Spanish Journal of Agricultural Research (2004) 2 (3), 459-471

Infiltration of water in disturbed soil columns as affected by clay dispersion and aggregate slaking

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Abstract

Soil crusting negatively affects the productivity and sustainability of irrigated agriculture, reducing water infiltration and plant emergence, and enhancing surface runoff and erosion. Clay dispersion and slaking of the aggregates at the soil surface are the main processes responsible for crusting. The infiltration rates (IR) of ten arid-zone soils in disturbed soil columns were measured and their relative susceptibilities to dispersion and slaking were determined. It was also examined whether the final soil IRs (FIR) could be estimated from various soil stability indices. The susceptibility to chemical dispersion was determined by measuring the IR of soil columns slowly pre-saturated from below with tap water and subsequently ponded with deionized (DW), canal irrigation (CW), and gypsum-saturated (GW) waters. The susceptibility to aggregate slaking was determined by comparing the IR measured in pre-saturated (slow wetting from below) and air-dry (fast wetting) soil columns ponded with CW. The FIRs of most soils decreased in the order GW > CW > DW. Seven soils were susceptible to clay dispersion induced by DW. Five soils were susceptible to clay dispersion induced by CW. Only two soils were susceptible to slaking. The fast wetting in these soils completely sealed the soil surface, reducing their IRs to zero from the start of leaching. Clay dispersion rather than aggregate slaking was the principal process inducing sealing and decreasing IR in these soils when subject to low-salinity waters. The indices WSA (water stable aggregates), MDC (mechanically dispersed clay) and MWD_{stir} (mean weight diameter of stirring aggregates after a prewetting treatment) gave consistent and significant relationships with FIRs.

Key words: infiltration rate, water quality, wetting, irrigation, aggregate breakdown, stability indices.

Resumen

Efecto de la dispersión de arcillas y de la ruptura de agregados por humectación rápida sobre la infiltración del agua en columnas de suelo alterado

El encostramiento del suelo afecta negativamente a la rentabilidad y sostenibilidad de la agricultura de regadío, reduciendo la infiltración y emergencia del cultivo, y aumentando la escorrentía y erosión. La dispersión de arcillas y la desagregación de la superficie del suelo por una humectación rápida («slaking») son los principales procesos responsables del encostramiento. Se han medido las tasas de infiltración de 10 suelos en columnas de suelo alterado, y se han determinado sus susceptibilidades a la dispersión y «slaking». Asimismo, se ha examinado si las tasas de infiltración final (IF) pueden ser estimadas a partir de índices de estabilidad estructural. La susceptibilidad a la dispersión se determinó comparando las IFs de suelos previamente saturados por capilaridad con agua de grifo y posteriormente lavados con aguas desionizada (AD), de riego (AC), y saturada en yeso (AY). La susceptibilidad al «slaking» se determinó comparando las IFs de suelos presaturados (humectación lenta por capilaridad) y secos al aire (humectación rápida) lavados con AC. Las IFs de los suelos disminuyeron en el orden: AY > AC > AD. Siete suelos fueron susceptibles a la dispersión inducida por el AD, cinco suelos fueron susceptibles a la dispersión inducida por el AC, y solamente dos suelos fueron susceptibles al «slaking». La dispersión química fue el principal proceso inductor del encostramiento y de la reducción de la IF de dichos suelos al lavarlos con aguas de baja salinidad. Se han encontrado correlaciones consistentes y significativas entre los índices AEA (agregados estables al agua), ADM (arcilla dispersa mecánicamente) y DMP_{agit} (diámetro medio ponderado de agregados frente a agitación) y las IFs de los suelos.

Palabras clave: tasa de infiltración, calidad del agua, humectación, riego, desagregación, índices de estabilidad.

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Received: 01-09-03; Accepted: 03-06-04.

Introduction

Chemical dispersion of clay particles and slaking or physical disintegration of soil aggregates are two of the main processes responsible for soil crusting. They release small particles that clogs the conducting pores immediately beneath the surface, developing disrupted layers or seals that form crusts upon drying. Crusted soils generally decrease infiltration rates, plant emergence and yield of crops, and increase surface runoff and erosion.

The relative importance of dispersion and slaking depends on various soil properties, particularly soil exchangeable sodium percentage (ESP), the rate of soil wetting and drying (i.e. irrigation management, and climatic factors such as rain and wind intensities), and the electrical conductivity (EC) of the applied water. Dispersion of soil clays is induced by low electrolyte concentrations (lower than the soil's flocculation value, FV) and high sodium adsorption ratio (SAR) and pH values in the soil and applied water (Shainberg and Letey, 1984). This mechanism is enhanced by the mechanical breakdown of aggregates and the subsequent exposure of new surfaces to chemical dispersion (slaking promotes dispersion) (Rengasamy *et al.*, 1984; Sumner *et al.*, 1998). The negative effects of clay dispersion, soil sealing and crusting on the infiltration rate of soils are well documented (Sumner and Stewart, 1992).

Slaking of aggregates is produced by the pressure build-up of entrapped air inside the micropores when dry soils are subject to rapid wetting. If the pressure is large enough to overcome the cohesive forces between the aggregates, they break into microaggregates of different sizes and strength, releasing the excess air pressure. Slaking is generally limited to the immediate soil surface (So and Cook, 1993), although the depth of slaking depends on aggregate size and stability (Collis-George and Green, 1979). Thus, Farres (1978) indicated that coarse aggregates are less prone to slaking because of the lower compression of the entrapped air. Several authors have suggested that the hydraulic properties of the seals and the susceptibility of soils to crusting depend on the size distribution of detached primary particles and/or aggregate fragments resulting from aggregate breakdown (Mullins *et al.*, 1987; Roth and Eggert, 1994; Bresson, 1995; Le Bissonnais, 1996).

Slaking during wetting of some hardsetting soils may predominate over dispersion, as shown by the greater proportion of slaked fragments (20 to 60 μm) over clay particles (< 2 μm) (Young and Mullins, 1991). The physical disintegration of aggregates due to slaking may be more important than the mechanical effect of the raindrop impact (Le Bissonnais and Singer, 1992; Loch and Foley, 1994). Chan and Mullins (1994) and Caron *et al.* (1996) found that cultivated soils were more prone to slaking and structural decline than uncultivated soils, and Ferruzzi *et al.* (2000) concluded that most cultivated soils in their studies were prone to slaking during the irrigation events. In summary, various internal and external factors affect the susceptibility of soils to slaking (Le Bissonnais, 1990).

