



Provided by the author(s) and NUI Galway in accordance with publisher policies. Please cite the published version when available.

Title	Comparison of a stratified and a single-layer laboratory sand filter to treat dairy soiled water from a farm-scale woodchip filter
Author(s)	Ruane, Eimear; Healy, Mark G.
Publication Date	2014-04
Publication Information	Ruane, E., Murphy, P. C., French, P., & Healy, M. Comparison of a Stratified and a Single-Layer Laboratory Sand Filter to Treat Dairy Soiled Water from a Farm-Scale Woodchip Filter. <i>Water, Air, & Soil Pollution C7 - 1915</i> , 225(5), 1-10.
Publisher	Springer
Link to publisher's version	http://dx.doi.org/10.1007/s11270-014-1915-z
Item record	http://hdl.handle.net/10379/4457
DOI	http://dx.doi.org/10.1007/S11270-014-1915-Z

Downloaded 2022-05-19T01:36:34Z

Some rights reserved. For more information, please see the item record link above.



1 PUBLISHED AS: RUANE, E.M., MURPHY, P.N.C., FRENCH, P., HEALY, M.G. 2014.
2 COMPARISON OF A STRATIFIED AND A SINGLE-LAYER LABORATORY SAND FILTER
3 TO TREAT DAIRY SOILED WATER FROM A FARM-SCALE WOODCHIP FILTER. WATER,
4 AIR AND SOIL POLLUTION 225: 1915. DOI 10.1007/S11270-014-1915-Z
5

6 **COMPARISON OF A STRATIFIED AND A SINGLE-LAYER LABORATORY**
7 **SAND FILTER TO TREAT DAIRY SOILED WATER FROM A FARM-**
8 **SCALE WOODCHIP FILTER**

9
10 EIMEAR M. RUANE^{a,b*}, PAUL N.C. MURPHY^{b,c}, PADRAIG FRENCH^b, MARK
11 G. HEALY^a

12
13 ^a Civil Engineering, National University of Ireland, Galway, Ireland.

14 ^b Livestock Systems Research Department, Animal and Grassland Research and
15 Innovation Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland.

16 ^c Agricultural Catchments Programme, Teagasc, Johnstown Castle, Co. Wexford,
17 Ireland.

18 * Corresponding author: eimear.ruane@teagasc.ie; Tel: +353 21 42410; Livestock
19 Systems Research Department, Animal and Grassland Research and Innovation
20 Centre, Teagasc, Moorepark, Fermoy, Co. Cork, Ireland.

21
22 **ABSTRACT**

23
24 Washing-down parlours and standing areas, following milking on dairy farms, produces
25 dairy soiled water (DSW) that contains variable concentrations of nutrients. Aerobic
26 woodchip filters can remove organic matter, nutrients and suspended solids (SS) in DSW,
27 but the effluent exiting the filters may have to be further treated before it is suitable for re-
28 use for washing yard areas. The performance of a single-layer sand filter (SF) and a

29 stratified SF, loaded at a $20 \text{ L m}^{-2} \text{ d}^{-1}$, to polish effluent from a woodchip filter was
30 investigated over 82 days. Average influent unfiltered chemical oxygen demand
31 (COD_T), total nitrogen (TN), ammonium-N ($\text{NH}_4\text{-N}$), ortho-phosphorus ($\text{PO}_4\text{-P}$) and
32 SS concentrations of 1991 ± 296 , 163 ± 40 , 42.3 ± 16.9 , 27.2 ± 6.9 and $84 \pm 30 \text{ mg L}^{-1}$ were
33 recorded. The single-layer SF decreased the influent concentration of COD_T , TN,
34 $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and SS by 39, 36, 34, 58 and 52%, respectively. Influent
35 concentrations of COD_T , TN_T , $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$ and SS were decreased by 56, 57, 41,
36 74 and 62% in the stratified SF. The single-layer SF and the stratified SF were
37 capable of reducing the influent concentration of total coliforms by 96 and 95%,
38 respectively. Although a limited amount of biomass accumulated in the upper-most
39 layers of both SFs, organic and particulate matter deposition within both filters
40 affected rates of nitrification. Both types of SFs produced final water quality in
41 excess of the standards for re-use in the washing of milking parlours.

42

43 *Keywords:* dairy soiled water; intermittent filtration; sand; treatment.

44

45 **INTRODUCTION**

46

47 Dairy soiled water (DSW) is water from concreted areas, hard stand areas, and
48 holding areas for livestock that has become contaminated by livestock faeces or urine,
49 chemical fertilisers and parlour washings (SI No. 610 of 2010), and contains high and
50 variable levels of nutrients such as nitrogen (N) and phosphorus (P), as well as other
51 constituents such as spilt milk and cleaning agents. It is legally defined in Ireland as
52 having a five-day biochemical oxygen demand (BOD_5) of less than $2,500 \text{ mg L}^{-1}$ and
53 less than 1% dry matter (DM) content (S.I. No. 610 of 2010). Application of DSW to

54 the land has long been the most common method of disposal employed by farmers
55 (Martínez-Suller et al., 2010). However, when DSW is land applied at rates that
56 exceed the nutrient requirements of the pasture, it can create a number of problems,
57 including the threat of loss of P and N in runoff and, depending on the soil type,
58 subsurface leaching of P and N (Knudsen et al., 2006; Regan et al., 2010). Therefore,
59 treatment of DSW and re-use of filtered water may be considered as a management
60 option to divert DSW from land application.

