 0.325$).



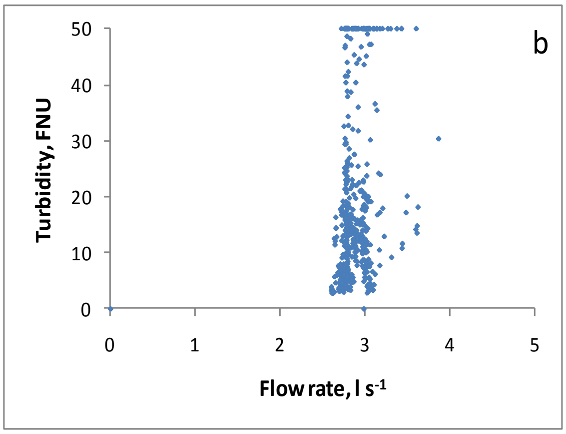


Fig. III-8. Relationships between turbidity of the applied effluent and both filtration cycle duration (a) and flow rate (b) during the experimental time.

Since there was only one filter type in the filtration unit in this study, it could be said that the filtration cycle duration depended mainly on the applied effluent quality and sand effective diameter, as it will be explained later. Therefore, and since a high effluent turbidity means in consequence high content of total suspended mater in the applied effluent, when turbidity values were high, cake on top of sand media was formed rapidly. Thus, the possibility of filter clogging increased at the end, causing a significant pressure drop that resulted in shorter filtration cycle duration (Aronino et al., 2009).

On contrary, flow rate was independent of turbidity values during the experiment (Fig. III-8 b) because the applied effluent was pressurized and forced to pass through the filter. Therefore, and assuming that flow rate was a constant variable in the relationship between turbidity and filtration cycle duration, the main reason for the short filtration durations was, first, the elevated turbidity that meant in consequence elevated total suspended matter in the applied effluent and, second, sand effective diameter as it will be discussed later.

III.4.4. Evolution of sand filter characteristics

As it was mentioned before in section III.3.1, sand media was changed once after the end of the second irrigation season. Fig. III-9 shows the sand media bed before and after being changed. The colour of the used sand media (Fig. III-9 a) was darker than the new one (Fig. III-9 b).

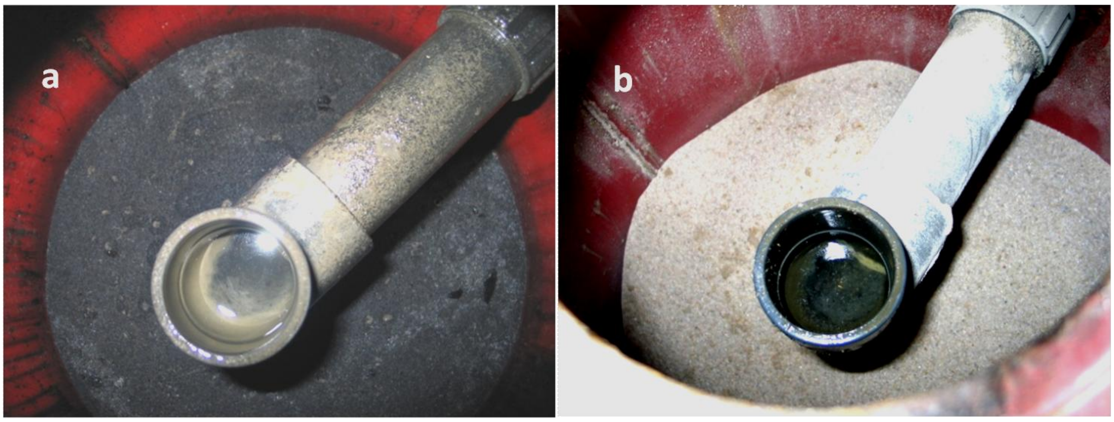


Fig. III-9. Sand media filter (a) before and (b) after, being changed at the end of the second irrigation season.

After calculating the percentage of the total accumulated sand mass sifted by each screen ($\%M_A$) using equation (III-3), the relationship between it and the screen pores' diameter was set to generate the granulometric curve (Fig. III-10). The granulometric curve was used to determine both sand effective diameter (d_e) and its uniformity coefficient (UC_s) (Table III-4).

Sand uniformity coefficient was greater than 1.5 during the experiment as recommended by Haman et al. (1994) and Burt and Styles (2000) except after the second irrigation season when sand was changed (Table III-4). This supports the adequacy and correctness of the decision of changing the filter used sand after 1080 h.

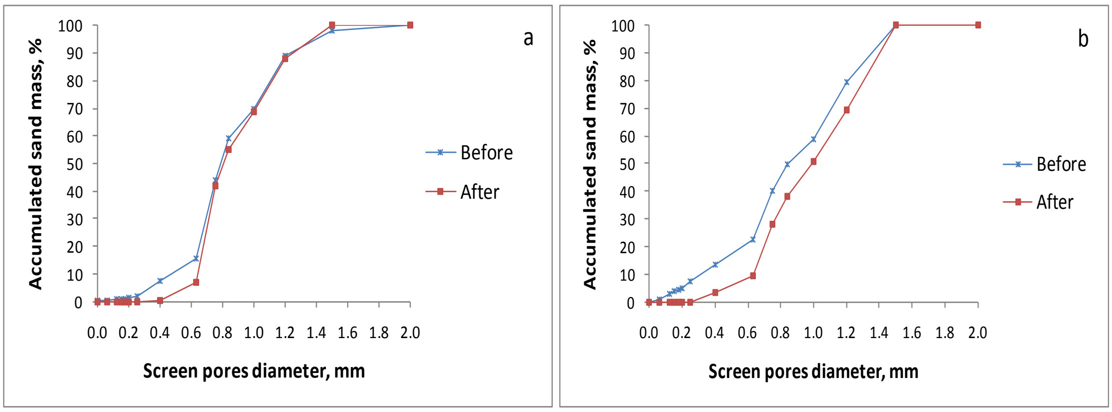


Fig. III-10. Sand granulometric curves (a) before the first and after the second irrigation seasons and (b) before and after the third irrigation season.

If a deep look is given to Fig. III-10 and Table III-4, it could be seen that sand effective diameter (d_e) increased during filter operation time from 0.47 to 0.64 mm and from 0.32 to 0.63 mm before and after changing the sand media. In consequence to that, the UC_s decreased from 1.81 to 1.40 before the first and after the second irrigation season, respectively and from 3.17 to 1.73 before and after the third irrigation season, respectively. This coincident with what was observed by Duran-Ros (2008) who pointed out an increasing in d_e from 0.40 mm to 0.41 mm and decreasing in UC_s from 2.41 to 1.58 before and after filtering a secondary effluent in sand filter, successively and from 0.27 mm to 0.52 mm, before and after filtering a tertiary effluent, respectively, which resulted in decreasing UC_s from 2.39 to 1.65 before and after operation, successively. This increasing in sand effective diameter indicated the loss of fine sand particles during the filtration process (Pitts et al., 1990; Sawa and Frenken, 2002). However, Gilbert et al. (1982) recommended a combination of sand and screen filtration to remove suspended solids. This could help to prevent the fine sand media particles from escaping to the lateral pipes causing clogging problems. It is important to point out that when sand was new or was changed, some manual backwashings were carried out to avoid small sand grain from releasing to the emitters. In the present experiment, the objective was to test the sand filter performance and normal backwashings were carried out previously to each irrigation season to avoid that small sand particles could entry in the irrigation laterals.

Table III-4. Sand effective diameter (d_e), sieves pores that let 60% of sand pass through it and uniformity coefficient of sand (UC_s) at different experiment times.

Time on base of irrigation season	Accumulated irrigation hours	Sieve pores that let pass		UC_s
		10% (d_e, mm)	60% (d_e, mm)	
Before the first	0	0.47	0.85	1.81
After the second	1820	0.64	0.90	1.40
Before the third	0	0.32	1.01	3.17
After the third	540	0.63	1.10	1.73

Since d_e is a measure of minimum sand size in the grade, it is considered as an indicator of particle size that could be removed by the media (Haman et al., 1994). The finer the media, the smaller the particle size that would be removed and so, the better the quality of filtration process (Pitts et al., 1990; Haman et al., 1994; Phillips 1995). However, smaller media size means in consequence more frequent cleaning (Haman et al., 1994).

III.4.5. Effectiveness of backwashing processes

The relationship between head loss across the filter (ΔH) and accumulated experimental time for each irrigation season is illustrated in Fig. III-11. The number of efficient and inefficient backwashing classified on base of filter capacity to recover the pressure loss across it, the volume of filtered effluent and backwashing water consumption for each season and the total time with the highest effluent turbidity values are pointed out in Table III-5.

In general, head loss across the filter varied between 20 – 52 kPa during the experiment. Duran-Ros et al. (2008) assigned a head loss between 28 – 40 kPa for clean media filters and backwashed the filters when the head loss across them reached 50 kPa. This is yet in the range of 20 – 55 kPa recommended by Haman et al. (1994) for clean media filters depending on the size of the media and flow rate used.

As it could be observed in Fig. III-11, filter head loss increased within time as contaminants accumulate and partially plug the filter (Haman et al., 1994). Therefore, in range of ΔH between 20 – 52 kPa, the wider the space between filtration cycles the longer was the filtration cycle and the cleaner the inlet effluent and vice versa, the narrower the space between the filtration cycles the dirtier the applied effluent.

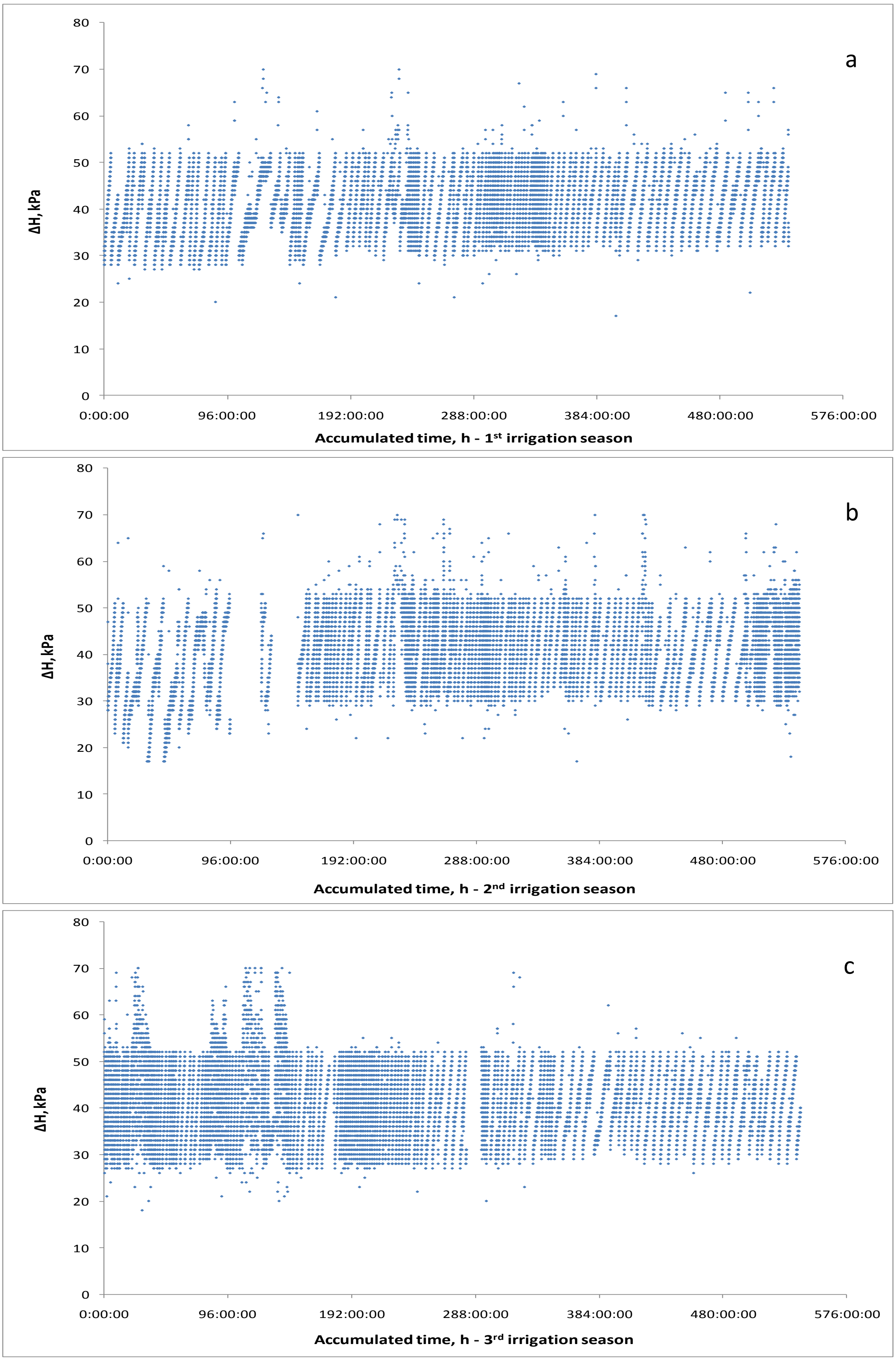


Fig. III-11. Evolution of head loss (ΔH) across the filter during the three irrigation seasons.

For the first irrigation season (Fig. III-11 a), the observed irregularity in the backwashing cycles between 104 – 113 h, 152 – 188 and 220 – 235 h of irrigation successively was due to pump technical problems that caused shortage in the effluent supply.

The beginning of the second irrigation season (Fig. III-11 b) suffered from a series of inefficient backwashing cycles (between 0 – 95 h) due to the bad quality of the applied effluent and its elevated turbidity. Because of technical problems, system was not able to register data from 95 to 111 and from 127 to 148 h even the irrigation was running. Besides, the beginning of this irrigation period suffered as well from shortage in effluent supply for technical problems.

For the third irrigation season, and due to the small sand effective diameter, system at the beginning was not capable of running effective backwashing cycles (Table III-4). This could explain the elevated head loss that reached 70 kPa sometimes during the first 31 h of irrigation and from 84 to 143 h successively. This problem disappeared during the rest of the third irrigation period due to the increasing of sand effective diameter from 0.32 mm to 0.63 mm. There was some missed data for 16 h after 276 h of irrigation during this season for technical problems as well.

Table III-5. Number of efficient and inefficient backwashing, volume of filtered effluent and filtered water used each season and total time with the highest effluent turbidity values.

Irrigation season	**First**	**Second**	**Third**
Total number of backwashings	105	202	372
Number of efficient backwashing	64	158	343
Inefficient backwashing, %	41	44	29
Total of filtered effluent per season, m^3	5836.88	5704.51	5484.74
Filtered water consumed by filter backwashing process, %	1.3	3.1	5.7
Number of minutes with turbidity ≥ 50 FNU	1455	2767	373

From Table III-5 it could be noticed that, despite the average of filtered effluent during the three irrigation seasons was around 5674 m^3, the total number of sand filter backwashing cycles, which were considered for further study, was 105 during the first irrigation period, 41% of them were inefficient. Backwashing cycles increased to 202 cycles during the second season to reach its maximum during the third irrigation season with 372 cycles. About 44 and 29 % of the filtration cycles were inefficient in the second and third irrigation seasons, respectively. Filters with inefficient backwash tend to accumulate aggregates of the suspended matter resulting at the end in a negative impact on filtrate turbidity and filter run time (Cleasby, 1990).

It was observed that effluent turbidity reached its highest (turbidity ≥ 50 FNU) during the second irrigation season for 2767 min, while it was only 1455 min (almost the half of the determined time in the second irrigation season) during the first irrigation one. Thus, the increasing in filter backwashing cycles during the second irrigation season was primarily due to the sand media clogging by trapped particles that were observed at the end of the second irrigation period (Table III-4). However, the difference between turbidity values among the three irrigation seasons was not statistically significant, as it was previously discussed.

Nevertheless, effluent turbidity during the third irrigation period reached its maximum (≥ 50 FNU) only for 373 min. Even though, sand effective diameter during the beginning of the third irrigation period was smaller (d_e = 0.32 mm) than what it was during the beginning of the first irrigation season (d_e = 0.47 mm), as it was explained before in section III.4.4. This difference between sand effective diameter explained the observed increasing in the backwashing cycles during the third irrigation season on base of the role that, the smaller the effective diameter, the higher the clogging possibility because media filters are not able to remove more particles (Haman et al., 1994).

This also explains why the third irrigation season consumed more backwashing water, which was obviously due to the higher frequency of filter clogging that increased the total number of the backwashing cycles than the other two seasons.

III.4.6. Effect of sand filtration unit on effluent characteristics

The evolution of DO and turbidity during each irrigation season was presented previously in Fig. III-5. The statistical results for the paired samples T test to study the significance degree of DO and turbidity removal efficiency are pointed out in Table III-6.

Since mean value for DO_{inlet}-DO_{outlet} pair in Table III-6 was negative for the first and third irrigation seasons, then, inlet effluent concentration of DO (DO_{inlet}) was significantly minor ($P < 0.001$) than what it was at filter outlet (DO_{outlet}) (Table III-6). Rowan et al. (2004) observed as well a reduction in the biological oxygen demand when using a sand bioreactor. The average DO concentration increased through the filter during the first and third irrigation seasons with an absolute value of 0.18 and 0.33 g m^{-3}, respectively (Table III-6), which was lower than the increasing in DO of 0.25 g m^{-3} observed by Maestre-Valero and Martínez-Álvarez (2010) corresponding to the circulation of water through the pump. Nevertheless, Maestre-Valero and Martínez-Álvarez (2010) detected an increasing in DO concentration of 1.96 and 3.15 g m^{-3} during the seepage of water into the soil and through the emitters, respectively. This was because of the minor air intrusions in the filter and pump compared with soil and emitters. On contrary, the difference between dissolved oxygen (DO) values before and after being filtered in the second irrigation season was not statistically significant ($P = 0.780$).

On the other hand, there was a significant decrease in effluent turbidity after being filtered ($P < 0.001$) for the three different irrigation seasons. This indicated the effectiveness of the sand filtration unit to reduce the total suspended mater in the outlet effluent.

Table III-6. Statistical results for the paired samples T test analysis between the inlet and outlet effluents DO and turbidity.

		Related differences				
Irrigation season	**Pairs**	**Mean**	**Standard deviation**	**Mean standard error**	**t**	**P significance level (two tailed)**
First	Do_{inlet}-Do_{outlet}	-0.179	0.226	0.031	-5.804	0.000
	$Turbidity_{inlet}$-$Turbidity_{outlet}$	6.854	6.777	0.930	7.363	0.000
Second	Do_{inlet}-Do_{outlet}	0.022	0.576	0.077	0.280	0.780
	$Turbidity_{inlet}$-$Turbidity_{outlet}$	6.110	3.921	0.524	11.662	0.000
Third	Do_{inlet}-Do_{outlet}	-0.328	0.220	0.048	-6.848	0.000
	$Turbidity_{inlet}$-$Turbidity_{outlet}$	6.511	6.648	0.888	7.329	0.000

III.4.7. Effect of different sand effective diameters on filter removal efficiency

The statistical results for the multivariate general linear model to determine if d_e had affected the removal efficiency of DO and turbidity or not are illustrated in Fig. III-12.

As it could be seen in Fig. III-12, there were statistical significant difference among different sand effective diameters (d_e). According to Duncan test results, removal efficiency for DO for the smallest d_e (0.32 mm) was, in absolute values, higher than the other two mean d_e of 0.47 and 0.64 mm respectively.

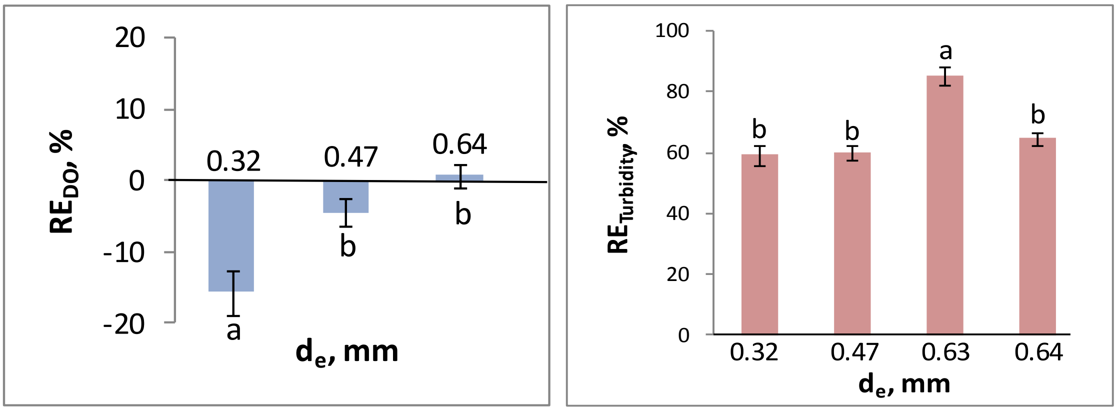


Fig. III-12. Average and standard error of DO (RE_{DO}) and turbidity ($RE_{Turbidity}$) removal efficiencies. Different letters mean significant differences ($P \leq 0.001$) among sand effective diameters.

Since removal efficiency depends on subtracting the parameter value after filtration from its value before being filtered (equation (III-6)), negative means indicate that parameter value was increased after the filtration. This is favourable for the plant because of the low dissolved oxygen concentration in the irrigation water may have critical consequences because it causes root oxygen deficiency, which in turn can result in agronomic problems (Maestre-Valero and Martínez-Álvarez, 2010).

As the removal efficiency of turbidity had positive values, turbidity was smaller at filter outlet than at inlet. The four different sand effective diameters were effective for removing most of the turbidity and TSS in the applied effluent. However, there was a statistical difference between removal efficiency of turbidity that also depended on sand effective diameter (Fig. III-12). Sand effective diameter of 0.63 mm achieved the highest removal efficiency for effluent turbidity (85.41%) even the 0.64 mm d_e achieved only a 65%. There were no significant difference in removal efficiency between sand effective diameter of 0.32, 0.47 and 0.64 mm. Nevertheless, Naghavi and Malone (1986) pointed out that effluent quality deteriorated when sand with a median grain size diameter of 0.34 is used for the filtration bed.

Sand filter achieved a reduction of 60 to 85% of the turbidity, which allowed an outlet effluent with less than 5 g TSS per m^3. Duran-Ros et al. (2009) observed a reduction of 57.6% and 66.4% of turbidity for two different secondary and tertiary effluent types with a sand effective diameter of 0.40 and 0.41 mm before and after being used, and 0.27 and 0.52 mm before and after being used, respectively. This coincided with the results by Nakhla and Farooq (2003) who reported a 33 – 56 % turbidity removal efficiency using coarse sand filters (d_e = 0.50 mm) and accomplished a removal efficiency of 40 – 62 % of turbidity in the fine media sand filters (d_e = 0.30 mm) when using an effluent with a turbidity of 0.2 – 0.95 FNU (TSS of 8 to 22 g m^{-3}). Furthermore, Tebbutt (1971) found that removal of suspended solids in secondary activated sludge effluent is primarily a function of the bed grain size, showing as well a significant improvement in TSS removal with finer media. Nevertheless, Naghavi and Malone (1986) who studied the algal removal by fine sand/silt filtration with five median sand sizes that varied between 0.064 to 0.335 mm, found that increasing median grain size diameter from 0.064 to 0.200 mm did not have significant effect on the effluent quality. Yet they found that effluent quality deteriorated when sand with a median grain size diameter of 0.335 mm was used for the filtration bed.

However, Adin and Elimelech (1989) found the opposite. Removal efficiency of TSS was increased with greater sand effective diameters. Nevertheless, Adin and Elimelech (1989) studied three media filters with effective diameters of 0.70, 0.84 and 1.20 mm, being these diameters higher than those used by Nakhla and Farooq (2003), Duran-Ros et al. (2009) and in the current study.

III.4.8. Effect of filter backwashing on filtration efficiency

The statistical significant differences between mean reduction in effluent turbidity ($RE_{Turbidity}$) and DO (RE_{DO}) removal efficiency for 10 min before and 10, 15, 30, 45, 60 and 120 min after filter backwashing are shown in Fig. III-13 and Fig. III-14, respectively. Results were used to determine the duration of filter ripening and whether it had a negative impact on $RE_{Turbidity}$ and RE_{DO} during it.

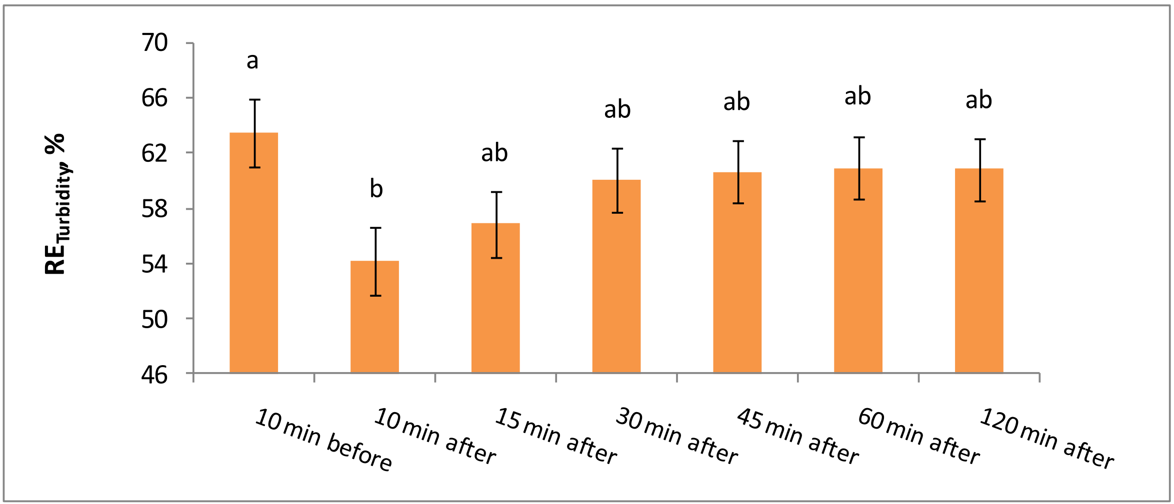


Fig. III-13. Average and standard error for turbidity removal efficiency ($RE_{Turbidity}$) at 10 min before backwashing and 10, 15, 30, 45, 60 and 120 min after it. Different letters show significant differences ($P \leq 0.009$).

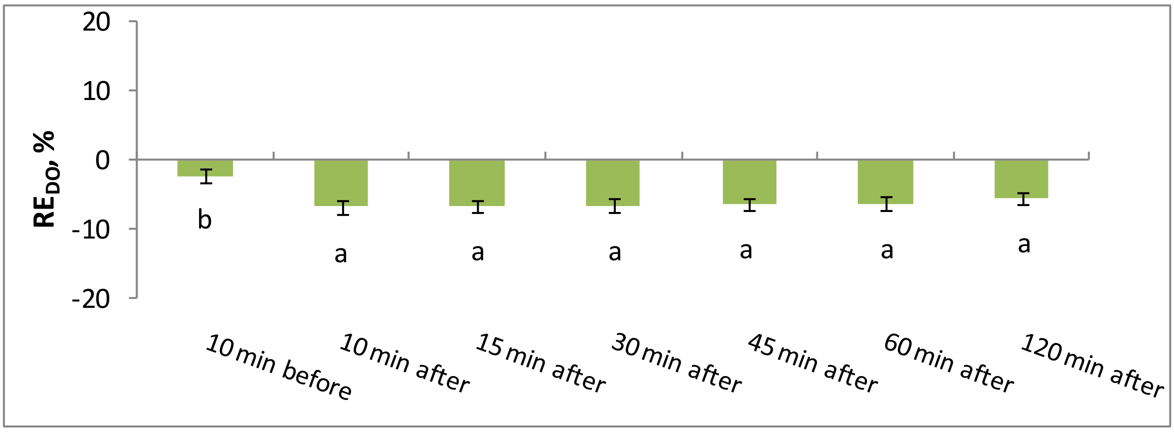


Fig. III-14. Average and standard error for DO removal efficiency (RE_{DO}) at 10 min before backwashing and 10, 15, 30, 45, 60 and 120 min after it. Different letters show significant differences ($P \leq 0.002$).

Removal efficiency of effluent turbidity decreased significantly from 63.5% at 10 min before backwashing to 54.2% at 10 min after it (Fig. III-13). This means that during the first 10 min after backwashing filter did not retain as solids as the almost clogged filter. However, at 15 min after backwashing, the filter regained its capacity to remove an average of 60.6% of the suspended solids from the filtered effluent. This coincided with what was pointed out by the United States Environmental Protection Agency (USEPA), which indicated that effluent quality gets its normal values within 15 min of starting filter backwashing (USEPA, 1998) and also, fell in the range of few minutes to 40 min after backwashing observed by Satterfield (2005). According to these results, it could be said that filter ripening during the experimental time did not exceed 15 min. There was no significant difference between $RE_{Turbidity}$ during the studied times of 15, 30, 45, 60 and 120 min after backwashing.

Removal efficiency for DO values decreased significantly ($P \leq 0.002$) after filter backwashing, which indicated more effectiveness in the elimination of organic contaminants once the sand filter has been backwashed (Fig. III-14). This improving in DO removal efficiency from -2.32% before backwashing to an average of -6.36% after it was lasted until the last studied time interval (120 min) after the filtration. There was no significant difference between RE_{DO} at the different investigated times after the backwashing. So, the clean sand filter was able to remove more organic contaminants increasing the outlet DO concentration in the filtered effluent after the backwashing. Even turbidity values increased during filter ripening in the outlet effluent, the organic contaminants removal efficiency was significantly increased during and after this period (Fig. III-14).

However, no statistical difference were found ($P > 0.05$) in the mean $RE_{Turbidity}$ for 0 - 10% time before backwashing and 10 – 20, 30 – 40, 50 – 60, 70 – 80 and 90 – 100% after (Fig. III-15). This would be because of the long interval of time that used in this analysis, which is 10% of the filtration cycle duration of 112 filtration cycles (about 63% of the analysed cycles) were longer than 15 min.