Although the degree of slaking and dispersion of field-undisturbed and laboratory-disturbed soils may differ, laboratory measurements are useful for diagnostic and screening purposes. Infiltration rate (IR) measures the amount of water passing through the soil in a given time and is an indication of the air porosity and pore conductivity. When slaking and/or dispersion occur, seals develop, decreasing the porosity and the IR until steady-state infiltration is reached. Hence, surface sealing may be quantified using infiltration measurements obtained in disturbed soil columns.

The first objective of this work was to determine the susceptibility of ten arid-zone soils (i) to clay dispersion by measuring the IR of pre-wetted soil columns subject to waters of different electrolyte concentrations, and (ii) to aggregate slaking by comparing the IRs measured in pre-wetted (i.e., slow wetting) and air-dry (i.e., fast wetting) soil columns.

Although IRs measured in disturbed soil columns are useful for the purposes already mentioned, they are time-consuming and difficult to perform in terms of reproducibility and accuracy (Abu-Sharar *et al.*, 1987). It is desirable to substitute these measurements by simple and reliable soil indices, provided they correlate significantly with IR. It was hypothesised that decreased IR, as a consequence of dispersion and/or slaking, might be related to different soil stability indices obtained at the macro-aggregate (i.e., slaking) and micro-aggregate (i.e., clay dispersion) levels, such as those indices proposed by Rengasamy *et al.* (1984), Kemper and Rosenau (1986), Le Bissonnais (1990, 1996), Amezketa and Aragüés (1995) and Amezketa *et al.* (1996). For example, Miller and Baharuddin (1986), Minhas and Sharma (1986), So and Cook (1993) and Levy *et al.* (1993) found that soil infiltration was inversely correlated with soil dispersibility.

The second objective was to determine whether the steady-state infiltration rates of the ten soils could be estimated from various macro- and micro-structural stability indices previously determined by Amezketa *et al.* (2003 a, b) for the same soils.

Material and Methods

Soils

Ten arid-zone soils located in the Bardenas I and Monegros I irrigation districts of the middle Ebro river basin (Aragón, Spain) were sampled (0-20 cm depth), air-dried, ground and sieved (< 2 mm). The soil samples were characterised by standard methods (Carter, 1993) and showed a wide range of chemical and physical properties (Table 1). Three soils were saline-sodic, one was saline-non sodic and the remaining six were non saline-non sodic. All the soils were calcareous ($CaCO_3$ values between 12 and 44%) and had organic matter contents between 1 and 4%. Five textural classes (clay loam, silt loam, silty clay loam, loam, and silty clay) were represented in these soils. X-ray diffraction patterns of the clay fraction indicated high proportions of hydrated micas (> 70% of total clay) and chlorites (5-20% of total clay) and low proportions of kaolinites (< 5% of total clay) and pyrophyllites (< 5% of total clay, except in Callén 1, Tramaced 2, Sariñena 4, Grañén T1 and Grañén 1, with values of 5-20% of total clay). Swelling smectites and vermiculites were not found.

These soils were selected because, despite their similar mineralogy, they differed substantially in several of their stability indices (Table 2) (Amezketa *et al.*, 2003a, 2003b). Except for the water stable aggregates (WSA) and the mean weight diameter of the aggregates in the slow-wetting treatment (MWD_{slow}), all the coefficients of variation (CV) of the means of the stability indices were greater than 24%. Moreover, some of the indices expressing clay dispersion (i.e., spontaneous and mechanically dispersed clay) had CV of the means close to or greater than 100%.

Susceptibility of soils to clay dispersion: effect of electrolyte concentration on infiltration rate

Four replicate soil columns of each soil were prepared by packing between 40 and 46 g of the < 2 mm-soils into small plastic methacrylate cylinders (4.4 cm in diameter by 12.0 cm long) at bulk densities of 1.3 to 1.5 Mg m^{-3}, depending on the soil. The cylinders were open at the top and closed at the bottom, except for a plastic outlet for collection of the leachates. The soils were carefully added to the cylinders to a total thickness of 2.0 cm over a 2.0 cm layer of acid-washed

Table 1. Physical and chemical properties of the ten soils studied

Soil	Soil saturation extract			Soil texture			Water content at		Total equivalent			CBD-extractable		
	EC_e (dS m^{-1})	SAR_e (mmol $L^{-1})^{0.5}$	pH_e (g kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	−0.03 MPa (g kg^{-1})	−1.5 MPa (g kg^{-1})	OM[1] (%)	$CaCO_3$ (%)	CEC[2] (cmol kg^{-1})	Mn[3] (g kg^{-1})	Fe[3] (g kg^{-1})	Al[3] (g kg^{-1})
Bardenas I														
SA 3/1	0.5	0.2	8.1	383	279	338	267	153	2.1	30.6	19.0	0.30	11.8	1.18
SA 20/1	0.9	2.3	8.8	286	500	214	221	108	1.1	42.2	22.0	0.19	6.6	0.47
SA 31/1	16.1	23.6	8.0	214	502	284	234	147	1.6	43.9	21.6	—	—	—
SA 81/1	2.9	2.9	8.3	66	486	448	327	210	—	23.8	24.7	0.38	12.3	1.13
SA 92/1	1.1	0.9	8.4	315	486	199	210	94	—	39.6	12.1	1.64	7.1	5.31
Monegros I														
Callén 1	19.1	111	9.1	453	362	185	—	—	1.5	21.4	11.8	0.27	11.7	0.89
Tramaced 2	4.1	5.6	—	82	543	375	—	—	3.1	20.5	17.6	0.35	18.2	1.31
Sariñena 4	0.8	0.3	—	316	364	320	—	—	4.1	12.1	26.0	0.48	19.0	1.81
Barbués 3/1	6.1	13.6	8.0	300	526	174	222	115	1.4	25.8	5.2	0.14	9.9	0.57
Grañén T1	1.8	0.8	8.3	153	467	380	246	163	2.2	29.6	15.3	0.27	11.5	0.92

[1] OM: organic matter content. [2] CEC: cation exchange capacity. [3] Mn, Fe, Al : citrate-dithionate-extractable.