61

62 Aerobic woodchip filters can decrease concentrations of organic matter, nutrients and
63 suspended solids (SS) in DSW (Ruane et al., 2011a), but their effluent may still
64 contain nitrate (NO_3) and coliforms (Ruane et al., 2011b), which means that it cannot
65 be re-used for wash-water for parlours (EC, 1980; IMQCS and Teagasc, 2004).

66 Therefore, before the use of aerobic woodchip filters can be recommended for on-
67 farm treatment of DSW, further treatment is needed. Intermittent sand filters (SFs)
68 may be used as a form of tertiary treatment for this wastewater. After passing through
69 a woodchip filter followed by further treatment in a SF, it is proposed that the effluent
70 could then be used to wash down a holding yard or milking parlour, depending on the
71 level of treatment achieved. This paper investigates the efficacy of two design
72 configurations of SFs – single layer and stratified.

73

74 Single-pass intermittent SFs (intermittently loaded SFs operated without recirculation
75 of a portion of the final effluent) have been employed as a tertiary treatment system to
76 polish several types of wastewaters (Leverenz et al., 2009; Healy et al., 2010). Their
77 ability to reduce the concentration of various water quality parameters, including N
78 and P, is well documented (Nakhla and Farooq, 2003; Healy et al., 2006). Stratified

79 SFs, containing sand media organised into layers of varying particle size, are also
80 commonly used to treat wastewater (Nichols et al., 1997; Rodgers et al., 2005), due to
81 the perception that the performance may be enhanced. Both types of SFs are also
82 noted for their ability to reduce the concentration of pathogenic bacteria and micro-
83 organisms (Bahgat et al., 1999; Stevik et al., 2004). However, operational problems
84 still exist. These are primarily associated with clogging within the matrix of the sand,
85 due to accumulation of particulate matter and micro-organisms on surfaces as
86 biofilms, and the finite ability of the SF to remove P (Campos et al., 2002; Rodgers et
87 al., 2005). As the presence of biofilm ultimately determines the longevity of a SF and
88 is related to organic loading rate (OLR) and the size of the filter media (Rodgers et al.,
89 2004), as well as hydraulic loading rate (HLR), filter dosing frequency and time of
90 operation (Leverenz et al., 2009), it is important to monitor biofilm development in
91 tandem with treatment efficacy when operating SFs. The deconstruction of SFs at the
92 end of an experimental trial period allows a unique opportunity to assess the extent of
93 biofilm development.

94

95 No study has compared the efficiency of stratified and single-layer SFs in treating
96 DSW under the same organic and HLRs. In addition, although the build-up of biofilm
97 on specific types of SFs has been well documented (sand - Rodgers et al., 2004;
98 crushed glass and soil - Healy et al., 2011), no study has evaluated the difference
99 between both filters vis-à-vis biofilm development. The build-up of biofilm,
100 combined with an evaluation of their relative performance, may be used to determine
101 the practicability of one design over another.

102

103 Physical and chemical mechanisms responsible for clogging, such as the field-
104 saturated hydraulic conductivity (K_{fs}) and the organic matter content of the media,
105 may be used to quantify the extent of biofilm build-up within a filter. In an
106 intermittent SF, loaded with synthetic wastewater resembling DSW and operated for a
107 period of 806 days, Rodgers et al. (2004) quantified the extent of biofilm build-up by
108 dismantling the filter and measuring the K_{fs} in 0.02 m-depth increments from the
109 surface of the filter. The reduction of K_{fs} appeared to extend deep into the sand filter
110 and only returned to a K_{fs} of virgin sand (packed to the same density as in the sand
111 filter) at a depth of 0.165 m below the filter surface. Rodgers et al. (2004) also used
112 loss on ignition (LOI; BSI, 1990) to give an indication of biomass distribution within
113 the SF and found similar trends to the K_{fs} measurements.

114

115 As the use of a SF is proposed as a final step in the overall treatment of DSW,
116 the aim of this study was to compare the efficacy of two common types of SFs,
117 stratified and single-layer, for their ability to polish effluent from farm-scale
118 woodchip filters. The purpose of investigating two alternative SF designs was to
119 propose a final tertiary treatment step as part of an overall on-farm system for the
120 treatment of DSW, which would incorporate woodchip filters and – potentially – SFs.

121

122 **MATERIALS AND METHODS**

123

124 Two types of SFs were compared at laboratory-scale: (1) stratified SFs and (2) single-
125 layer SFs (Figure 1). There were three replicates of each filter type. Filters were 0.3 m in
126 diameter; stratified SFs were 1 m deep and single-layer SFs were 0.9 m deep. The stratified
127 SF consisted of a 0.25 m-deep layer of distribution stone (6 - 10 mm diameter), underlain