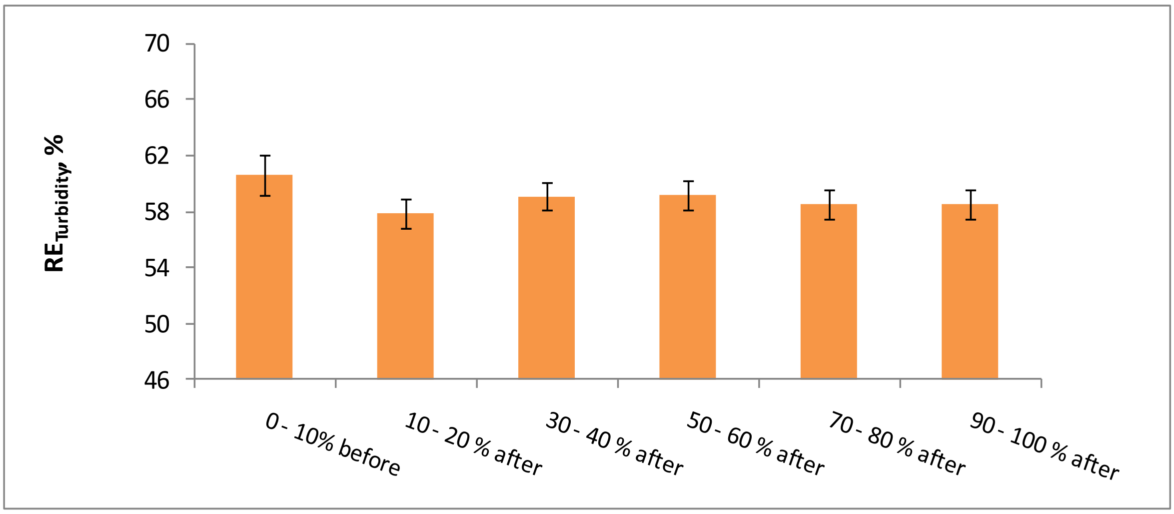


Fig. III-15. Average and standard error before and after backwashing for turbidity removal efficiency ($RE_{Turbidity}$) at 10% of normal filtration cycle duration before backwashing and from 10 to 100% after it.

On the other hand, the RE_{DO} was decreased from average -5.5% at 10% of time before backwashing to -8.3% at 10 - 20% of time after it. The filter conserved its significant improvement ($P \leq 0.006$) of organic contaminants until 70 – 80% of its cycle duration. At 90 – 100% of filter cycle duration the average RE_{DO} did not differ significantly ($P > 0.05$) from 00 – 10% of filtration cycle before the backwashing (Fig. III-16).

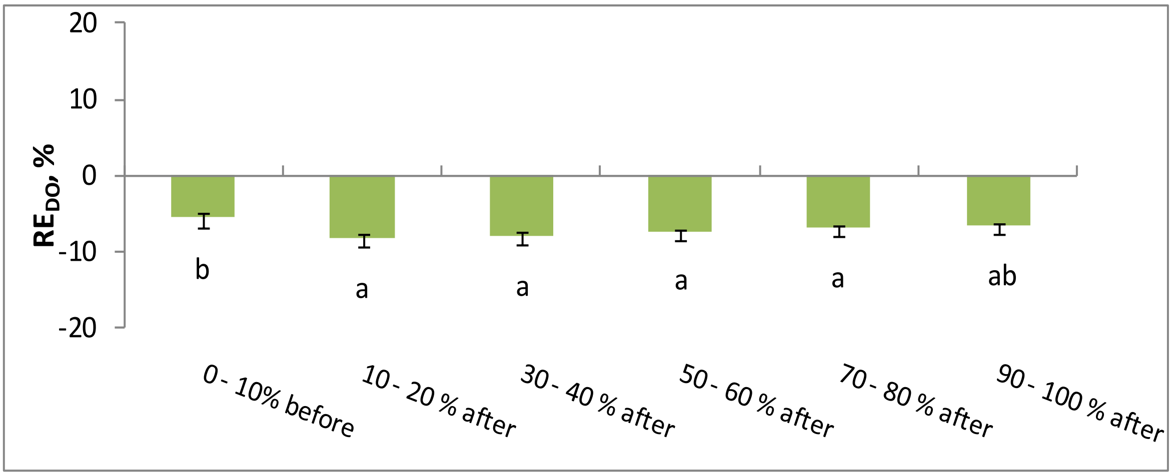


Fig. III-16. Average and standard error before and after backwashing for DO removal efficiency (RE_{DO}) at 10% before backwashing and from 10 to 100% after it. Different letters show significant differences ($P \leq 0.006$).

In view of the fact that backwashing cause turbulence in the stability of the sand, some of the filter finer sand particles escape with the effluent during the backwashing causing the noticed increase in effluent turbidity after backwashing (Pitts et al., 1990; Sawa and Frenken, 2002). Amirtharajah (1985) experienced that the highest backwash remnant particle concentration occurs at the level of the outlet effluent because that water passed through the filter while the media possessed the highest concentration of solids. Colton et al. (1996) recommended restricting the rate of flow through the filter (slow start) for one hour or until the filtrate quality is acceptable. This explains also the increase of sand effective diameter during filter operation. According to Nakayama et al. (2007), these fine particles may travel through the filters as individual particles, but then flocculate or become attached to organic residues and eventually become large enough to clog emitters. This may elucidate as well the presence of sand and other mineral particles in the driplines and emitters. After backwashing, the filter was clear and apparently no particles were trapped. These retained particles could help to improve removal efficiency of particles resulting in less outlet turbidity but allowed to reduce organic pollutant removal that led in consequence to higher DO concentration in the outlet effluent.

III.5. Conclusions

According to the research conducted throughout this chapter, it could be concluded that:

- For the filter operation time:
  - A significant reverse relationship ($P < 0.001$) was found between effluent turbidity and filtration cycle duration. However, the adjusted coefficient of determination was low (0.325).
- For the filtration unit:
  - Sand media characteristics changed during the filtration because of the loss of fine particles during the backwashing process. Sand effective diameter (d_e) increased during the filtration from 0.47 mm to 0.64 mm after 1080 h of filtration, and from 0.32 mm to 0.63 mm after 540 h, which indicated the loss of the finer sand media from the filter.
- For the effect of sand filter and backwashing cycles on effluent quality:
  - Sand media filter improved the filter effluent quality. Effluent turbidity was significantly decreased ($P < 0.001$) by 59 - 64% after filtration independently from d_e during the experiment except for d_e = 0.63 mm. Dissolved oxygen was significantly increased ($P < 0.001$) in the filtered effluent, depending on sand media effective diameter. The smaller the d_e, the higher the DO removal efficiency. Sand effective diameter of 0.32 mm improved the DO values with 15.7% in the filtered effluent, while when d_e increased to 0.47 mm, it improved only 4.5% of DO values.
  - Filter ripening period was of 15 min during the experiment. During filter ripening, turbidity values increased significantly ($P < 0.009$), which indicated that clean filters remove less particles than they are almost clogged. On contrary, the DO values increased significantly ($P > 0.002$) and lasted until 70 - 80% of the filter cycle duration. At 90 – 100% of filter cycle duration, it was observed no significant difference between DO values before and after the backwashing ($P > 0.05$).

IV. Applying dimensional analysis to predict head loss and filter cycle duration in sand filters

IV.1. Introduction

Science begins with observation and description, but its ultimate goal is to infer from those observations laws that express the phenomena of the physical world in the simplest and most general terms. Dimensional analysis offers a method for reducing complex physical problems to the simplest form prior to obtaining a quantitative answer (Sonin, 2001). Moreover, dimensional analysis is most useful in the case that a mathematical model is not known (Price, 2003). According to Bridgman (1969), the principal use of dimensional analysis is to deduce from a study of the dimensions of the variables in any physical system certain limitations on the form of any possible relationship between those variables. In addition, Sonin (2001) thinks that the main utility of this analysis derives from its ability to contract, or make more succinct, the functional form of physical relationships. Also, he points out that dimensional analysis must be well supported by experimental facts.

One of the famous theorems that provides and describes the procedure of the dimensional analysis is Buckingham's pi theorem. This theorem derives its name from Buckingham's use of the Greek symbol π for the dimensionless independent parameters in his original 1915 paper. According to Buckingham (1915), the theorem tells us that when dimensional analysis is applied to study a physical phenomenon that depends on m independent parameters, it is possible to find an equivalent equation for this phenomenon that is only a function of $m - r$ dimensionless independent parameters, being r the phenomenon dimensional matrix range.

This reduction of parameters considerably simplifies the experiments that must be carried out. Nevertheless, dimensional analysis is not enough to determine whether the generated model is suitable in real physical world and describes well a phenomenon (Sonin, 2001). Therefore, it must be followed by statistical analysis that studies the relationship between the real experimental data that describe the phenomenon and the values calculated by the model. Regression analysis is an adequate statistical technique for investigating and modeling the relationship between variables. Also, it is capable of studying the relation between the variables values predicted by the model and the real values for same phenomena.

The main objective of the regression analysis is to estimate the unknown parameters in the regression model and then check the adequacy of the model (Wisniak and Polishuk, 1999).

As it has been mentioned before, a good filtration process in the microirrigation system would help to prevent clogging in emitters. Different works have been set to study the filtration process such as Adin and Alon (1986) and McCabe et al. (2001). These works are used traditionally to study the filtration process using parameters related to filtration cake characteristics, which are difficult to estimate because of variations that occur during any filtration cycle. However, Puig-Bargués et al. (2005a) developed a mathematical model for calculating head loss across sand, screen and disc filters, being the constant value and coefficients different from filter type to another. The model that Puig-Bargués et al. (2005a) found for describing head loss phenomena in sand filters was:

$$\frac{\mu}{\Delta H^{0.25} \cdot Q^{0.50} \cdot C^{0.75}} = \mathbf{8.61E-8} \cdot \left(\frac{\Delta H^{0.75} \cdot V}{C^{0.75} \cdot Q^{1.50}}\right)^{-0.14} \cdot \left(\frac{\Delta H^{0.50} \cdot A}{C^{0.50} \cdot Q}\right)^{0.81} \cdot \left(\frac{\Delta H^{0.25} \cdot d_e}{C^{0.25} \cdot Q^{0.50}}\right)^{0.69} \cdot \left(\frac{\Delta H^{0.25} \cdot D_P}{C^{0.25} \cdot Q^{0.50}}\right)^{-0.18} \cdot \left(\frac{\rho}{C}\right)^{0.52} \quad \text{(IV-1)}$$

where μ is water viscosity in Pa s, ΔH is head loss across the filter in Pa, Q is filtered liquid flow rate in m^3 s^{-1}, C is suspended solids concentration in kg m^{-3}, V is filtered liquid volume in m^3, A is total filtration surface in m^2, d_e is sand effective diameter in m, D_p is mean diameter of suspended particle size distribution in m, and ρ is water density in kg m^{-3}.

Duran-Ros et al. (2010) found also an equation useful for computing head loss in disc, screen and sand filters, being also, the constant value and coefficients different from one filter type to another. The constant values and coefficients defined in equation (IV-2) were found by Duran-Ros et al. (2010) for sand filters only:

$$\frac{v \cdot C^{0.5}}{\Delta H^{0.5}} = \mathbf{2.7E+2} \cdot \left(\frac{\rho}{C}\right)^{-0.9870} \cdot \left(\frac{\mu}{\Delta H^{0.5} \cdot C^{0.5} \cdot d_p}\right)^{1.0053} \quad \text{(IV-2)}$$

where *v* is filtration velocity in m s^{-1} and d_p is inside diameter of the inlet and outlet pipe in m.

Besides Puig-Bargués et al. (2005a) and Duran-Ros et al. (2010) mathematical models, other models have been developed using dimensional analysis to predict head losses inside different types of filters for drip irrigation systems, such as disc filters (Yurdem et al., 2008) and hydrocyclone filters (Yurdem et al., 2010).

IV.2. Objectives

The planned objectives of this chapter are twofold:

- Apply the dimensional analysis using Buckingham's pi theorem to develop mathematical models for computing head loss across sand filters.
- Develop a mathematical model for calculating sand filter operating time between backwashings using dimensionless independent parameters generated by the Buckingham's theorem.

IV.3. Material and methods

IV.3.1. Generating the dimensionless parameters

A dimensional analysis was set using Buckingham's theorem for 575 filtration cycles to develop mathematical models that are able to describe head loss across sand filters and the time between sand filter backwashing cycles. Other filtration cycles that contained missed data for some variables due to technical problems did not inter in this study. Filter and effluent characteristics were determined previously in Chapter III. Length (L), mass (M), and time (θ) were the three dimensions used for analyzing any physical phenomena unit in this study.

The first step in modelling any physical phenomena is the identification of the relevant variables that could explain the phenomena. Therefore, different sets of variables for describing head loss across sand filters and their adequate functional time before a backwashing must be carried out were selected. Those variables are pointed out in Table IV-1. The dimensionless matrix for this set of variables is shown in Table IV-2.

Some of these variables were constant during the experimental period, while others were dynamic through it. The constant variables during the experiment were the internal sand filter diameter (d_f), filtration media height ($Ø_f$), total filtration surface (A), sand mass inside the filter (m_s), water viscosity (μ), water density (ρ), and acceleration of gravity (g). Effluent viscosity and density were considered 1.0E-3 Pa s and 1000 kg m^{-3}, respectively at a reference temperature of 20^oC.

Three variables from each set of variables were selected as a recurring set of variables, which was used as a base to generate different dimensionless parameters according to Buckingham's theorem.

Table IV-1. Variables used for predicting head loss and time between backwashing cycles in sand filter.

No.	Variable	Symbol	Unit	Dimension
1	Head loss across the filter	ΔH	Pa	$L^{-1} M \Theta^{-2}$
2	Sand effective diameter	d_e	m	L
3	Internal sand filter diameter	d_f	m	L
4	Filtration media height	$Ø_f$	m	L
5	Total filtration surface	A	m^2	L^2
6	Filtered effluent volume per filtration cycle	V	m^3	L^3
7	Acceleration of gravity	g	$m\ s^{-2}$	$L \Theta^{-2}$
8	Duration for every filtration cycle	t	s	Θ
9	Suspended solids average concentration per filtration cycle	C	$kg\ m^{-3}$	$L^{-3} M$
10	Sand mass inside the filter	m_s	kg	M
11	Water viscosity	µ	Pa s	$L^{-1} M \Theta^{-1}$
12	Water density	ρ	$kg\ m^{-3}$	$L^{-3} M$
13	Filtration velocity	v	$m\ s^{-1}$	$L\Theta^{-1}$
14	Filtered liquid flow rate	Q	$m^3\ s$	$L^3\Theta^{-1}$

Table IV-2. Dimensional matrix for variables presented in Table IV-1.

	ΔH	**d_e**	**d_f**	**$Ø_f$**	**A**	**v**	**V**	**Q**	**C**	**m_s**	**µ**	**ρ**	**g**	**t**
L	-1	1	1	1	2	1	3	3	-3	0	-1	-3	1	0
M	1	0	0	0	0	0	0	0	1	1	1	1	0	0
Θ	-2	0	0	0	0	-1	0	-1	0	0	-1	0	-2	1

IV.3.1.1. Dimensionless parameters π_1 to π_9

The recurring set of variables that was used to generate the dimensionless parameters for only the first twelve variables of Table IV-1 included the variables filtration media height ($Ø_f$), water density (ρ) and duration for every filtration cycle (t). As the number of variables was m = 12 and matrix range r = 3, then the number of dimensionless independent parameters that need to be found were $m - r$ = 12 - 3 = 9. The predicted dimensionless independent parameters were:

$\pi_1 = \frac{\Delta H \cdot t^2}{\rho \cdot \varnothing_f{}^2}$ $\pi_2 = \frac{d_e}{\varnothing_f}$ $\pi_3 = \frac{d_f}{\varnothing_f}$

$\pi_4 = \frac{A}{\varnothing_f{}^2}$ $\pi_5 = \frac{V}{\varnothing_f{}^3}$ $\pi_6 = \frac{C}{\rho}$

$\pi_7 = \frac{m_s}{\rho \cdot \varnothing_f{}^3}$ $\pi_8 = \frac{\rho \cdot \varnothing_f{}^2}{\mu \cdot t}$ $\pi_9 = \frac{\varnothing_f}{t^2 \cdot g}$

IV.3.1.2. Dimensionless parameters π_{10} to π_{20}

Another recurring set of variables was used for variables shown in Table IV-1 in order to generate more dimensionless groups. These new groups included the Reynolds number (*Re*), which relates inertial and viscous forces, Froude number (*Fr*), which relates inertial forces with gravitational ones, and Euler number (*Eu*), which relates inertial forces with pressure forces. The relationships between these three numbers were studied. The recurring set of variables consisted on internal sand filter diameter (d_f), water density (ρ) and duration for every filtration cycle (t).

Since the number of variables was m = 14 and matrix range r = 3, then it should be $m–r$ = 14 – 3 = 11 dimensionless independent parameters. The dimensionless parameters that were found were:

$\pi_{10} = \frac{\Delta H}{\rho \cdot v^2} = \boldsymbol{Eu}$ $\pi_{11} = \frac{d_e}{d_f}$ $\pi_{12} = \frac{\varnothing_f}{d_f}$

$\pi_{13} = \frac{A}{d_f{}^2}$ $\pi_{14} = \frac{V}{d_f{}^3}$ $\pi_{15} = \frac{v^2}{d_f \cdot g} = \boldsymbol{Fr}$

$\pi_{16} = \frac{v \cdot t}{d_f}$ $\pi_{17} = \frac{C}{\rho}$ $\pi_{18} = \frac{m_s}{\rho \cdot d_f{}^3}$

$\pi_{19} = \frac{\rho \cdot v \cdot d_f}{\mu} = \boldsymbol{Re}$ $\pi_{20} = \frac{Q}{d_f{}^2 \cdot v}$

IV.3.1.3. Dimensionless parameters π_{21} to π_{29}

A new recurring set of variables for the same first twelve variables in Table IV-1 was selected for predicting another set of dimensionless groups. This recurring set of variables consisted of sand effective diameter (d_e), suspended solids average concentration per filtration cycle (C) and acceleration of gravity (g).

Again, as the number of variables was *m* = 12 and matrix range *r* = 3, then it should be 9 dimensionless parameters. These dimensionless parameters were:

$$\pi_{21} = t \cdot \sqrt{\frac{g}{d_e}} \qquad \pi_{22} = \frac{\rho}{C} \qquad \pi_{23} = \frac{\mu}{C \cdot {d_e}^{1.5} \cdot \sqrt{g}}$$

$$\pi_{24} = \frac{m_s}{C \cdot {d_e}^3} \qquad \pi_{25} = \frac{V}{{d_e}^3} \qquad \pi_{26} = \frac{A}{{d_e}^2}$$

$$\pi_{27} = \frac{\emptyset_f}{d_e} \qquad \pi_{28} = \frac{d_f}{d_e} \qquad \pi_{29} = \frac{\Delta H}{d_e \cdot C \cdot g}$$

IV.3.1.4. Dimensionless parameters π_{30} to π_{40}

A new recurring set of variables for all variables in Table IV-1 was set for developing the new dimensionless independent parameters. These variables were sand effective diameter (d_e), suspended solids average concentration per filtration cycle (C) and duration of every filtration cycle (t).

Being the number of variables *m* = 14 and matrix range *r* = 3, then it should be *m* – *r* = 14 - 3 = 11 dimensionless parameters, which were:

$$\pi_{30} = \frac{\Delta H \cdot t^2}{C \cdot {d_e}^2} \qquad \pi_{31} = \frac{d_f}{d_e} \qquad \pi_{32} = \frac{\emptyset_f}{d_e}$$

$$\pi_{33} = \frac{A}{{d_e}^2} \qquad \pi_{34} = \frac{v \cdot t}{d_e} \qquad \pi_{35} = \frac{V}{{d_e}^3}$$

$$\pi_{36} = \frac{Q \cdot t}{{d_e}^3} \qquad \pi_{37} = \frac{m_s}{C \cdot {d_e}^3} \qquad \pi_{38} = \frac{\mu \cdot t}{C \cdot {d_e}^2}$$

$$\pi_{39} = \frac{\rho}{C} \qquad \pi_{40} = \frac{g \cdot t^2}{d_e}$$

IV.3.1.5. Dimensionless parameters π_{41} to π_{51}

Another recurring set of variables was used to generate more dimensionless parameters to study whether it would help to predict the head loss inside the filter and its adequate functional time before a backwashing needs to be carried out. This set of variables included sand effective diameter (d_e), suspended solids average concentration per filtration cycle and (C) and acceleration of gravity (g).

As the number of variables was m = 14 and matrix range r = 3, then $m - r$ = 14 - 3 = 11 dimensionless parameters. These parameters were:

$\pi_{41} = t \cdot \sqrt{\frac{g}{d_e}}$ $\pi_{42} = \frac{\rho}{C}$ $\pi_{43} = \frac{\mu}{C \cdot d_e^{1.5} \cdot \sqrt{g}}$

$\pi_{44} = \frac{m_s}{C \cdot d_e^{3}}$ $\pi_{45} = \frac{Q}{d_e^{2.5} \cdot \sqrt{g}}$ $\pi_{46} = \frac{V}{d_e^{3}}$

$\pi_{47} = \frac{v}{\sqrt{d_e \cdot g}}$ $\pi_{48} = \frac{A}{d_e^{2}}$ $\pi_{49} = \frac{\emptyset_f}{d_e}$

$\pi_{50} = \frac{d_f}{d_e}$ $\pi_{51} = \frac{\Delta H}{d_e \cdot C \cdot g}$

IV.3.1.6. Dimensionless parameters π_{52} to π_{54}

Using only some of the variables presented previously in Table IV-1, another group of the dimensionless parameters were developed. Those variables are presented in Table IV-3.

Table IV-3. New set of variables used for predicting head loss and duration of filtration cycle in sand.

No.	Variable	Unit	Symbol	Dimension
1	Head loss across the filter	Pa	ΔH	L^{-1} M θ^{-2}
2	Sand effective diameter	m	d_e	L
5	Total filtration surface	m^2	A	L^2
8	Duration for every filtration cycle	s	t	θ
9	Suspended solids average concentration per filtration cycle	kg m^{-3}	C	L^{-3} M
14	Filtrated liquid flow rate	m^3 s^{-1}	Q	L^3 θ^{-1}

The recurring set of variables that was used for generating this group of dimensionless parameters were head loss across the filter (ΔH), total filtration surface (A) and suspended solids average concentration per filtration cycle (C).

As the number of variables was m = 6 and matrix range r = 3, therefore $m - r$ = 6 - 3 = 3 dimensionless independent parameters. The dimensionless parameters were:

$\pi_{52} = \frac{d_e}{A^{0.5}}$ $\pi_{53} = \frac{Q \cdot \Delta H^{0.5}}{A^{2} \cdot C^{0.5}}$ $\pi_{54} = \frac{t \cdot \Delta H^{0.5}}{A^{0.5} \cdot C^{0.5}}$

IV.3.1.7. Dimensionless parameters π_{55} to π_{58}

It was thought also that using only variables depending on time of Table IV-1 would help to get new results and predict new dimensionless independent parameters to determine the filter functional time. This new set of inconstant variables within time is pointed out in Table IV-4.

The recurring set of variables that was used for generating dimensionless independent parameters had sand effective diameter (d_e), filtration velocity (v) and suspended solids average concentration per filtration cycle (C).

Table IV-4. New set of time dependent variables to predict the duration of filtration cycle.

No.	Variable	Unit	Symbol	Dimension
1	Head loss across the filter	Pa	ΔH	L^{-1} M θ^{-2}
2	Sand effective diameter	m	d_e	L
6	Filtered liquid volume per filtration cycle	m^3	V	L^3
8	Time duration for every filtration cycle	s	t	θ
9	Suspended solids concentration	kg m^{-3}	C	L^{-3} M
13	Filtration velocity	m s^{-1}	v	L θ^{-1}
14	Filtered liquid flow rate	m3 s^{-1}	Q	L^3 θ^{-1}

Since the number of variables was *m* = 7, and the matrix range *r* = 3, it should be 4 dimensionless groups. The dimensionless parameters that were generated from variables shown in Table IV-4 were:

$$\boldsymbol{\pi_{55}} = \frac{\Delta H}{v^2 \cdot C} \qquad \boldsymbol{\pi_{56}} = \frac{V}{{d_e}^3} \qquad \boldsymbol{\pi_{57}} = \frac{Q}{{d_e}^2 \cdot v} \qquad \boldsymbol{\pi_{58}} = \frac{v \cdot t}{d_e}$$

IV.3.2. Developed equations

Each group of dimensionless parameters described in sections IV.3.1.1 to IV.3.1.7 were related following the equations from equation (IV-3) to equation (IV-8) to study and predict head loss across the filter. The dimensionless parameters in section IV.3.1.5 was excluded for having some dimensionless groups in common with section IV.3.1.3, which resulted at the end in the same mathematical model.

$$\boldsymbol{\pi}_1 = \mathbf{f}(\boldsymbol{\pi}_2, \boldsymbol{\pi}_3, \boldsymbol{\pi}_4, \boldsymbol{\pi}_5, \boldsymbol{\pi}_6, \boldsymbol{\pi}_7, \boldsymbol{\pi}_8, \boldsymbol{\pi}_9) \quad \text{(IV-3)}$$

$$\boldsymbol{\pi}_{10} = \mathbf{f}(\boldsymbol{\pi}_{11}, \boldsymbol{\pi}_{12}, \boldsymbol{\pi}_{13}, \boldsymbol{\pi}_{14}, \boldsymbol{\pi}_{15}, \boldsymbol{\pi}_{16}, \boldsymbol{\pi}_{17}, \boldsymbol{\pi}_{18}, \boldsymbol{\pi}_{19}, \boldsymbol{\pi}_{20}) \quad \text{(IV-4)}$$

$$\boldsymbol{\pi}_{29} = \mathbf{f}(\boldsymbol{\pi}_{21}, \boldsymbol{\pi}_{22}, \boldsymbol{\pi}_{23}, \boldsymbol{\pi}_{24}, \boldsymbol{\pi}_{25}, \boldsymbol{\pi}_{26}, \boldsymbol{\pi}_{27}, \boldsymbol{\pi}_{28}) \quad \text{(IV-5)}$$

$$\boldsymbol{\pi}_{30} = \mathbf{f}(\boldsymbol{\pi}_{31}, \boldsymbol{\pi}_{32}, \boldsymbol{\pi}_{33}, \boldsymbol{\pi}_{34}, \boldsymbol{\pi}_{35}, \boldsymbol{\pi}_{36}, \boldsymbol{\pi}_{37}, \boldsymbol{\pi}_{38}, \boldsymbol{\pi}_{39}, \boldsymbol{\pi}_{40}) \quad \text{(IV-6)}$$

$$\boldsymbol{\pi}_{54} = \mathbf{f}(\boldsymbol{\pi}_{52}, \boldsymbol{\pi}_{53}) \quad \text{(IV-7)}$$

$$\boldsymbol{\pi}_{55} = \mathbf{f}(\boldsymbol{\pi}_{56}, \boldsymbol{\pi}_{57}, \boldsymbol{\pi}_{58}) \quad \text{(IV-8)}$$

Moreover, on the light of the obtained results from equations (IV-3) to (IV-8), the dimensionless parameters defined in sections IV.3.1.1 to IV.3.1.7 were related again considering one of the dimensionless independent parameters that consist of the variable time duration for every filtration cycle (t) as the dependent variable as following:

$$\boldsymbol{\pi}_9 = \mathbf{f}(\boldsymbol{\pi}_1, \boldsymbol{\pi}_2, \boldsymbol{\pi}_3, \boldsymbol{\pi}_4, \boldsymbol{\pi}_5, \boldsymbol{\pi}_6, \boldsymbol{\pi}_7, \boldsymbol{\pi}_8) \quad \text{(IV-9)}$$

$$\boldsymbol{\pi}_{16} = \mathbf{f}(\boldsymbol{\pi}_{10}, \boldsymbol{\pi}_{11}, \boldsymbol{\pi}_{12}, \boldsymbol{\pi}_{13}, \boldsymbol{\pi}_{14}, \boldsymbol{\pi}_{15}, \boldsymbol{\pi}_{17}, \boldsymbol{\pi}_{18}, \boldsymbol{\pi}_{19}, \boldsymbol{\pi}_{20}) \quad \text{(IV-10)}$$

$$\boldsymbol{\pi}_{21} = \mathbf{f}(\boldsymbol{\pi}_{22}, \boldsymbol{\pi}_{23}, \boldsymbol{\pi}_{24}, \boldsymbol{\pi}_{25}, \boldsymbol{\pi}_{26}, \boldsymbol{\pi}_{27}, \boldsymbol{\pi}_{28}, \boldsymbol{\pi}_{29}) \quad \text{(IV-11)}$$

$$\boldsymbol{\pi}_{41} = \mathbf{f}(\boldsymbol{\pi}_{42}, \boldsymbol{\pi}_{43}, \boldsymbol{\pi}_{44}, \boldsymbol{\pi}_{45}, \boldsymbol{\pi}_{46}, \boldsymbol{\pi}_{47}, \boldsymbol{\pi}_{48}, \boldsymbol{\pi}_{49}, \boldsymbol{\pi}_{50}, \boldsymbol{\pi}_{51}) \quad \text{(IV-12)}$$

$$\boldsymbol{\pi}_{58} = \mathbf{f}(\boldsymbol{\pi}_{55}, \boldsymbol{\pi}_{56}, \boldsymbol{\pi}_{57}) \quad \text{(IV-13)}$$

The attempt to predict time duration for filtration cycle had been difficult using the dimensionless parameters defined in equation (IV-6) that corresponds to section IV.3.1.4 for having the variable t in five dimensionless independent parameters. Since the dependent variable π_{54} consists of ΔH and t, equation (IV-7) was used to predict both phenomena.

IV.3.3. Applying regression analysis to define the mathematical model

The relationships between the logarithms values of the variables that appear from equation (IV-3) to equation (IV-13) were determined by applying a linear regression analysis using the SPSS statistical program (SPSS Inc., Chicago, Illinois, USA). The same program was used for a curve estimation analysis between the dependent variable and each independent one in the developed models. Models were checked at both 0.01 and 0.05 significance level.