Table 2. Macro- and microaggregate stability indices of the ten soils studied

Soil	WSA (%)	MWD_{fast} (mm)	MWD_{slow} (mm)	MWD_{stir} (mm)	$MWD_{microag}$ (μm)	FV ($mmol_cL^{-1}$)	SDC (%)	MDC (%)
SA 3/1	96.3	0.50	1.42	0.96	33.1	3.5	0.14	20.9
SA 20/1	86.2	0.33	1.36	0.76	23.0	2.4	0.18	44.8
SA 31/1	64.6	0.46	1.26	0.84	27.0	2.2	0.03	0.09
SA 81/1	90.9	0.42	1.35	0.95	—	3.1	0.01	0.17
SA 92/1	85.0	0.29	1.12	0.31	—	5.0	0.05	35.5
Callén 1	83.4	0.40	1.25	0.61	26.8	1.4	0.98	100
Tramaced 2	75.3	0.33	1.25	0.78	13.5	2.1	0.16	5.4
Sariñena 4	90.2	0.44	1.35	0.97	47.1	3.2	0.21	25.7
Barbués 3/1	76.6	0.61	1.08	0.93	—	2.3	0.08	76
Grañén T1	73.1	0.31	1.05	0.69	—	3.3	0.00	45
CV (%)	12	24	10	26	39	35	157	93

WSA: water stable aggregates, as % of total clay (Kemper and Rosenau, 1986). MWD_{fast}: mean weight diameter of aggregates-fast wetting treatment (Amezketa *et al.*, 1996). MWD_{slow}: mean weight diameter of aggregates-slow wetting treatment (Amezketa *et al.,* 1996). MWD_{stir}: mean weight diameter of aggregates-stirring after prewetting treatment (Amezketa *et al.,* 1996). $MWD_{microag}$: mean weight diameter of the particle size distribution resulting from macroaggregate breakdown (Kemper and Rosenau, 1986). FV: flocculation value (Amezketa and Aragüés, 1995). SDC: spontaneously dispersed clay, as % of total clay (Rengasamy *et al.,* 1984). MDC: mechanically dispersed clay, as % of total clay (Rengasamy *et al.,* 1984).

quartz sand, 1-2 mm in diameter. The soil columns were slowly prewetted from below with tap water (TW, EC ≈ 1.70 dS m^{-1}). The slow 2-3 h pre-wetting by capillarity prevented slaking. The high EC of the tap water, well above the FV of the soil clays (Table 2), prevented clay dispersion. The saturated columns were left to stand for about 13 h to increase aggregate mechanical strength (Levy *et al.*, 1997).

Following saturation, the flow direction was reversed and the columns were ponded and leached using a 3 cm-constant-head device. Three leaching waters were used: (i) canal irrigation water (CW, EC ≈ 0.38 dS m^{-1}, SAR ≈ 0.5 for the Bardenas soils, and EC ≈ 0.42 dS m^{-1}, SAR ≈ 0.8 for the Monegros soils), (ii) deionized water (DW, EC < 0.01 dS m^{-1}), which simulates rain water and leads to maximum clay dispersion, and (iii) saturated gypsum water (GW, EC ≈ 2.2 dS m^{-1}), which represents conditions without clay dispersion.

The leachates were collected in appropriate volume increments, and their ECs were periodically measured. The infiltration rate (IR, equivalent to the saturated hydraulic conductivity) of the soil columns was calculated using:

$$IR = \frac{\Delta Q}{A\Delta t}$$

where ΔQ is the volume of water collected during a given time period Δt, and A is the cross sectional area of the soil columns. The leaching process was continued until both a final steady-state effluent EC and infiltration rate (FIR) were achieved. These steady-states were reached in about 1-74 pore volumes, depending on the soil type.

A soil was considered susceptible to clay dispersion when the FIRs obtained with DW and/or CW were significantly lower ($P < 0.05$) than the FIR obtained with GW. For comparison of the susceptibility of soils to DW and CW, the FIRs were expressed in relative terms (RFIR), given by the ratio of FIR for a given solution (DW or CW) to that for GW. Thus, $RFIR_{DW}$ and $RFIR_{CW}$ represent stability indices of infiltration against clay dispersion produced by rainwater (DW) and irrigation canal water (CW), respectively. Low RFIR values indicate susceptibility to clay dispersion and high RFIR values indicate resistance to clay dispersion.

Susceptibility of soils to aggregate slaking: effect of fast wetting on infiltration rate

The preparation of the soil columns and the leaching process for this test was done as described above. The only difference was that air-dry soils were used instead of pre-saturated soils, and that only irrigation canal water (CW) was used for leaching. This fast wetting treatment was compared with the previously described slow wetting-CW leaching treatment.

A soil was considered susceptible to slaking when the FIR obtained in the fast-wetting treatment was significantly lower ($P < 0.05$) than the FIR obtained in the slow-wetting treatment. For comparison of the susceptibility of soils to slaking, the FIRs were expressed in relative terms (RFIR), given by the ratio of FIR for fast-wetting treatment to that for the slow-wetting treatment. Thus, the RFIRs of the air-dry (non-presaturated, «ns») soils leached with CW ($RFIR_{CWns}$) represent stability indices of infiltration against aggregate slaking produced by the fast-wetting of soils. Low $RFIR_{CWns}$ values indicate susceptibility to slaking and high $RFIR_{CWns}$ values indicate resistance to slaking.

Statistical analysis

Each soil and treatment was replicated four times. Eighty percent of the coefficients of variation (CV) of the mean FIRs were lower than 30%, and the average CV for all the treatments and soils was 28%. According to other studies (Abu-Sharar *et al.*, 1987; Chiang *et al.*, 1987), these values were considered satisfactory.

Results were analysed using the Statgraph *Plus* 2.1 software. One-way ANOVA was carried out to compare the means of the FIR among soils and treatments. Where the analyses showed significant differences at $P \leq 0.05$, Duncan's multiple range tests were conducted to separate FIR values from individual treatments. Also, correlation analysis, a non- parametric statistical test (Spearman rank correlation test), and simple regressions were employed. The Spearman rank correlation test is resistant to outliers since it is based on the ranks of the data rather than on the data itself. Statistical significances were reported at the 0.05 ($P < 0.05$,*) and 0.01 ($P < 0.01$,**) probability levels.

Results

Susceptibility of soils to clay dispersion: effect of electrolyte concentration on infiltration rate

The mean IRs as a function of cumulative time of leaching for the ten soils pre-saturated with tap water and subjected to deionized water (DW), canal irrigation water (CW) and gypsum-saturated water (GW) are presented in Fig. 1. Changes in IR were attributed to clay dispersion, since slaking was prevented (the soils were pre-saturated before leaching; i.e., no soil matric potential gradient and no entrapped air in the soil columns). Decreases in IR_{GW} during leaching were generally negligible, indicating the lack of clay dispersion when the soils where equilibrated with the gypsum-saturated water. On the other hand, some soils exhibited pronounced decreases in their IRs, especially when subject to DW, indicating clay dispersion and sealing. In most soils the IR_{DW} were lower than the IR_{GW} from the start of leaching, suggesting that clay dispersion induced by DW was almost instantaneous.