128 by a 0.2 m-deep layer of coarse sand (effective size, D_{10} , 0.5 - 1.0 mm), a 0.075 m-deep
129 layer of distribution stone, a 0.1 m-deep layer of medium sand (D_{10} , 0.4 - 0.8 mm), a 0.075
130 m-deep layer of distribution stone and a 0.2 m-deep layer of fine sand (D_{10} , 0.2 – 0.63 mm).
131 The bottom layer of sand was underlain by a 0.1 m-deep layer of distribution stone. The
132 sand depth and classification specifications were based on a study by Gross and Mitchell
133 (1985), who obtained good removal efficiency with this design. The stratified SF consisted
134 of a 0.1 m-deep distribution layer (6 -10 mm in size) underlain by a 0.7 m-deep layer of fine
135 sand (D_{10} , 0.2 – 0.63 mm) and a 0.1 m-deep layer of washed stone (6-10 mm in size). The
136 design specifications used for the single-layer SF are based on recommendations
137 made in previous studies and by the USEPA, which state that a single-pass, single-
138 layer SF should have a depth of 0.61 – 0.91 m and a D_{10} of 0.33 mm (USEPA, 1980;
139 Ball and Denn, 1997; Loomis and Dow, 1999). Double-leaf CorriPipe™ (a locally
140 sourced, commercially available pipe; JFC Ltd., Tuam, Co. Galway), 0.3 m in
141 diameter (after Rodgers et al., 2005), was used to contain the sand. A steel mesh was
142 attached to the base of the filters to hold the sand columns in place, and a plastic
143 container was placed under the base of each SF to collect the treated effluent.
144
145 Each single-layer SF was instrumented with an access tube (type ATL1, Delta-T
146 Devices Ltd., Cambridge, UK) to allow volumetric water content to be measured at
147 various depths. A capacitance probe (type PR1/6d-02, Delta-T Devices Ltd.,
148 Cambridge, UK) was inserted into the access tube and readings taken using a
149 voltmeter (type HR2 Delta-T Devices Ltd., Cambridge, UK). Readings were taken at
150 0.3, 0.4 and 0.6 m depth. These readings were then converted into volumetric water
151 content ($\text{m}^3 \text{m}^{-3}$) using the manufacturer's calibration curve.
152

153 Effluent from a farm-scale woodchip filter treating fresh DSW (Ruane et al., 2011b)
154 was collected every three days, stored in a tank, and loaded onto the SFs at a HLR of
155 $20 \text{ L m}^{-2} \text{ d}^{-1}$. The HLR was based on the average effluent COD concentration from the
156 farm-scale woodchip filters (Ruane et al., 2011b) and was chosen so as the OLR on
157 the SFs would not exceed approximately $25 \text{ g COD m}^{-2} \text{ d}^{-1}$ – the OLR above which
158 sand filters cease to be effective (Rodgers et al., 2005). Effluent from the woodchip
159 filters was pumped onto the surface of all six SFs every two hours using a peristaltic
160 pump (Masterflex L/S 16, Illinois, USA) delivering 118 mls per dose via a spiral
161 distribution manifold, positioned on the surface of each SF. The total study duration
162 was 82 days.

163

164 A 50-ml sample was collected from the influent for the SFs (discharge effluent from
165 the woodchip filter) and from the effluent at the base of each SF for analysis twice
166 weekly. After collection of the 50-ml sample the buckets beneath each sand filter
167 were emptied and cleaned. Therefore, the 50-ml sample is a subsample of the effluent
168 collected during a three or four-day period. Samples were frozen immediately and
169 tested within a period of 14 days. A closed reflux method was used to test for
170 unfiltered COD (COD_T) and filtered COD (COD_F). Total N and filtered TN (TN_F)
171 were measured using the persulfate method. Suspended solids were measured by
172 filtering a 10-ml sample through a filter paper ($1.4 \mu\text{m}$) and drying the solids captured
173 and the filter paper for 24 hours at $103 - 105 \text{ }^\circ\text{C}$. Filtered samples were measured for
174 ammonium-N ($\text{NH}_4\text{-N}$), nitrite-N ($\text{NO}_2\text{-N}$), total oxidized N (TON) and ortho-
175 phosphorus ($\text{PO}_4\text{-P}$) using a Konelab 20 nutrient analyser (Fisher Scientific, Waltham,
176 Massachusetts). Nitrate-N was calculated by subtracting $\text{NO}_2\text{-N}$ from TON. Dissolved
177 organic N (DON) was calculated by subtracting $\text{NO}_2\text{-N}$, $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ from

178 TN_F . Particulate N (PN) was calculated by subtracting TN_F from TN. Inorganic N
179 comprised NH_4-N , NO_2-N and NO_3-N . Total organic N (TON) was calculated by
180 subtracting inorganic N from TN. Samples of influent and effluent from all six SFs,
181 taken on days 62 and 75, were also analysed for total coliform (TC) content. All tests
182 were carried out in accordance with the standard methods (APHA-AWWA-WEF,
183 1995).

184

185 Removal of nutrients and other water quality parameters was calculated as the influent
186 concentration minus the effluent concentration, expressed as a percent of the influent
187 concentration. Descriptive statistics were used to characterise influent and effluent
188 concentrations and removal rates. Percent removal data were analysed using ANOVA
189 (SAS Institute, 2004) in a one-factorial design to test the effect of filter type on
190 performance.