Only unstandardized coefficients in three decimals were used for estimating the unknown parameters, the constant coefficient and the exponent of each equation. This is because of that the unstandardized coefficients for any product term are not affected by changes in the mean (Althauser, 1971; Allison, 1977). These changes are often called changes of scale or linear transformation data. For example, choosing to measure distance in meters rather than feets is not a matter for theoretical physicist or statistician to worry about. But since such changes affect the value of numbers, they may have an impact on a researcher whose goal is to evaluate the relative importance of different explanatory variables (Henry, 2001).

IV.3.4. Comparison with experimental data

Since dimensional analysis is not sufficient to determine the accuracy and adequacy of the developed models in real physical world (Sonin, 2001), experimental real data were compared with the calculated one by the developed model. Experimental data was registered continuously every minute using the SCADA system as it had been described previously in Chapter III section III.3.2.

IV.3.5. Choosing among alternative models

After applying the statistical analysis, came the step of choosing among alternative models. The procedure for choosing among alternative models was to select the one that fits the best, that is, the one that has the highest adjusted coefficient of determination (R_{adj}^2) and has not an evident pattern on the behaviour of its residuals.

Moreover, standard deviation and root mean square error (RMSE) defined in equation (IV-14) are also two important criteria in the process of choosing among alternative models.

$$\mathbf{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \hat{x}_i)^2} \tag{IV-14}$$

Where n is the total number of observations, x_i is the observed phenomena value in the real experimental data and $\hat{x}_i$ is calculated phenomena value with the model.

Therefore, the following criteria were taken into consideration in the selection procedure:

- Adjusted coefficient of determination for the developed model.
- Sample range minimum and maximum values for both observed phenomena and calculated one by the model.
- Sample mean value for both experimented and computed values using the model.
- Standard deviation for both observed phenomenon and calculated one by the model.
- Coefficient of variation, which is the standard deviation divided by the mean value.
- Minimum value that could be obtained using the experimental data (minimum value of digital data) which was determined by applying the minimum value for each variable in the developed model while making the calculations.
- Root mean square error.
- Analysis of residuals.

Nevertheless, all of the adjusted coefficient of determination, root mean square error and analysis of residuals are the most three important criteria for deciding the best generated mathematical model. The best selected model was compared at the end with Puig-Bargués et al. (2005a) (equation IV-1) and Duran-Ros et al. (2010) (equation IV-2) developed models. Both models were readjusted again applying the collected data in this study by the SCADA system.

IV.4. Results and discussion

IV.4.1. Predicting head loss across sand filters using Buckingham's theorem

IV.4.1.1. Developed models for head loss calculation

A regression analysis was applied for those models defined from equation (IV-3) to equation (IV-8) that had dimensionless groups as a dependent variable that included head loss (ΔH). The unstandardized coefficients and the significance level for each model are pointed out in Table IV-5. The relationship between dependent variable and each independent one for same model is pointed out in Table IV-6. Using data in Table IV-5, the following mathematical models have been generated:

$$\frac{\Delta H \cdot t^2}{\rho \cdot \emptyset_f^{\,2}} = 15.014 \cdot \left(\frac{V}{\emptyset_f^{\,3}}\right)^{-0.040} \cdot \left(\frac{C}{\rho}\right)^{0.021} \cdot \left(\frac{\emptyset_f}{t^2 \cdot g}\right)^{-1.005} \quad \text{(IV-15)}$$

$$\frac{\Delta H}{\rho \cdot v^2} = 2.19E+13 \cdot \left(\frac{V}{d_f^{\,3}}\right)^{-0.031} \cdot \left(\frac{C}{\rho}\right)^{0.021} \cdot \left(\frac{\mu}{\rho \cdot v \cdot d_f}\right)^{-2.011} \quad \text{(IV-16)}$$

$$\frac{\Delta H}{d_e \cdot C . g} = 16.216 \cdot \left(\frac{\rho}{C}\right)^{0.980} \cdot \left(\frac{V}{d_e^{\,3}}\right)^{-0.031} \cdot \left(\frac{d_f}{d_e}\right)^{1.087} \quad \text{(IV-17)}$$

$$\frac{\Delta H \cdot t^2}{C \cdot d_e^{\,2}} = 7.752 \cdot \left(\frac{d_f}{d_e}\right)^{0.109} \cdot \left(\frac{V}{d_e^{\,3}}\right)^{-0.039} \cdot \left(\frac{\rho}{C}\right)^{0.979} \cdot \left(\frac{g \cdot t^2}{d_e}\right)^{1.005} \quad \text{(IV-18)}$$

$$\frac{t \cdot \Delta H^{0.5}}{A^{0.5} \cdot C^{0.5}} = 195.98 \cdot \left(\frac{d_e}{A^{0.5}}\right)^{1.297} \cdot \left(\frac{Q \cdot \Delta H^{0.5}}{A^2 \cdot C^{0.5}}\right)^{3.908} \quad \text{(IV-19)}$$

$$\frac{\Delta H}{v^2 \cdot C} = 2.01E+8 \cdot \left(\frac{V}{d_e^{\,3}}\right)^{0.254} \cdot \left(\frac{Q}{d_e^{\,2} \cdot v}\right)^{-0.135} \quad \text{(IV-20)}$$

Table IV-5. Unstandardized coefficients and significance level developed through regression analysis for different variables in each mathematical model.

Equation no.	R_{adj}^2	Dependent variable	Independent variables	Unstandardized coefficients		T-test	P-value
				B	Standard error		
(IV-15)	1.000	$\ln \pi_1$	Constant	2.709	0.060	45.487	0.000
			$\ln \pi_5$	-0.040	0.007	-5.521	0.000
			$\ln \pi_6$	0.021	0.004	5.404	0.000
			$\ln \pi_9$	-1.005	-1.025	0.000	0.000
(IV-16)	0.939	$\ln \pi_{10}$	Constant	30.719	0.208	148.010	0.000
			$\ln \pi_{14}$	-0.031	0.002	-18.851	0.000
			$\ln \pi_{17}$	0.021	0.004	5.385	0.000
			$\ln \pi_{19}$	-2.011	0.022	89.520	0.000
(IV-17)	0.995	$\ln \pi_{29}$	Constant	2.786	0.065	42.552	0.000
			$\ln \pi_{22}$	0.980	0.004	240.271	0.000
			$\ln \pi_{25}$	-0.031	0.002	-18.615	0.000
			$\ln \pi_{28}$	1.087	0.009	116.829	0.000
(IV-18)	1.000	$\ln \pi_{30}$	Constant	2.048	0.085	24.007	0.000
			$\ln \pi_{31}$	0.109	0.021	5.189	0.000
			$\ln \pi_{35}$	-0.039	0.007	-5.432	0.000
			$\ln \pi_{39}$	0.979	0.004	238.731	0.000
			$\ln \pi_{40}$	1.005	0.004	248.907	0.000
(IV-19)	0.546	$\ln \pi_{54}$	Constant	5.278	1.502	3.515	0.000
			$\ln \pi_{52}$	1.297	0.212	6.106	0.000
			$\ln \pi_{53}$	3.908	1.149	26.239	0.000
(IV-20)	0.389	$\ln \pi_{55}$	Constant	19.117	0.659	28.998	0.000
			$\ln \pi_{56}$	0.254	0.013	18.799	0.000
			$\ln\pi_{57}$	-0.135	0.051	-2.639	0.009

Table IV-6. R_{adj}^2, significance level and unstandardized parameter estimates predicted by curve estimation analysis between dependent variable and each independent one in the same mathematical model.

Equation no.	Dependent variable	Independent variable	R_{adj}^2	F-test	Significance level	Unstandardized parameter estimates	
						Constant	B
(IV-15)	ln π_1	ln π_5	0.970	18363.911	0.000	14.139	1.742
		ln π_6	0.453	473.792	0.000	-11.053	-2.850
		ln π_9	1.000	1913560.682	0.000	2.782	-0.980
(IV-16)	ln π_{10}	ln π_{14}	0.091	57.737	0.000	12.574	-0.036
		ln π_{17}	0.035	21.002	0.000	13.034	0.053
		ln π_{19}	0.837	2938.138	0.000	30.197	-1.990
(IV-17)	ln π_{29}	ln π_{22}	0.884	4382.534	0.000	9.583	0.971
		ln π_{25}	0.486	543.047	0.000	13.377	0.284
		ln π_{28}	0.202	145.035	0.000	10.636	1.391
(IV-18)	ln π_{30}	ln π_{31}	-0.002	0.022	0.882	36.470	0.093
		ln π_{35}	0.859	3476.864	0.000	-6.414	1.819
		ln π_{39}	0.617	922.901	0.000	-5.368	3.893
		ln π_{40}	0.979	27162.286	0.000	9.226	1.140
(IV-19)	ln π_{54}	ln π_{52}	0.004	2.124	0.146	18.649	0.454
		ln π_{53}	0.518	616.813	0.000	-2.770	3.771
(IV-20)	ln π_{55}	ln π_{56}	0.383	356.104	0.000	17.577	0.242
		Lnπ_{57}	0.014	8.274	0.004	20.986	0.177

As it is stated in Table IV-6, the relationship between the dependent variable π_{30} and the independent one π_{31} at equation (IV-18) was not statistically significant. Therefore, the independent variable π_{31} was removed from equation (IV-18) and the regression analysis was set again between the dependent variable and the significantly independent ones. The resulted mathematical model was defined in equation (IV-21). While applying the regression analysis it was found that π_{35} was not statistically significant at a 0.01 significance level, therefore, it was eliminated from the new model defined in equation (IV-21) also. The new model was significant ($P \leq 0.001$).

$$\frac{\Delta H \cdot t^2}{C \cdot d_e^{\ 2}} = 10.869 \cdot \left(\frac{\rho}{C}\right)^{0.978} \cdot \left(\frac{g.t^2}{d_e}\right)^{0.983} \quad \text{(IV-21)}$$

The significant relationship between observed and calculated π_{30} and also the residual plot of equation (IV-18) is shown in Fig. IV-1. Also, the significant relationship between the observed and calculated π_{30} and the residual plot of equation (IV-21) is presented in Fig. IV-2.

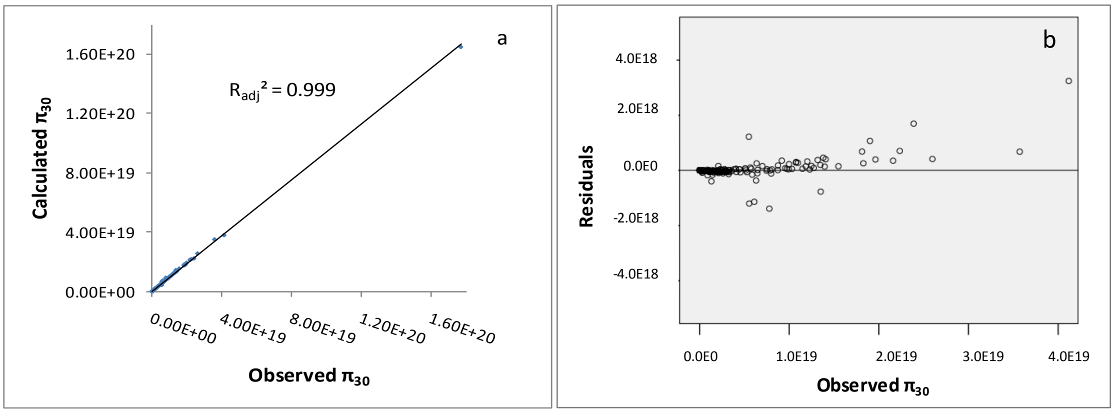


Fig. IV-1. (a) Significant relationship (P ≤ 0.001) between observed and calculated π_{30} with equation (IV-18) and (b) relationship between observed π_{30} and residuals for the same equation.

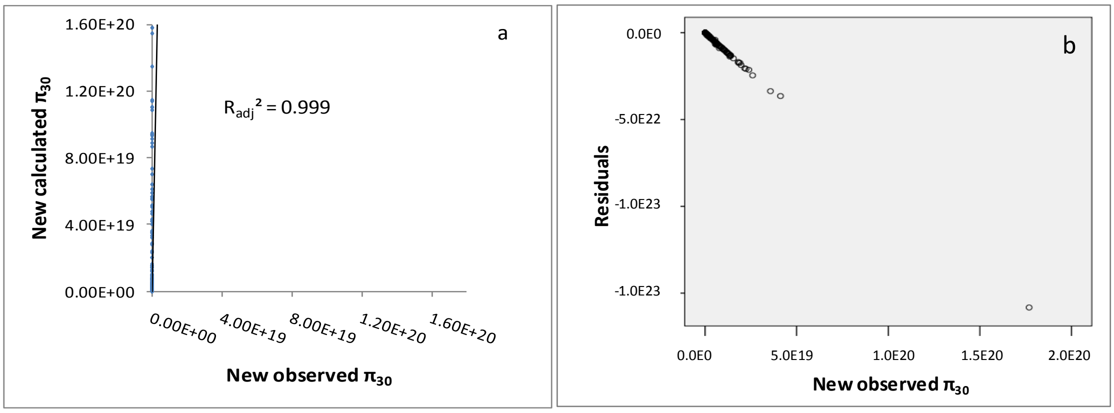


Fig. IV-2 (a) Significant relationship (P ≤ 0.001) between new observed and calculated π_{30} with equation (IV-21), and (b) relationship between new observed π_{30} and residuals for the same equation.

The performance of the model defined by equation (IV-21) had a bad relationship between calculated and observed π_{30} (Fig. IV-2 a). Besides, residual plot presented an accumulation of residuals shaping a linear form (Fig. IV-2 b). On the other hand, the relationship between predicted and observed values was very good for the model defined in equation (IV-18) (Fig. IV-1 a). Moreover, the residual plot of this model (Fig. IV-1 b) presented a band of residuals, above and below, the value zero, which indicates that the assumptions of the regression were met. According to Wisniak and Polishuk (1999), when preparing a plot of the residuals it is important that the limits of the residual axis are not much different than the larger residual present; larger limits will tend to agglomerate the residuals, obscure their real value, and deform the general aspect of the distribution which means at the end that the assumptions of the regression are not met. In addition, the RMSE for equation (IV-21) equals to 7.80E+21 which was higher than the 5.34E+17

RMSE value for equation (IV-18). Therefore, the mathematical model in equation (IV-18) was better than the one in equation (IV-21).

Since the relationship between the independent variable π_{52} and π_{54} dependent one neither was not statistically significant (Table IV-6), it had been removed from equation (IV-19) which is re-defined as following:

$$\frac{\mathbf{t \cdot \Delta H^{0.5}}}{\mathbf{A^{0.5} \cdot C^{0.5}}} = \mathbf{0.063} \cdot \left(\frac{\mathbf{Q \cdot \Delta H^{0.5}}}{\mathbf{A^{2} \cdot C^{0.5}}}\right)^{\mathbf{3.771}} \quad \text{(IV-22)}$$

The significant relationship between observed and calculated π_{30} by equation (IV-22) and also the residual plot for same equation is illustrated in Fig. IV-3.

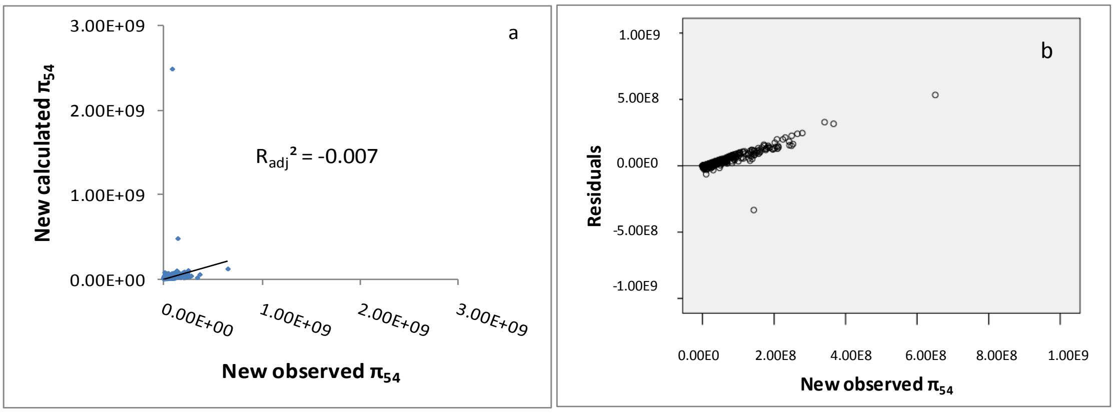


Fig. IV-3. (a) Significant relationship (P ≤ 0.001) between the new observed and calculated π_{54} with equation (IV-22) and (b) relationship between new observed π_{54} and residuals for the same equation.

The relationship between the new observed and calculated π_{54} was bad (Fig. IV-3 a) and the residual plot presented an agglomeration of residuals in a very small area around the zero value (Fig. IV-3 b). Despite the bad relationship between the observed and calculated π_{54} defined by equation (IV-19) with R_{adj}^2 = 0.546 (Fig. IV-4 d) and the obvious structural pattern in its residual plot (Fig. IV-5 d), which made us decide that the model was not adequate, the model defined with equation (IV-22) was worse than the one defined by equation (IV-19) for having smaller adjusted coefficient of determination.

There were no relationships between any of π_{10} and π_{19} (*Eu* and *Re* numbers respectively) with *Fr* number presented in π_{15} dimensionless independent parameter.

Values in Table IV-6 were used to generate equation (IV-23) for computing the relationship between the Euler number (*Eu*) and Reynolds number (*Re*). The adjusted coefficient of determination for this relationship was equal to 0.837 and model was significant (P ≤ 0.001).

$$\boldsymbol{Eu = 1.30\mathrm{E} + 13 \cdot Re^{-1.990}} \qquad \text{(IV-23)}$$

According to the model defined in equation (IV-23), *Eu* number can be described by *Re* number which means that any decrease in *Re* number will conduct to an increase in *Eu* number. In other words, when the relationship between inertial and viscous forces decrease the relationship between inertial and pressure forces will increase in consequence.

Nevertheless, the relationship between the observed and calculated *Eu* number had a low coefficient of determination of 0.359 (Fig. IV-4 f) and had a structure pattern in its residual plot (Fig. IV-5 f). However, data range (minimum and maximum values) between the observed and calculated Euler number were almost the same. Also the coefficient of variation was 0.147 for the observed *Eu* and 0.119 for the calculated one. Adding to that, RMSE of the model defined in equation (IV-23) was lower than the minimum value that could be calculated by the model which means in consequence high model accuracy (Table IV-7). Yurdem et al. (2008) found also a significant relationship between *Eu* and *Re* numbers with other five dimensionless numbers (R_{adj}^2 = 0.902) in disc filters. Moreover, Duran-Ros et al. (2010) also found a significant relationship between *Eu* and *Re* numbers with three more dimensionless terms for sand, screen and disc filters although the coefficient of determination for this relationship was low (< 0.255).

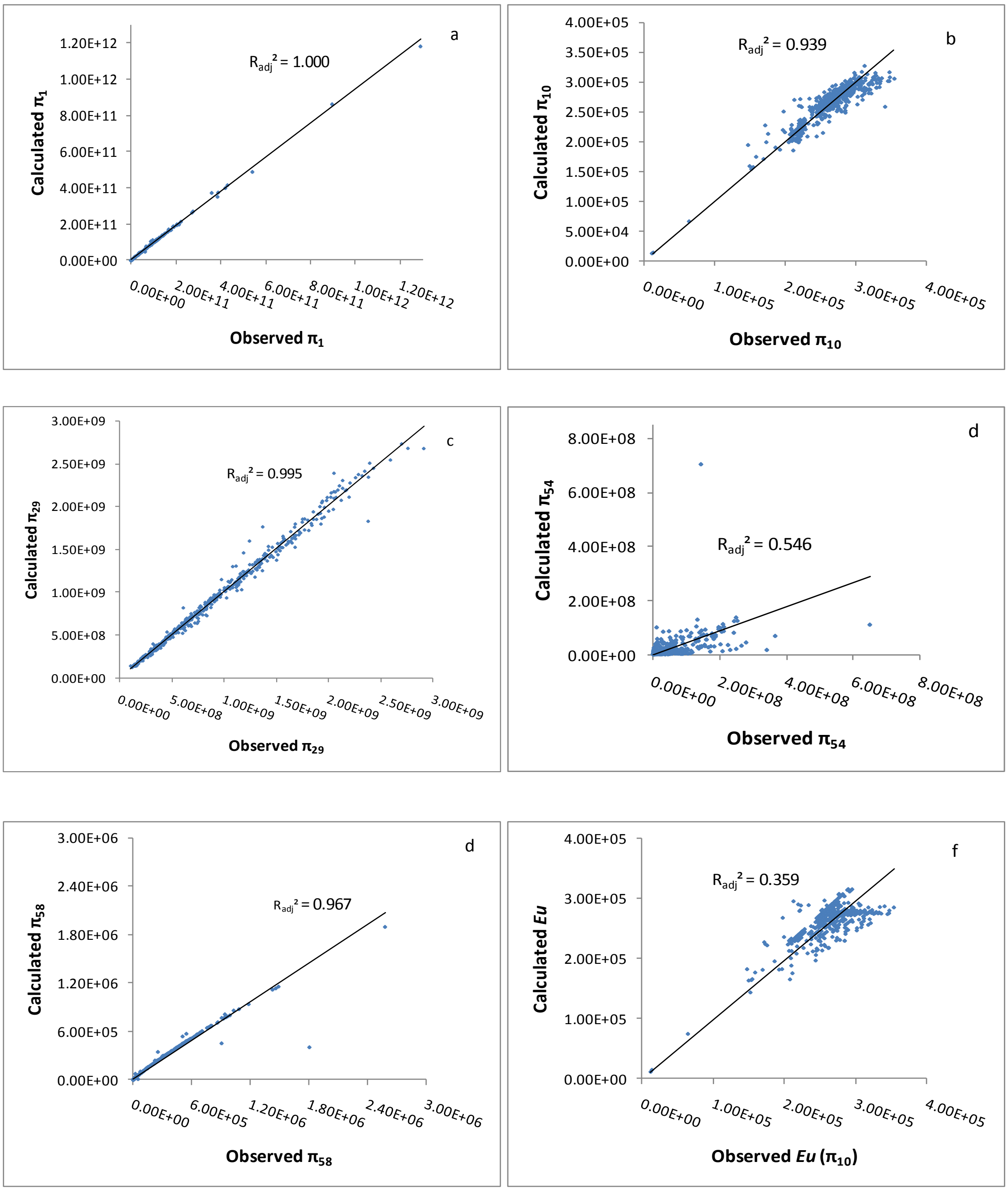


Fig. IV-4. Relationship between the observed dependent value and the calculated one for each mathematical model: (a) equation (IV-15), (b) equation (IV-16), (c) equation (IV-17), (d) equation (IV-19), (e) equation (IV-20) and (f) equation (IV-23). All relationships are significant (P ≤ 0.009).

Furthermore, the relationship between the observed dependent variable and the calculated one by each mathematical model previously determined in equations (IV-15) to (IV-20) and equation (IV-23) are presented in Fig. IV-4. Additionally, the residual plots shown in Fig. IV-5 demonstrate the relationship between residuals and observed phenomenon for each mathematical model.

Relationships presented in Fig. IV-7 were statistically significant (P ≤ 0.009). Table IV-7 presents other statistical parameters related with the goodness of fit of the predefined mathematical models.

Table IV-7. Minimum, maximum, mean, standard deviation (St.dv), R_{adj}^2, and root mean square error (RMSE) for both observed (Obs.) and calculated (Calc.) head loss for the predicted models from equation (IV-15) to (IV-20) and (IV-23).

Equation no.	Equation (IV-15)		Equation (IV-16)		Equation (IV-17)		Equation (IV-18)	
Dependent variable	π_1		π_{10}		π_{29}		π_{30}	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
R_{adj}^2	1.000		0.939		0.995		1.000	
Maximum	1.29E+12	1.18E+12	3.54E+05	3.28E+05	2.91E+09	2.73E+09	1.77E+20	1.65E+20
Minimum	3.34E+06	3.64E+06	1.16E+04	1.18E+04	1.06E+08	1.25E+08	1.93E+13	2.16E+13
RMSE	6.05E+09		1.50E+04		5.74E+07		5.34E+17	
Mean	2.88E+10	2.80E+10	2.61E+05	2.61E+05	7.99E+08	8.09E+08	1.80E+18	1.77E+18
St.dv.	8.82E+10	8.33E+10	3.83E+04	3.48E+04	5.93E+08	5.98E+08	8.42E+18	7.94E+18
Coefficient of variation	3.067	2.974	0.147	0.134	0.742	0.740	4.68	4.49
Minimum value of digital data	5.76E+04		1.29E+04		8.31E+07		3.66E+16	

Equation no.	Equation (IV-19)		Equation (IV-20)		Equation (IV-23)	
Dependent variable	π_{54}		π_{55}		*Eu*	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
R_{adj}^2	0.548		0.389		0.837	
Maximum	6.51E+08	3.89E+10	7.61E+10	4.37E+10	3.54E+05	3.15E+05
Minimum	2.49E+05	4.02E+06	8.43E+08	2.92E+09	1.16E+04	1.14E+04
RMSE	1.94E+09		1.22E+10		2.49E+04	
Mean	3.48E+07	2.54E+08	1.90E+10	1.62E+10	2.61E+05	2.60E+05
St.dv.	6.33E+07	1.93E+09	1.45E+10	8.05E+09	3.83E+04	3.08E+04
Coefficient of variation	1.82	7.62	0.765	0.498	0.147	0.119
Minimum value of digital data	8.68E+07		4.07E+09		3.15E+05	

All the relationships between the calculated and observed dimensionless independent parameters that were shown in Fig. IV-4 were good except for π_{54} (Fig. IV-4 d) and π_{55} (Fig. IV-4 e). On the other hand, the residual plot shown in Fig. IV-5 presented an accumulation of residuals with a structural pattern for all the models except the defined by equation (IV-17) presented in Fig. IV-5 c. This means that the assumption of regressions for this model was met. It was noticed also that some of the data were scattered around the trendline (Fig. IV-5 c and d) and the others were overlapped and concentrated in small area around it.

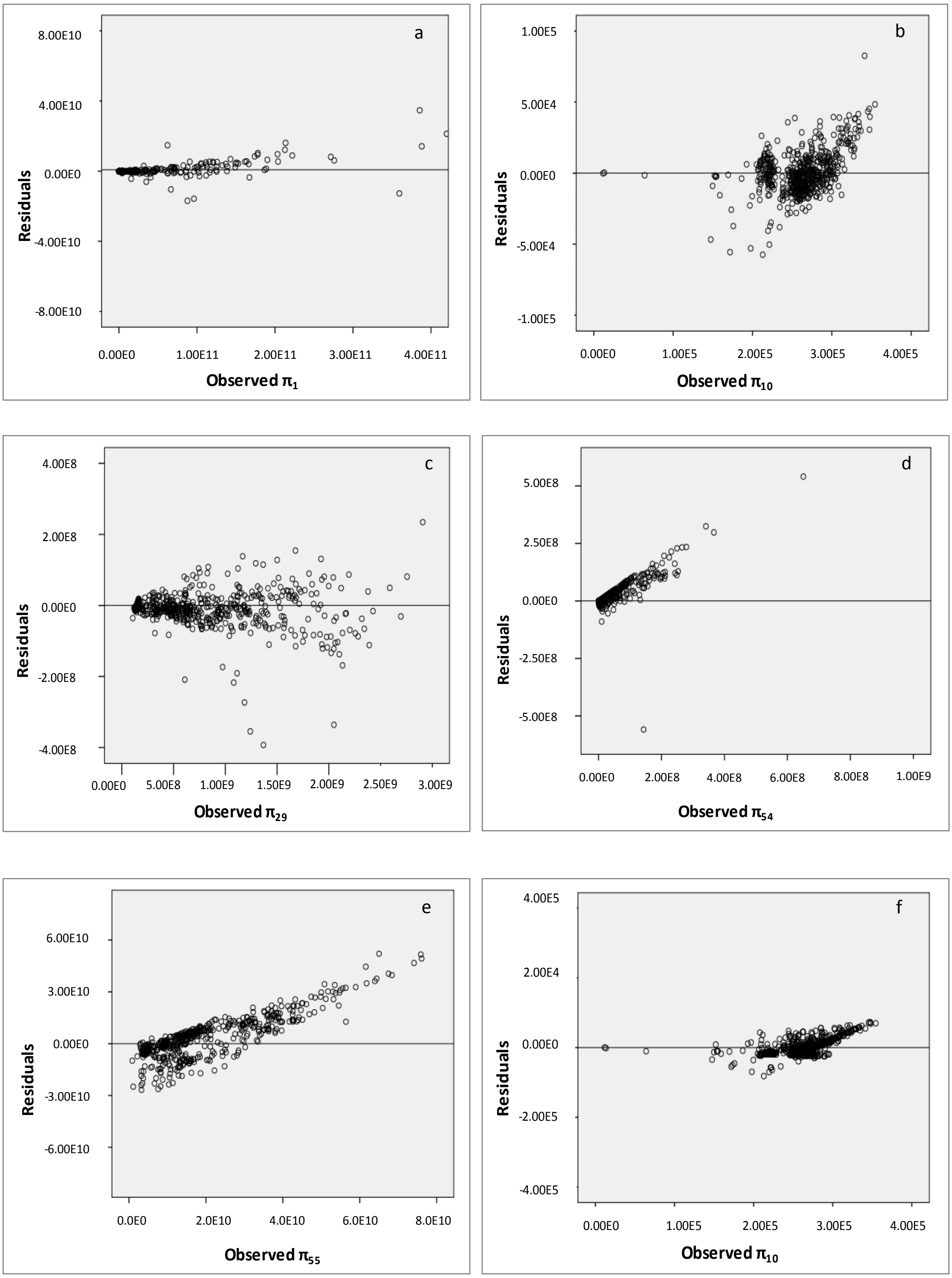


Fig. IV-5. Residual plots for the relationship between residuals of each mathematical model and: (a) observed π_1, (b) observed π_{10}, (c) observed π_{29}, (d) observed π_{54}, (e) observed π_{55} and (f) observed Euler number.

