PORE SIZE DISTRIBUTION IN SOILS IRRIGATED WITH SODIC WATER AND WASTEWATER[1]

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SUMMARY

Soil porosity, especially pore size distribution, is an important controlling factor for soil infiltration, hydraulic conductivity, and water retention. This study aimed to verify the effect of secondary-treated domestic wastewater (STW) on the porosity of a sandy loam Oxisol in the city of Lins, state of São Paulo, Brazil. The two-year experiment was divided into three plots: soil cultivated with corn and sunflower and irrigated with STW, soil cultivated and irrigated with sodic groundwater, and non-irrigated and non-cultivated soil (control). At the end of the experiment, undisturbed core samples were sampled from 0 to 2.0 m (8 depths). The water retention curves were obtained by tension plates and Richard's pressure plate apparatus, and the pore size distribution inferred from the retention curves. It was found that irrigation with treated wastewater and treated groundwater led to a decrease in microporosity (V_{MI}), defined as the pore class ranging from 0.2 to 50 μm diameter. On the other hand, a significant increase in cryptoporosity (V_{CRI}) (< 0.2 μm) was identified throughout the soil profile. The presence of Na^+ in both waters confirmed the role of this ion on pore size distribution and soil moisture (higher water retention).

Index terms: sodic wastewater, soil porosity, clay dispersion, soil sodicity.

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RESUMO: *DISTRIBUIÇÃO DE POROS EM SOLOS IRRIGADOS COM ÁGUA SALINA E COM ÁGUA RESIDUÁRIA*

A porosidade do solo, principalmente a distribuição dos poros, é um fator importante que controla a infiltração de água, condutividade hidráulica e retenção da água no solo. Este estudo teve como objetivo verificar os efeitos do efluente de estação de tratamento de esgoto (TSE) na porosidade de um Latossolo de textura média. A área experimental foi dividida em três parcelas: solo cultivado com milho e girassol e irrigado com TSE (STW); solo cultivado e irrigado com água subterrânea sódica (W); e solo não cultivado e não irrigado (C-controle). No final de dois anos de experimento, amostras não deformadas de solo foram coletadas de 0 a 2,0 m (oito amostras). As curvas de retenção de água no solo foram obtidas com mesas de tensão e câmara de Richards, e a distribuição de poros no solo foi calculada a partir da derivação dessas curvas. Foi observado decréscimo da microporosidade V_{MI} (poros com diâmetro entre 0,2 e 50 μm) no solo irrigado com TSE e água tratada. Por outro lado, observou-se aumento significativo da criptoporosidade V_{CRI} (< 0,2 μm). A presença de Na^+ nos dois tipos de água confirmou o papel desse íon na distribuição dos poros e na umidade do solo (maior retenção de água no solo).

Termos de indexação: água residuária sódica, porosidade do solo, dispersão de argilas, sodicidade do solo.

INTRODUCTION

The disposal of solid and liquid wastes on soil is regarded as a partial solution to the environmental problem of sewage disposal into fresh water bodies (Darwish et al., 1999). A number of soil treatment systems are available for domestic treated wastewater (TW), e.g., infiltration basins or wetlands, but crop irrigation is the most accessible (Feigin et al., 1991) and efficient method (Darwish et al., 1999), principally in developing countries where policies of domestic sewage treatment are lacking.