191

192 *1.1. Phosphorus adsorption isotherms*

193 A P adsorption isotherm test was carried out on the three sands used in the SFs. A
194 sample of each sand (n=3) was first washed in distilled water diluted with 10%
195 hydrochloric acid to eliminate interference from the native P content of the sand.
196 Solutions containing four known concentrations of PO_4-P (21.5, 46.1, 61.4 and 92.1
197 $mg PO_4-P L^{-1}$) were used. Approximately 15 g of each type of sand - fine, medium
198 and coarse - was added to separate containers and mixed with 115 ml of each solution
199 concentration. Each mixture was then shaken for 24 hours using an end-over-end
200 mixer. The solids were separated from the mixture using a centrifuge and the
201 supernatant water was tested for PO_4-P . The data obtained was then modelled using a
202 Langmuir adsorption isotherm (McBride, 2000):

203

$$204 \quad \frac{x}{m} = q_{MAX} \left(\frac{k_A Ce}{1 + k_A Ce} \right) \quad [1]$$

205

206 where x/m is the quantity of P adsorbed per gram of sand, Ce is the equilibrium P
207 concentration in the pore water (g m^{-3}) at the end of the test, k_A ($\text{m}^3 \text{g}^{-1}$) is a measure
208 of the affinity of the P for the sand, and q_{MAX} (g P g^{-1} sand) is the maximum amount of
209 P that can be adsorbed onto the sand.

210

211 *1.2. Assessing biomass build-up*

212 After 82 days of operation, two columns from each set of SFs were destructively
213 sampled so that the build up of biomass within each filter could be quantified using
214 LOI (BS 1377-3:1990; BSI, 1990). For determination of the mass LOI, replicated
215 sand samples ($n=3$) were taken from four layers below the surface distribution gravel:
216 0 - 0.03 m, 0.03 - 0.06 m, 0.06 - 0.09 m and 0.09 - 0.12 m. Samples were dried at 50
217 °C until a constant weight was achieved, then ground down until they passed through
218 a 425 μm sieve. The prepared samples were placed in a cool muffle furnace and then
219 heated to 450 °C for over 3 hours. The LOI from the dismantled SFs were then
220 compared with virgin sand samples.

221

222 Physical changes in the single-layer SFs were also investigated by measuring the K_{fs}
223 (m s^{-1}) (constant-head method; BSI, 1990) of samples taken at the same depth
224 increments as the LOI samples. To measure K_{fs} , an open-ended circular container,
225 0.05 m in diameter, was used to extract a sand core of height, l (30 mm in height).
226 Three replicate samples were taken from two single-layer SFs. Water was supplied to

227 the container and an overflow pipe maintained a constant head in the container, z (20
228 mm). Once constant flow rates were maintained, the flow rate, Q , was measured by
229 calculating the time taken for a known volume of water to be collected. Taking the
230 base of the open-ended cell as datum, the hydraulic gradient was defined as:

$$231 \quad \frac{dH}{dZ} = 1 + \frac{z}{l} \quad [2]$$

232

233 The K_{fs} was then calculated using Darcy's Law (Craig, 1997):

$$234 \quad \frac{Q}{A} = K_{fs} \frac{dH}{dZ} \quad [3]$$

235

236 where A is the cross-sectional area of the open-ended cell.

237

238 **RESULTS AND DISCUSSION**

239 *2.1 Organic carbon (COD) and SS removal*

240 The influent COD concentration in this study was higher than most other studies
241 using SFs to treat wastewater that had undergone at least primary treatment (Table 1).
242 Influent concentrations of COD_T were, on average, $1991 \pm 296 \text{ mg L}^{-1}$. The single-
243 layer SF decreased the influent concentration by 39% to $1204 \pm 270 \text{ mg L}^{-1}$ (Table 2).
244 The performance of the stratified SF was significantly better ($P < 0.001$), achieving an
245 average decrease of 56%, resulting in an effluent concentration of $871 \pm 121 \text{ mg L}^{-1}$. A
246 study by Rodgers et al. (2005) found that, after 230 days, a stratified SF treating
247 synthetic DSW at the same HLR achieved a removal rate of 96%, decreasing an
248 influent concentration of $1340 \pm 285 \text{ mg L}^{-1}$ to $60 \pm 125 \text{ mg L}^{-1}$. However, the better
249 performance achieved by Rodgers et al. (2005) may be a result of the enhanced
250 straining effects of the medium due to the higher deposition of organic materials,

251 sediment and bacteria on the SF surface over a longer operational period (230 days
252 versus 82 days in the present study).

253

254 An average influent COD_F concentration of 1073±221 mg L⁻¹ was measured and
255 removal rates of 38 and 55% were achieved by the single-layer and the stratified SF,
256 respectively. The removal rates achieved by the stratified SF were significantly better
257 (P<0.001) for both COD_T and COD_F. This would indicate that the stratified SFs were
258 better at decreasing the soluble fraction of the influent as well as the fraction
259 associated with influent SS. Therefore, both physical filtration and the oxidation of
260 organic compounds may have contributed to the decrease in concentrations of COD_T
261 and COD_F.

262

263 Influent SS concentrations were, on average, 84±30 mg L⁻¹ (Table 2). The single-layer
264 SF achieved an average decrease of 52%, giving an effluent concentration of 41±8 mg
265 L⁻¹. Effluent concentrations of 32±6 mg L⁻¹ were achieved by the stratified SF; a
266 decrease of 62% on the influent concentration. Removal rates for the stratified SF
267 were significantly better than the single-layer SF (P<0.001). Straining is the main
268 mechanism of removing SS in SFs with interception, impaction and adhesion also
269 contributing to the overall reduction of solids in the effluent (Prochaska and
270 Zouboulis, 2003).