IV.4.1.2. Choosing among alternative models for head loss

As it can be seen in Table IV-5, most of the indicated models have an R_{adj}^2 of at least 0.939 except those that were defined by equation (IV-19) and (IV-20) which had R_{adj}^2 smaller than 0.546. All the unstandardized coefficients were significant ($P \leq 0.009$).

Like it is pointed out in Table IV-7, the minimum and maximum values for both observed and calculated dependent variables were almost at the same range except those of the dependent variable π_{54} and π_{55} which were calculated with equations (IV-19) and (IV-20). Moreover, both mean and coefficient of variation values were close when comparing the observed and calculated dependent variables except for the π_{54} and π_{55} dependent variables again. This means that the precision of the measurements made by the predefined models was high except with equations (IV-19) and (IV-20), which had the lowest measurements precision.

Furthermore, RMSE of the developed models were higher than the minimum value that could be calculated using the same model (minimum value of digital data), except for equation (IV-17) and for equation (IV-23) that describes *Eu* number as a function of *Re* number (Table IV-7). Since having a low RMSE means in consequence high model accuracy, mathematical model defined in equation (IV-17) for describing head loss across sand filters through the dimensionless independent parameter π_{29} had a higher accuracy than the other models.

The residual plot of equations (IV-15) and (IV-17) (Fig. IV-5 a and c) presented a band of residuals, above and below, the value zero, with relatively constant width and independent of the fitted value. This indicates that the assumptions of the regression for these models were met.

On the other hand, the other residual plots presented in Fig. IV-5 presented an accumulation of residuals shaping a linear form, which means that the assumptions of the regression for those models were not met (Wisniak and Polishuk, 1999).

Therefore, equation (IV-17) was the adequate for describing head loss across sand filters with high measurements precision and accuracy. In contrary, the mathematical models defined in equation (IV-19) and equation (IV-20) were the worst.

IV.4.1.3. Comparing the best selected models with other models

The best selected model in section IV.4.1.1 defined by equation (IV-17) for describing head loss across sand filter was compared with Puig-Bargués et al. (2005a) (equation IV-1) and Duran-Ros et al. (2010) (equation IV-2) ones. A curve estimation analysis was set between calculated head loss with equations (IV-1) and (IV-2) and (IV-17).

Despite the relationships were all significant ($P \leq 0.001$ for both F- and T- tests), the adjusted coefficient of determination was low (≤ 0.399). This means that the calculated ΔH by equations (IV-1) and (IV-2) were not coincident with the calculated one by equation (IV-17).

In the case of Puig-Bargués et al. (2005a) study, only five variables (filtrated effluent volume per filtration cycle, suspended solids concentration, water density, sand effective diameter and head loss across the filter) were common with the selected model in the present study. Puig-Bargués et al. (2005a) used in their developed model other variables such as water viscosity, filtrated liquid flow rate and mean diameter of effluent particle size distribution. The model developed in equation (IV-17) took into consideration diameter occupied by sand inside the filter and acceleration of gravity.

In the same way, even there were three variables in common in the model defined in equation (IV-2) developed by Duran-Ros et al. (2010) and the selected model in this study (suspended solids concentration, water density and head loss across the filter), the other parameters were different. Duran-Ros et al. (2010) used two more parameters in their developed model (inside diameter of the inlet and outlet pipe and filtration velocity) while in this study, the acceleration of gravity, sand effective diameter, filtration effluent volume per filtration cycle and the inside diameter of sand filter were used.

The differences between the experimental conditions of the three studies also may explain why the models did not coincide. In the study of Puig-Bargués et al. (2005a), several effluents with different origins (meat industry and urban) from various wastewater treatment plants were used. The TSS values in this study varied between 4.9 and 176 g m^{-3}. On the other hand, Duran-Ros et al. (2010) used only two effluent types (secondary and tertiary reclaimed urban and industrial wastewater) with a range of TSS between 4.4 and 18.0 g m^{-3}. The current study applied a tertiary reclaimed effluent of urban and industrial origin with a concentration of TSS that varied between a minimum 3.8 and maximum 68.6 g m^{-3}.

Furthermore, another reason that would explain the difference between these studies is the effective diameter and uniformity coefficient of sand that was used to fill the filter. In the study of Puig-Bargués et al. (2005a), the sand effective diameter was the same before and after being used (0.65 mm) even the uniformity coefficient had been decreased from 1.32 before beginning the filtration experiment to 1.26 after finishing it.

The effective diameter of used sand in the experiment of Duran-Ros et al. (2010) was of 0.40 and 0.41 mm before and after being used with the secondary treated effluent and was 0.27 and 0.52 before and after being used to filter the tertiary treated effluent. The uniformity coefficient of the sand used by Duran-Ros et al. was 2.41 and 1.88 before and after irrigating 1000 h with a secondary reclaimed effluent and it was 2.89 and 1.65 before and after irrigating 1000 h with the tertiary reclaimed effluent consecutively. In the current experiment, the effective diameter was 0.47 mm before filtration and 0.64 mm at the end of the second irrigation season and of 0.32 and 0.63 mm before starting and at the end of the third irrigation season respectively.

Moreover, the flow registered during this study varied between 2.71 – 3.03 l s^{-1} which was higher than the flow registered by Puig-Bargués et al. (0.25 - 1.1 l s^{-1}) and by Duran-Ros et al. (2.1 - 2.5 l s^{-1}).

Additionally, the applied SCADA system allowed more intensive frequency of sampling, which permitted to take into account an incessant observation for effluent characteristics variability.

Data obtained through a SCADA system during this study were applied to the previously developed equations (IV-1) (Puig-Bargués et al., 2005a) and (IV-2) (Duran-Ros et al., 2010) to extract new adjusted constant values and exponents adequate for the present available data and applied effluent characteristics. The new adjusted model for equation (IV-1) was defined in equation (IV-24) and for equation (IV-2) was defined in equation (IV-25). Two dimensionless independent parameters defined in equation (IV-1) $\left(\frac{\Delta H^{0.5} \cdot A}{C^{0.5} \cdot Q} \text{ and } \frac{\Delta H^{0.25} \cdot d_e}{C^{0.25} \cdot Q^{0.5}}\right)$ had unstandardized coefficients of zero. However, the different constant values and exponents of the readjusted previously available models (equations IV-24 and IV-25) can be explained by the differences in experimental conditions and effluent quality between the three studies of Puig-Bargués et al. (2005), Duran-Ros et al. (2010) and the current one.

$$\frac{\mu}{\Delta H^{0.25} \cdot Q^{0.50} \cdot C^{0.75}} = 6.33E-3 \cdot \left(\frac{\Delta H^{0.75} \cdot V}{C^{0.75} \cdot Q^{1.50}}\right)^{0.014} \cdot \left(\frac{\Delta H^{0.25} \cdot D_P}{C^{0.25} \cdot Q^{0.50}}\right)^{0.811} \cdot \left(\frac{\rho}{C}\right)^{0.548} \qquad \text{(IV-24)}$$

$$\frac{v \cdot C^{0.5}}{\Delta H^{0.5}} = 4.60E+03 \cdot \left(\frac{\rho}{C}\right)^{-1.079} \cdot \left(\frac{\mu}{\Delta H^{0.5} \cdot C^{0.5} \cdot d_p}\right)^{1.130} \qquad \text{(IV-25)}$$

The new adjusted models defined in both equations had an adjusted coefficient of determination higher than 0.931 and were significant (P ≤ 0.001). Relationship between the observed and calculated dependent variable determined by equations (IV-24) and (IV-25) and also the residual plots for same models are shown in Fig. IV-6 and Fig. IV-7, respectively.

The residual plots for the same models presented a good distribution above and below zero value which indicate that the assumptions of the regression were met for both models. The RMSE was 1.05E-03 and 1.6E-06 for models defined in equations (IV-24) and (IV-25), respectively. The RMSE was smaller than the minimum digital value that could be calculated by both models (8.54E-02 and 4.05E-06), sequentially, which indicated also the high precision of the new adjusted models.

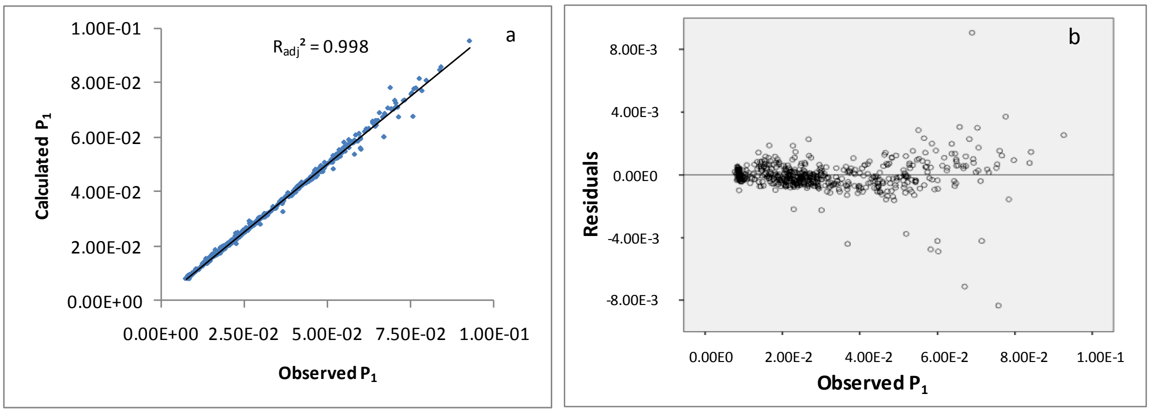


Fig. IV-6. (a) Significant relationship (P < 0.001) between observed and calculated dependent variable defined in equation (IV-24) (P_1) and (b) the residual plot for the same model.

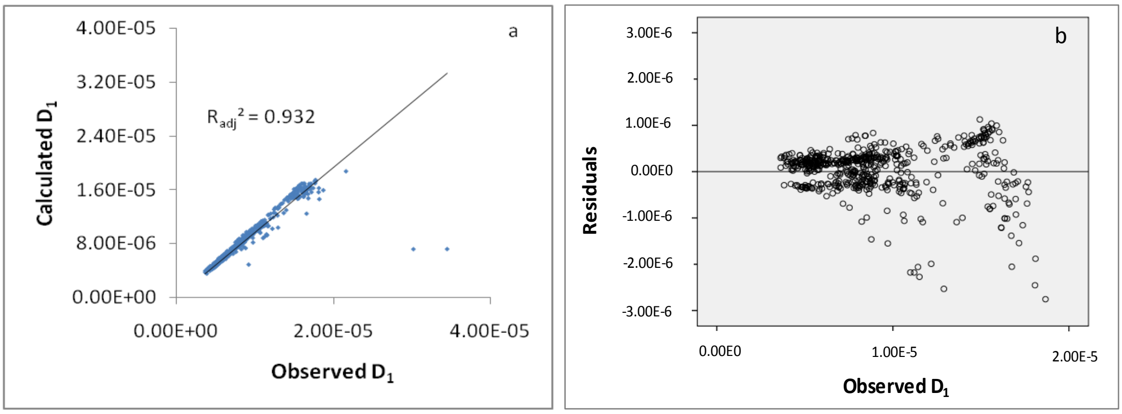


Fig. IV-7. (a) Significant relationship (P < 0.001) between observed and calculated dependent variable defined in equation (IV-25) (D_1) and (b) the residual plot for the same model.

IV.4.2. Predicting the filter cycle duration

IV.4.2.1. Developed models for computing filtration cycle time

Once the regression analyses had been applied between the dependent variable and the independent ones for each of the predefined mathematical models in equations from (IV-9) to (IV-13), developed models were generated using unstandardized coefficients to calculate filter cycle duration.

Model defined in equation (IV-9) presented no relationship among variables in the regression analysis. The unstanderdized coefficients were used to generate the models defined in equations (IV-26), (IV-27), (IV-28) and (IV-29). The unstandardized coefficients and significance level were pointed out in Table IV-8.

Despite the developed model defined in equation (IV-18) had high adjusted coefficient of determination (Table IV-7) and good distribution of residuals (Fig. IV-1 b), it was excluded when determining filter cycle duration because it had RMSE higher than the minimum value that could be calculated using this model. Moreover, the developed model defined in equation (IV-19) was excluded, as well, because it had a small adjusted coefficient of determination (Table IV-7) and an obvious pattern in its residual plot (Fig. IV-5 d).

Results for the relationship between the dependent variable and each independent one for models presented in equations (IV-26), (IV-27), (IV-28) and (IV-29) are in Table IV-9. All the mathematical models were significant ($P \leq 0.001$).

$$\frac{v \cdot t}{d_f} = 2.09E-04 \cdot \left(\frac{d_e}{d_f}\right)^{0.172} \cdot \left(\frac{V}{{d_f}^3}\right)^{0.889} \cdot \left(\frac{\mu}{\rho \cdot v \cdot d_f}\right)^{1.173} \quad \text{(IV-26)}$$

$$t \cdot \sqrt{\frac{g}{d_e}} = 1.05E+03 \cdot \left(\frac{V}{{d_e}^3}\right)^{0.889} \cdot \left(\frac{\emptyset_f}{d_e}\right)^{-2.334} \quad \text{(IV-27)}$$

$$t \cdot \sqrt{\frac{g}{d_e}} = 8.08E+02 \cdot \left(\frac{V}{{d_e}^3}\right)^{0.888} \cdot \left(\frac{A}{{d_e}^2}\right)^{-1.168} \quad \text{(IV-28)}$$

$$\frac{v \cdot t}{d_e} = 5.033 \cdot \left(\frac{V}{{d_e}^3}\right)^{0.888} \cdot \left(\frac{Q}{{d_e}^2 \cdot v}\right)^{-0.908} \quad \text{(IV-29)}$$

The relationships between the observed dependent variables and the calculated ones by the mathematical models in equations (IV-26), (IV-27), (IV-28) and (IV-29) are shown in Fig. IV-8. The residual plot for each observed dependent variable in these models is presented in Fig. IV-9.

Table IV-8. Unstandardized coefficients and significance level developed through regression analysis for different variables in each mathematical model in equations (IV-26), (IV-27), (IV-28) and (IV-29).

Equation no.	R_{adj}^2	Dependent variable	Independent variables	Unstandardized coefficients		T-test	P-value
				B	Standard		
(IV-26)	0.939	$\ln \pi_{16}$	Constant	-8.471	1.070	-7.918	0.000
			$\ln \pi_{11}$	0.172	0.045	3.790	0.000
			$\ln \pi_{14}$	0.889	0.006	141.053	0.000
			$\ln \pi_{19}$	1.173	0.116	10.083	0.000
(IV-27)	0.972	$\ln \pi_{21}$	Constant	6.953	0.313	22.222	0.000
			$\ln \pi_{25}$	0.889	0.006	140.896	0.000
			$\ln \pi_{27}$	-2.334	0.048	-48.733	0.000
(IV-28)	0.972	$\ln \pi_{41}$	Constant	6.695	0.309	21.678	0.000
			$\ln \pi_{46}$	0.888	0.006	140.556	0.000
			$\ln \pi_{48}$	-1.168	0.024	-48.712	0.000
(IV-29)	0.967	$\ln \pi_{58}$	Constant	1.616	0.335	4.828	0.000
			$\ln \pi_{56}$	0.888	0.007	129.639	0.000
			$\ln \pi_{57}$	-0.908	0.026	-34.939	0.000

Table IV-9. R_{adj}^2, test significance level and the unstandardized parameter estimates predicted by curve estimation analysis between dependent variable and each independent one in the same mathematical model.

Equation no.	Dependent variable	Independent variables	R_{adj}^2	F-test	Significance level	Unstandardized coefficients	
						Constant	B
(IV-26)	$\ln \pi_{16}$	$\ln \pi_{11}$	0.008	4.886	0.027	7.882	0.598
		$\ln \pi_{14}$	0.967	16791.378	0.000	0.807	0.889
		$\ln \pi_{19}$	0.003	1.690	0.194	-4.297	0.906
(IV-27)	$\ln \pi_{21}$	$\ln \pi_{25}$	0.856	3404.207	0.000	-6.608	0.788
		$\ln \pi_{27}$	0.000	0.186	0.667	13.031	-0.116
(IV-28)	$\ln \pi_{41}$	$\ln \pi_{46}$	0.855	3384.455	0.000	-6.626	0.788
		$\ln \pi_{48}$	0.001	0.308	0.579	13.240	-0.075
(IV-29)	$\ln \pi_{58}$	$\ln \pi_{56}$	0.897	4999.500	0.000	-8.738	0.810
		$\ln \pi_{57}$	0.003	1.859	0.173	8.156	0.185

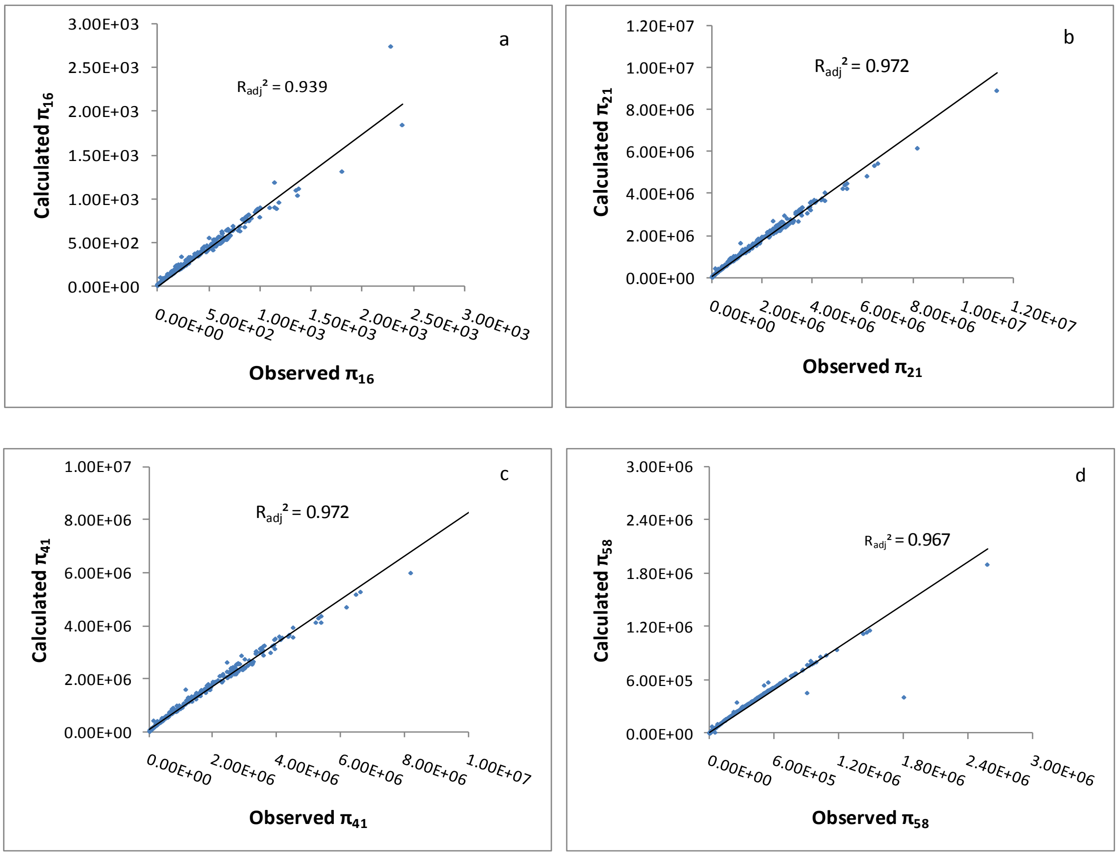


Fig. IV-8. Relationship between the observed dependent value and the calculated one for each mathematical model: (a), equation (IV-26), (b) equation (IV-27), (c) equation (IV-28) and (d) equation (IV-29). All the relationships were significant (P ≤ 0.001).

As it is shown in Fig. IV-8, the relationships between the observed and calculated dependent variable for equations (IV-26), (IV-27), (IV-28) and (IV-29) were all significant (P ≤ 0.001) and had a $R_{adj}^2 \geq 0.939$.

Although the good relationship between the calculated and predicted dependent variables using equations (IV-26), (IV-27), (IV-28) and (IV-29), all of them presented an accumulation of residuals shaping a linear form in their residual plots (Fig. IV-9). This means that calculating filter cycle duration in sand filters applying these mathematical models gave low accurate results.

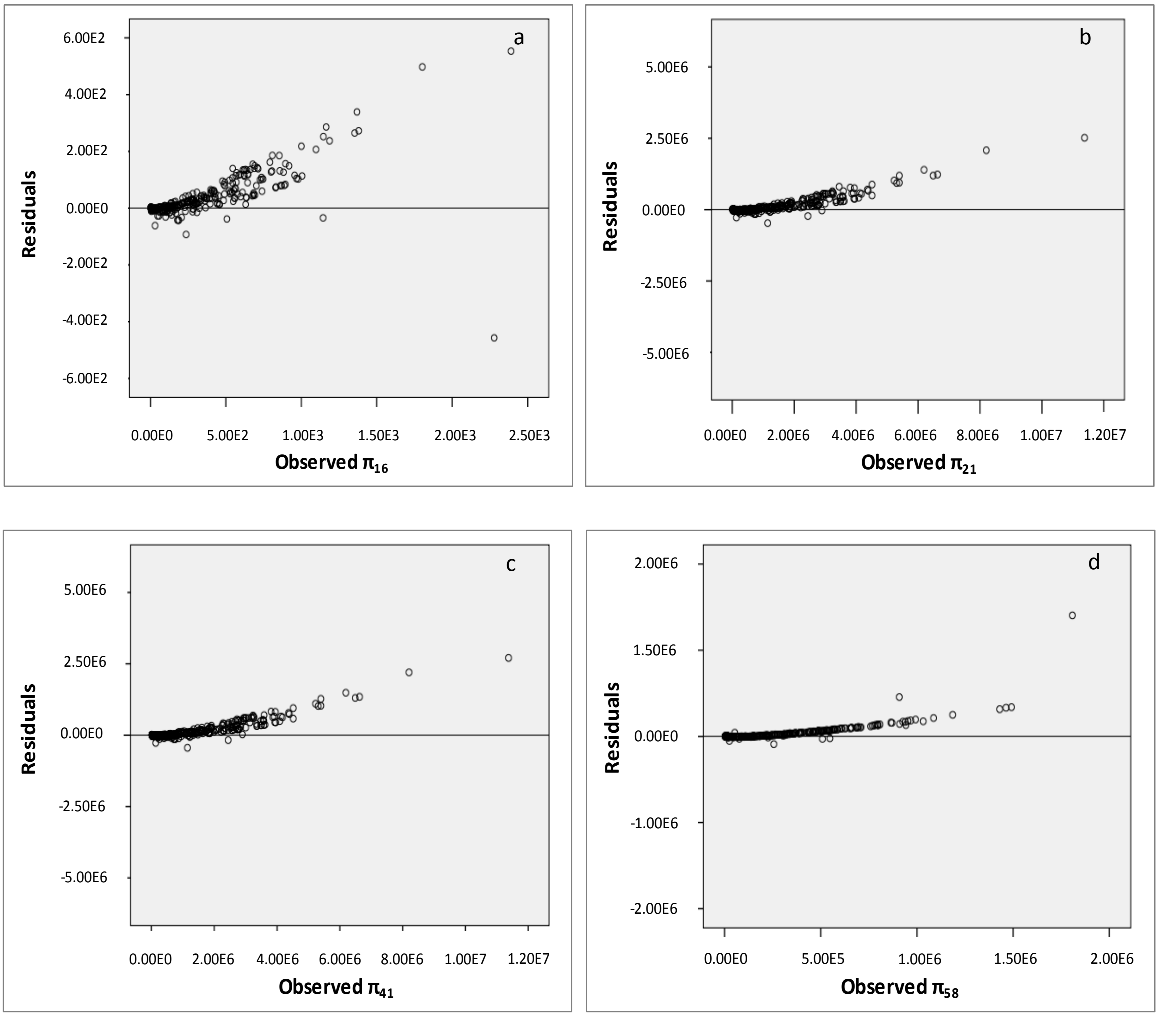


Fig. IV-9. Residual plots for the relationship between residuals of each mathematical model and: (a) observed π_{16}, (b) observed π_{21}, (c) observed π_{41} and (d) observed π_{58}.

The curve estimation of the analysis' results (Table IV-9) demonstrated that the relationship between π_{16} with π_{19}, π_{21} with π_{27}, π_{41} with π_{48}, and π_{58} with π_{57} in equations (IV-26), (IV-27), (IV-28) and (IV-29), respectively, were not significant ($P > 0.05$). Therefore, these insignificant independent variables were excluded and the models were redefined using the unstandardized coefficients for significant variables in Table IV-9. After excluding the insignificant variables in equations (IV-27) and (IV-28), it was found that the new developed models on base of these two equations contained the same variables. Thus, they are presented in the same model defined in equation (IV-31). The new developed mathematical models were as following:

$$\frac{\mathbf{v \cdot t}}{\mathbf{d_f}} = \mathbf{6.32} \cdot \left(\frac{\mathbf{d_e}}{\mathbf{d_f}}\right)^{\mathbf{0.150}} \cdot \left(\frac{\mathbf{V}}{\mathbf{d_f}^{\mathbf{3}}}\right)^{\mathbf{0.888}} \qquad \text{(IV-30)}$$

$$\mathbf{t} \cdot \sqrt{\frac{\mathbf{g}}{\mathbf{d_e}}} = \mathbf{0.001} \cdot \left(\frac{\mathbf{V}}{\mathbf{d_e}^{\mathbf{3}}}\right)^{\mathbf{0.788}} \qquad \text{(IV-31)}$$

$$\frac{\mathbf{v \cdot t}}{\mathbf{d_e}} = \mathbf{1.60E-04} \cdot \left(\frac{\mathbf{V}}{\mathbf{d_e}^{\mathbf{3}}}\right)^{\mathbf{0.810}} \qquad \text{(IV-32)}$$

The new relationships between the observed phenomena and the calculated one using these new mathematical models are presented in Fig. IV-10 and the residual plots are shown in Fig. IV-11.

As it could be seen in Fig. IV-10, the relationships between observed and calculated time by equations (IV-31) and (IV-32) had a strange trend dispersed in three lines, but not equation (IV-30) (Fig. IV-10 a). These trends were worse than the one line trend found for the initial equations (IV-26), (IV-27), (IV-28) and (IV-29) (Fig. IV-8) and also had smaller coefficients of determination.

In addition, the residual plots presented in Fig. IV-11 demonstrated also an agglomeration of residuals shaping three separated lines connected at the zero point only except the residual plot of equation (IV-30) that presented an accumulation of residuals that forms only one line (Fig. IV-11 a). This means that the new models had a worst precision than those defined in equations (IV-26), (IV-27), (IV-28) and (IV-29) even they were statistically significant except this defined in equation (IV-30) that had almost the same adjusted coefficient of determination of its original model defined in equation (IV-26).

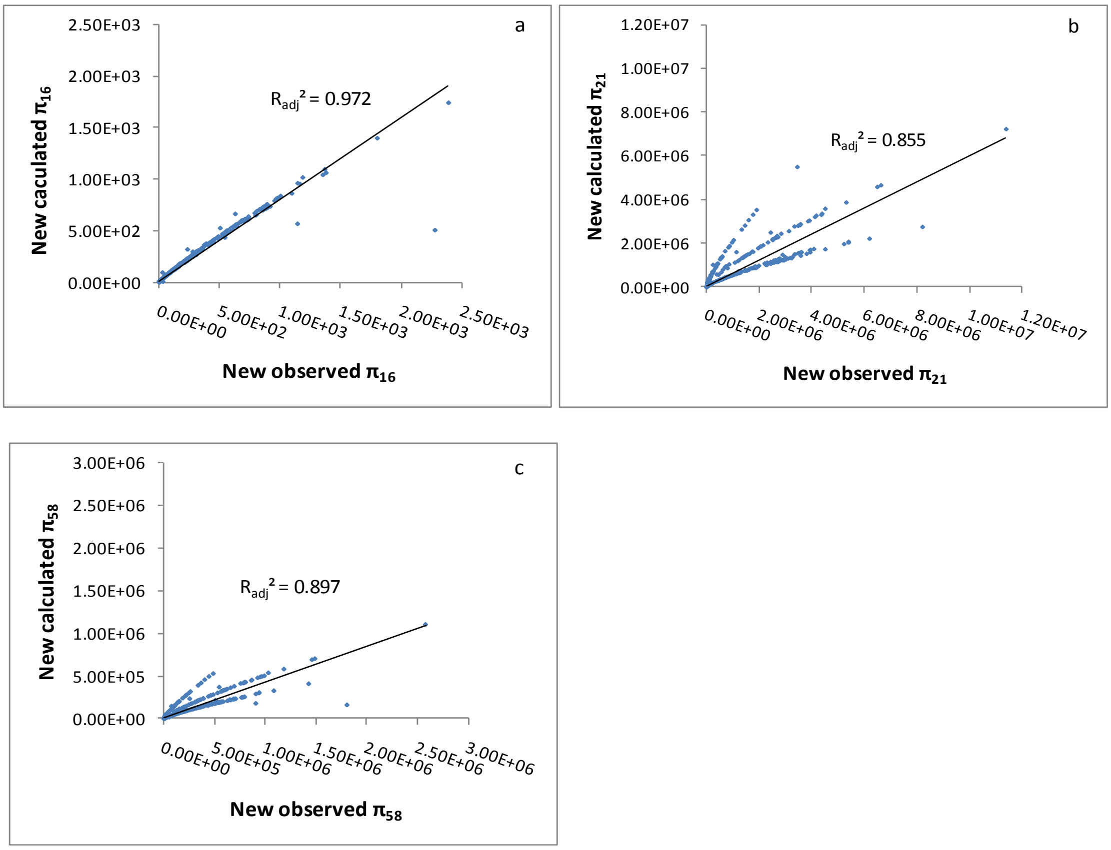


Fig. IV-10. Relationship between the observed dependent value and the calculated one for each mathematical model: (a) equation (IV-30), (b) equation (IV-31) and (c) equation (IV-32). Relationships were significant (P < 0.001).