It took 1 to 5 h to achieve the steady-state or final infiltration rate (FIR). Approximately 1 to 145 pore volumes were passed through the columns in order to equilibrate the exchange phase of the soil with the composition of the solution and to obtain a constant EC of the leachates (data not given). The mean FIRs of the soils studied varied from 955 mm h^{-1} (FIR_{CW} of Sariñena 4) to 0.1 mm h^{-1} (FIR_{DW} of Callén 1).

The final infiltration rates in most soils decreased in the order: $FIR_{GW} > FIR_{CW} > FIR_{DW}$ (Table 3), following the well-established effect of increased clay dispersion and partial plugging of conducting pores (> 50 μm) with decreasing electrolyte concentrations.

The FIR_{CW} was significantly lower ($P < 0.05$) than FIR_{GW} for five of the ten soils (Table 3). These five soils had $RFIR_{CW}$ values lower than 70% (Table 3).

Seven out of the ten soils leached with deionized water (i.e., simulated rainwater) had FIR_{DW} significantly lower ($P < 0.05$) than the corresponding FIR_{GW} (Table 3). These seven soils had $RFIR_{DW}$ values lower than 60% (Table 3). Two (i.e., SA 3/1 and Sariñena 4) out of the three remaining soils also exhibited FIR_{DW} values 35 to 45% lower than the corresponding FIR_{GW} values, but they were not significantly different due to their relatively large standard errors.

Susceptibility of soils to aggregate slaking: effect of fast wetting on infiltration rate

The susceptibility of soils to slaking was analysed by comparing the IRs of the presaturated (i.e., slow wetting) and air-dry (i.e., fast wetting) soil columns subject to CW (Fig. 1). The IRs in five of the ten air-dry soil columns (IR_{CWns}) increased during the first minutes of leaching, probably due to dissolution and/or escaping of the entrapped air within the pores and the rearrangement of the soil particles during the fast-wetting process. Thereafter, IR_{CWns} remained constant or decreased slowly during the leaching process.

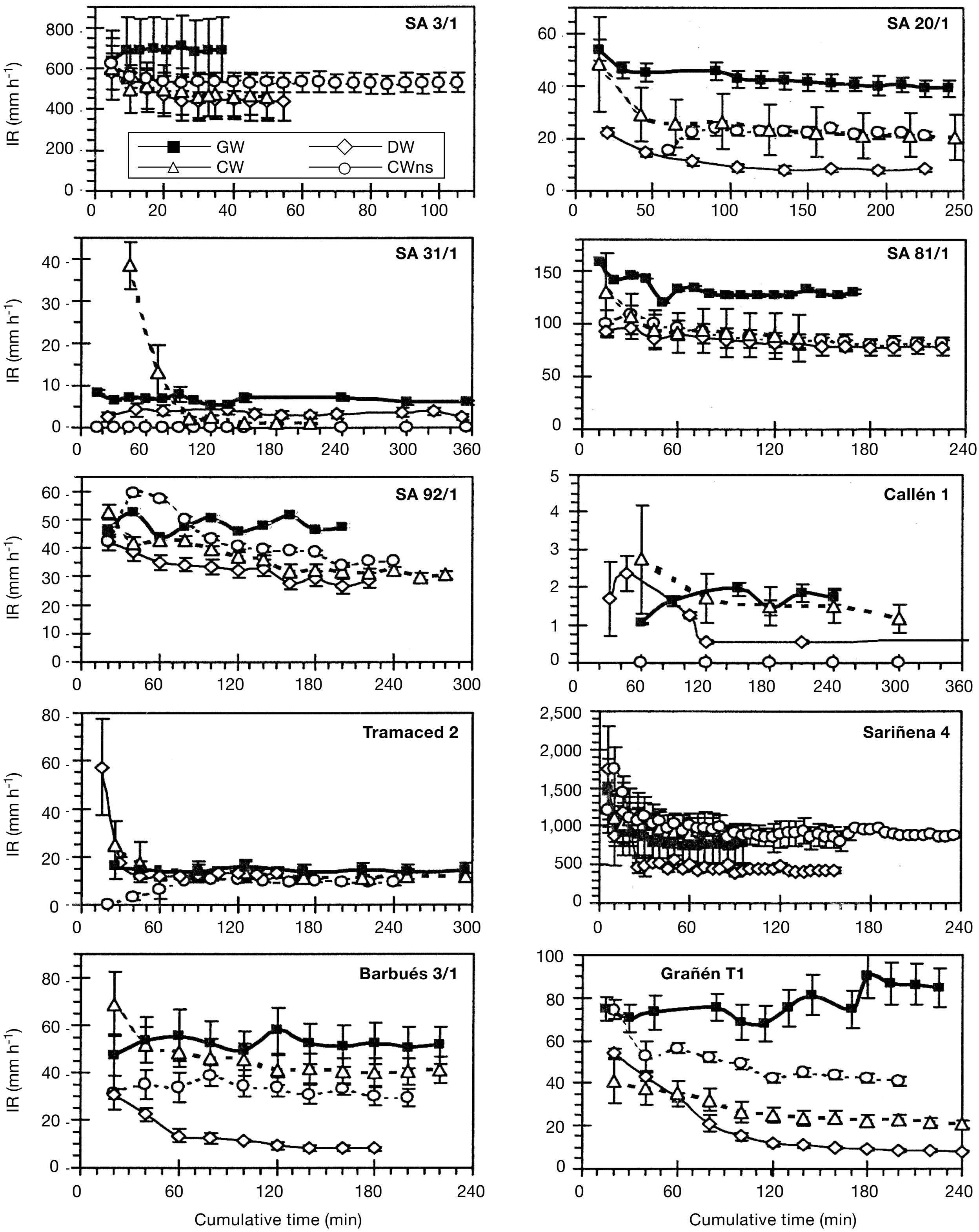

Figure 1. Infiltration rate (IR) as a function of cumulative time for the ten soils pre-saturated with tap water and leached with deionized water (DW, EC < 0.01 dS m^{-1}), canal irrigation water (CW, EC ≈ 0.4 dS m^{-1}, SAR < 1), and gypsum-saturated water (GW, EC = 2.2 dS m^{-1}) and of ten non pre-saturated soils leached with CW (CW$_{ns}$). Vertical bars represent standard errors of the means of four replications.