271

272 *2.2 Nitrogen removal and conversion*

273 Influent concentrations of TN ranged from 124 mg L⁻¹ to 250 mg L⁻¹ with a mean of
274 163 mg L⁻¹. The single-layer SF decreased the influent by, on average, 36% to 104±18
275 mg L⁻¹ and the stratified SF by 57% to 70±21 mg L⁻¹ (P<0.001) (Table 2). The

276 influent TN_F concentration of $113 \pm 25 \text{ mg L}^{-1}$ was decreased by an average of 38% for
277 the single-layer SF to $61 \pm 21 \text{ mg L}^{-1}$ and by 41% for the stratified SF to $59 \pm 21 \text{ mg L}^{-1}$
278 ($P > 0.05$) (Table 2). Influent PN was, on average, $57 \pm 45 \text{ mg L}^{-1}$. The stratified SF
279 outperformed the single-layer SF, decreasing the influent concentration by 80%
280 compared to 25% for the single-layer SF (Table 2). Given its direct association with
281 the SS concentration, it is most likely that the PN was reduced primarily by filtration
282 and straining.

283

284 At $89 \pm 42 \text{ mg L}^{-1}$, TON (dissolved and particulate) accounted for, on average, 54% of
285 the influent TN concentration. The single-layer SF decreased the influent
286 concentration by an average of 39%, producing an effluent with a TON concentration
287 of $54 \pm 15 \text{ mg L}^{-1}$. The stratified SF produced an effluent concentration of $22 \pm 19 \text{ mg L}^{-1}$
288 ¹; an average decrease of 76% (Table 2). The principal mechanisms of removing and
289 transforming influent concentrations of TON in these aerobic SFs are likely to be
290 filtration and mineralisation. As with SS, physical straining of particulate organic N as
291 the influent water interacts with the porous media, is likely the main mechanism of
292 removing SS in SFs.

293

294 Dissolved organic N in the influent was, on average, $39 \pm 25 \text{ mg L}^{-1}$ over the duration
295 of the study. The single-layer SF achieved a decrease of 65% to produce an effluent
296 concentration of $13 \pm 16 \text{ mg L}^{-1}$. The stratified SF produced an effluent concentration
297 of $15 \pm 18 \text{ mg L}^{-1}$, which represented an overall decrease of 61%. Mineralisation of
298 DON was likely the main transformation mechanism for decreasing the influent
299 concentration of DON. Oxygen is transported into the filter with the intermittently
300 applied influent water and by diffusion in porous and unsaturated media (Schwager

301 and Boller, 1997). As DON decreases were likely due to mineralisation, it might have
302 been expected that $\text{NH}_4\text{-N}$ concentrations might increase in the effluent. However, the
303 influent $\text{NH}_4\text{-N}$ concentration decreased from $42\pm 17 \text{ mg L}^{-1}$ to $24\pm 7 \text{ mg L}^{-1}$ in the
304 single-layer SF and to $21\pm 4 \text{ mg L}^{-1}$ in the stratified SF, representing a decrease of 34
305 and 41%, respectively ($P>0.05$) (Table 2). Influent inorganic N concentration was, on
306 average, $74\pm 22 \text{ mg L}^{-1}$ over the duration of the study. Of this, $\text{NH}_4\text{-N}$ accounted for
307 the largest fraction at 57%. As the SFs were aerobic, the principal mechanism for the
308 decrease in $\text{NH}_4\text{-N}$, despite the presumed production of additional $\text{NH}_4\text{-N}$ via
309 mineralisation, was nitrification. Sorption of NH_4^+ was possible but, as the clay
310 content of the filter sands was negligible, this was very unlikely.

311

312 As $\text{NH}_4\text{-N}$ decreases were likely due to nitrification, it might have been expected that
313 $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations might increase in the effluent. However, the single-
314 layer SF decreased $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ by 33 and 27% and the stratified SF by 50 and
315 4%, respectively ($P>0.05$). During the first 40 days, there was an increase in $\text{NO}_3\text{-N}$
316 and a decrease in $\text{NH}_4\text{-N}$ that would indicate that nitrification was occurring. After 40
317 days, effluent concentrations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ reach an equilibrium suggesting
318 that biofilm may have established itself and $\text{NO}_3\text{-N}$ may have been taken up into
319 biomass in biofilms growing on the filter medium (Bouwer et al., 2000). A more
320 likely scenario would be due to the retention of PN and TON within both sets of
321 filters: mineralisation of organic N would have affected $\text{NH}_4\text{-N}$ removals, which, in
322 turn, may have affected nitrification rates. The high retention of PN and TON in the
323 stratified SF (80% and 76%, respectively) would appear to be related to the $\text{NO}_3\text{-N}$
324 removal rate of 4%. This was much lower than the single-layer SF (27%), which had
325 comparatively low removals of PN and TON (25 and 39%, respectively). This,

326 combined with the high OLR applied to the filters (approximately $40 \text{ g COD}_T \text{ m}^{-2} \text{ d}^{-1}$),
327 may have suppressed nitrification activity. US EPA guidelines (US EPA, 1980)
328 recommend a maximum COD_T loading rate of approximately $10 \text{ g COD}_T \text{ m}^{-2} \text{ d}^{-1}$.
329 Operating within this OLR, other studies achieved almost complete nitrification
330 (Nichols et al., 1997; Rodgers et al., 2005).