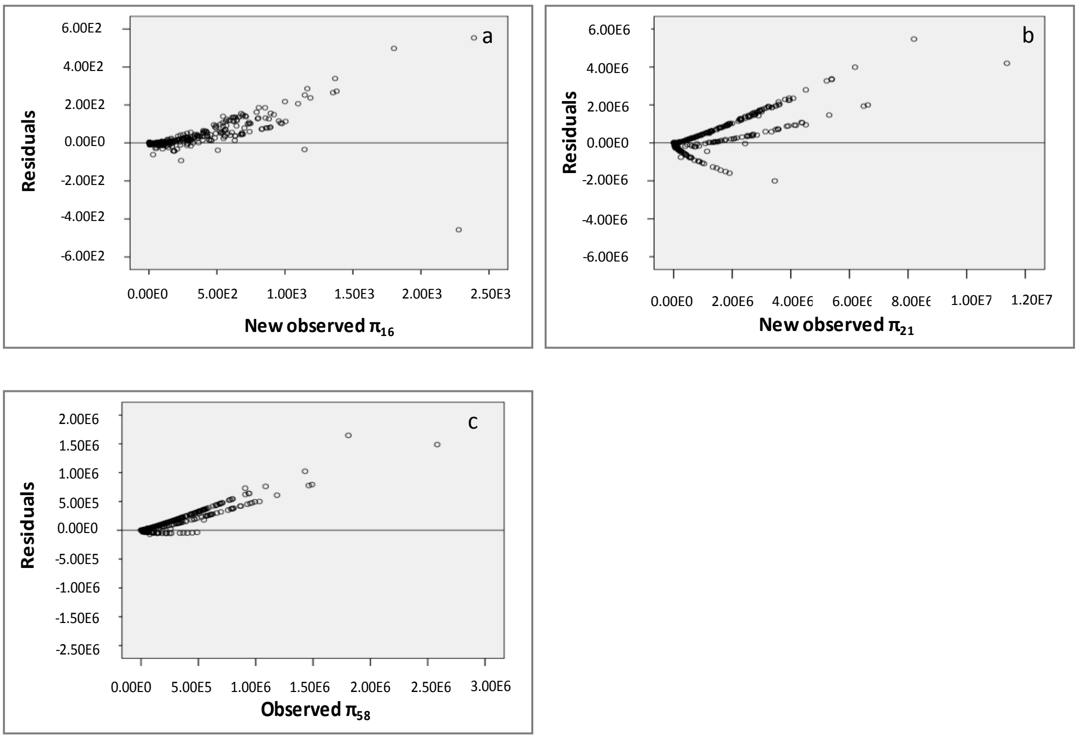


Fig. IV-11. Residual plots for the relationship between residuals of each mathematical model and: (a) new observed π_{16}, (b) new observed π_{21}, and (c) new observed π_{58}.

Table IV-10. Minimum, maximum, root mean square error (RMSE), mean, standard deviation (St.dv), coefficient of variation, R_{adj}^2 for the predicted models.

	Equation (IV-26)		Equation (IV-27)		Equation (IV-28)		Equation (IV-29)	
	π_{16}		π_{21}		π_{41}		π_{58}	
	Observed	Calculated	Observed	Calculated	Observed	Calculated	Observed	Calculated
R_{adj}^2	0.939		0.972		0.972		0.967	
Maximum	2.39E+03	2.73E+03	1.14E+07	8.86E+06	1.14E+07	8.67E+06	2.58E+06	1.89E+06
Minimum	3.35E+00	2.28E-01	1.50E+04	1.03E+03	1.50E+04	1.02E+03	2.70E+03	1.90E+02
RMSE	6.22E+01		2.51E+05		2.72E+05		8.25E+04	
Mean	1.85E+02	1.66E+02	8.35E+05	7.56E+05	8.30E+05	7.39E+05	1.69E+05	1.48E+05
St.dv.	3.05E+02	2.67E+02	1.33E+06	1.12E+06	1.32E+06	1.09E+06	2.77E+05	2.20E+05
Coefficient of variation	1.64	1.60	1.59	1.48	1.59	1.48	1.64	1.48
Minimum value of digital data	1.84E-01		2.10E+04		2.10E+04		4.97E+03	

	Equation (IV-30)		Equation (IV-31)		Equation (IV-32)	
	π_{16}		π_{21}		π_{58}	
	Observed	Calculated	Observed	Calculated	Observed	Calculated
R_{adj}^2	0.972		0.855		0.897	
Maximum	2.39E+03	1.75E+03	1.14E+07	7.18E+06	2.58E+06	1.10E+06
Minimum	3.35E+00	2.36E-01	1.50E+04	1.27E+03	2.70E+03	1.52E+02
RMSE	9.64E+01		7.68E+05		1.95E+05	
Mean	1.85E+02	1.62E+02	8.35E+05	5.93E+05	1.69E+05	8.50E+04
St.dv.	3.05E+02	2.41E+02	1.33E+06	8.45E+05	2.77E+05	1.22E+05
Coefficient of variation	1.64	1.48	1.59	1.42	1.64	1.44
Minimum value of digital data	2.13E-01		6.31E+03		1.19E+03	

It had been noticed in Table IV-10 that all mathematical models defined in equations from equation (IV-26) to (IV-32) had a high adjusted coefficient of determination (≥ 0.855). Despite the elevated R_{adj}^2, the minimum and maximum values (data range) were not well coincided between the observed and calculated dependent variables.

In addition, the coefficient of variation between them did not coincide either. Moreover, the RMSE were higher than the minimum value that could be calculated with the mathematical model. This reduces the accuracy of the mathematical models results. Adding to that, the agglomeration behaviour of the residual plots indicates that the assumptions of the regressions were not met.

From what it was indicated previously, it could be decided that the mathematical models defined by equations (IV-31) and (IV-32) are worse than those determined by equations from (IV-26) to (IV-30) (Table IV-10).

Time between sand filters backwashing cycles was calculated through the mathematical models defined in equations (IV-26), (IV-27), (IV-28), (IV-29) and (IV-30) that presented the highest adjusted coefficient of determination in order to decide if the RMSE would be acceptable or not in real experiments and projects. The relationships between the observed time during the experiment and the calculated one through these models are defined in Fig. IV-12, while the statistical characteristics for these new relationships are shown in Table IV-11.

The relationships were almost as same as they were in Fig. IV-8 and they were well coincided between the observed and calculated time. Time determined by equation (IV-27) had the lowest RMSE with 31.5 min and it is of 34 min for time defined by equations (IV-28) and (IV-29) and 35 min for equations (IV-26) and (IV-30) (Table IV-11). Besides, the coefficient of variation for models defined in Table IV-11 was same and varies between 1.49 to 1.59.

Nevertheless, all these models may need further investigation in order to reduce the RMSE and improve the residual behaviour in the residual plots. Improving these characteristics could lead to develop an adequate model with high accuracy to calculate filter cycle duration of sand filters. This might be achieved if the new suggested experiment in Chapter VI section VI.3 was set.

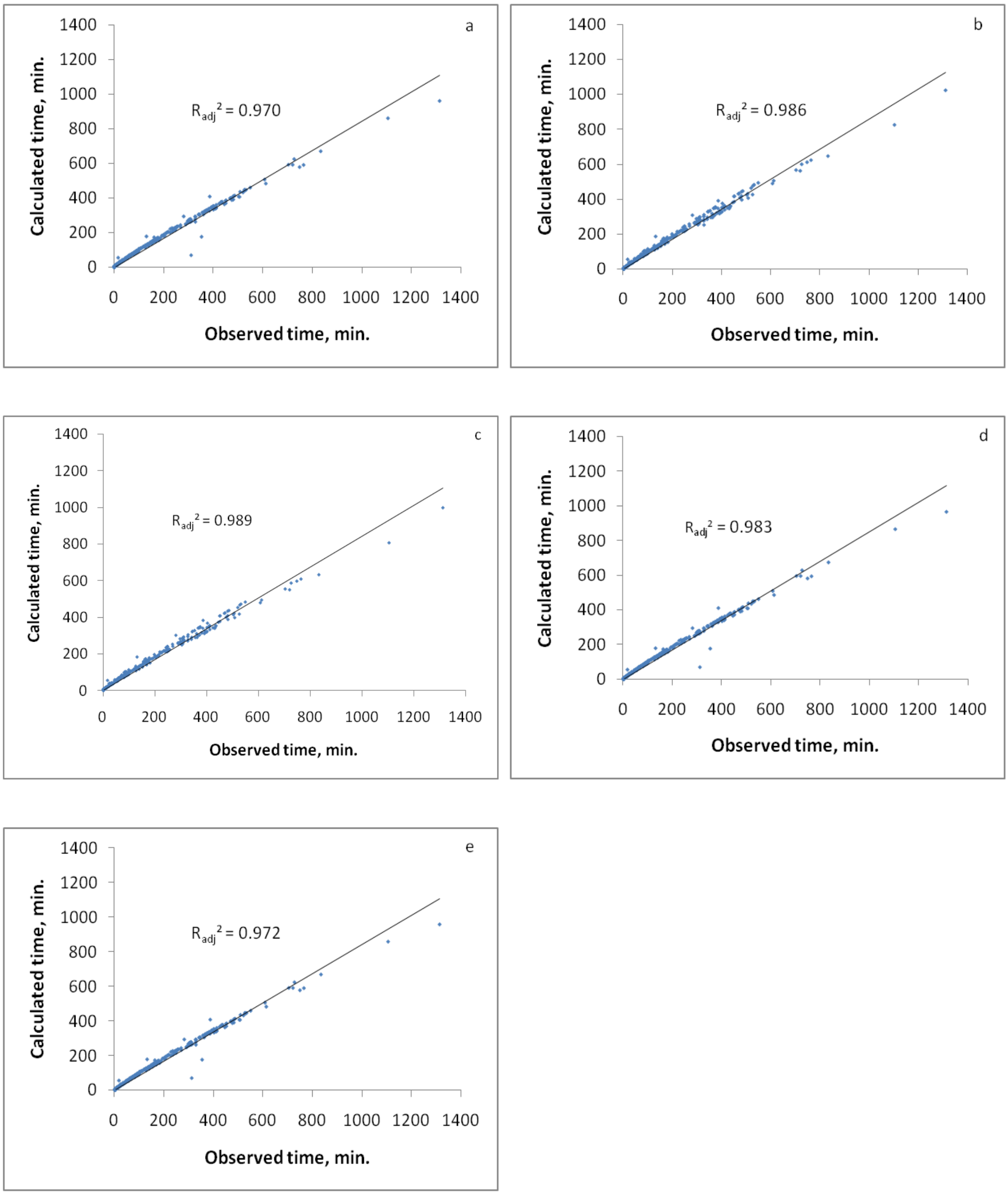


Fig. IV-12. Relationship between the observed time and the calculated one in minutes for each mathematical model defined in equations: (a) (IV-26), (b) (IV-27), (c) (IV-28), (d) (IV-29) and (e) (IV-30). All relationships are significant ($P \leq 0.001$).

Table IV-11. Minimum, maximum, root mean square error (RMSE), mean, standard deviation (St.dv), coefficient of variation and minimum value of digital data, R_{adj}^2 for both observed (Obs.) and calculated (Calc.) time in minutes (min.) for models defined in equations (IV-26), (IV-27), (IV-28), (IV-29) and (IV-30).

	Time, min.									
Equation no.	**(IV-26)**		**(IV-27)**		**(IV-28)**		**(IV-29)**		**(IV-30)**	
	Obs.	**Calc.**	**Obs.**	**Calc.**	**Obs.**	**Calc.**	**Obs.**	**Calc.**	**Obs.**	**Calc.**
R_{adj}^2	0.970		0.986		0.989		0.983		0.972	
Maximum	1313	1009	1313	1023	1313	1000	1313	966	1313	960
Minimum	2.00	0.13	2.00	0.14	2.00	0.14	2.00	0.11	2.00	0.11
RMSE	35.00		31.50		34.00		34.00		35.0.0	
Mean	105	93	105	95	105	93	105	94	105	94
St.dv.	168	139	168	141	167	139	167	140	168	139
Coefficient of variation	1.59	1.49	1.59	1.48	1.59	1.48	1.59	1.48	1.59	1.48
Minimum value of digital data	0.12		0.12		0.12		0.09		0.14	

IV.5. Conclusions

The obtained results of this chapter could be concluded as following:

- Computing head loss across sand media filter.
    - Only one model among the developed models using dimensional analysis for computing head loss across sand filter proved its high accuracy and measurement precision. This model calculates head loss (ΔH) using sand effective diameter (d_e), suspended solids average concentration per filtration cycle (C), acceleration of gravity (g), water density (ρ), water volume (V), and internal sand filter diameter (d_f). The model is defined as:

$$\frac{\Delta H}{d_e \cdot C.g} = 16.216 \cdot \left(\frac{\rho}{C}\right)^{0.980} \cdot \left(\frac{V}{{d_e}^3}\right)^{-0.031} \cdot \left(\frac{d_f}{d_e}\right)^{1.087}$$

    - The calculation of head loss across the filter using the developed model did not coincide with the models of Puig-Bargués et al. (2005a) and Duran-Ros et al. (2010) for having different experimental and effluent conditions. However, these two previous models presented good statistical indicators after being readjusted with the experimental data of the present study.
    - The model developed in this study and the readjusted models of Puig-Bargués et al. (2005a) and Duran-Ros et al. (2010) are adequate for computing head loss across sand filters for having high R_{adj}^2, low RMSE and no pattern in the residual plots. Selection among these three models depends mainly on available information about effluent characteristics and experimental conditions such as, the applied effluent origin and filtration media type and characteristics.
- Computing filter cycle duration.
    - The developed models for determining filter cycle duration presented indicators of low accuracy and precision despite their high adjusted coefficient of determination. These models need further research to improve the measurements precision and model accuracy through applying different effluents with sand filters with diverse dimensions, media sizes and operation parameters.

V. Effect of flushing frequency, emitter type, emitter location and clogging on DI and SDI systems performance

V.1. Introduction

Emitter clogging is one of the most serious problems associated with microirrigation use that can severely hamper water application uniformity (Pitts et al., 1990). Emitter clogging can result from physical, biological and chemical causes (Bucks et al., 1979) and frequently, is caused by a combination of more than one of these factors (Pitts et al., 1990) as it was mentioned before in Chapter I.

Clogging of emitters has been a major problem in dripline systems because of the high levels of suspended solids and nutrients associated with treated wastewater effluents (Rowan et al., 2004). Emitter clogging hazards are a major consideration in selecting drip irrigation systems because it is difficult to detect and expensive to clean, or replace, clogged emitters (Adin and Sacks, 1991; Ravina et al., 1997; Capra and Scicolone, 2004).

The microirrigation system should be designed so that it can be flushed properly. To be effective, flushing must be done often enough and at an appropriate velocity to dislodge and transport the accumulated sediments (Nakayama et al., 2007), as previously pointed out in Chapter I.

There is not a general agreement on what is the best flushing frequency for microirrigation system. Several researches have studied different flushing frequencies: daily with stored treated effluents (Ravina et al., 1997), twice per week (Tajrishy et al., 1994) and once per week (Tajrishy et al., 1994; Hills et al., 2000) with a secondary clarified effluent, every two weeks with stored effluents (Ravina et al., 1997) and with a secondary effluent (Hills and Brenes, 2001) or fortnightly and monthly with stored groundwater (Hills et al., 2000). However, in many areas only one flushing is carried out at the beginning and/or at the ending of irrigation season (Puig-Bargués et al., 2010b).

Determining system uniformity is one of the methods to recognize the performance of a microirrigation system. The uniformity of water application from a microirrigation system is affected both by the water pressure distribution in the pipe network and by the hydraulic properties of the emitters used. The emitter hydraulic properties include the effect of emitter design, water quality, water temperature and other factors on emitter discharge (Smajstrla et al., 1997). Several methods had been set to determine system uniformity, such as FAO method by Vermeiren and Jobling (1986), ASAE method (ASAE Standards, 1998) and the ITRC of California Polytechnic State University method (Burt, 2004).

V.2. Objectives

The foremost objectives of this study are the following:

- Compare between FAO, ASAE and ITRC methods for computing microirrigation system uniformity.
- Study the performance of laterals flow rates in DI and SDI microirrigation systems as a function of emitter type, irrigation season and flushing frequency.
- Identify the main factors for clogging problems in the investigated microirrigation systems.
- Distinguish the effect of microirrigation system on the performance of a pressure and a non-pressure compensating emitters.
- Determine the most effective laterals flushing frequency that reduces emitter clogging in DI and SDI microirrigation systems.
- Describe the effect of emitter type and location on clogging problems for surface and subsurface microirrigation systems.
- Find out the best suitable emitter type for DI and SDI microirrigation systems.

V.3. Materials and methods

V.3.1. Experimental setup

The filtration unit previously described in section III.3.1 was connected to 48 drip laterals each of 87 m long. Twenty-four of them were placed on the field surface (surface drip irrigation, DI) while the other 24 were installed approximately at a depth of 25 cm (subsurface drip irrigation, SDI (Fig. V-1 b)). The experiment was divided into three irrigation seasons each of 540 h.

Subsurface laterals were placed in a trench prepared with an AFT65 tractor mounted trencher (AFT Trenchers Ltd., Sudbury, England) (Fig. V-1 a). Then the trenches were carefully backfilled with the previously removed soil (Fig. V-1 c).

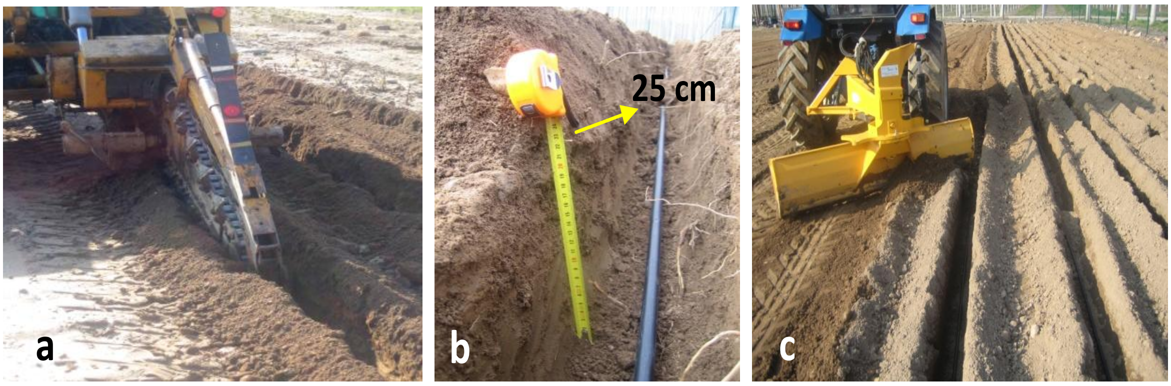


Fig. V-1. Preparation for subsurface irrigation system. (a) Trench digging for the subsurface drip irrigation system, (b) depth of the set trench and (c) recovering the prepared trenches with the previously removed soil.

Two types of drip laterals were used each with a different emitter type (Netafim, Tel Aviv, Israel). The first was the pressure compensating emitter Ram 17012 (Fig. V-2 a). The other emitter (non-pressure compensating) was a Tiran 16010 (Fig. V-2 b). The two emitters types used had injection molded dripper construction and were welded onto the interior drip lateral wall. The primary emitter and lateral characteristics are shown in Table V-1. A ball valve was installed at the inlet to each dripline for onsite flow control and at every lateral end for flushing (Fig. V-3).

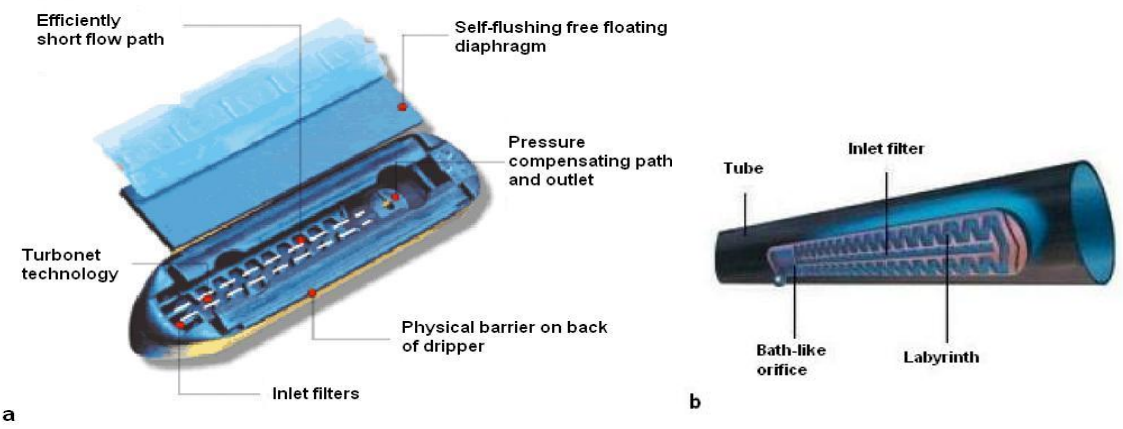


Fig. V-2. (a) Pressure compensating emitter type Ram 17012 and (b) non-pressure compensating emitter type Tiran 16010 (Netafim, 2003).

Table V-1. Main emitter and dripline characteristics, according to manufacturer's specifications.

Characteristic	Pressure compensating	Non-pressure compensating
Nominal flow rate, l h^{-1}	2.30	2.00
Nominal pressure, kPa	50 - 400	100
Maximum operating pressure, kPa	400	350
External diameter, mm	17.00	16.10
Distance between emitters, m	1.00	1.00
Flow exponent x	0.05	0.46
Manufacturer variation coefficient, %	< 3	< 3
Water passage width, mm	1.15	0.76
Water passage depth, mm	0.95	1.08
Water sectional area, mm^2	1.09	0.82
Water passage length, mm	22.00	75.00
Water passage filtering area, mm^2	8.00	70.00

The experimental plot was treated periodically with herbicide in order to prevent weed growth that might have resulted in root intrusion into the subsurface drip irrigation (SDI) system emitters.

The applied laterals flushing frequencies were no flushing (T1), only one flushing at the end of each irrigation season (T2) and monthly flushing during the irrigation season (T3) with both emitter types. The accumulated irrigation time for when flushing events were carried out are pointed out in Table V-2. Flushing was carried out for five minutes at a velocity of 0.60 m s^{-1}, slightly greater than the recommended by Hills and Brenes (2001) and the double of the minimum flushing velocity of 0.30 m s^{-1} recommended for microirrigation systems by the ASAE Standards (2003). The hydraulic diagram of the microirrigation system and location of monitoring and control equipment previously described in Chapter III is shown in Fig. V-3. The arrangement of the emitter and flushing treatment to the laterals was random.

Table V-2. Flushing dates and accumulated irrigation time for when flushing events were carried out.

Irrigation season	Flushing	Flushing date	Irrigation time, h
First	Monthly	October 5, 2007	107
	Monthly	November 2, 2007	307
	Monthly / end of the season	December 7, 2007	540
Second	Monthly	April 10, 2008	753
	Monthly	May 15, 2008	995
	Monthly / end of the season	June 26, 2008	1080
Third	Monthly	August 4, 2008	1339
	Monthly / end of the season	September 8, 2008	1620

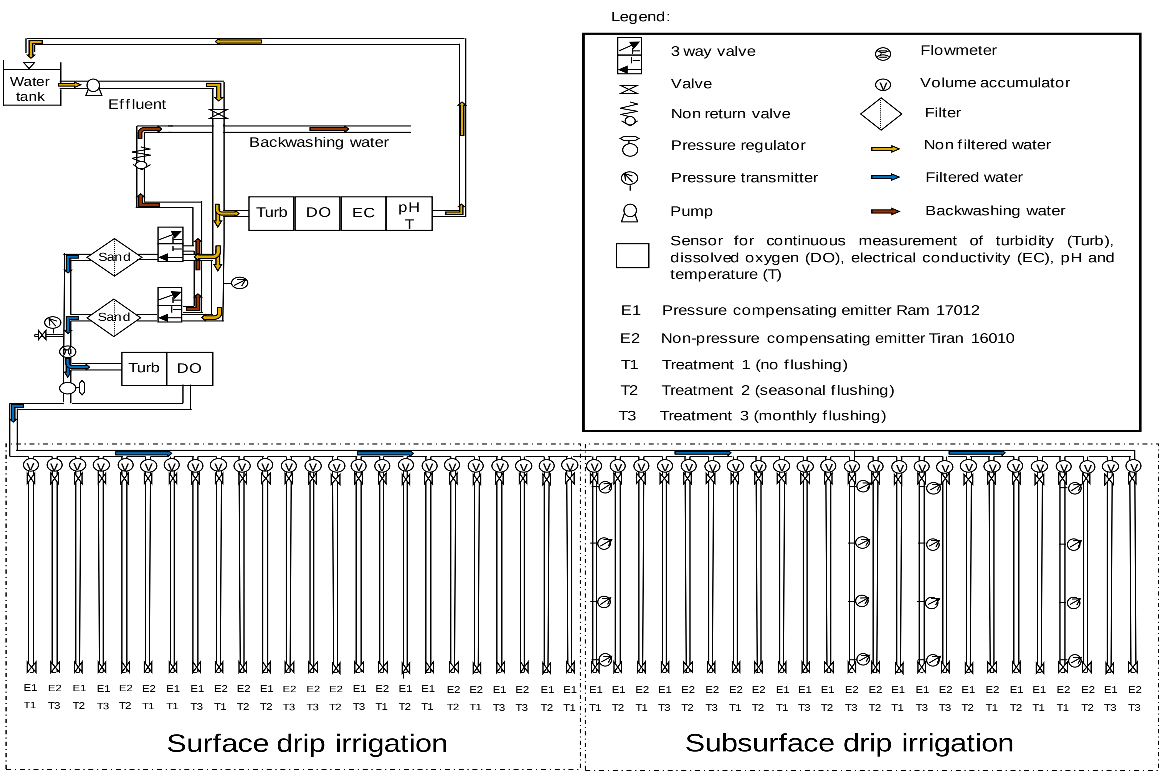


Fig. V-3. Hydraulic diagram of the microirrigation system and location of monitoring and control equipment.

V.3.2. Microirrigation system uniformity

System uniformity was determined at the beginning of the experiment following the FAO method (Vermeiren and Jobling, 1986). After that, system uniformity was computed after 540, 1080 and 1620 h (end of the experiment), respectively for DI system applying FAO method and ASAE Standards EP458 (ASAE Standards, 1998). For the SDI system, the uniformity was determined only at the end of the experiment (after 1620 h) using the two mentioned before methods in addition to the ITCR of California Polytechnic State University method (Burt, 2004) to determine the distribution uniformity only for the pressure compensating emitter with seasonal flushing treatment and with the non-pressure compensating emitter type that was never flushed during the experiment.

The discharge of non-pressure compensating emitters, those in which the flow is a function of emitter pressure, had been corrected to the reference pressure. This transformation of the flow permitted to compare the flow regardless to the difference caused by different pressures. The calculation for the transformation that took place was:

$$\mathbf{Q_{P\ nom}} = \mathbf{Q_{P\ field}} \cdot \left(\frac{\mathbf{P_{nom}}}{\mathbf{P_{field}}}\right)^{\mathbf{x}} \qquad \text{(V-1)}$$

where $Q_{P\ nom}$ is the emitter discharge at the nominal pressure in l h^{-1}, $Q_{P\ field}$ is the emitter discharge to the pressure measured in field in l h^{-1}, P_{nom} is the nominal pressure in kPa, P_{field} is the pressure measured in the field in kPa and x is the flow exponent (Table V-1).

Emitter discharge was determined by collecting the volume released by each emitter for 5 min in a plastic container with 5 cm in height and 20 cm in diameter (Fig. V-4 a). The pressure measured within the lateral using pressure intake (Eintal, Or-Akica, Israel), a digital manometer model Leo 2 (Keller, Winterthur, Switzerland) and a needle adapter (Fig. V-4 b). This manometer had a maximum error of 0.065% of the value as calibration certificate issued by the manufacturer.

Fig. V-4. (a) Distribution of the plastic containers and (b) the digital manometer while measuring lateral pressure manually.

V.3.2.1. FAO method

Distribution uniformity was determined according to FAO (Vermeiren and Jobling, 1986) as following:

- Select four lateral lines for each emitter type.
- Choose two contiguous emitters in each lateral pipe (at the beginning, one third, two thirds and at the end of the lateral).
- Measure the pressure in normal operation conditions at the middle of the distance between the two chosen adjacent emitters.
- Measure all the selected emitters discharge at 5 min so as to produce a volume of between 100 – 250 ml per emitter, which means 32 measures by 16 points.
- Calculate the average discharge of each pair formed by two contiguous emitters, making 16 volume measurements.
- Calculate the average of the four smallest values, which represent the minimum 25% of discharge distribution.
- Compute the overall average of 16 values, representing the average flow rate of emitter discharge.
- Calculate the distribution uniformity ($DU_{lq\ flow}$) from the data measured in field per each emitter type and drip irrigation surface as defined in equation (V-2).

$$\mathbf{DU_{Iq\ flow}} = \frac{\mathbf{q_{25}}}{\mathbf{\bar{q}}} \cdot \mathbf{100} \qquad \text{(V-2)}$$

where q_{25} is the average discharge of 25% of emitters that provide the smaller emitter discharge and $\bar{q}$ is the average emitter discharge rate.

- Calculate the pressure uniformity ($DU_{Iq\Delta P}$) from the data measured in field per each emitter type and drip irrigation as following:

$$\mathbf{DU_{Iq\Delta P}} = \left(\frac{\mathbf{P_{25}}}{\mathbf{\bar{P}}}\right)^{\mathbf{x}} \cdot \mathbf{100} \qquad \text{(V-3)}$$

being P_{25} the average pressure of 25% of emitters with the smaller pressure, $\overline{P}$ the overall average pressure and x the emitter flow exponent (Table V-1).