Although irrigation with TW can solve the immediate problem of contamination of water bodies by nutrient loads, this practice requires careful management due to some water characteristics. Several authors have already pointed out damaging effects on physical soil properties, such as infiltration (Cook et al., 1994), permeability (Meenner et al., 2001), water retention capacity (Jnad et al., 2001), and soil hydraulic conductivity (Balks et al., 1998; Magesan et al., 1999; Bagarello et al., 2005; Gonçalves, 2007). Most of these observations are associated to the high Na content in TW, that can lead to a dispersion and/ or expansion of clay particles, pore size distribution (Shainberg & Letey 1984; So & Aylmore, 1993; Sumner, 1993; Halliwell et al., 2001). This indicates that the study of soil porosity may be a reasonable approach to detect changes in the soil physical properties. Pores can be defined as a function of the aggregate structure organization (Libardi, 2005) and classified as: (a) cryptopores or residual pores related to the intra-aggregate arrangement and particle type (clay, oxides), where hygroscopic water is highly bound by molecular attraction (sorption) (pore diameter -Ø- smaller than 0.2 μm), (b) micropores where capillarity forces are predominant (0.2 < Ø < 50 μm) and (c) macropores where the water flow occurs by convection due to gravitational forces (Ø > 50 μm); micropores and macropores depend on the inter-aggregate arrangement.

The purpose of this study was the investigation of changes in soil porosity and pore size distribution after irrigation with treated sewage effluent or sodic ground water.

MATERIAL AND METHODS

Experimental field

The study was carried out in the city of Lins (São Paulo State, Brazil, 49 º 50 ' W -22 º 21 ' S), where the annual rainfall varies from 1,100 to 1,300 mm and the average annual temperature from 18 to 22 ºC. The experimental area is located near the sewage stabilization pond system (Australian treatment system). The soil was classified as Oxisol with a sandy loam texture (Table 1). Four crop cycles (two cycles with corn (*Zea mays* L). and two cycles with sunflower (*Helianthus annuus* L.) were alternately drip-irrigated with effluent from the stabilization pond for two years. The three plots were treated as follows: irrigation with soil domestic treated sewage effluent – STW plot (irrigation = 1,809 mm and precipitation = 743 mm), irrigation with naturally sodic, treated ground water – plot W (I = 1,809 mm and P = 743 mm), and non-irrigated, non- cultivated soil, as control plot C (P = 743 mm).

Table 1. Soil texture for 25 cm soil layers according to ABNT (NBR 6502/95)

Depth	Coarse sand [1]	Medium sand [2]	Fine sand [3]	Sand	Silt [4]	Clay [5]
m			g kg^{-1}			
0.125	22.4	473.8	188.7	701.0	190.4	124.7
0.375	21.7	503.4	237.0	704.0	90.7	147.2
0.625	18.8	452.8	221.0	692.6	101.8	205.6
0.875	14.5	451.5	233.2	699.2	95.3	205.5
1.125	13.8	444.5	234.9	693.2	102.8	204
1.375	18.7	458.9	223.4	701.0	99.5	199.5
1.625	19.5	455.8	228.7	704.0	99.9	196.1
1.875	19.1	457.8	224.1	702.0	98.8	199.2

[1] 0.6 < Ø ≤ 2 mm. [2] 0.2 < Ø ≤ 0.6 mm. [3] 0.06 < Ø ≤ 0.02 mm. [4] 0.002 < Ø ≤ 0.06 mm. [5] Ø ≤ 0.002 mm.

Analysis of soil physical properties

The soil water retention was determined in core soil samples (height 0.05 m) collected after the four crop cycles by a Uhland sampler at three positions in each plot, at depths of 0.125, 0.375, 0.625, 0.875, 1.125, 1.375, 1.625, and 1.875 m (each sample represents a soil layer of 0.25 m). The tension table was used to determine water retention in the soil samples for ψ_m of 1, 2, and 4 kPa, while water retention for ψ_m of 10, 30, 50, 100, 500, and 1,500 kPa was determined using Richard's pressure plate apparatus (Richards, 1965). The experimental data were fitted to the van Genuchten (1980) equation.

Pore size distribution curves were obtained by deriving the water retention curves, considering the matric potential h_i as independent variable. The equivalent pore radius r_i was calculated by the equation of capillarity (equation 1) using the h_i values. The water content θ was calculated from the matric potential between 1 and 1,500 kPa, where $\log(h_{i+1}) = \log(h_i) + 0.05$. The variations $(\theta_{i+1} - \theta_i)$ were calculated for each h_i.

$$r_i = -\frac{2\sigma\cos\beta}{\rho g h_i} \quad (1)$$

where r_i is the pore radius (m); σ is the surface tension (N m^{-1}); β is the contact angle (°); ρ is the specific water mass (Mg m^{-3}); g is the acceleration of gravity (m s^{-2}) and h_i is the matric potential (m).