Table 3. Absolute (FIR) and relative (RFIR) steady-state or final infiltration rates measured in four replicate slowly-pre-wetted soil columns leached with gypsum-saturated water (GW), deionized water (DW), and canal irrigation water (CW), and in four replicate air-dry soil columns leached with CW (CWns). For each soil, FIR values with different letters were significantly different at $P < 0.05$

Soil	Slowly pre-wetted soil			Air-dry soil			
	FIR_{GW} ($mm\ h^{-1}$)	FIR_{DW} ($mm\ h^{-1}$)	FIR_{CW} ($mm\ h^{-1}$)	FIR_{CWns} ($mm\ h^{-1}$)	$RFIR_{DW}$ (%)	$RFIR_{CW}$ (%)	$RFIR_{CWns}$ (%)
SA 3/1	690 a	437 a	468 a	530 a	63.3	67.8	113.2
SA 20/1	39.6 b	8.4 a	20.9 a	21.1 a	21.3	52.8	101.1
SA 31/1	7.75 c	2.46 b	1.05 ab	0.00 a	31.7	13.5	0.0
SA 81/1	131 b	77.2 a	86.8 a	81.9 a	59.2	66.5	94.3
SA 92/1	47.5 b	28.7 a	28.7 a	35.3 a	60.3	60.4	123.1
Callén 1	1.73 b	0.10 a	1.16 b	0.00 a	5.8	67.1	0.0
Tramaced 2	14.2 a	13.3 a	11.6 a	9.12 a	93.6	82.2	78.4
Sariñena 4	767 a	418 a	955 a	831 a	54.5	124.4	87.0
Barbués 3/1	51.7 c	7.83 a	41.3 bc	29.4 b	15.1	79.9	71.2
Grañén T1	84.8 c	7.96 a	20.6 a	40.8 b	9.4	24.3	198.5

Except for the first 60 to 90 min of leaching, the IR curves of the fast wetting and slow wetting soils were parallel and quite similar in eight of the ten soils. Only soils SA 31/1 and Callén 1 had unparalleled IR_{CWns} and IR_{CW} curves because of the impervious character of their air-dry soil columns (i.e., $IR_{CWns} = 0\ mm\ h^{-1}$) from the start of leaching, indicating that slaking took place immediately after ponding with CW. It is noted that the IR curves were parallel in Grañén T1, but IR_{CWns} was greater than IR_{CW} from the start and during the leaching process, indicating that the fast wetting in this soil increased and maintained the proportion of conducting pores.

The final infiltration rate (FIR) of the slowly pre-wetted (i.e., no slaking) and the air-dry (i.e., potential slaking) soils were similar (i.e., not significantly different at $P > 0.05$) in eight of the ten soils studied (Table 3).

Predicting steady-state infiltration rates from macro and micro-aggregate stability indices

We first analysed potential relationships between the relative final infiltration rates (RFIR) of the ten soils studied and the corresponding stability indices presented in Table 2. No clear relations were found in general between RFIR and these stability indices, although WSA (Water Stable Aggregate) *vs*. $RFIR_{CW}$, and MDC (Mechanically Dispersed Clay) *vs*. $RFIR_{DW}$ showed an apparent threshold behaviour. Thus, $RFIR_{CW} > 50\%$ were only obtained when $WSA > 75\%$, and $RFIR_{DW} > 30\%$ when $MDC < 45\%$.

In addition, $RFIR_{DW}$ was satisfactorily estimated from the mechanical dispersed clay (MDC) through:

$$RFIR_{DW} = \frac{1}{(0.0032 + 0.0013\,MDC)}\ ;\ R^2 = 0.692^{**}$$

This equation indicates that the most dispersible soils on the basis of the MDC (a measure of the stability of clays against the mechanical and chemical dispersion; Rengasamy *et al.*, 1984) are also those presenting the lowest $RFIR_{DW}$. In addition, the Spearman correlation coefficient ($r_s = -0.71^*$) shows that $RFIR_{DW}$ and MDC ranked the soils in a similar inverse order.

Secondly, we analysed potential relationships between the final infiltration rates (FIR) of the ten soils and the corresponding stability indices presented in Table 2. This analysis was carried out using the Ln FIR in order to normalise their log-normal distribution values. WSA was the only index with some significant correlation coefficients (r) when the ten soils were included in the analysis. Thus, Ln FIR_{CW} and Ln FIR_{CWns} were positively and significantly ($P < 0.05$) correlated with WSA, although the R^2 only explained about 50% of the Ln FIR variances.

The graphical representations of Ln FIR *vs.* WSA (Fig. 2) show that the Callén soil was a clear outlier in these relationships (i.e., its WSA of 83% is much higher than the expected value given by the general linear tendency). This is probably because of its very high SAR (111), which promoted the complete breakdown of aggregates in the WSA test, so that the detached particles totally blocked the 250 mm-sieve, giving an erroneous result.