V.3.2.2. ASAE method

The ASAE standard EP458 (ASAE Standards, 1998) used the statistical uniformity term (U_s) for evaluating water application uniformity within submain unit or throughout a microirrigation system. This ASAE method to evaluate the statistical uniformity was slightly modified and used.

- Determine four lateral lines on a secondary pipe for each emitter type.
- Choose two contiguous emitters in six different locations in each lateral pipe: at the beginning, at one third (29 m) of lateral length, at two thirds (58 m), at 60 m, at 66 mm and at the end of the lateral (87 m). For experiment simplification, the current study did not follow the random selection even it is recommended by the ASAE standard EP458.
- Measure the pressure in normal operation conditions at the middle of the distance between each two selected contiguous emitters.
- Measure all selected emitters discharge at a determined number of minutes, which means 36 measures by 18 points.
- Calculate the overall average of 18 values, representing the average discharge rate of emitters.

- Determine the coefficient of variation for the submain unit (V_{qs}) as follows:

$$\mathbf{V_{qs}} = \frac{\mathbf{S_q}}{\bar{\mathbf{q}}} \quad \text{(V-4)}$$

being S_q the standard deviation for emitter discharge rate and $\bar{q}$ the average emitter discharge.

- Compute the statistical uniformity of emitter discharge (U_s).

$$\mathbf{U_s} = \mathbf{100} \cdot (\mathbf{1} - \mathbf{V_{qs}}) \quad \text{(V-5)}$$

- Compute the hydraulic coefficient of variation (V_{hs}) and the statistical pressure uniformity (U_{hs}) applying equations (V-6) and (V-7), respectively.

$$\mathbf{V_{hs}} = \frac{\mathbf{S_h}}{\bar{\mathbf{P}}} \quad \text{(V-6)}$$

$$\mathbf{U_{hs}} = \mathbf{100} \cdot (\mathbf{1} - \mathbf{V_{hs}}) \quad \text{(V-7)}$$

were S_h is the pressure standard deviation and $\overline{P}$ is the overall pressure average.

In the current study, as plants were not considered, the V_{qs} did not need to be adjusted by dividing it by the square root of the number of emitters per plant to correct the emitter discharge coefficient and the statistical uniformity.

- Determine emitter discharge coefficient of variation due to hydraulics (V_{qh}).

$$\mathbf{V_{qh}} = \mathbf{x} \cdot \mathbf{V_{hs}} \quad \text{(V-8)}$$

were x the emitter flow exponent.

- Compute emitter performance coefficient of variation (V_{pf}).

$$\mathbf{V_{pf}} = \left(\mathbf{V_{qs}}^2 - \mathbf{V_{qh}}^2\right)^{\mathbf{0.5}} \quad \text{(V-9)}$$

- Calculate the statistical uniformity of emitter performance (U_{pf}).

$$\mathbf{U_{pf}} = \mathbf{100} \cdot (\mathbf{1} - \mathbf{V_{pf}}) \quad \text{(V-10)}$$

When taking into consideration emitter clogging factor, the emitter discharge coefficient of variation including this factor (V_{qp}) would be calculated as:

$$\mathbf{V_{qp}} = \left[\frac{\mathbf{1}}{(\mathbf{1}-\mathbf{C_t})} \cdot \left(\mathbf{V_{qs}}^{\mathbf{2}} + \mathbf{1}\right) - \mathbf{1}\right]^{\mathbf{0.5}} \quad \text{(V-11)}$$

being (1-C_t) the proportion (decimal) of emitters openly flowing where C_t is number of clogged emitters

- At the end, the statistical uniformity of the emitter discharge rate including emitter clogging factor (U_{qp}) should be computed as:

$$\mathbf{U_{qp}} = \mathbf{100} \cdot \left(\mathbf{1} - \mathbf{V_{qp}}\right) \quad \text{(V-12)}$$

V.3.2.3. ITCR Method

The ITRC of California Polytechnic State University determined the distribution uniformity (DU) for an irrigation system following the next steps (Burt, 2004):

- At the SDI plot, select three laterals with the pressure compensating emitter and seasonal flushing frequency. One of them in the right of the plot, one in the middle and the third in the left of the plot. By the same way select other three laterals with the non-pressure compensating emitter and a no flushing frequency treatment.
- Select the first 16 contiguous emitters for the first lateral; another 16 adjacent emitters at the middle of the second lateral and the last 28 adjacent emitters of the third lateral line for each emitter type and treatment.
- Measure the pressure in normal operation conditions at the beginning of each previously selected lateral line. Then, measure it at the first and last selected emitters for each lateral.
- Calculate the average of fifteen (25%) smallest values, which represent the minimum pressure distribution.
- Calculate the overall average of the 9 values, representing the average pressure.
- Measure the discharge of all selected emitters during 5 min, which mean 60 measurements for 60 points.

- Calculate the average of fifteen (25%) smallest values, which represent the minimum flow distribution.
- Calculate the overall average discharge of the 60 emitters.
- Determine the distribution uniformity for flow $DU_{Iq\ flow}$ and pressure $DU_{Iq\Delta P}$ as defined in equations (V-2) and (V-3), respectively.
- Compute the all system distribution uniformity (DU) as:

$$\mathbf{DU = DU_{Iq\Delta P} \cdot DU_{Iq\ flow}} \qquad \text{(V-13)}$$

V.3.2.4. Microirrigation system uniformity acceptability degree

The acceptability degree of applied microirrigation system uniformity was defined according to Rodríguez (1990) for values obtained by FAO method while those that obtained by ASAE and ITRC methods were classified on base of ASAE EP458 (ASAE Standards, 1998), previously defined in Chapter I.

Furthermore, the diagram prepared by Rodríguez (1990), previously presented in section I.4.8.2 as well was used to recognize the reasons and causes for the observed low quality flow distribution in determined experiment times.

V.3.3. Analysis of clogged emitters

Clogging of emitters could be a partial or completely clogging. As it is difficult to evaluate the partial clogging, the clogging evaluation was taken by using only the completely clogged emitters.

V.3.3.1. Percentage of totally clogged emitters

The percentage of totally clogged emitters was determined for each DI lateral at the end of each irrigation season (after 540, 1080 and 1620 h, respectively) and for each SDI lateral only at the end of the third irrigation period using the formula defined in equation (V-14).

$$\mathbf{n_{tc} = \frac{n_c}{n^{\circ}} \cdot 100} \qquad \text{(V-14)}$$

where n_{tc} is the percentage of totally clogged emitters, n_c the number of totally clogged emitter and n° is the number of all observed emitters. An emitter was considered totally clogged when its discharge was 0 l h^{-1}.

V.3.3.2. Visual observation

Seventeen totally clogged and unclogged emitters at the end of the lateral (87 m long) and other 24 emitters randomly selected at two thirds of lateral length (58 m) from DI and SDI microirrigation systems were visually studied. Emitters were removed at the end of the experiment (after 1620 h) from the driplines to the laboratory where they were carefully opened and their components were examined. The visual observation for totally clogged and no clogged emitters was made before and after opening them to recognize clogging reasons, but the observed precipitates were not quantified. The observed emitters were photographed using a Cyper-shot DSC-W50 digital camera 6.0 MP (Sony Electronics Inc., San Diego, California, USA).

V.3.4. Statistical analyses

The statistical analysis was carried out using SPSS statistical program (SPSS Inc., Chicago, Illinois, USA). Results were checked at 0.05 significance level.

V.3.4.1. System distribution uniformity methods

A general linear model with Duncan test was run between system uniformity values that were calculated by the three methods (FAO, ASAE and ITRC) after 1620 h of irrigation for the non-flushed non-pressure compensating emitter and the seasonally flushed pressure compensating emitter. The analysis aimed to study whether these three methods results were coincident together or not in the subsurface drip irrigation system (SDI).

For the same reason as well, the general linear model was set between the calculated system uniformity ($DU_{lq\ flow}$ and U_s) by FAO and ASAE methods, respectively at different experimental times (540, 1080 and 1620 h, successively) in DI and SDI microirrigation systems.

Besides, a statistical regression analysis was set between $DU_{lq\ flow}$ and U_s system uniformity values at 540, 1080 and 1620 h experiment to set a formula that allow to convert system uniformity computed by one method to the other.

V.3.4.2. Analysis of totally clogged emitters

A general linear model with Duncan test analysis was used to study whether it existed a significant effect of irrigation system, emitter type and flushing frequency on the number of the totally clogged emitters after 1620 h of irrigation. The significant interactions were studied separately applying the general linear model, as well.

V.3.4.3. Analysis of lateral flow rate

Average lateral flow rate for every 10 h of experiment during the three irrigation seasons was determined for both surface drip irrigation (DI) and subsurface drip irrigation (SDI) systems when applied three flushing frequencies (T1, T2 and T3). The analysis aimed of lateral flow rates to study the behaviour of the used laterals with pressure compensating and non-pressure compensating emitters under different flushing frequencies in both microirrigation systems throughout the experiment.

In addition, a general linear model with Duncan test analysis was set to check if it existed a significant effect of irrigation system, irrigation season, emitter type and flushing frequency on laterals flow rate. Moreover, the significant interactions between variables were studied deeply applying the same statistical model between them. Data were an average of every 10 h of experiment for each irrigation season. The analysis considered the flow rate as a dependent variable and all of irrigation season, irrigation system, emitter type and flushing frequency as fix factors.

V.3.4.4. Analysis of relative emitter discharge

Discharge and pressure for emitters located at the beginning, at one third, at two thirds and at the end of the laterals were measured at the field after 1620 h of irrigation. The flow rate was corrected to the reference pressure (equation V-1) and then divided by the emitter nominal flow rate to compute the relative emitter discharge, which allowed the comparison between emitters regardless the pressure variable.

The relative emitter discharge was analyzed to study the performance of the used pressure and non-pressure compensating emitters under different flushing frequencies and irrigation systems.

The statistical analysis was made applying the general linear model considering relative emitter discharge as the dependent variable and all of irrigation system, emitter type, flushing frequency and emitter location and interaction between them as the fix variables. The resulted significant interaction between variables was studied separately as well applying the general linear model with Duncan test when necessary.

V.4. Results and discussion

V.4.1. System uniformity

V.4.1.1. DI system uniformity

The evolution of $DU_{lq\ flow}$ and U_s for DI system and its acceptability degree through 1620 h of experiment computed by FAO and ASAE methods, respectively are shown in Fig. V-5. $DU_{lq\ flow}$ was firstly determined at the beginning of the experiment, while U_s at the end of the first irrigation season (540h).

The acceptability degree varied depending on the classification method (Fig. V-5). Thus, it was found that the $DU_{lq\ flow}$ acceptability degree was “excellent” for the pressure compensating emitter when it was flushed monthly or not flushed during the first 540 h in DI system, but it varied from “good” according to Rodríguez (1990) classification to “very good” according to the ASAE Standards (1998) classification when applying only one flushing at the end of 540 h of irrigation.

On the other hand, the non-pressure compensating emitter type had both “excellent” $DU_{lq\ flow}$ and U_s (Fig. V-5) after 540 h of experiment, independently from the applied flushing frequency and classification method.

Pressure and non-pressure compensating emitter $DU_{lq\ flow}$ for no flushing treatment decreased from the “excellent” degree during the first 540 h of experiment to the “good”, then to the “acceptable” degree during the following 540 h of experiment (1080 h of irrigation) and lastly to “unacceptable” on base of Rodríguez (1990) classification after 1620 h experiment (Fig. V-5).

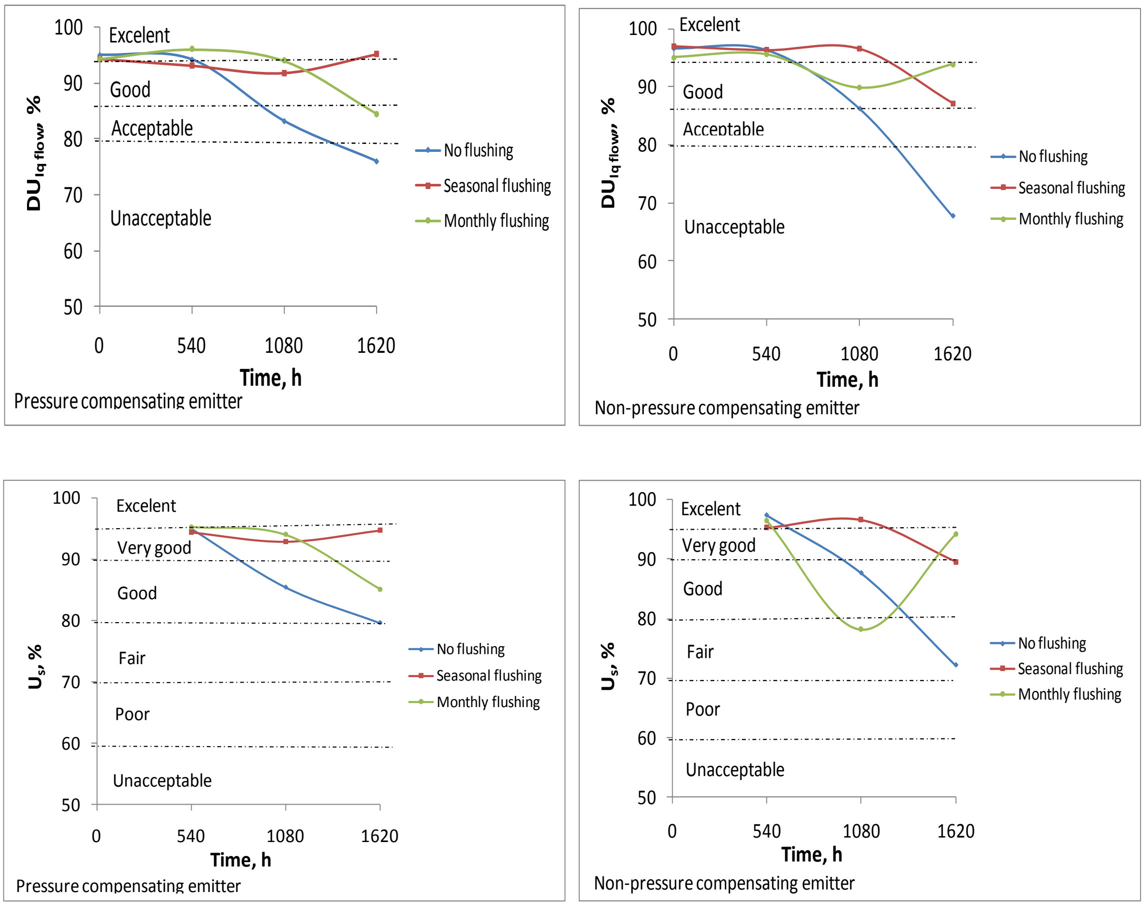


Fig. V-5. System acceptability for flow uniformity computed by FAO methods ($DU_{lq\ flow}$) on base of Rodríguez (1990) and ASAE method (U_s) on base of ASAE Standards EP458 (ASAE, 1998) for each emitter type and flushing frequency in DI system.

The seasonal flushed pressure compensating emitters presented a smooth decrease in its $DU_{lq\ flow}$ and U_s during the first 1080 h of experiment to vary from “excellent” to “good” degree on base of Rodríguez (1990) classification. Its distribution uniformity was increased again during the last 540 h of experiment to reach the “excellent” degree again.

The $DU_{lq\ flow}$ for the monthly flushed non-pressure compensating emitter was decreased from “excellent” to “good” after the first 540 h of experiment and then increased again to reach the “excellent” degree. The U_s as well, illustrated the same behaviour, which reduced from the "excellent" degree after 540 h of irrigation to "fair" degree after 1080 h, then, it increased again to "very good" degree after 1620 h of irrigation (Fig. V-5). This was due to the recovering of the discharge of some emitters at the end of the experiment again and the observed increasing of other non clogged emitters' discharge that will be explained later in section V.4.3.

The non-pressure compensating emitter that was flushed seasonally maintained its "excellent" $DU_{lq\ flow}$ and U_s acceptability degree during the first 1080 h of experiment, and then it was decreased to the "good" degree after 1620 h.

The monthly flushed pressure compensating emitter conserved its "excellent" $DU_{lq\ flow}$ and U_s acceptability degree during the first 1080 and after that started to be reduced during the last 540 h of experiment (up to 1620 h of irrigation) to "acceptable" and "good" degree for $DU_{lq\ flow}$ and U_s, respectively (Fig. V-5).

From the previously obtained results illustrated in Fig. V-5, it was obvious that a seasonal flushing frequency gave greater $DU_{lq\ flow}$ and U_s than the monthly one with the pressure compensating emitter and the contrary, the monthly flushing frequency gave greater $DU_{lq\ flow}$ and U_s with the non-pressure compensating emitter after 1620h of experiment. This was not appearing consistent with typical hypothesis that increased flushing frequency will help increase system performance and distribution uniformity. However, Puig-Bargués et al. (2010a) detected during a one month experiment with a total of 371 h of irrigation and three laterals flushing frequencies (no flushing, once every 15 days and once at the end of experiment) that the average of solids removed from driplines was higher with one only flushing after 30 days (TSS = 27.0 ± 6.0 g m^{-3}) than flushing each 15 days (TSS = 21.0 ± 1.8 g m^{-3}). This might be due to that when sediments were allowed to accumulate and coagulate over time increasing the aggregate sizes, these coagulated particles might have some dragging effect on other sediments during flushing and thus solids removal might be greater.

Therefore and, on the light of these results, it could be said that the most suitable flushing frequency depends on the expected life of the drip irrigation system. Thus, system performance was similar up to 540 h with or without flushing. Until 1080 h of irrigation, no flushing the laterals is not a recommended practice, as $DU_{lq\ flow}$ and U_s were smaller than with both flushing treatments. After 1620 h of operation, a seasonal flushing was enough for the pressure compensating emitter. However, the non-pressure compensating emitter, which was more prone to clogging, as it will be discussed later on, required a monthly flushing.

However, global uniformity indices, such as $DU_{lq\ flow}$ and U_s, do not allow the causes of lack of uniformity to be identified. Thus, pressure measures are, at least, necessary to separate hydraulic effects (Capra and Scicolone, 1998) as the diagnostic diagram shown in Fig. I-3. A proposed distribution uniformity evaluation procedure is reasonably accurate if pressure distribution follows a systematic variation, whereas it has less accuracy if the pressure distribution within the field is random (Styles et al., 2008). The $DU_{lq\Delta P}$ and U_{hs} are illustrated in Fig. V-6. System $DU_{lq\Delta P}$ and U_{hs} were higher than 97% during the 1620 h of experiment independently of flushing frequency in DI system. The elevated $DU_{lq\Delta P}$ and U_{hs} values indicated the correct hydraulic design of the irrigation systems (Rodríguez, 1990).

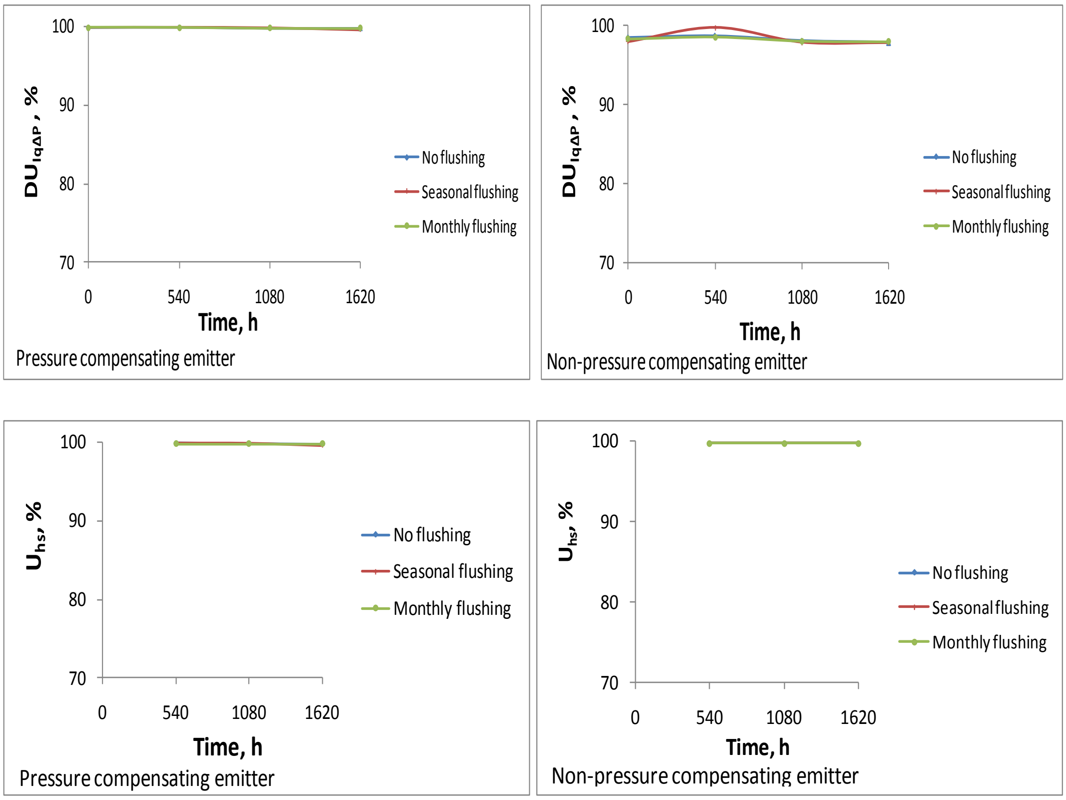


Fig. V-6. System pressure uniformity computed by FAO ($DU_{lq\Delta P}$) and ASAE methods (U_{hs}) at different times of experiment for DI system for the pressure and non-pressure compensating emitters and different flushing frequencies.

V.4.1.2. SDI system uniformity

Subsurface drip irrigation system flow and pressure uniformity after 1620 h of experiment are pointed out in Table V-3 for the pressure and non-pressure compensating emitters with different laterals' flushing treatments. The acceptability degree of the SDI system is determined in Table V-4.

Table V-3. System flow and pressure uniformity computed by FAO, ASAE and ITRC methods after 1620 h of experiment for subsurface drip irrigation system (SDI) with different flushing frequency.

Emitter type	Flushing frequency	Flow uniformity indicator, %			Pressure uniformity indicator, %		
		FAO	ASAE	ITRC	FAO	ASAE	ITRC
Pressure compensating	No flushing	54.01	46.04	-	99.07	99.76	-
	Seasonal flushing	80.13	83.61	63.70	99.66	99.74	99.60
	Monthly flushing	87.74	88.99	-	99.70	99.76	-
Non-pressure compensating	No flushing	24.27	32.39	35.90	97.28	99.79	98.00
	Seasonal flushing	46.99	49.18	-	97.59	99.80	-
	Monthly flushing	69.41	69.17	-	97.46	99.79	-

Table V-4. Acceptability degree of applied microirrigation system uniformity according to Rodríguez (1990) for FAO values and ASAE Standards (1998) for ASAE and ITRC values during the experiment for SDI system after 1620 h of experiment.

Emitter type	Flushing frequency	Acceptability degree for SDI system		
		FAO	ASAE	ITRC
Pressure compensating	No flushing	Unacceptable	Unacceptable	-
	Seasonal flushing	Acceptable	Good	Poor
	Monthly flushing	Good	Good	-
Non-pressure compensating	No flushing	Unacceptable	Unacceptable	Unacceptable
	Seasonal flushing	Unacceptable	Unacceptable	-
	Monthly flushing	Unacceptable	Poor	-

The U_s and $DU_{lq\ flow}$ of the subsurface drip irrigation system without flushing was reduced considerably after 1620 h of experiment for both emitter types. The U_s and $DU_{lq\ flow}$ for the pressure compensating emitter was reduced to 46 - 54%, depending on the calculation method (ASAE and FAO), respectively, while it was 32 - 24% for the non-pressure compensating one, respectively (Table V-3). Both system distribution uniformities were not acceptable neither on base of Rodríguez (1990) nor on ASAE Standards (1998) classifications. Moreover, after 1620 h of experiment it was found that the acceptability degree was "unacceptable" for the non-pressure compensating emitter independently from the applied flushing frequency and classification method. System uniformity for this emitter type did not exceed the 69% under any flushing treatment (Table V-3).

On the other hand, after 1620 h of experiment in SDI system, the pressure compensating emitter had $DU_{lq\ flow}$ and U_s between 80 to 83%, respectively, for the seasonal flushing treatment and 87 - 88%, respectively, for the monthly flushing one (Table V-3). The acceptability degree for this emitter was “acceptable” according to Rodríguez (1990) classification and “good” on base of ASAE Standards (1998) classification for the seasonal flushing frequency treatment and for both methods was “good” for the monthly flushing frequency one (Table V-4). However, as same as the DI system, the pressure distribution uniformity was high (> 97%), which indicated a correct system pressure distribution, being emitter clogging the main cause of the decreasing in system $DU_{lq\ flow}$ and U_s.

V.4.1.3. Comparison between DI and SDI systems

When comparing DI with SDI systems, it was observed that $DU_{lq\ flow}$ and U_s were smaller in SDI system than in DI for both emitter types. This was coincident with what was observed by Camp et al. (1997) who found that the $DU_{lq\ flow}$ for the surface system (96.6%) was greater than the subsurface one (83.2%) due to emitter clogging after eight years of experiment. Camp et al. (1997) applied during their experiment chlorinated municipal and well effluents filtered in 100 mesh cartridge filter and applying lateral flushing treatment at the beginning and the end of each irrigation season injecting the laterals with a higher-concentration chlorine solution for 1 h before the flushing.

However, soil hydraulic properties can affect the discharge from a subsurface emitter, besides the manufacturer’s variability, dripline pressure differences and clogging. Warrick and Shani (1996) experienced a variation in emitter uniformity depending on soil properties. Therefore, the smaller $DU_{lq\ flow}$ and U_s in SDI system could be partly related with soil heterogeneity, which was the condition of the present experiment.

In addition, the $DU_{Iq\Delta P}$ and U_{hs} were higher than 97% during the experiment, which eliminate the possibility of a bad system hydraulic design and focus on emitters clogging the reason for the low statistical and distribution uniformity (Rodríguez, 1990). A few clogged emitters can greatly reduce the uniformity of water application (Bralts et al., 1981; Nakayama and Bucks, 1991). Therefore, a seasonal or monthly flushing treatment during 1620 h of irrigation was the best procedure to obtain good water distribution uniformity with the pressure compensating emitter in SDI systems. For the non-pressure compensating emitter, a monthly flushing was necessary to conserve a high $DU_{Iq\ flow}$ and U_s after 1620h experiment in SDI system.

V.4.1.4. Comparison between FAO, ASAE and ITRC methods for system uniformity calculation

No significant differences (P > 0.05) were observed between system uniformity at the end of the experiment using the FAO, ASAE and ITRC calculation methods in the SDI system. There were no significant differences as well (P > 0.05) between the FAO and ASAE calculation results of system uniformity at different experiment times (after 540, 1080 and 1620 h respectively) for DI and SDI microirrigation systems. However, the ITRC values were in general the lowest while the ASAE values were the highest, even the difference between ASAE and FAO values was minimum. This is consisting with what was experienced by Camp et al. (1997) who pointed out that $DU_{Iq\ flow}$ values were generally lower than U_s values when significant emitter plugging (emitter discharge < 1.5 l h^{-1}) was included in the study even both methods can be used to evaluate drip irrigation system uniformity.

The no significant difference between values computed by each method in the current study may be due to the sampling process or the computation method. Despite the ITRC and FAO methods use the same formula to compute the $DU_{Iq\ flow}$ (equation (V-2)), the sampling method was different. While the FAO method uses two contiguous emitters at the beginning, at one third, at two thirds and at the end of the lateral with total of 32 emitters, which make the sample more representative and homogeneous but smaller, the majority of sampled emitters with the ITRC method (28 of total of 60 emitters) were taken from the end of the lateral where more clogging incidences occurred. However, according to Capra and Scicolone (1998), a sample of 16 emitters is sufficient to test uniformity distribution if it is chosen in different positions on the lateral.

On the other hand, while the FAO method calculated the distribution uniformity taking into consideration the average discharge of the lowest 25% sampled emitters that provide the smaller emitter discharge, the ASAE method take into consideration the total number of the totally clogged emitters in the entire irrigation system, which might affect the resulted values computed by each method.

V.4.1.5. Relationship between system uniformity computed by FAO and by ASAE methods

After applying the regression analysis for flow distribution uniformity ($DU_{lq\ flow}$) determined by FAO method and statistical uniformity (U_s) by ASAE method, a mathematical model was generated to convert from U_s to $DU_{lq\ flow}$ and vice versa. The generated model was defined in equation (V-15). The model was significant ($P \leq 0.001$) and had an R_{adj}^2 of 0.991.

$$\mathbf{U_s = 1.016\ DU_{lq\ flow}} \quad \text{(V-15)}$$

Fig. V-7 presents the relationship between the calculated statistical uniformity applying formula defined in equation (V-15) and the residual plot for same formula.

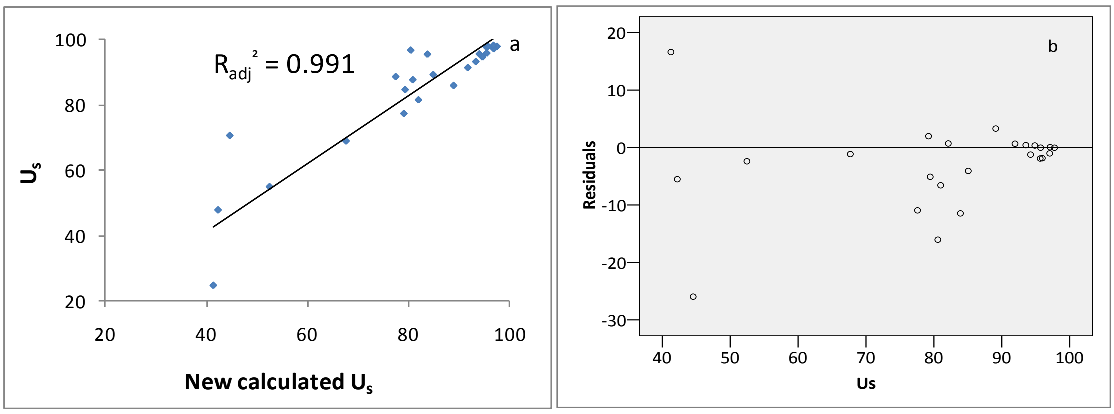


Fig. V-7. (a) Significant relationship ($P \leq 0.001$) between the experimental statistical uniformity (U_s) and the calculated U_s by equation (V-15) and (b) the residual plot for the same equation.