Pores with a diameter larger than 0.05 mm were called "macropores" (water retained with matric potencial ψ_m higher than -6 kPa); "micropores" correspond to pores with diameter between 0.05 and 0.0002 mm ($-1{,}500 < \psi_m < -6$ kPa), and "cryptopores", pores with diameter smaller than 0.0002 mm ($\psi_m < -1{,}500$ kPa) (Klein & Libardi, 2002).

The soil bulk density (d_s) was calculated by the ratio between the dry sample mass and the core volume (Blake & Hartge, 1986).

The water content at field capacity (θ_{FC}) was obtained from the inflexion point method of the h(θ) curve (Ferreira & Marcos, 1983), adapted by Mello et al.(2002). In this method, the θ_{FC} value corresponds to the θ value at which $d^2h(\theta)/d\theta^2 = 0$, using cubic polynomial regressions for modeling the h(θ) curves (r^2 always > 0.956).

Soil samples were also collected for analysis of water-dispersed clay (WDC) by the pipette method (Camargo et al., 1986).

Statistical analysis

The analysis of variance and comparison of means (Tukey tests, 5 %) were performed using the GLM procedure of the SAS program, using a sub-divided plot model (3 plots = 3 treatments; 8 depths = 8 sub-treatments) and log-transformed values.

RESULTS AND DISCUSSION

The values of sodium adsorption ratio (SAR) were higher in treated groundwater than in STW (Table 2) due to the lower concentrations of Ca^{2+} and Mg^{2+}; the risk of soil sodification (impact on soil infiltration) by STW irrigation was defined as low to moderate (high when groundwater is used), according to Ayers & Westcot (1991). Typically, high concentrations of NH_4^+ and dissolved organic carbon (DOC) were found in STW.

Soil physical properties

Variation of soil bulk density was insignificant throughout the soil profile and between plots; the mean value was 1,540 kg m^{-3} for the control plot and 1,490 and 1,510 kg m^{-3} for the STW and W plots, respectively. Magesan et al. (1999) found similar results after seven years of irrigation (3,120 mm $year^{-1}$). On the other hand, a significant effect of irrigation on soil porosity was detected from the analysis of the curves dθ/dh for the three plots (Table 3); values of the mean pore diameter corresponding to the peak of the pore size distribution curve (value of h when $d^2\theta/dh^2 = 0$) revealed an increase of mean pore diameter in irrigated soil, more pronounced in deeper layers,

Table 2. Chemical composition of secondary-treated wastewater and of treated groundwater in Lins, São Paulo. Mean values followed by minimal and maximal values in brackets

Parameter	Wastewater	Water
pH	7.7 (7.5-8.2)	9.4 (9.1-10.1)
EC (µS cm^{-1})(1)	736 (624-848)	408 (358-474)
TDS (mg L^{-1})(1)	691 (621-761)	429 (396-455)
SAR (1)	10.4 (9.1-13.3)	19.8 (19.1-20.9)
Na^+ (µmol L^{-1})	5577 (4882-6402)	4483 (4192-4702)
K^+ (µmol L^{-1})	322 (267-383)	19 (13-24)
Ca^{2+} (µmol L^{-1})	195 (66-254)	42 (35-47)
Mg^{2+}(µmol L^{-1})	100 (59-141)	10 (8-12)
Cl^- (µmol L^{-1})	1193 (932-1465)	165 (141-196)
SO_4^{2-} (µmol L^{-1})	178 (32-407)	152 (118-170)
NO_3^- (µmol L^{-1})	69 (2-151)	26 (8-60)
NH_4^+ (µmol L^{-1})	1331 (833-1980)	0.10 (0-0.61)
Alkalinity (µmol L^{-1})	7136 (6386-7941)	4775 (4429-5067)
DOC (mg L^{-1})(1)	20.2 (8.4-46.1)	1.7 (0.2-6.3)

(1) EC: electric conductivity, TDS: total of dissolved salts, SAR: Sodium adsorption ratio, DOC: dissolved organic carbon.