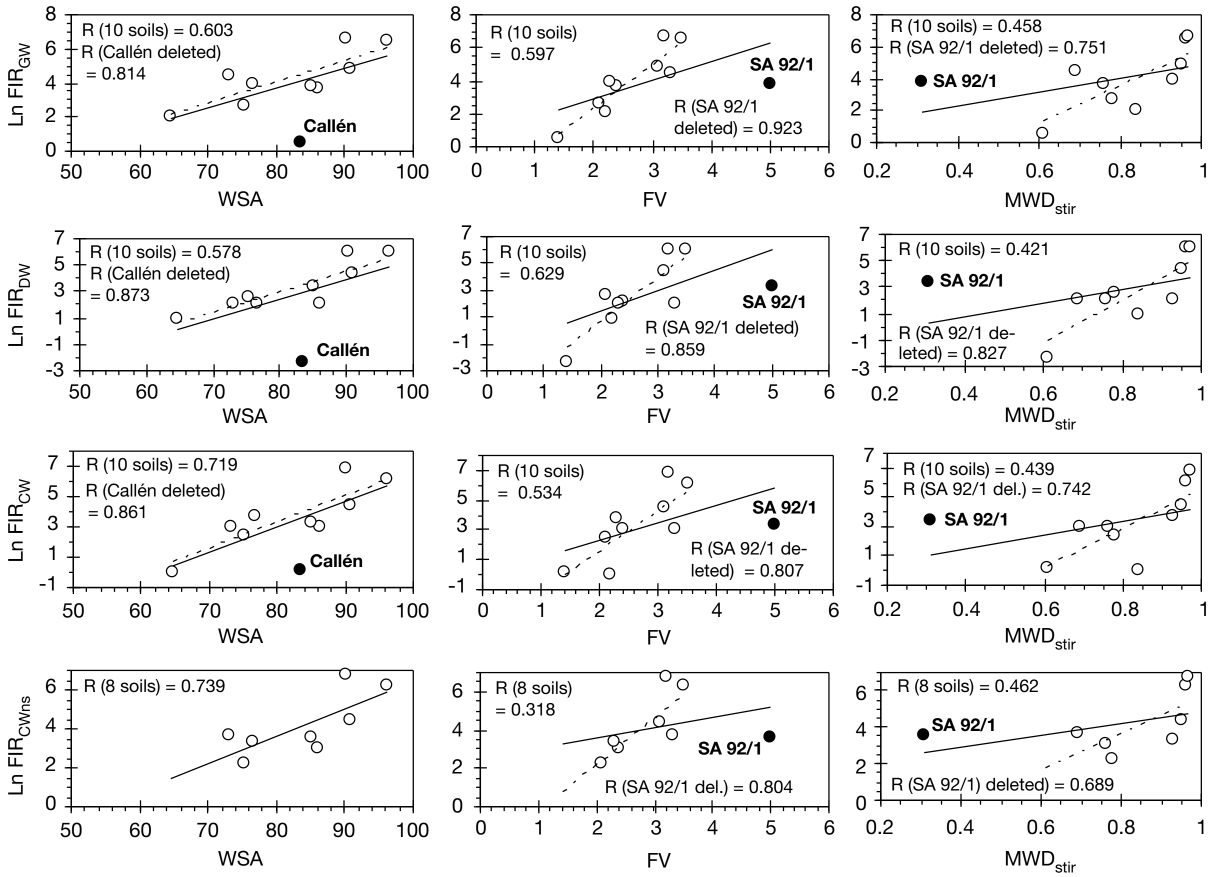

Figure 2. Relationships between Ln of final infiltration rates (FIR_{GW}, FIR_{DW}, FIR_{CW} and FIR_{CWns}) of the soils studied and the corresponding stability indices WSA, FV and MWD_{stir}, with indication of their linear correlation coefficients. Solid lines are for the ten soils (eight for $LnFIR_{CWns}$), and dashed lines are for the nine soils (seven for $LnFIR_{CWns}$) (i.e., black-dot soils excluded from regressions).

When the Callén soil (represented in Fig. 2 by a black dot) was excluded from the regressions, the correlation coefficients increased to greater than 0.8 (significant at $P < 0.01$) for Ln FIR_{GW}, Ln FIR_{DW} and Ln FIR_{CW} (Table 4). The Spearman rank correlation test lead to the same correlations (data not shown), and thus to similar qualitative conclusions. These positive correlations are conceptually consistent, since both WSA and FIRs were obtained under similar treatment conditions (slow wetting, certain mechanical stress and certain chemical dispersion, except in the gypsum leaching treatment). The mechanical stress consisted of a light stirring of the soil samples in the WSA test, and of a light soil disturbance due to the water flow in the infiltration studies. In summary, the more stable the aggregates, the greater the steady-state soil infiltration rates. WSA may therefore be used to estimate FIR with a high level of confidence.

Similarly, the graphical representations of Ln FIR *vs.* MWD_{stir} and FV show that the SA 92/1 was an outlier (black dots in Fig. 2). No apparent reasons were found for the abnormal behaviour of this soil. When excluded, all the regressions (except those with Ln FIR_{CWns}) were significant at $P < 0.01$ (FV) or $P < 0.05$ (MWD_{stir}), indicating that these stability indices could be apparently used to estimate the FIRs in this set of soils. The Spearman rank correlation coefficients also indicated that these indices ranked the soils in the same order as the infiltration parameters (data not given).

The positive correlations between the infiltration parameters (Ln FIR_{GW}, Ln FIR_{CW}, Ln FIR_{DW}) and the MWD_{stir} index are conceptually consistent since they were obtained after presaturation and certain mechanical stress and chemical dispersion (except in the gypsum leaching treatment). Presaturation was performed by capillarity in the infiltration studies, and with ethanol in the Le Bissonnais test. The mechanical stress consisted of a light stirring of the soil samples in DW in the Le Bissonnais test, and of a light disturbance of the soil due to the water flow in the infiltration

Table 4. Correlation matrix between the natural logarithms of the final infiltration rates (Ln FIR) of the soils studied and the corresponding stability indices that gave significant correlation coefficients at $P < 0.05$ (*) and $P < 0.01$ (**).

Stability index	Ln FIR_{GW}	Ln FIR_{DW}	Ln FIR_{CW}	Ln FIR_{CWns}
WSA	0.603^{NS}	0.578^{NS}	0.719*	0.739*[1]
WSA; Callén soil excluded	0.814**	0.873**	0.861**	0.739*[1]
MWD_{stir}; SA 92/1 soil excluded	0.751*	0.826**	0.742*	0.689^{NS2}
FV; SA 92/1 soil excluded	0.923**	0.859**	0.807**	0.804*[2]

[1] Eight soils. [2] Seven soils.

studies. In addition, certain chemical dispersion occurred in those tests, except in the gypsum leaching treatment. Thus, infiltration increased as aggregate stability (i.e., MWD_{stir}) increased.

On the other hand, the positive correlations between the steady-state infiltration values and the FV index (Fig. 2, soil SA 92/1 excluded) were opposite to the expected ones, since the higher the FV of a soil, the higher its tendency to disperse and, therefore, the lower its FIR. Although these results are not conclusive since only nine (seven for Ln FIR_{CWns}) soils were included in this analysis, they raise doubts about the use of the FV as an index of the stability of soils against clay dispersion and the subsequent reductions in soil infiltration rate.

It is remarkable to note the lack of significant correlations between the infiltration rates and the rest of the stability indices (MWD_{fast}, MWD_{slow}, $MWD_{microag}$ and SDC). We expected to find reliable and positive relationships between FIR_{CWns} (i.e., fast wetting of soils with canal water) and MWD_{fast} values, since the last index measures the stability of aggregates *versus* fast wetting (i.e., potential slaking of aggregates). However, only two soils were susceptible to slaking according to the FIR_{CWns}, whereas all soils (except Barbués 3/1) were very sensitive to slaking according to MWD_{fast} ($MWD_{fast} < 0.5$ mm; Amezketa *et al.*, 2003a). This suggests that MWD_{fast} overestimates the actual slaking observed in the infiltration experiments.

Discussion

Susceptibility of soils to clay dispersion: effect of electrolyte concentration on infiltration rate

No clear relationships were found between the FIRs obtained with the three solutions and the soil properties presented in Table 1. Nevertheless, the two soils exhibiting the highest FIRs (SA 3/1 and Sariñena 4) had the lowest SAR and EC in the saturation extract, whereas the two soils exhibiting the lowest FIRs (SA 31/1 and Callén 1) had the highest SAR and EC. The low FIRs of SA 31/1 and Callén 1 soils, close to 1 mm h^{-1} with the canal irrigation water (Table 3), indicate that they are not cultivable without amelioration. The reclamation is feasible using gypsum-saturated waters in soil SA 31/1, since its FIR_{GW} increased to 7.8 mm h^{-1}, but not in soil Callén 1, whose FIR_{GW} of 1.7 mm h^{-1} was still insufficient for leaching purposes.