When the formula in equation (V-15) was applied on FAO values of Table V-3 to obtain the relative values of statistical uniformity, it was found that the classification was homogenized and was as same as the ASAE classification presented in Table V-4 except for the non-pressure compensating emitter with the monthly flushing treatment. Even though, the calculated U_s values of this emitter type and its applied flushing frequency were close (70.52%) to the real ones (69.17%).

V.4.2. Lateral flow rates

The lateral flow rates of pressure compensating emitter were increasing during the experiment for both DI and SDI systems (Fig. V-8) with all flushing frequencies. In previous studies, it was found that pressure compensating emitters may exhibit, in some cases, an increase in flow rate due to their elastic membrane degradation, or because of the trapped effluent particles between elastic parts (Ravina et al., 1992; Cararo et al., 2006; Trooien and Hills, 2007; Duran-Ros et al., 2009). This could explain the increase of pressure compensating emitter discharge during the experiment (Fig. V-8).

On contrary, flow rate for non-pressure compensating emitter laterals (Fig. V-9) increased for DI system and decreased for SDI after 390 h of experiment and conserved the same behaviour until the end of the experiment independently from the applied flushing frequency. Duran-Ros (2008) detected that the same model of non-pressure compensating emitter smoothly increased its discharge in DI system during 1000 h of irrigation working with a sand filter and a tertiary reclaimed effluent. Even though, when the study was extended here to 1620 h of irrigation, it was detected that lateral flow rate for the non-pressure compensating emitters and DI system was extremely increased. However, the greater non-pressure compensating emitter lateral flow rates in DI might probably be due to the observed but unexplained emitter failures resulting in a flow increase, as no other leaks to mechanical or rodent damage were detected in the surface laterals. The noticed drop in average dripline flow at the beginning of the second irrigation season was because of shortage in effluent supply for technical problems.

On the other hand, the observed decreasing in lateral flow rate for the non-pressure compensating emitter during the third irrigation season in SDI whereas it increased in the DI system during the third irrigation season could be explained by the elevated percentage of the totally clogged emitters. The totally clogged emitters varied between 4.0 - 4.9% in the SDI system, which was greater than what detected in the DI system (0.3 - 1.4%). Besides, the backpressure phenomenon may explain an additional reduction in emitter discharge for the non-pressure compensating emitters when they were used in SDI rather than in DI (Fig. V-9).

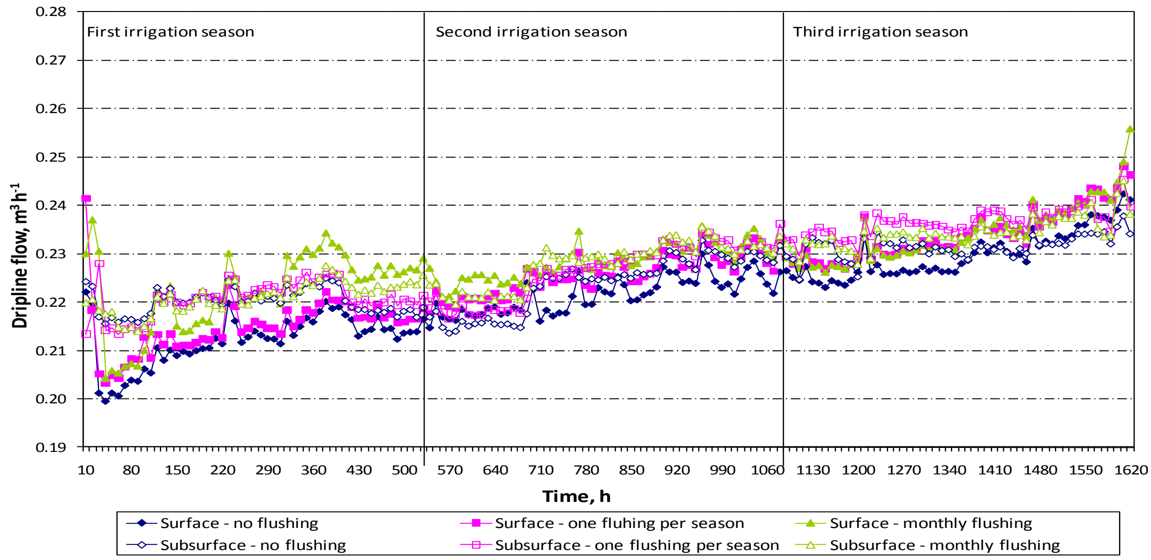


Fig. V-8. Average pressure compensating emitter lateral flow rates for every 10 h of experiment.

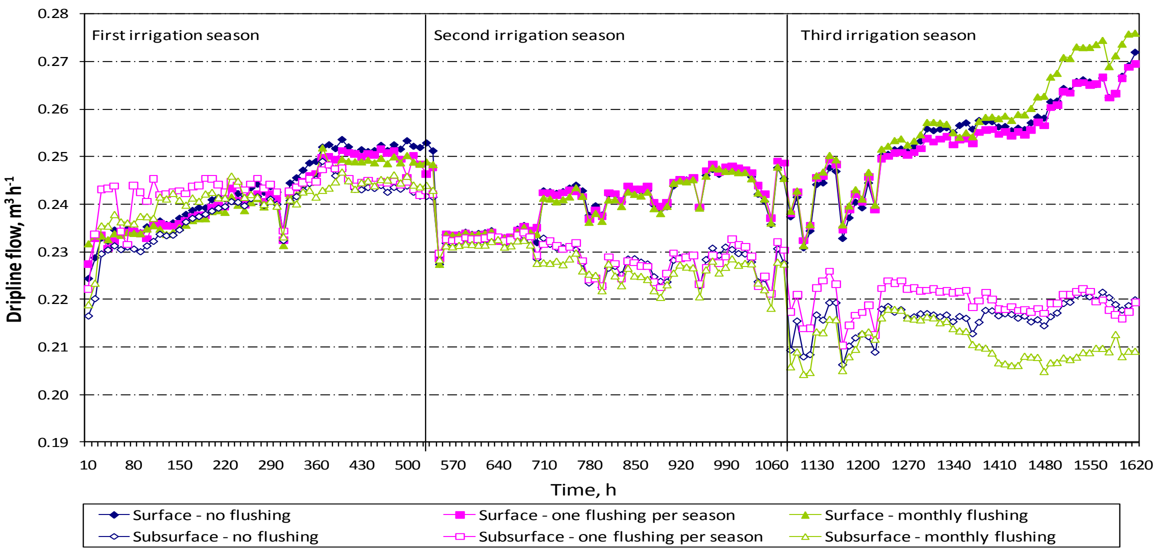


Fig. V-9. Average non-pressure compensating emitter lateral flow rates for every 10 h of experiment.

The significance levels of the statistical model and each factor and interaction for explaining flow rate variability during 1620 h of irrigation are shown in Table V-5. It was found that lateral flow rates were function of microirrigation system, irrigation season, emitter type and flushing frequency and their interaction (Table V-5). Therefore, the significant interaction between variables were studied and discussed separately.

Table V-5. P-value of statistical model and each factor and intersection for lateral flow rate variability during the experiment.

	P-value
Model	***
Irrigation season	***
Irrigation system	***
Emitter type	***
Flushing frequency	***
Irrigation season x irrigation system	***
Irrigation season x emitter type	***
Irrigation system x emitter type	***
Irrigation season x flushing frequency	***
Irrigation system x flushing frequency	***
Emitter type x flushing frequency	***

*** $P \leq 0.001$

V.4.2.1. Interaction of irrigation system and season

Lateral flow rates for irrigation system and season are shown in Fig. V-10. Results showed a significant ($P \leq 0.001$) increasing in lateral flow rates for DI system and decreasing in the flow rate for the SDI system after 1620 h of experiment. As it will be explained later, the elevated percentage of totally clogged emitters was higher for SDI system than DI and was the main reason for lateral flow decrease. However, emitter clogging not only reduces emitter discharge but also causes the discharge of non clogged emitters to increase (Bralts et al., 1981), which partially explain the case for DI beside the observed but unexplained emitter failures of non-pressure compensating emitter resulting as well in flow increase.

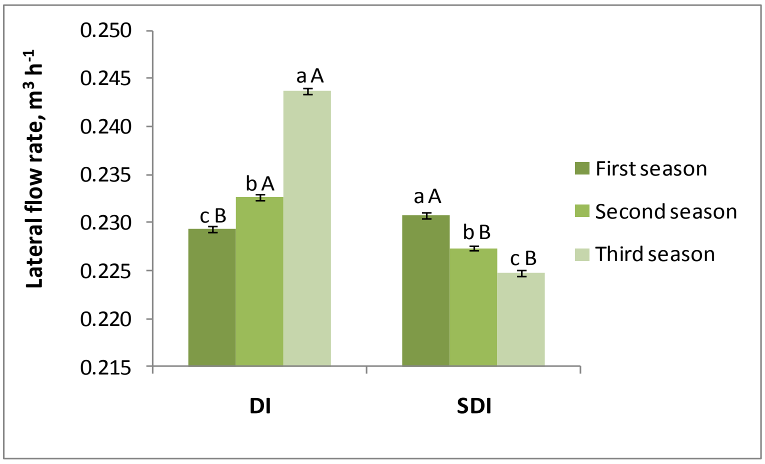


Fig. V-10. Average and standard error of lateral flow rates of every 10 h of experiment for DI and SDI systems at different irrigation seasons. Different small letters mean significant differences between irrigation seasons for each microirrigation system and different capital letters mean significant differences between irrigation systems for each season ($P \leq 0.001$).

V.4.2.2. Interaction of emitter and irrigation season

Lateral flow rates with regard to emitter type and irrigation season are shown in Fig. V-11. Lateral flow rates depended significantly on emitter type ($P \leq 0.001$) for the first and second irrigation seasons. The non-pressure compensating emitter presented in general a higher flow rate than the pressure compensating one during the experiment except after 1620 h of irrigation ($P = 0.175$). Additionally, the pressure compensating emitter presented an increasing in its lateral flow rates during the experimental time to reach its maximum after 1620 h of irrigation (Fig. V-11), which coincide with the monitored evolution of lateral flow rates shown in Fig. V-8. This behaviour fits with what was observed in other previous studies (Ravina et al., 1992; Cararo et al., 2006; Trooien and Hills, 2007; Duran-Ros, 2008) of flow rate increasing due to emitter pressure compensating emitter degradation. The non-pressure compensating emitter discharge was higher after 540 h of irrigation than after 1080 and 1620 h, which were not significantly different (Fig. V-11).

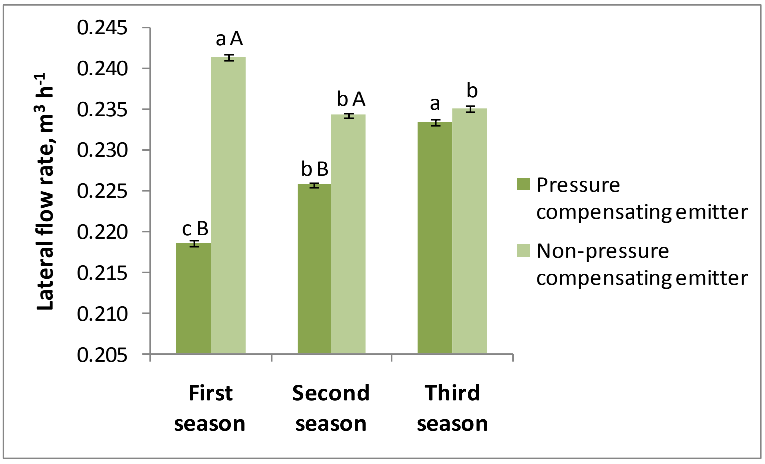


Fig. V-11. Average and standard error of lateral flow rates of every 10 h of experiment depending on emitter type at different irrigation seasons. Different small letters mean significant differences between irrigation seasons for each emitter type discharge while different capital letters mean significant differences between emitters discharge for each irrigation season ($P \leq 0.001$).

V.4.2.3. Interaction of emitter type and irrigation system

Lateral flow rates as a function of emitter type and irrigation system are presented in Fig. V-12. Lateral flow rates for the non-pressure compensating emitter were significantly higher than for the pressure compensating one during 1620 h of experiment in both irrigation systems ($P < 0.05$). On contrary, the pressure compensating emitter lateral flow rates for DI system was smaller than the SDI one ($P \leq 0.001$). This could be explained by the clogging problem because clogged emitters increased the pressure inside of the drip tubing which increases the flow rate from non-pressure compensating emitters. It was found that the previously sampled emitters for measuring the distribution uniformity with FAO method had average discharge of 2.22 and 2.32 l h^{-1} for the pressure compensating and non-pressure compensating emitters, respectively in DI system at the end of the experiment and had an average pressure of 150 kPa for both emitter types. Nevertheless, in SDI system, where more clogged emitters were observed, the emitter discharge significantly reduced ($P \leq 0.001$) to 1.45 l h^{-1} in the non-pressure compensating emitter increasing in consequence, the average pressure to 164 kPa. In addition, the pressure compensating emitter discharge in the SDI system was reduced, as well, to 2.16 l h^{-1} resulting at the end in increasing the average pressure to 161 kPa.

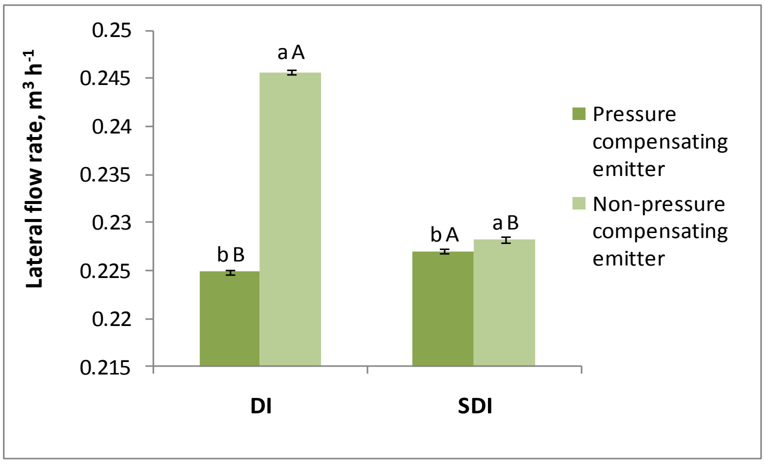


Fig. V-12. Average and standard error of lateral flow rates of every 10 h depending on emitter type and irrigation system. Different small letters mean significant differences between emitter types for each irrigation system and different capital letters mean significant differences between irrigation systems for each emitter type (P < 0.05).

V.4.2.4. Effect of irrigation season and flushing frequency

The effect of flushing frequency treatments and irrigation seasons on lateral flow rates are shown in Fig. V-13. Flushing frequency did not affect lateral flow rates during the first and last irrigation seasons (P > 0.05). However, lateral flow rates were higher with seasonal or monthly flushing than without flushing during the second irrigation season (P ≤ 0.01). Furthermore, during the third irrigation season, it was found that lateral flow rates with the three flushing frequencies were higher than what they were during the first and the second ones (P ≤ 0.05).

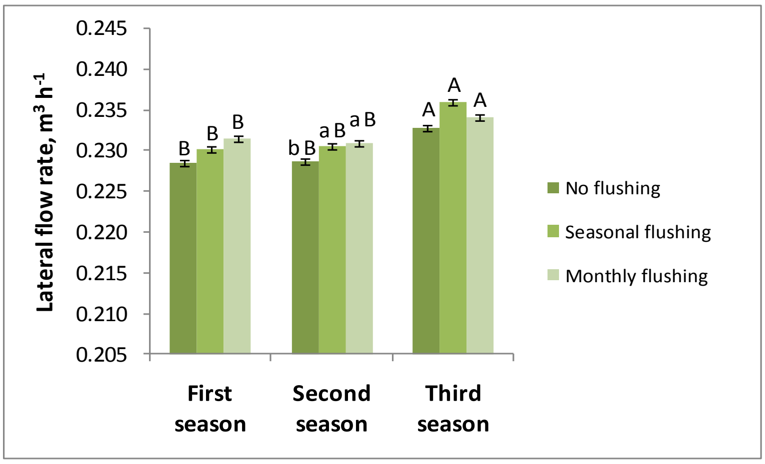


Fig. V-13. Average lateral flow rate and standard error of every 10 h of experiment as a function of lateral flushing treatment. Different small letters mean significant differences between flushing treatments per each irrigation season and different capital letters mean significant differences between irrigation seasons for a same flushing frequency (P ≤ 0.05).

V.4.2.5. Interaction of irrigation system and flushing treatment

The effect of different flushing frequencies on lateral flow rates in each microirrigation system can be seen in Fig. V-14.

Lateral flow rates in DI system were significantly higher than in SDI one (P ≤ 0.001) which confirms the results obtained previously. In DI system, the flow rates of the monthly flushed laterals were higher than the no flushed ones (P ≤ 0.01). Nevertheless, the seasonal flushed lateral flow rates in DI system had no significant difference when compared with the no flushed and the monthly flushed ones.

In SDI system, the flow rates of the seasonal flushed laterals were higher than the monthly flushed and the no flushed ones (P ≤ 0.001). This is coincided with what observed with Puig-Bargués et al. (2010a) who found that when laterals were flushed only once at the end of 30 day irrigation was capable of removing more suspended materials from the dripline than when it flushed twice during the same period. It is possible that the long functional time before flushing allowed the sediments to accumulate and aggregate, which might have a dragging effect on the sediments during flushing and thus, the solids removal might be greater and flushing be more effective.

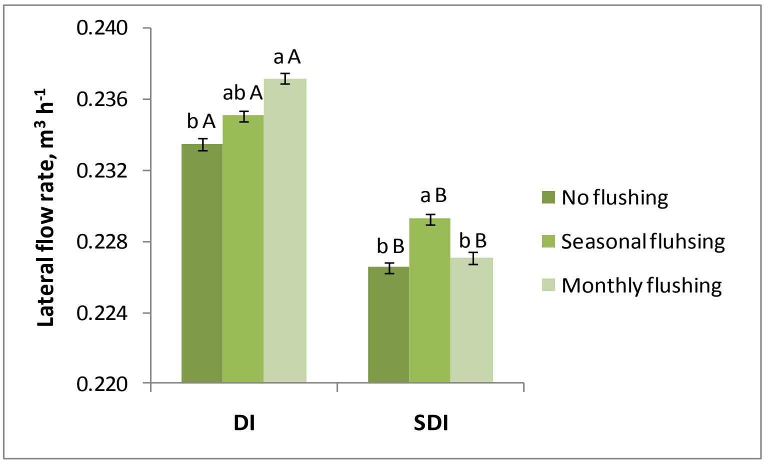


Fig. V-14. Average standard error and lateral flow rates of every 10 h of experiment from a flushing frequency to another in both microirrigation systems. Different small letters mean significant differences between flushing treatments per each irrigation system and different capital letters mean significant differences between irrigation systems for a same flushing frequency (P ≤0.01).

V.4.2.6. Interaction between emitter type and flushing treatment

The interaction between emitter type and the applied flushing frequency is presented in Fig. V-15.

The flow rates of the non-pressure compensating emitter laterals were significantly higher ($P \leq 0.001$) than the pressure compensating emitter ones for all the studied flushing frequencies (no flushing, seasonal flushing and monthly flushing).

The pressure compensating emitter lateral flow rate increased when flushing frequency was more intense. The monthly flushed laterals had a flow rate higher than the seasonal flushed ones, which had a flow rate higher than the no flushed laterals ($P \leq 0.001$). On contrary, there were no significant differences ($P = 0.276$) in non-pressure compensating emitter lateral flow rates as a function of flushing frequency treatment (Fig. V-15). This is might be because of the detected emitter clogging during the experiment as previously explained (Fig. V-9).

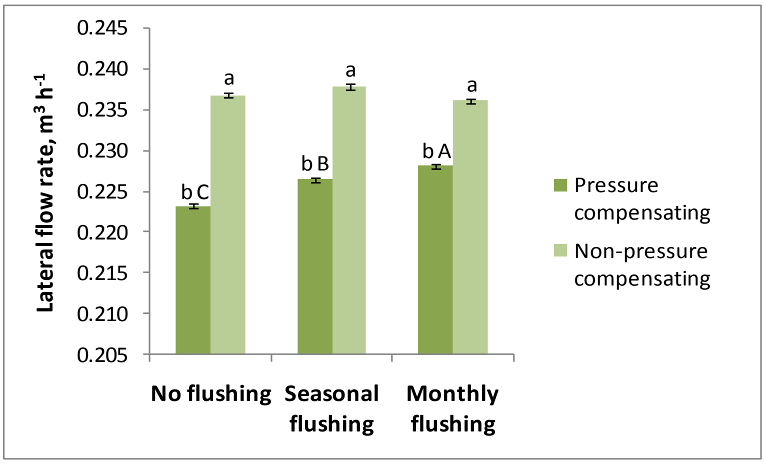


Fig. V-15. Average and standard error of lateral flow rates at every 10 h of experiment from a flushing frequency to another as a function of emitter type. Different small letters mean significant differences between emitters for each flushing frequency and different capital letters mean significant differences between flushing treatments for a same emitter (P ≤ 0.001).

V.4.3. Analysis of clogged emitters

V.4.3.1. Percentage of totally clogged emitters

The percentages of totally clogged emitters computed with equation (V-14) at different experiment times for both emitters in the DI and SDI microirrigation systems are shown in Table V-6. There was only a small number of completely clogged emitters with the greatest amounts (4.0 – 4.9%) for the non-pressure compensating emitter with SDI system. This would be because of the smaller discharge of the non-pressure compensating emitter (2.0 l h^{-1}) compared with the pressure compensating one (2.3 l h^{-1}), which may had led to a greater clogging as has been reported in other studies (Ravina et al., 1997; Trooien et el., 2000). Besides, emitter discharge in the SDI system can be decreased as a result of positive pressure in the soil water matrix that creates a backpressure at the emitter orifice as explained before (Warrick and Shani, 1996; Gil et al., 2008).

Nevertheless, it should be pointed out that the partial clogging is more frequent than the total clogging (Ravina et al., 1992). However, since the partially clogged emitters are difficult to evaluate, only the totally clogged emitters were determined in the present experiment.

Table V-6. Percentage of totally clogged emitters for both emitter types and microirrigation systems.

Emitter type	Flushing frequency	Totally clogged emitters, %			
		DI			SDI
		540 h	1080 h	1620 h	1620 h
Pressure compensating	No flushing	0.0	0.6	0.3	1.4
	Seasonal flushing	0.0	0.0	0.9	0.3
	Monthly flushing	0.0	0.0	0.0	0.3
Non-pressure compensating	No flushing	0.0	0.6	1.4	4.9
	Seasonal flushing	0.0	0.0	0.9	4.0
	Monthly flushing	0.0	0.0	0.6	4.9

After 540 h of experiment, there were no clogging problems for any emitter types and flushing frequencies in DI, which explained the excellent acceptability degree for the microirrigation system during this irrigation period (Fig. V-5). Even though, 0.6% of the emitters were totally clogged in DI system after 1080 h of experiment for the no flushed laterals of both emitters with same percentage. This could explain the reduction in system uniformity for this flushing frequency with both emitter types in the DI system that was shown previously in Fig. V-5.

Moreover, the percentage of totally clogged emitters increased after 1620 h compared with what it was at 1080 h experiment for DI system except for the no flushed pressure compensating emitters. The decrease in clogged emitter percentage after 1620 h for the non flushed pressure compensating emitters was due to the noticed recovered flow for some emitters at the end of the experiment. Duran-Ros et al. (2009) observed also that some emitters recovered their initial flow rate after an initial clogging.

The SDI system registered the highest percentage of clogged emitters independently from flushing frequency and especially with the non-pressure compensating emitter, which had the highest clogged emitter ratio (4.9%). Capra and Scicolone (1998) pointed out that when the percentage of the totally clogged emitters exceed 4%, it will significantly reduce the system distribution uniformity. This fact confirms the observed reduction in SDI system distribution uniformity that was higher than in DI one pointed out in Fig. V-5 and Table V-3. In previous studies (Ravina et al., 1997; Capra and Scicolone, 1998; Puig-Bargués et al., 2005b), it was found as well that emitter clogging greatly reduced water distribution uniformity in irrigated fields.

V.4.3.2. Effect of emitter type and irrigation system on emitter clogging

The significance levels of the statistical analysis and of each factor and interaction for explaining completely clogged emitter variability at the end of the experiment are pointed out in Table V-7. The factors that statistically affected the number of completely clogged emitters were irrigation system, emitter type and the interaction between them. The significant interaction between irrigation system and emitter type is illustrated in Fig. V-16.

Table V-7. P-value of the statistical model and each factor and interaction for the completely clogged emitters after 1620 h of irrigation.

	P - value
Model	***
Irrigation system	***
Emitter type	***
Flushing frequency	n.s.
Irrigation system x emitter type	***
Irrigation system x flushing frequency	n.s.
Emitter type x flushing frequency	n.s.

n.s. no significant, *** P ≤ 0.001

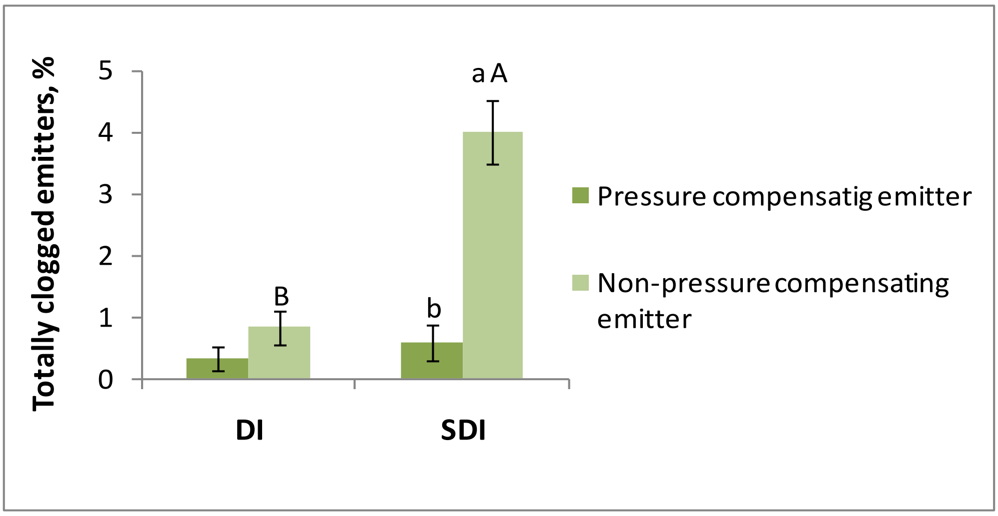


Fig. V-16. Average percentage and standard error of totally clogged emitters at the end of the experiment. Different small letters mean significant differences between different emitter types for a same irrigation system and different capital letters mean significant differences between different irrigation systems for a same emitter.

For the DI system, there was no significant difference (P > 0.05) between both emitter types in the average percentage of the totally clogged emitters. In addition, there was no significant difference as well between the average percentage of the totally clogged pressure compensating emitters between DI and SDI systems.

However, it was detected that the average percentage of totally clogged non-pressure compensating emitter was significantly higher (P ≤ 0.001) than the pressure compensating one in SDI system. This agreed with the reduction in dripline flow rates observed after the first irrigation season for the SDI laterals of the non-pressure compensating emitter type. Besides, the average of totally clogged non-pressure compensating emitters was significantly higher (P ≤ 0.001) in SDI system than in DI one.

V.4.3.3. Visual observation of clogged emitters

It had been observed during the visual observation that two adjacent emitters could perform differently with one clogged and the other unclogged, which agreed with the study made by Adin and Sacks (1991). The visual presentation for clogged and no clogged emitters in DI and SDI systems with different flushing treatments are shown in Fig. V-17, Fig. V-18 and Fig. V-19.

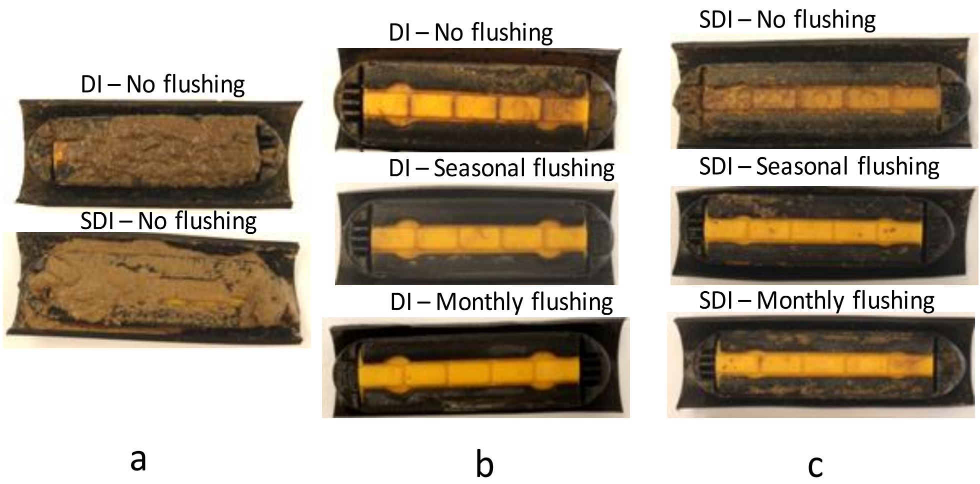


Fig. V-17. Internal view of pressure compensating emitter (a) clogged emitters with no flushing treatment for DI and SDI systems, (b) three flushing treatments for three different no clogged emitters at 2/3 of lateral length for DI systems and (c) three flushing treatments for three different no clogged emitters at 2/3 of lateral length for SDI systems.