331

332 *2.3 Phosphorus retention*

333 The influent concentration of $\text{PO}_4\text{-P}$ was, on average, $27.3 \pm 6.9 \text{ mg L}^{-1}$ (Table 2). The
334 single-layer SF decreased the influent concentration by 58% to an average effluent
335 concentration of $11.4 \pm 7.3 \text{ mg L}^{-1}$. The stratified SF achieved an average decrease of
336 74%, producing an average effluent concentration of $7.1 \pm 3.2 \text{ mg L}^{-1}$ ($P < 0.05$). For the
337 single-layer SF, which consisted solely of medium sand (D_{10} , 0.4 – 0.8 mm), using the
338 Langmuir isotherm, the theoretical maximum mass of P adsorbed per mass of sand
339 was calculated to be 379 mg P kg^{-1} sand. The maximum mass of P adsorbed per mass
340 of sand was calculated as $759.2 \text{ mg P kg}^{-1}$ for the fine sand (D_{10} , 0.2 – 0.63 mm) and
341 $1452.3 \text{ mg P kg}^{-1}$ for the coarse sand (D_{10} , 0.5 – 1 mm). The high adsorbancy of the
342 coarse sand may have been related to its mineralogy (not tested). These results are
343 consistent with other studies showing a strong link between P sorption capacity of a
344 filter medium and P removal. Healy et al. (2010) used three media (crushed glass –
345 0.5 to 1.1 mm in size; sand – D_{10} , 0.15 mm; and a shallow podzolized soil sieved to
346 less than 5 mm) in 0.65 m-deep filters to treat low-strength domestic wastewater. The
347 respective P adsorption capacities of the filter media (measured using a Langmuir
348 adsorption isotherm) were: 10.3, 85 and $1043 \text{ mg P kg}^{-1}$ and decreases of $\text{PO}_4\text{-P}$ of
349 2.4, 4.3 and 100% were achieved in the glass, sand and soil filters.

350

351 *2.4 Microbial analysis*

352 Influent TC values of $8.5 \times 10^6 \pm 7.1 \times 10^5$ CFU 100 mls⁻¹ were measured on days 62 and
353 75 of operation. Both the single-layer SFs and the stratified SFs recorded similar very
354 high rates of removal of 96 and 95 %, reducing the concentration of TC to $3.2 \times 10^5 \pm$
355 1.6×10^5 CFU 100 mls⁻¹ and $4.2 \times 10^5 \pm 13.2 \times 10^5$ CFU 100 mls⁻¹, respectively. Physical
356 filtration and adsorption, or adhesion, are believed to be the principal mechanisms for
357 removing pathogenic bacteria from wastewater in a SF (Stevik et al., 2004). However,
358 the water supply for cleaning operations in the milking parlour must be of potable standard
359 (IMQCS and Teagasc, 2004) and for a treated wastewater to reach a standard of potable
360 water, no coliforms may be present (EC, 1980). Therefore, some form of disinfection
361 would be required to bring the treated effluent from the SFs used in this study to the
362 standard of potable water. A UV treatment may be suitable for this purpose.

363

364 *2.5 Pore-water profile and biomass build-up*

365 Analysis of the volumetric water content of the single-layer SFs to a depth of 0.6 m
366 indicated there was no significant change with depth or with time from the start of
367 operation (Figure 3). Rodgers et al. (2005) examined a stratified SF loaded for 342
368 days with synthetic DSW at a HLR of $20 \text{ L m}^{-2} \text{ d}^{-1}$ and a SS loading rate of between
369 5.2 and $12 \text{ g SS m}^{-2} \text{ d}^{-1}$ and found that the volumetric water content increased to a
370 maximum value of approximately 40% at the filter surface. The present study was
371 only operational for 82 days at a SS loading rate of approximately $1.7 \text{ g m}^{-2} \text{ d}^{-1}$.
372 Therefore, the volumetric water contents indicated that significant amounts of biofilm,
373 which could be detected by a capacitance probe, did not build up in the filter media.

374

375 Analysis of the LOI showed that most organic matter resided in the top 0.03 m in the
376 single-layer SF (Figure 4). The LOI in this layer, at $0.52 \pm 0.02\%$, was more than five
377 times the LOI of the virgin coarse sand ($0.09 \pm 0.045\%$). For the stratified SF, LOI
378 was also greatest in the top layer at $0.38 \pm 0.14\%$ (Figure 4). Loss on ignition in the
379 0.03 - 0.06 m layer for the stratified SF was $0.19 \pm 0.04\%$, compared with 0.3 ± 0.07
380 % in the single-layer filter. This could suggest that organic matter build-up extends
381 slightly deeper in the single-layer SF. Rodgers et al. (2004) measured maximum LOI
382 values of approximately 2.3% in the uppermost layer (to a depth of 0.02 m below the
383 filter surface) of a stratified SF loaded at OLRs ranging from 6.5 to 76 g COD_T m⁻² d⁻¹
384 over an 806-day period.