A remarkable result is that even though the electrolyte concentration of the canal water (3.8 to 4.2 $mmol_c\ L^{-1}$) was greater than the soils' FVs (except in soil SA 92/1, with a FV of 5.0 $mmol_c\ L^{-1}$), FIR_{CW} was significantly lower ($P < 0.05$) than FIR_{GW} for five of the ten soils (Table 3). Since there were no swelling clays in these soils and aggregate slaking was negligible in the slow-presaturated soil columns, clay dispersion should be mainly responsible for the decreased FIRs. This implies that FV was not an appropriate index of dispersion for those soils. Nevertheless, it should be noted that the electrolyte concentration of the canal water was only slightly greater than the FVs. Furthermore, the SAR value of the canal water was between 0.5 and 0.8, whereas the FVs were obtained with $CaCl_2$ solutions (i.e., SAR = 0). The evidence that clay dispersion was induced by the low EC of the canal water is substantiated by the fact that eight of the ten soils had FIR_{CW} values not significantly different ($P > 0.05$) from the FIR_{DW} values (Table 3).

The susceptibility of soils to clay dispersion and sealing induced by CW may be classified in three different groups on the basis of their relative final infiltration rates ($RFIR_{CW} = 100FIR_{CW}/FIR_{GW}$) (Table 3): (i) very susceptible soils (SA 31/1 and Grañén T1), with $RFIR_{CW} < 25\%$ (i.e., reductions greater than 75%

compared to the corresponding FIR values obtained with GW, and significantly different at $P<0.05$), (ii) susceptible soils (SA 20/1, SA 81/1 and SA 92/1), with $RFIR_{CW}$ between ~50 and ~70% (i.e., reductions of between 50 and 30% of FIR_{GW}, and significantly different at $P<0.05$), and (iii) resistant soils (SA 3/1, Callén-1, Tramaced-2, Sariñena-4 and Barbués 3/1), with $RFIR_{CW} > \sim70\%$ (i.e., reductions lower than 30% of the FIR_{GW}, and not significantly different at $P > 0.05$). In summary, four of the five soils irrigated with the Bardenas canal water and one of the five soils irrigated with the Monegros canal water were very sensitive or sensitive to clay dispersion, soil sealing and crusting.

The substantial reductions in FIR_{DW} with respect to the FIR_{GW} values for the seven soils (Table 3) were attributed to clay dispersion induced by the very low electrolyte concentration (<0.1 $mmol_c\ L^{-1}$) of deionized water, well below the 1.4 to 5.0 $mmol_c\ L^{-1}$ soils' FVs (Table 2). The dispersed clay particles were retained within the soil columns, since no clay was collected in the leachates (data not given). The lodgement of clay particles in soil columns leached with distilled water were also reported by Felhendler *et al.* (1974), Frenkel *et al.* (1978), Pupinsky and Shainberg (1979), Chiang *et al.* (1987), and Amezketa and Aragüés (1995). Even soils with very low SAR levels (i.e., SA 20/1, SA 92/1, Grañén T1) exhibited these reductions in FIR_{DW}, in agreement with Amezketa and Aragüés (1995). Similar results were obtained by Agassi *et al.* (1981), Shainberg *et al.* (1992) and Mamedov *et al.* (2000) in sprinkler-irrigated soils, where the beating action of raindrops enhanced clay dispersion and exacerbated the negative effect of SAR. However, less documentation is available concerning the negative effects of very low SAR levels on infiltration in flood-irrigated soils, where the drop-impact mechanism is irrelevant.

The susceptibility of soils to clay dispersion induced by DW may be classified in three different groups on the basis of their relative final infiltration rates ($RFIR_{DW} = 100FIR_{DW}/FIR_{GW}$) (Table 3): (i) very susceptible soils (SA 20/1, SA 31/1, Callén-1, Barbués 3/1 and Grañén T1), with $RFIR_{DW} \leq 30\%$ (i.e., reductions greater than 70% compared to the corresponding FIR values obtained with GW, and significantly different at $P < 0.05$), (ii) susceptible soils (SA 3/1, SA 81/1, SA 92/1 and Sariñena-4), with $RFIR_{DW}$ between 55 and 65% (i.e., reductions of between 45 and 35% of FIR_{GW}, and depending on soils significantly different at $P<0.05$ or not significantly different at $P > 0.05$), and (iii) resistant soils (Tramaced 2) with $RFIR_{DW} = 94\%$, not significantly different to the FIR_{GW} at $P>0.001$. In summary, nine (seven from a statistical point of view) out of the ten soils examined were very sensitive or sensitive to clay dispersion induced by simulated rainwater. The addition of chemical (i.e., gypsum, soil conditioners, etc.) and physical (i.e., soil mulching) amendments to the surface of these soils are recommended practices to avoid or minimise clay dispersion and soil crusting under rainfall conditions.

Susceptibility of soils to aggregate slaking: effect of fast wetting on infiltration rate

In eight of the ten soils studied, the similar final infiltration rate (FIR) of the slowly pre-wetted (i.e., no slaking) and the air-dry (i.e., potential slaking) soils (Table 3) indicated that slaking did not determine their FIR values. Although slaking took place in soil SA 31/1, its FIR_{CWns} value was similar (i.e., not significantly different at $P > 0.05$) to the FIR_{CW} value (which was very low because of the high clay dispersion produced by the CW in the slowly pre-wetted treatment; Fig. 1). Of the two soils with significant differences ($P < 0.05$) between FIR_{CWns} and FIR_{CW}, Grañén T1 had a higher FIR_{CWns} value (i.e., as previously indicated, fast wetting and particle rearrangement promoted infiltration) whereas Callén 1 had a lower FIR_{CWns} (i.e., fast wetting induced slaking and decreased infiltration). In summary, slaking provoked by fast wetting was relevant in two soils (SA 31/1 and Callén 1), but only in Callén 1 the final infiltration rate of the slaked soil was significantly lower ($P < 0.05$) than in the unslaked soil.