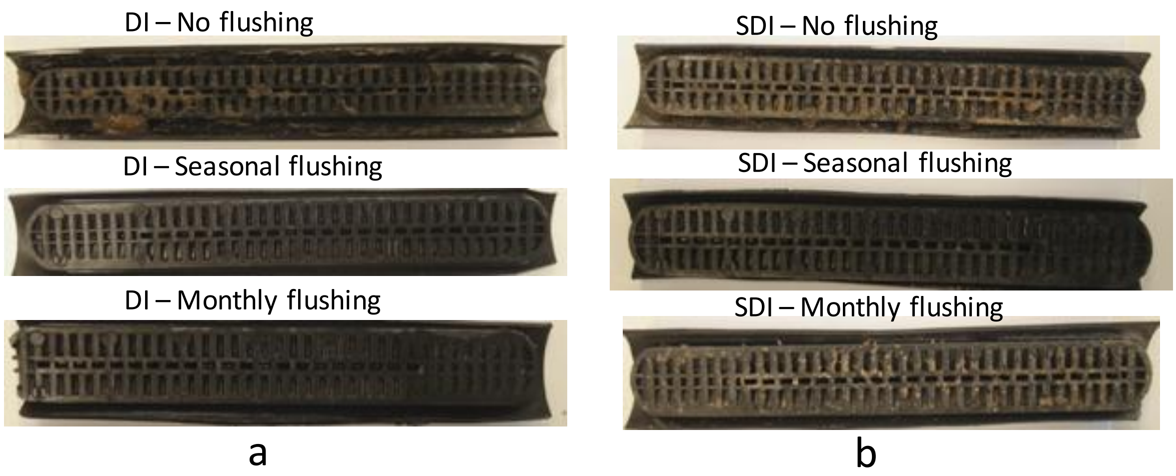


Fig. V-18. Internal view of not clogged non-pressure compensating emitter at 2/3 of lateral length for (a) DI system, and (b) SDI system.

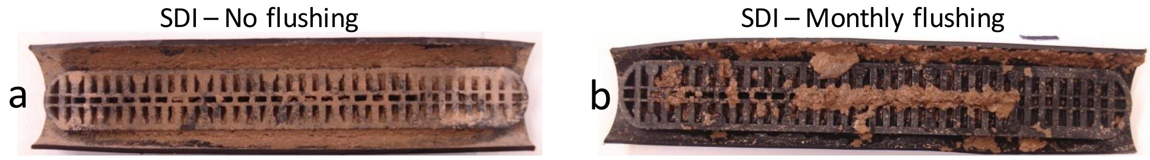


Fig. V-19. Internal view of no clogged non-pressure compensating emitter located at end of the lateral with (a) no flushing and (b) monthly flushing.

The visual observation revealed that particles were entrapped in the two emitter types even it was noticed that more soil particles and sand sediments concentration were found in the SDI system because of the external soil particles that ingested through the emitter as a result of the backsiphoning effect when the system shutdown (Lamm and Camp, 2007). This explained also the lower distribution and statistical uniformity of SDI system when compared with the DI. Camp et al. (1997), after 8 years of operation, found smaller system distribution uniformity in SDI than DI emitters due to emitter clogging in SDI system caused by soil particles that entered during the installation process. When there is no emitter clogging, the distribution uniformity of DI and SDI systems are similar (Camp et al., 1997; Capra and Scicolone, 2007). However, installation of air/vacuum relief valves at the high elevation points can help prevent soil ingestion in SDI (Lamm and Camp, 2007). Even though, the performance of emitters in SDI system under vacuum conditions depends on soil texture. Coelho et al. (2009) found out that a vacuum level of -40 kPa caused higher levels of flow rate disturbance for both sandy and clay soil textures. These devices were not installed in the irrigation system because it was not anticipated that soil ingestion would be a problem for the shallow depth and for the topography of the field site. Table V-8 and Table V-9 summarize the observed sedimentation for the selected emitters' sample for both DI and SDI systems. However, the observed precipitations and deposits inside the emitters were not quantified in the laboratory.

Table V-8. Observed sediments in the pressure and non-pressure compensating emitters sample for DI system.

Emitter type	Flushing frequency	DI		Sediment observed
		Total no.	Completely clogged, %	
Pressure compensating	No flushing	3	33	More sand particles accumulation than soil deposits and biological growth
	Seasonal flushing	2	0	Biological growth
	Monthly flushing	2	0	Biological growth
Non-pressure compensating	No flushing	3	33	More sand particles accumulation than soil deposits and biological growth
	Seasonal flushing	3	33	Biological growth
	Monthly flushing	2	100	More sand particles accumulation than soil deposits and biological growth

Table V-9. Observed sediments in the pressure and non-pressure compensating emitters sample for SDI system.

Emitter type	Flushing frequency	SDI		Sediments observed
		Total no.	Completely clogged, %	
Pressure compensating	No flushing	6	66	Sand and soil particles accumulation, soil particles were more than sand ones
	Seasonal flushing	2	0	Biological growth
	Monthly flushing	2	0	Biological growth
Non-pressure compensating	No flushing	8	50	2 emitters with roots, 1 with biological growth with sand accumulation and one with soil particles
	Seasonal flushing	4	50	Soil particles accumulation, few sand particles and one no clogged emitter with biological growth
	Monthly flushing	4	50	Sand accumulation and biological growth

It was also noticed during the visual observation of different emitters in the sample that most of precipitations were due to biofilm formation in the DI emitters (Fig. V-17 a, Fig. V-17 c and Fig. V-19 a). Other studies founded out as well that formation of biofilm was attached to reclaimed wastewater use in microirrigation system laterals, which increased emitter clogging (Dazhuang et al., 2009; Yan et al., 2010; Li et al., 2010; Li et al., 2011). Smajstrla and Boman (1998) pointed out that the organic growth in pipelines is difficult to completely eliminate because they provide the “glue” that sticks small particles together. Moreover, many types of algae are too small to be filtered, and so they readily enter in the pipelines. In addition, biofilm removal by flushing is made difficult by its low specific gravity and high adhesive characteristics (Puig-Bargués et al., 2010b). The sediment buildup begins with the deposition of amorphous slimes, to which other particles adhere (Adin and Sacks, 1991). Therefore, this biofilm problem was exacerbated in the SDI emitters because external soil particles and the escaped sand particles from the filter became stuck in the biofilm at the emitter outlet leading to increased clogging (Fig. V-17 a and Fig. V-19 b) (Pitts et al., 1990; Puig-Bargués et al., 2010b). Nevertheless, since it was visually observed that the majority of particles were accumulated around the emitter orifice than in its labyrinth, which indicated that soil particles were backsiphoned into the emitter, it could be concluded that the majority of the observed particles in clogged emitters were from the soil than from the filter while backwashing process.

Additionally, the no clogged pressure compensating emitters for DI system (Fig. V-17 b) were in general cleaner than those for SDI system (Fig. V-17 c) at two thirds of lateral length. On the other hand, the majority of non-pressure compensating emitters not clogged had low precipitation with all flushing frequencies for DI and SDI systems (Fig. V-18). The presence of roots was observed only in two non-pressure compensating emitters in SDI system (Fig. V-20). The roots did not cause complete clogging, neither blocking neither the emitter outlet nor the emitter labyrinth. However, Choi and Suarez-Rey (2004) concluded that effluent acidification can be used for reducing root intrusion when it is needed.

Fig. V-20. A no clogged non-pressure compensating emitter at 2/3 of lateral length from SDI system with root intrusion.

V.4.4. Relative emitter discharge

The significance levels of the statistical model and of each interaction for explaining the relative emitter discharge variability at the end of the experiment are shown in Table V-10. Irrigation system, emitter type, flushing frequency and emitter location had a significant effect on relative emitter discharge, as well as the interactions between irrigation system and emitter type, irrigation system and emitter location, emitter type and its location, and flushing frequency and emitter location. There was no significant relationship neither in the interaction between irrigation system and flushing frequency nor emitter type and flushing frequency.

Table V-10. P-value of the statistical model and each interaction between studied variables for explaining the relative emitter discharge variability after 1620 h of experiment.

	P-value
Model	***
Irrigation system	***
Emitter type	***
Flushing frequency	***
Emitter location	***
Irrigation system x emitter type	***
Irrigation system x flushing frequency	n.s.
Emitter type x flushing frequency	n.s.
Irrigation system x emitter location	*
Emitter type x emitter location	**
Flushing frequency x emitter location	*

n.s. not significant; $P > 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P \leq 0.001$

V.4.4.1. Interaction between irrigation system and emitter type

The statistical effect of the interaction between irrigation system and emitter type is presented in Fig. V-21. It was found that relative emitter discharge of the pressure and non-pressure compensating emitters was statistically the same in DI system (P = 0.849). On contrary, the pressure compensating emitter presented a higher discharge after

1620 h of irrigation than the non-pressure compensating emitter in SDI system due to the higher percentage of non-pressure compensating clogged emitters in SDI system (4.0 – 4.9%).

On the other hand, the non-pressure compensating emitter gave a higher discharge in DI system than in SDI, but the pressure compensating emitter had the same performance independently from the applied irrigation system (P = 0.414) (Fig. V-21).

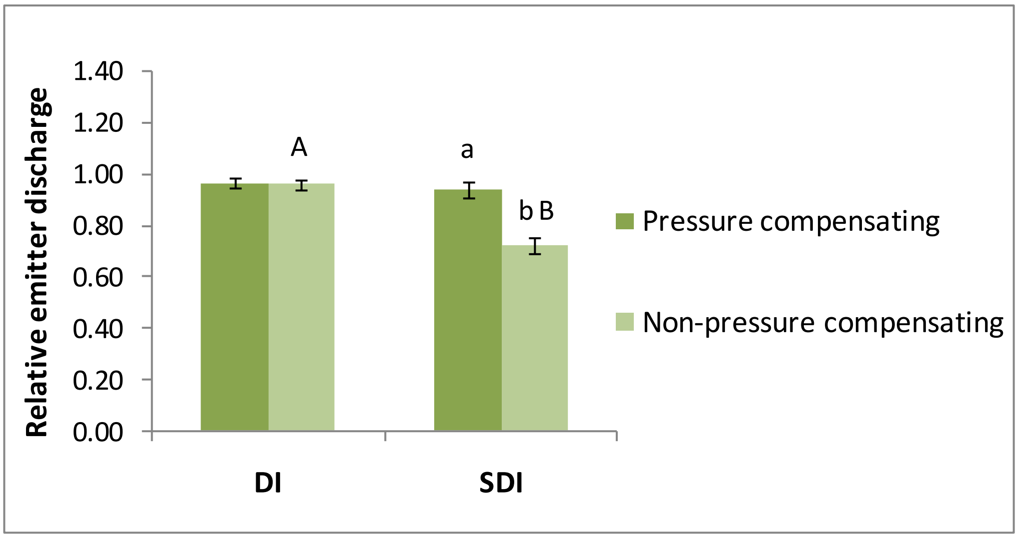


Fig. V-21. Average and standard error of relative emitter discharge for each irrigation system and emitter type. Different small letters mean significance different between emitter types for a same irrigation system and different capital letters mean significant differences between different irrigation systems for a same emitter type (P < 0.05).

V.4.4.2. Interaction between emitter location and irrigation system

The statistical results for the interaction between emitter location and irrigation system for explaining the variability in relative emitter discharge are presented in Fig. V-22. In DI system, relative emitter discharge did not change as a function of its location (P = 0.316), but in SDI system, relative emitter discharge varied from one location to another. The lowest flow rate was at the beginning and at the end of the lateral length.

Other studies (Adin and Sacks, 1991; Ravina et al., 1992, 1997; Trooien et al., 2000; Duran-Ros et al., 2009; Puig-Bargués et al., 2010a) showed that emitters at the end of the laterals experienced a higher percentage of clogging than those situated in the beginning or in the middle. In spite of that, effect of emitter location is not constant. Rowan (2004) as well, observed more clogged emitters at the beginning of laterals than at the end. The elevated percentage of clogged emitters at the end of driplines would be due to the debris mainly accumulated at the end of the pipeline near the flush valve (Smajstrla and Boman, 1998) attributable to the lower velocity at this point which favors particle settling (Shannon et al., 1982). However, in the present study, it was detected lower relative emitter discharge as a consequence of its clogging at the beginning and at the end of the lateral. The observed clogged emitters at the beginning of the lateral length were due to the observed flooded area around the laterals during the experiment due to soil bad drainage.

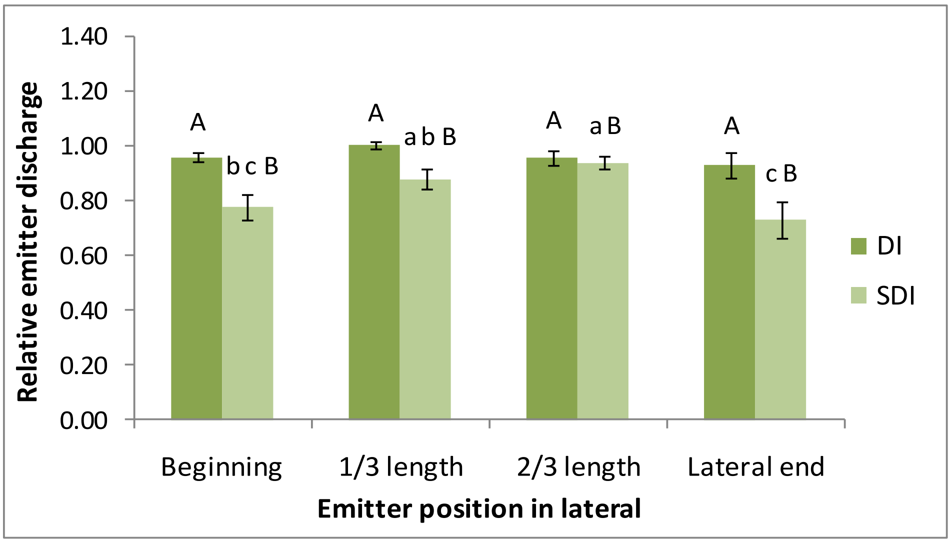


Fig. V-22. Average relative emitter discharge and standard error as a function of emitter location and irrigation system. Different small letters mean significant differences between different locations for a same irrigation system and different capital letters mean significant differences between both irrigation systems for a same emitter location ($P < 0.05$).

V.4.4.3. Interaction between emitter type and its location

The pressure compensating relative emitter discharge was not affected by its location after 1620 h of irrigation while the non-pressure compensating one presented different performances for different locations (Fig. V-23). The discharge of the non-pressure compensating emitter at the beginning and at the end was significantly the same ($P > 0.05$) and it was lower than at one third and two thirds, which was significantly the same as well. This could be explained by the percentage of totally clogged emitters that was higher in the non-pressure compensating emitters than the pressure compensating ones.

The pressure compensating emitter had higher discharges at the beginning and at the end of the lateral than the non-pressure compensating emitter. No significant differences were found between both emitter types performance at one third and two thirds of the lateral length after 1620 h of experiment (Fig. V-23).

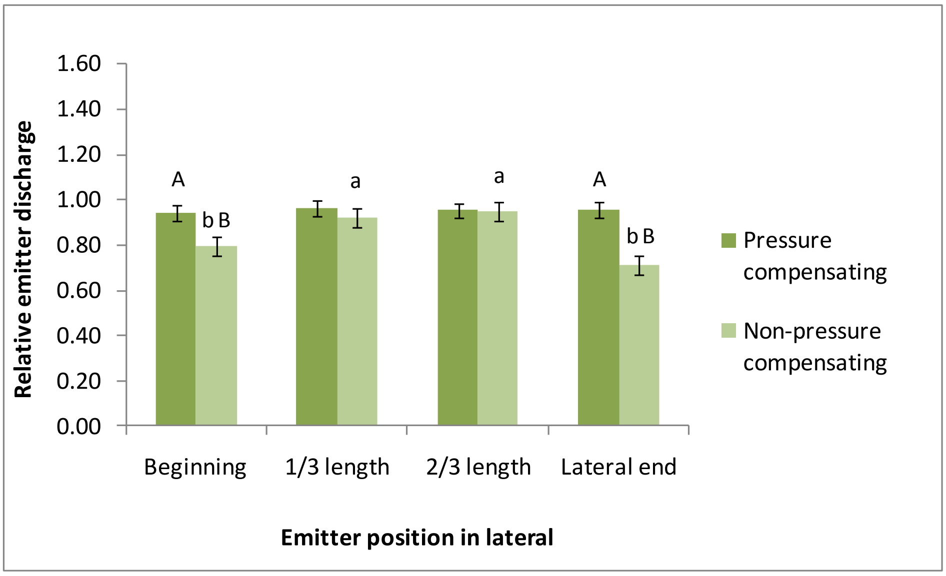


Fig. V-23. Average and standard error of relative emitter discharge as a function of emitter type and its location. Different small letters mean significant differences between emitter locations and different capital letters mean significant differences between emitter types for a same location (P < 0.05).

V.4.4.4. Interaction between flushing frequency and emitter location

After 1620 h of irrigation, the no flushing treatment presented its lowest relative emitter discharge at the end of the lateral (at 87 m) (Fig. V-24). Relative emitter discharge was statistically the same at the beginning, one third and two thirds of lateral length and was higher than what it was at the end of the lateral. On contrary, there was no significant difference in relative emitter discharge between different locations when applied the seasonal and the monthly flushing treatment (Fig. V-24). Similarly, Ravina et al. (1997) did not find differences in emitter clogging when flushing the drip laterals daily or every two weeks. Puig-Bargués et al. (2010a) did not find a consistent effect of a fortnight and month flushing frequency for most of the flushing velocities that they analyzed. In the present study, the monthly and seasonal flushing frequencies seemed to be sufficient to remove the accumulation of sediments in the laterals. However, more frequent flushing did not result in greater distribution uniformity.

Furthermore, there was no significant effect of the applied flushing frequency on relative emitter discharge at same location from the beginning of the lateral until one third of its length. At two thirds of lateral length until the end of it, it was noticed that the discharge of the no flushed emitters was significantly reduced because of emitter clogging while there was no significant difference between the performance of seasonal and monthly flushed emitters.

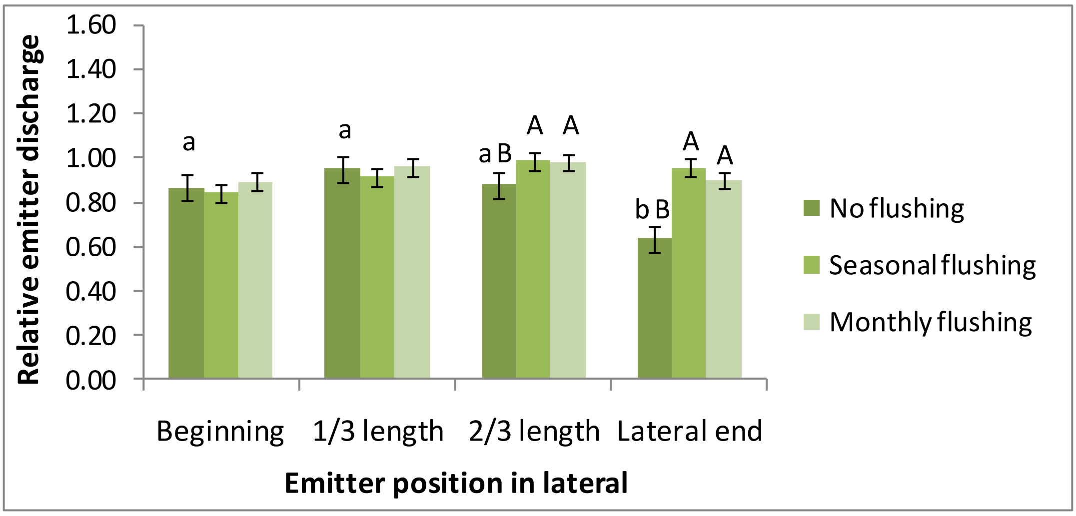


Fig. V-24. Average and standard error of relative emitter discharge for emitter location and flushing frequency. Different small letters mean significance differences between different locations for a same flushing frequency and different capital letters mean significant differences between the three flushing frequency at a same emitter location (P < 0.05).

V.5. Conclusions

According to the obtained and discussed results in Chapter V, it could be concluded the following:

- Distribution uniformity:
  - The U_s and $D_{UIq\ flow}$ were smaller in SDI than in DI system for both emitter types after 1620 h experiment, due to emitter clogging, while was higher with SDI.
  - The seasonal flushing frequency gave greater U_s and $DU_{Iq\ flow}$ than the monthly one after 1620 h of irrigation using the pressure compensating emitter in DI system. It might be due to that when sediments were allowed to accumulate and settle over time, they might have some dragging effect on other sediments during flushing and thus removal might be greater. On contrary, the monthly flushing frequency for the non-pressure compensating emitters in DI system gave higher U_s and $DU_{Iq\ flow}$ than the seasonal flushing at the end of the experiment. However, both flushing frequencies (seasonal and monthly) had high uniformity that varied from "very good" to "good" in case of seasonal flushing and "very good" to "excellent" in case of monthly flushing treatment.
  - In SDI system, it was found that the pressure compensating emitter with both monthly and seasonal flushing frequency conserved its good U_s uniformity.
  - There were no significant differences (P > 0.05) between system distribution uniformity computed by FAO, ASAE and ITRC methods after 1620 h of experiment in DI and SDI systems. However, a significant equation (P < 0.001) described as $\mathrm{U_s = 1.016\ DU_{Iq\ flow}}$ was generated with adjusted coefficient of determination equals 0.991 to relate U_s with $DU_{Iq\ flow}$ and vice versa.
- Lateral flow rates:
  - Lateral flow rates behaved as a function of irrigation system, emitter type, irrigation season and flushing frequency.
  - Lateral flow rates increased significantly within time throughout the 1620 h of irrigation in DI system but decreased in SDI one (P ≤ 0.001). The detected increasing in lateral flow rate for DI system was partially explained by the over

flow of the non clogged emitters. The high percentage of totally clogged emitters in SDI system was the main reason in the reduction of laterals flow.

- The laterals with non-pressure compensating emitters had a significantly higher flow rate ($P \leq 0.001$) than those with pressure compensating one in both DI and SDI systems except after 1620 h of irrigation, where it was higher too but not significant ($P = 0.175$).
- In DI system, the different flushing frequency treatments had no significant effect ($P > 0.05$) on lateral flow rate during the first and third irrigation seasons. Even though, during the second irrigation season, the seasonal and monthly flushing frequencies, that were statistically the same, gave a higher flow rate than the no flushing frequency treatment.
- The more the flushing frequency in DI system, the more the lateral flow rate. This could be due to the observed emitter damage and clogging that resulted in the overflow non clogged emitters.
- In SDI system, it was observed that the seasonal flushing frequency gave a higher flow rate than the no flushing and monthly flushing frequencies, which were significantly the same.

➢ Emitter clogging:

- In DI system, the visual observation revealed that the majority of totally clogged emitters were due to biofilm formation. There were also no significant differences ($P > 0.05$) in the average of the totally clogged pressure and non-pressure compensating emitters in DI system.
- The main clogging factor in SDI system was a combination of biological and physical factors. Biofilm problem was exacerbated in the SDI emitters because external soil particles stuck in the biofilm at the emitter outlet leading to increased clogging. Besides, in SDI system, the non-pressure compensating emitter gave a significant ($P \leq 0.001$) higher average percentage of totally clogged emitters (4.0 – 4.9%) than the pressure compensating one (0.3 – 1.4%).

- The average percentage of completely clogged non-pressure compensating emitters was significantly higher ($P \leq 0.001$) in SDI system (4.0 – 4.9%) than in DI one (0.6 – 1.4%) as a result of biofilm formation inside the emitters, backsiphoned soil particles at the emitter orifice and soil hydraulic properties that affected the discharge of subsurface emitters increasing the percentage of clogged emitters.

➢ Emitter discharge:

- Emitter discharge varied during the experiment on function of the irrigation system, emitter type, flushing frequency and emitter location.
- In DI system, the performance of the pressure and non-pressure compensating emitters was statistically the same. The non-pressure compensating emitter had a significantly higher discharge in DI system than in SDI ($P < 0.05$), in accordance with was observed for lateral flow rates.
- In general, the pressure compensating emitter discharge was not statistically affected by its location at the end of the experiment ($P > 0.05$). The non-pressure compensating emitter discharge at the beginning and at the end of lateral was significantly lower than what it was at one third and two thirds of it ($P < 0.05$).
- As expected, after 1620 h of experiment, the no flushing treatment for DI and SDI system presented the lowest emitter discharge at the end of the lateral (at 87 m length). The seasonal and monthly flushing frequencies presented no significant difference in emitter performance in function of their location ($P > 0.05$), while the no flushing frequency gave a significant lower discharge at the end of the lateral compared with other locations ($P < 0.05$).
- In DI system, there was no statistical variability in emitter discharge in function of its location. In SDI, the lowest emitter discharge was observed at the beginning and at the end of lateral length ($P < 0.05$). This reduction in emitter discharge at the beginning and at the end of lateral length was due to the higher percentage of emitter clogging in these two locations.

VI. General conclusions, recommendations and future perspectives

VI.1. General conclusions

The presented dissertation aimed to compare between the surface and subsurface drip irrigation system when applying tertiary reclaimed effluent previously filtered in a sand media filter. The foremost results of the current study could be summered up as following:

- **The applied effluent quality influenced significantly the filtration cycle duration.**

  The worse the quality the shorter was the filter operating time. Sand media filter improved the effluent turbidity values and its dissolved oxygen concentration. Sand effective diameter was reduced during the experiment due to the loss of fine sand particles mainly attributable to backwashing process.

- **Head loss across sand filter (ΔH, kPa) could be described by the model:**

  $$\frac{\Delta H}{d_e \cdot C.g} = 16.216 \cdot \left(\frac{\rho}{C}\right)^{0.980} \cdot \left(\frac{V}{d_e{}^3}\right)^{-0.031} \cdot \left(\frac{d_f}{d_e}\right)^{1.087}$$

  where, d_e is sand effective diameter, C is suspended solids average concentration per filtration cycle, g is acceleration of gravity, ρ is water density, V is water volume and d_f is internal sand filter diameter.

  The most relevant advantage of this defined model is that it used some variables easily known by the irrigation system engineer like effluent volume and internal sand filter diameter, while the other variables are easy to estimate in the field location with portable instruments or a SCADA system in contrary of the other traditionally equations for computing head loss. In addition, this new equation presents valuable information about the factors that could affect head loss across sand filters.

- **After 1620 h of irrigation, seasonal and monthly lateral flushing were capable of maintaining an acceptable distribution uniformity, which also depended on the emitter type.**

  For surface drip irrigation system, the pressure compensating and non-pressure compensating emitters conserved a reasonable distribution uniformity during all the 1620 h of irrigation. However, in subsurface drip irrigation system, only the pressure compensating emitter maintained its *good performance and the best distribution uniformity. A higher percentage of clogged emitters was found in subsurface drip irrigation system than in surface drip irrigation one and with non-pressure compensating emitter than the pressure compensating type. Most of clogged emitters were observed at the beginning and at the end of the lateral. Emitter clogging was primarily due to the biofilm formation inside the emitter labyrinth in the DI system. However, clogging percentage was higher in the SDI system for the combination of biofilm formation and the backsiphoned soil particles through the emitter orifice.*

In DI system, there were no significance differences in pressure and non-pressure compensating emitter discharge at different locations on the lateral, while in SDI system; it was observed a significant decrease in non-pressure compensating emitter discharge at the beginning and at the end of the lateral.

VI.2. Recommendations

On base of the aforementioned conclusions, it would be recommended the following:

- When using a sand filter, it is recommended to change the sand media each approximately 1000 h of operation because around this time, the removal of filter efficiency decrease and the emitter clogging risk will be greater.
- Sand effective diameter of 0.63 or 0.64 mm is recommended for improving the turbidity values in the filtered effluent.
- More frequent unnecessary backwashing during irrigation would increase the total escaped sand filter particles during the backwashing that may increase at the end the possibility of clogging incidence.
- Pressure and/or non-pressure compensating emitter types can be used in surface drip irrigation system carrying out a lateral flushing each 540 h of irrigation.
- For a subsurface drip irrigation system, it is recommended to use a pressure compensating emitter type with one lateral flushing treatment each approximately 540 h of irrigation.

- Installing an air/vacuum valve in subsurface irrigation system could help to prevent the backsiphoning of soil particles through the emitter orifice.

However, it is important to mention that these recommendations are useful for microirrigation systems that use of effluents with similar characteristics that the one that was used in the experiments. Obviously, if effluent properties substantially vary, the results and the conclusions derived from them might be different.

VI.3. Future perspectives

On the light of the obtained results and during the investigation research presented in the current study, it was thought that the following research lines could be carried out in further investigations:

- **Improving of the mathematical model to compute filter cycle duration and developing an equation for describing the relationship between effluent turbidity and the filtration cycle duration with high precision.**

  This would be achieved by setting a new experiment with different effluents qualities and sand media filters with different dimensions, sand mass and effective diameters. During this proposed experiment, effluent turbidity, dissolved oxygen and pH, volume and velocity of filtered effluent and filtration cycle duration will be determined and then correlated with the developed models.

- **Identification of the best water quality evaluation method capable of representing potential of filter and emitter clogging.**

  This experiment would improve the management of the microirrigation systems as there were no other effective studies set since the study of Capra and Scicolone (1998).

  In order to reach this objective, it would be better to apply a combination of different effluents with diverse physical, chemical and biological characteristics, qualities, filtration systems, microirrigation systems and emitter types. After that, the correlation between factors and clogging will *be used to determine the best management of each investigated microirrigation system. At the end, it could be able to classify the clogging hazards for both filters and emitters on base of filter type, irrigation system and used emitter type.*

- **Study of the effect of lateral flushing frequency on removing the sediment aggregates from the lateral wall.**

    This will be a long term experiment for 1000 and/or 1500h, where different laterals with different emitter types will be installed in microirrigation system applying diverse flushing frequencies and effluent velocities. The total suspended solids will be determined in the flushed effluent from the end of the lateral as an indication for the total removed sediments and aggregates through the flushing. Besides, the system distribution uniformity will be measured to study whether the correlation between flushing frequency, emitter type and effluent velocity have a significant effect on it or not.

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