Table 3. Mean pore diameter (d*) for the dθ/dh maximum curve and difference in the area under the curve when compared with control (Δarea). C: non-irrigated control plot, STW: wastewater-irrigated plot and W: water-irrigated plot

Depth	d*			Δ area	
	C	STW	W	STW	W
m	µm			%	
0.125	23	12	36	-33	-33
0.375	46	26	8	1	-8
0.625	46	73	36	11	-22
0.875	41	115	33	-6	-27
1.125	23	58	65	-4	5
1.375	16	16	102	-15	-1
1.625	41	51	73	-7	-4
1.875	46	26	65	-20	0
Mean value ± σ	35±12	47±35	52±30	-9	-11

probably caused by leaching of salt and DOC to depth of about 1 m, as observed by Gloaguen et al. (2007). Moreover, irrigation led to a wider range of d^* values within the soil profile (CV = 74 % and 57 % for STW plot and plot W, respectively), whereas d^* remained relatively constant in the C plot (16–46 µm), what signifies a vertical variation of soil porosity due to irrigation. Despite the larger mean pore diameter in irrigated soil, lower values of the area under the curves dθ/dh for the plots STW and W (Δarea) evidenced a decrease in porosity almost in the whole profile.

The pore volume for each pore class was calculated from the pore size distribution curves, by summing the volumes obtained for each r_i: macropore (V_{MA}; > 50 µm), micropore (V_{MI}; 0.2–50 µm), cryptopore (V_{CRI}; ≤ 0.2 µm), and solids ($V_S = 1-(V_{MA} + V_{MI} + V_{CRI})$) volumes (Table 4). The interaction Plot *vs* Depth was significant for V_S, V_{MA} and V_{CRI}.

Obviously, the volume of solids remained unaltered after irrigation porosity almost in the whole profile. The variation reached -7 % and -11 % when soil was irrigated with effluent and water, respectively, which might indicate the beginning of an eluviation process of Na-dispersed clay, as reported by Sumner (1993), in soil sodificated by wastewater irrigation (Gloaguen et al., 2007).

On the other hand, variations in pore size distribution and pore volume were significant. Irrigation caused a decrease in V_{MA} at depths of 0.125 and 0.375 m in the STW plot and at 0.125, 0.375, 0.625, and 0.875 m in the W plot. A similar decrease was mentioned by Jnad et al.(2001), where the authors defined macroporosity as pores with diameter larger than 22 µm after STW irrigation of 1,500 mm.

Jnad et al. (2001) explained the changes in porosity by several factors: (a) Na^+ accumulation in the suspension (Bouma, 1975), (b) deposition of organic matter on the pore surface (Siegrist 1987), and (c) increase of Na^+ in the soil and clay dispersion/ expansion (Shainberg & Shalhevelt, 1984). In our study, despite a greater decrease in V_{MA} at the soil surface for the STW plot, the dissolved organic carbon (DOC) input by the effluent cannot explain this process, since a decrease of V_{MA} was also observed in the W plot (very low DOC concentration in treated groundwater). These results are supported by Sort & Alcañiz (1999), who observed no variations in macropores after sewage application despite the high organic C input (226 g kg^{-1} of sewage). This suggests that organic C has no effect on this pore class and that the main cause of the modification would be the Na^+ soil content in both irrigation waters, resulting in disaggregation of the soil structure (with consequent change in soil porosity) by dispersing clay minerals, as described by Summer (1993). On the other hand, higher soil macroporosity was observed in the second meter of the soil profile, perhaps due to leaching of organic C and Ca^{2+}, facilitating the flocculation and formation of macro-aggregates.