The $RFIR_{CWns}$ (i.e., $100FIR_{CWns}/FIR_{CW}$) values (Table 3) were: (i) greater than 100% in three soils (i.e., fast wetting promoted infiltration), although this increase was only significant ($P < 0.05$) in Grañén T1, (ii) very high (close to 100%) in two soils (i.e., infiltration was not affected by fast wetting), (iii) high (between 70 and 90%) in three soils (i.e., infiltration was low to moderately affected by fast wetting) and (iv) zero (i.e., fast wetting induced slaking and lead to impermeable soils) in two soils characterised by their already low or very low permeability irrespective of the leaching solutions. Thus, in general, slaking was not a significant process of aggregate breakdown, seal formation and plugging of conducting pores in the soils studied. In contrast, Le Bissonnais and Singer (1992) found that the infiltration rate in two initially air-dry soils was 20 times lower than that for the prewetted soils after 40 mm rainfall due to slaking. Levy *et al.* (1997) and Mamedov and Levy (2001) also observed that slaking reduced significantly the final infiltration rate in two and five soils respectively. The above authors concluded that the rate of surface aggregate prewetting prevails in determining aggregate slaking, susceptibility to sealing and low IR. These studies were performed under simulated rainfall, where the raindrop impact exacerbated the slaking effect on infiltration. In contrast, there are very few studies quantifying the effect of slaking on IR under flood irrigation, despite the evidences of slaking and slumping of aggregates during irrigation in field and in column studies (Ferruzzi *et al.*, 2000; Mace and Amrhein, 2001). Auerswald (1995) observed that percolation (i.e., the amount of water that percolated in 10 min) of air-dry aggregates flood-irrigated with DW was much smaller than that of the same slowly-wetted aggregates, due to slaking. In general, percolation linearly increased and slaking was reduced with increasing antecedent moisture contents. Levy *et al.* (1997) ascribed the sensitivity of the aggregates to slaking to the high silt-to-clay ratio (1.63), whereas Mamedov and Levy (2001) found that soil susceptibility to slaking increased with increases in clay content up to 40%. None of these reasons could explain our results, since half of our soils had silt-to-clay ratios greater than 1.6 and only two of them slaked. In addition, the only two soils that slaked had clay contents lower than 40%, while the only soil with clay content higher than 40% (SA 81/1) did not slake.

In terms of water management, the two soils susceptible to slaking should be irrigated using systems of low application rates (i.e., drip, sprinklers of low pluviometry, etc.). If furrow or flood irrigation systems must be used, slaking could be prevented or minimised by forming raised-beds (Chan and Mullins, 1994) and adding organic matter (Chenu *et al.*, 2000; Ferruzzi *et al.*, 2000) or hydrophobic polymers such as polyacrylamides (Ferruzzi *et al.*, 2000) to the soil surface. These polymers prevent or slow down the entry of water into the aggregates, and increase the internal cohesion and binding of aggregates.

Finally, considering that seven and five soils were susceptible to clay dispersion induced by DW and CW, respectively, and that only two soils were susceptible to aggregate slaking, it can be concluded that clay dispersion rather than aggregate slaking was the principal mechanism controlling the infiltration rates of these arid-zone soils when subject to rainfall and canal irrigation waters.

Predicting steady-state infiltration rates from macro and micro-aggregate stability indices

The significant correlations found between $RFIR_{DW}$ and MDC indicate that MDC could be a reliable screening index of the relative susceptibility of soils to clay dispersion induced by rainwater (DW) if these preliminary results are validated in a wider spectrum of soils.

Sumner (1993) suggested that MDC could reflect the behaviour of clays when the velocity of water in the soil pores is high enough to cause clay particles to become dispersed. Miller and Baharuddin (1986) found that a number of south-eastern USA soils were dispersible when shocked in DW, and obtained significant ($P < 0.01$) and negative correlations between several measures of soil dispersibility and soil infiltration. Particularly, the dispersible clay measured after 36 h of shaking at an 8:1 water:soil ratio, and a time-weighted dispersible clay index had the highest correlation coefficients ($r \approx -0.5$ to -0.6). Levy *et al.* (1993) also found a significant ($P < 0.01$) and negative relation between the percentage of dispersed clay (i.e., clay dispersed in DW after 1 h- shaking at an 15:1 water:soil ratio) and the logarithm of the final infiltration rate in 23 soils, although the correlation only explained 55% of the FIR variance. Minhas and Sharma (1986) found a negative relation between the relative hydraulic conductivity of soils leached with DW (RHC_{DW}) and the degree of clay dispersion (CD) calculated as the percent of total clay that dispersed after shaking (end-over-end, twenty times in a 50:1 water:soil ratio). The correlation coefficients were -0.67^{**} and -0.78^{**} for sandy loam and clay loam soils, respectively. However, the prediction capability was improved when log RHC_{DW} was plotted as a function of log CD (r increased to –0.90 and –0.97 for the two soils, respectively). So and Cook (1993) showed for 152 soils that the hydraulic conductivity values of slaked and dispersed soils were strongly dependent on the amount of dispersed clay (i.e., percent of total clay that dispersed in DW after shaking end-over-end for 30 min in a 20:1 water:soil ratio) or the amount of dispersed silt+clay. The most suitable relationships were logarithmic with a significant level at $P < 0.001$. These results are consistent with those found in our work.

The positive correlations found in our work between WSA and FIRs may indicate that WSA may be used to estimate FIR with a high level of confidence. Reanalysing the data of Ramos and Nacci (1997), we also found a significant correlation between WSA and the hydraulic conductivity of 11 mulched soils. Roth *et al.* (1986) (cited in Roth, 1992) also found a positive and significant correlation between WSA and FIR obtained under simulated rainfall.

Similar to our findings, Amezketa *et al.* (1996) obtained significant correlations between MWD_{stir} and the infiltration rates of 10 California soils. Reanalysing the data of Ramos and Nacci (1997), we also found significant correlations between MWD_{stir} and the hydraulic conductivity of 11 mulched soils. Le Bissonnais and Arrouays (1997) also found a significant positive correlation between wet stirring MWD (similar to MWD_{stir}) and an infiltration coefficient (i.e., the ratio between infiltration and rainfall) under simulated rainfall.

In summary, of the eight stability indices examined as possible estimators of FIR, the WSA (water stable aggregates), MDC (mechanically dispersed clay) and MWD_{stir} (mean weight diameter of stirring aggregates after a prewetting treatment) indices gave consistent and significant relationships with FIRs. The validity of the WSA, MDC and MWD_{stir} indices to rank and predict the infiltration rate of soils subject to clay dispersion and aggregate slaking should be ascertained in a wider spectrum of soils.

Acknowledgments

This work was financially supported by the Spanish National Institute for Agricultural and Food Research and Technology (INIA). We wish to thank Rafael Rodriguez (University of Lleida) for the X-ray analysis.

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