385

386 Measurements of K_{fs} , carried out on the single-layer SFs (Figure 5) showed decreases
387 in K_{fs} in upper layers, indicating that some organic matter build-up occurred in the
388 upper layer of the filters. In the 0-0.03 m layer, K_{fs} was, on average, $1.34 \times 10^{-4} \pm 4.23 \times 10^{-5}$ m s⁻¹
389 and increased to $2.09 \times 10^{-4} \pm 7.05 \times 10^{-5}$ m s⁻¹ in the 0.03 - 0.06 m
390 layers, and to $2.3 \times 10^{-4} \pm 7.01 \times 10^{-5}$ m s⁻¹ in the 0.06-0.09 m layers. Analysis of the
391 single-layer SFs, on which both LOI and K_{fs} were measured, suggests a correlation
392 between measurements for K_{fs} and the build-up of organic matter to a depth of 0.06 m
393 in the single-layer SFs. The decreasing LOI with depth implies a decrease in the
394 build-up of organic matter on the filter medium with depth. The organic matter build-
395 up may be due to both entrapment of SS from the influent and also the growth of a
396 biofilm on the filter medium. The growth of biofilm in soil and sand filters receiving
397 DSW and septic tank effluent has been elucidated by Rodgers et al. (2004) and Nie et
398 al. (2011), amongst others. The growth of such a biofilm would be consistent with

399 uptake by microorganisms of NO₃ released through mineralisation and nitrification in
400 these aerobic filters.

401

402 **CONCLUSION**

403

404 Both types of SFs were capable of decreasing the concentrations of influent water
405 quality parameters. Both filters, however, produced an effluent with an NO₃-N
406 concentration greater than the MAC and total coliform limits for re-use in the washing
407 of milking parlours. Analysis of the distribution and build-up of organic matter within
408 the top layers of both SFs indicated that some organic matter build-up had occurred.
409 However, the build-up was only pronounced in the very top layers of both filters.
410 Over time, this build-up might be expected to increase. This might increase filter
411 effectiveness but may also lead, eventually, to problems of filter clogging.

412

413 On the basis of this study, stratified SFs are more effective in organic carbon, nutrient
414 and SS removal. The reason for this improved performance is likely the more tortuous
415 flow path and greater retention time that is likely in a SF compared to a single-layer
416 SF. However, issues such as difficulty in construction and the sourcing of sand of an
417 appropriate size hinder their implementation at farm-scale. Both filters ultimately do
418 not provide water of a quality suitable for discharge or for the cleaning of milking
419 parlours, and the final effluent may only be used for cleaning of the holding yard or
420 for landspreading.

421

422 **ACKNOWLEDGEMENTS**

423

424 The authors are grateful to Teagasc for the award of a Walsh Fellowship to the first
425 author and for financial support provided by the Research Stimulus Fund (Department
426 of Agriculture, Fisheries and Food). The authors appreciate the technical help of J.
427 Kennelly and D. Minogue (Teagasc).

428

429

430

431

432

433

434 **REFERENCES**

- 435 APHA-AWWA-WEF., 1995. Standard methods for the examination of water and
436 wastewater. 19th edition. American Public Health Association. Washington, USA.
437
- 438 Bahgat M., Dewedar A., Zayed A. (1999) Sand-filters used for wastewater treatment:
439 buildup and distribution of microorganisms. *Water Research* **33**, 1949-1955.
440
- 441 Bouwer, E.J., Rijnaarts, H.H.M., Cunningham, A.B., Gerlach, R. (2000) Biofilms in
442 porous media. pp. 123–158 In: Bryers, J.D. (Ed.), *Biofilms II: Process Analysis and*
443 *Applications*. Wiley, New York,
444
- 445 BS 1377: 3: 1990: 4. Determination by mass-loss on ignition. British standard method
446 of test for soils for civil engineering purposes. Chemical and electro-chemical tests.
447
- 448 BS 1377: 5: 1990: 5. Determination of permeability by the constant-head method.
449 British standard method of test for soils for civil engineering purposes.
450 Compressibility, permeability and durability tests.
451
- 452 Campos L.C., Su M.F.J., Graham N.J.D., Smith S.R. (2002) Biomass development in
453 slow sand filters. *Water Research* **36**, 4543-4551.
454
- 455 Craig, R.F. (1997) *Soil Mechanics*. 6th edition. (485 pp.) E & FN Spon, London.
456
- 457 EC (1980) Council Directive of 15 July 1980 relating to the quality of water intended
458 for human consumption (80/778/EEC)
459
- 460 Gill L.W., O' Suilleabhain C., Misstear B.D.R., Johnston P.M. (2009) Comparison of
461 stratified sand filters and percolation trenches for on-site wastewater treatment.
462 *Journal of Environmental Engineering* **135**, 8-16.
463
- 464 Healy M.G., Rodgers M., Mulqueen J. (2006) Denitrification of a nitrate-rich
465 synthetic wastewater using various wood-based media materials. *Journal of*

466 *Environmental Science and Health - Part A Toxic/Hazardous Substances and*
467 *Environmental Engineering* 41, 779-788.
468

469 Healy, M.G., Rodgers, M., Mulqueen, J. (2007) Treatment of dairy wastewater using
470 constructed wetlands and intermittent sand filters. *Bioresource Technology* 98, 2268-
471 2281.
472

473 Healy, M.G., Burke, P., Rodgers, M. (2010) The use of laboratory sand, soil and
474 crushed-glass filter columns for polishing domestic-strength synthetic wastewater that
475 has undergone secondary treatment. *Journal of Environmental Science and Health,*
476 *Part A: Toxic/Hazardous Substances and Environmental Engineering* 45, 1635-1641.
477

478 Healy, M.G., Rodgers, M., Burke, P. (2011) Quantification of biofilm build-up in
479 filters when intermittently loaded with low-strength synthetic wastewater.
480 *Desalination* 271 (1-3), 105-110.
481