Irrigation with STW and with sodic water also resulted in a decrease in V_{MI}, with a difference, compared to the C plot, of -34 to +8 % in the STW plot (mean value for the soil profile: -20 %, representing a loss of 0.037 m^3 m^{-3} in microporosity), and of -42 to -7 % in the W plot (mean value for soil profile: -21 %, or -0.040 m^3 m^{-3}). These decreases were related to the reduction of inter-aggregate porosity induced by clay dispersion after the high Na input (2.4 tons by STW, 1.8 tons by sodic water).

Table 4. Solids (V_S), macropores (V_{MA}), micropores (V_{MI}) and cryptopores (V_{CRI}) in the control (C), wastewater-irrigated (STW) and water-irrigated (W) plots

Depth	V_S			V_{MA} - Ø > 50 µm		
	C	STW	W	C	STW	W
m	$m^3\ m^{-3}$					
0.125	0.604 a[1]	0.608 a	0.614 a	0.114 a	0.058 b	0.088 ab
0.375	0.628 a	0.613 a	0.588 a	0.093 a	0.088 a	0.089 a
0.625	0.611 a	0.577 a	0.603 a	0.101 a	0.127 a	0.093 a
0.875	0.594 a	0.555 a	0.608 a	0.099 ab	0.14 a	0.079 b
1.125	0.586 a	0.574 a	0.558 a	0.096 a	0.122 a	0.13 a
1.375	0.591 a	0.596 a	0.552 a	0.091 a	0.09 b	0.167 a
1.625	0.569 a	0.538 a	0.506 a	0.103 b	0.147 ab	0.175 a
1.875	0.56 a	0.566 a	0.508 a	0.11 a	0.106 a	0.154 a
Mean	0.593 a	0.578 a	0.567 a	0.101 a	0.11 a	0.122 a
	V_{MI} - 0.2 µm < Ø ≤ 50 µm			V_{CRI} - Ø ≤ 0.2 µm		
	C	STW	W	C	STW	W
0.125	0.207	0.137	0.121	0.087 a	0.197 a	0.177 a
0.375	0.142	0.153	0.122	0.138 a	0.146 a	0.165 a
0.625	0.150	0.146	0.113	0.137 b	0.151 ab	0.191 a
0.875	0.176	0.128	0.132	0.131 b	0.177 ab	0.181 a
1.125	0.200	0.148	0.164	0.119 a	0.156 a	0.149 a
1.375	0.192	0.155	0.155	0.125 a	0.158 a	0.154 a
1.625	0.209	0.171	0.174	0.120 a	0.144 a	0.145 a
1.875	0.209	0.164	0.195	0.122 b	0.164 a	0.143 ab
Mean	0.186 a	0.150 b	0.147 b	0.122 b	0.162 a	0.163 a

[1] At each depth, same letters represent no significant difference between plots (Tukey test, $p < 0.05$).

The analysis of cryptoporosity indicated an increase of V_{CRI} in the irrigated plots throughout the soil profile, from +6 to +127 % (mean value for soil profile: +33 %, or +0.040 $m^3\ m^{-3}$) and from +17 to +105 % (mean value for soil profile: +34 or +0.041 $m^3\ m^{-3}$), respectively, for the STW and W plots. These results can be compared to the increase in soil microporosity reported Jnad et al. (2001): they defined microporosity as the volume of pores with diameter smaller than 6 µm, which included cryptoporosity and part of the microposity of the present study. The insignificant differences between the use of sodic STW or sodic water confirmed that pore size distribution is mainly altered by Na^+, as mentioned by Jnad et al. (2001), whereas it seems that the role of organic C concentration is rather insignificant. Cryptopores are related to the intra-aggregate porosity and its increase was probably associated to the aggregate expansion by Na^+ intrusion, associated to SAR, a phenomenon explained by Sumner (1993). As demonstrated by Gloaguen et al. (2009), the soil solution in cryptoporosity is much more concentrated than in micro- or macroporosity, as the salt concentrations increase exponentially when the pore diameter decreases. As equivalent increases of Na^+, Ca^{2+} and Mg^{2+} result in higher SAR ($Na^+/\sqrt{(Ca^{2+} + Mg^{2+})}$), higher impact of Na^+ is expected in cryptoporosity (within the micro-aggregates), resulting in aggregate expansion instead of dispersion, more common at lower Na^+ concentrations.