482 IMQCS and Teagasc (2004) Recommendations for the installation and testing of milking
483 machines. Irish Milk Quality Co-operative Society, Dublin, Ireland.
484

485 Knudsen, M.T., Kristensen, I.B.S., Berntsen, J., Petersen, B.M., Kristensen, E.S.
486 (2006) Estimated N leaching losses for organic and conventional farming in Denmark.
487 *Journal of Agricultural Science* 144, 135-149.
488

489 Leverenz H.L., Tchobanoglous G., Darby J.L. (2009) Clogging in intermittently dosed
490 sand filters used for wastewater treatment. *Water Research* 43, 695-705.
491

492 Martínez-Suller L., Provolo G., Carton O.T., Brennan D., Kirwan L., Richards K.G.
493 (2010) The composition of dirty water on dairy farms in Ireland. *Irish Journal of*
494 *Agricultural and Food Research* 49, 67-80.
495

496 McBride, M.B. (2000) Chemisorption and precipitation reactions. In: M.E. Sumner
497 (ed). *Handbook of Soil Science*. (p. B-265 – B-302) CRC Press. Boca Raton, Fl.
498

499 Nakhla G., Farooq S. (2003) Simultaneous nitrification-denitrification in slow sand
500 filters. *Journal of Hazardous Materials* 96, 291-303.
501

502 Nichols D.J., Wolf D.C., Gross M.A., Rutledge E.M. (1997) Renovation of septic
503 effluent in a stratified sand filter. *ASTM Special Technical Publication* 1324, 235-247.
504

505 Nie, J.Y., Zhu, N.W., Zhao, K., Hu, Y.H. (2011) Analysis of the bacterial community
506 changes in soil for septic tank effluent treatment in response to bio-clogging. *Water*
507 *Science and Technology* 63 (7), 1412-1417.
508

509 Prochaska C.A., Zouboulis A.I. (2003) Performance of intermittently operated sand
510 filters: A comparable study, treating wastewaters of different origins. *Water, Air, and*
511 *Soil Pollution* 147, 367-388.
512

513 Regan, J.T., Rodgers, M., Healy, M.G., Kirwan, L., Fenton, O. (2010) Determining
514 phosphorus and sediment release rates from five Irish tillage soils. *J Environ Qual* 39,
515 185-192.
516

517 Rodgers M., Mulqueen J., Healy M.G. (2004) Surface clogging in an intermittent
518 stratified sand filter. *Soil Science Society of America Journal* 68, 1827-1832.
519

520 Rodgers M., Healy M.G., Mulqueen J. (2005) Organic carbon removal and
521 nitrification of high strength wastewaters using stratified sand filters. *Water Research*
522 39, 3279-3286.
523

524 Rolland L., Molle P., Liénard A., Bouteldja F., Grasmick A. (2009) Influence of the
525 physical and mechanical characteristics of sands on the hydraulic and biological
526 behaviors of sand filters. *Desalination* 248, 998-1007.
527

528 Ruane, E.M., Murphy, P.N.C., Clifford E., O'Reilly, E., French, P., Rodgers, M.
529 (2011a) Performance of a woodchip filter to treat dairy soiled water. *Journal of*
530 *Environmental Management* 95 (1), 49-55.
531

532 Ruane, E.M., Murphy, P.N.C., Healy, M.G., French, P., Rodgers, M. (2011b) On-
533 farm treatment of dairy soiled water using aerobic woodchip filters. *Water Research*
534 45, 6668-6676.
535
536 SAS Institute (2004) SAS online. Version 9.1. SAS Inst., Cary, NC.
537
538 Schwager, A., Boller, M. (1997) Transport phenomena in intermittent filters. *Water*
539 *Science and Technology* 35(6), 13-20.
540
541 *Standard methods for the examination of water and wastewater*. 1995. 19th edition.
542 APHA-AWWA-WEF. American Public Health Association. Washington, USA.
543
544 Statutory Instrument No. 610 of 2010. European communities (good agricultural
545 practice for protection of waters) regulations 2010.
546 <http://www.irishstatutebook.ie/2010/en/si/0610.html>. Accessed July 30, 2013.
547
548 Stevik T.K., Aa K., Ausland G., Hanssen J.F. (2004) Retention and removal of
549 pathogenic bacteria in wastewater percolating through porous media: A review. *Water*
550 *Research* 38, 1355-1367.
551
552 Torrens A., Molle P., Boutin C., Salgot M. (2009) Impact of design and operation
553 variables on the performance of vertical-flow constructed wetlands and intermittent
554 sand filters treating pond effluent. *Water Research* 43, 1851-1858.
555
556
557
558
559
560
561
562
563

565 **LIST OF FIGURES**

566

567 **Figure 1.** Schematic design of a stratified sand filter (a) and a single-layer sand filter
568 (b).

569

570 **Figure 2.** Comparison of the concentration of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the effluent from
571 the single-layer SF (top) and stratified SF (bottom).

572

573 **Figure 3.** Volumetric water content measurements in a single-layer SF. Each point is
574 an average of measurements taken on three different occasions (after 34, 47 and 82
575 days of operation)

576

577 **Figure 4** Mass loss on ignition in the upper layer of medium sand of a laboratory-
578 scale single-layer sand filter (top) and stratified sand filter (bottom)

579

580 **Figure 5.** Field saturated hydraulic conductivity measurements for the single-layer
581 sand filters.

582

583

584