These changes in soil porosity were more apparent in the first soil meter that was directly affected by irrigation and water infiltration, but the impact was also observable to a soil depth of 2 m. Actually, a small increment of Na^+ content in the second soil meter, resulting from the easy leaching of Na^+ during rain events, can rapidly cause structural soil damage due to the common low Ca^{2+} and Mg^{2+} contents at this depth in Oxisols.

Changes in the pore size distribution evidently modify soil water retention. The direct relation between pore size distribution and the soil water content can be defined as followed: macropores control the water content at soil saturation (θ_S), micropores the water content at field capacity (θ_{FC}), and cryptopores the residual water content (θ_R).

The mean θ_R values were significantly higher in the plots irrigated with STW and water than in the control plot (Table 5), as also observed by Jnad et al. (2001). No difference was observed between the W and STW plots (only 0.001 $m^3\ m^{-3}$), expressing the predominant effect of Na^+ in θ_R. The θ_S values were also always higher in the W and STW plots than in C, although the differences were not significant. The third characteristic water content, θ_{FC}, reveals a higher water retention capacity in the irrigated plots (STW and W), probably due to the clogging of macropores by clay dispersion, limiting water drainage.

Table 5. Water content at field capacity (θ_{FC}), saturation (θ_S) and residual water content (θ_R) in the control (C), wastewater-irrigated (STW) and water-irrigated (W) plots

Depth	θ_R			θ_{FC}			θ_S		
	C	STW	W	C	STW	W	C	STW	W
m	$m^3\ m^{-3}$								
0.125	0.084 a	0.196 a	0.176 a	0.242 a	0.270 a	0.272 a	0.399 a	0.392 a	0.386 a
0.375	0.130 a	0.143 a	0.166 a	0.241 a	0.280 a	0.267 a	0.375 a	0.390 a	0.408 a
0.625	0.141 a	0.148 a	0.189 a	0.257 a	0.250 a	0.285 a	0.392 a	0.424 a	0.397 a
0.875	0.126 b	0.172 ab	0.178 a	0.252 a	0.300 a	0.272 a	0.408 a	0.446 a	0.393 a
1.125	0.134 a	0.154 a	0.146 a	0.257 a	0.280 a	0.281 a	0.405 a	0.426 a	0.444 a
1.375	0.125 a	0.159 a	0.146 a	0.253 a	0.270 a	0.287 a	0.409 a	0.410 a	0.450 a
1.625	0.115 a	0.138 a	0.137 a	0.262 a	0.290 a	0.304 a	0.440 a	0.465 a	0.495 a
1.875	0.116 b	0.160 a	0.140 ab	0.274 a	0.290 a	0.298 a	0.455 a	0.439 a	0.491 a
Mean	0.121 b	0.159 a	0.160 a	0.255 b	0.279 a	0.283 a	0.410 a	0.424 a	0.433 a

(1) At each depth, same letters represent no significant difference between the plots (Tukey test, $p < 0.05$).

CONCLUSIONS

1. Irrigation with treated wastewater and with water (both sodic waters) modifies the soil pore size distribution by slightly increasing macroporosity (pore diameter higher than 50 µm) and decreasing microporosity (0.2–50 µm).

2. The cryptoporosity (< 0.2 µm) increased due to the high Na^+ concentration in small pores that causing expansion of microaggregates.

3. A consequence of changes in soil pore distribution was higher residual soil moisture and higher moisture at field capacity.

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