Soil hydraulic conductivity as affected by physical and chemical properties of effluents

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SUMMARY

The objective of this work was to evaluate the contributions of the physico-chemical factors which may cause reduction in soil hydraulic conductivity (K_{sat}) upon land disposal of sewage effluent. In particular the binding of polyvalent metals by organic molecules and the plugging by suspended solids were studied. The binding capacity of effluents discharged from oxidation ponds was determined with the aid of gel chromatography. The range of binding capacity found lies between 8 and 25 % of the total Ca + Mg content of the effluent. The effect of this binding on the exchangeable sodium percentage (ESP) of two soils and a standard clay was determined. Columns packed with a sand and a sandy loam were leached with unfiltered effluents and with the same effluents after different degrees of filtration. Subsequently, distilled water was applied to the same columns. Filtered effluent caused approximately a 20 % reduction in K_{sat} for both soils, whereas more than double this reduction was caused by unfiltered effluent. The results show that the main mechanism responsible for the immediate decrease in soil K_{sat} upon effluent application may be the physical pore plugging by suspended solids. The binding of polyvalent cations may cause a further reduction in K_{sat} when irrigation with high quality water or rain succeed the effluent application.

Additional key words: *Sewage water, physical plugging, suspended solids, polyvalent cations binding, sodium adsorption ratio.*

RÉSUMÉ

Effet des propriétés physiques et chimiques des effluents d'eaux résiduaires sur la conductivité hydraulique des sols.

L'objectif de ce présent travail est de faire la part respective des facteurs physico-chimiques qui peuvent provoquer une réduction de la conductivité hydraulique (K_{sat}) des sols lors de l'épandage d'eaux résiduaires. La complexation des métaux polyvalents par les molécules organiques et le colmatage par les matières en suspension (MES) ont été étudiés en particulier. La capacité de complexation dans des effluents obtenus à la sortie de bassins d'oxydation a été déterminée à l'aide de la chromatographie sur gel. Les valeurs de capacité de complexation trouvées sont comprises entre 8 et 25 p. 100 de la concentration totale en Ca + Mg de l'effluent. L'effet de cette complexation sur le pourcentage en sodium échangeable de deux sols et d'une argile standard a été déterminé. Des colonnes remplies d'un sable et d'un sable limoneux ont été lessivées avec des effluents non filtrés et ces mêmes effluents après divers degrés de filtration. Par la suite, de l'eau distillée a été versée sur ces mêmes colonnes. L'effluent filtré provoque approximativement une réduction de K_{sat} de 20 p. 100, tandis que l'effluent non filtré provoque au moins une réduction double. Les résultats obtenus indiquent que le principal mécanisme responsable de la décroissance immédiate de K_{sat} des sols, due à l'application d'effluents, semble être le colmatage physique des pores par les MES. La complexation des cations polyvalents pourrait provoquer une réduction supplémentaire de K_{sat} , au cas où une irrigation avec une eau de bonne qualité ou la pluie succède à l'irrigation avec ces effluents.

Mots clés additionnels: *Eaux résiduaires, colmatage physique, matières en suspension, complexation des cations polyvalents, sodium adsorption ratio.*

I. INTRODUCTION

The nonbiological reduction of hydraulic conductivity (K_{sat}) upon effluent disposal has been explained in different ways. The clogging of soils has often been attributed to the accumulation of suspended solids (THOMAS *et al.*, 1966 ; DE VRIES, 1972 ; DANIEL & BOUMA, 1974 ; KRISTIANSEN,

1981). The effect of the suspended solids content of effluent on the K_{sat} was studied recently by VINTEN *et al.* (1983).

The contribution of the quantity and nature of the electrolytes in the sewage effluent to the hydraulic properties of soils has been treated in the past in a similar way to that used in conventional irrigation water (THOMAS & LAW, 1968 ; BURNS & RAWITZ, 1981). The recently demonstrated

capacity of organic solutes in sewage water to bind polyvalent cations (SPOSITO *et al.*, 1978; ACHER *et al.*, 1981) motivated the redefinition of the effective sodium adsorption ratio (SAR) of effluents as related to the effect of effluent disposal on soil K_{sat} . It was shown that binding of Ca^{2+} and Mg^{2+} increased the effective SAR of sewage effluent and thus contributed to the decrease in hydraulic conductivity observed in soils to which the effluents were applied (PISTOL, 1981).

Since sewage effluents are characterized by the simultaneous presence of organic and inorganic solids, organic solutes and inorganic electrolytes at various concentrations and ionic ratios, their effect on soil K_{sat} is probably due to a number of interrelated factors. The present study deals with the effect of various physical and chemical properties of sewage effluents on the hydraulic properties of soils. This information is of great importance for irrigation with effluents and for land disposal technology in general. The contribution of the suspended particles and of the binding of soluble bivalent metals in the applied effluents to the change in soil K_{sat} upon land disposal of the effluent is emphasized.

II. MATERIALS AND METHODS

A. Materials

Two soils were investigated and their characteristics are presented in table 1. Soil samples which passed through a 1 mm sieve were used. Effluents from Eilat, Gan Raveh and Ramat Hasharon municipal treatment plants were studied. Table 2 summarizes the properties of the effluents. Fisher bentonite (Na), Sephadex G10 and analytical grade chloride salts (MgCl_2 , CaCl_2 , NaCl) were used.

B. Procedure

1. Cation binding

The procedure for the separation of bound and free Ca^{2+} and Mg^{2+} ions using Sephadex gel was described by ACHER *et al.* (1981). Samples of 1 cm^3 volume were applied to the top of a gel column and then eluted with 50 ml of 0.01 N CaCl_2 . Ca^{2+} and Mg^{2+} concentrations were determi-

TABLE 1

Characteristics of the soils used in the experiments.
Caractéristiques des sols utilisés dans nos expériences.

Soil	Sand ($> 20 \mu$)	Silt ($2-20 \mu$) %	Clay ($< 2 \mu$)	CEC meq/100 g	CaCO_3 %	pH	Organic matter %	Dominant clay minerals
Netanya (a) Sand	92	5	3	2.7	0	7.7	0.05	Montmorillonite and Kaolinite
Bet Dagan (b) Sandy loam	86	0	14	8.5	2.3	7.9	0.7	Montmorillonite

(a) C Horizon.
(b) A Horizon.

TABLE 2

Characteristics of the sewage effluents used in the experiments (a).
Caractéristiques des effluents d'eaux résiduaires utilisés dans nos expériences (a).

Source of the effluent	Ca^{2+} ----- meq . l^{-1}	Mg^{2+} ----- meq . l^{-1}	Na^{+} ----- meq . l^{-1}	EC^c ----- mmho . cm^{-1}	SAR ^d	pH	COD ^e mg . l^{-1}	Suspended solids mg . l^{-1}
Eilat	12.3	10.2	25.0	5.1	7.4	8.1	170	120
Gan Raveh	5.0	3.0	13.0	1.8	6.5	8.35	140	160
Ramat Hasharon (b) Oxidation Pond	3.8	1.2	6.3	1.1	4.0	n.d.	133	180
Ramat Hasharon (b) Clarification Pond	2.7	1.1	6.1	1.1	4.4	n.d.	68	110

(a) All parameters were checked for the effluent filtered through Whatman 91 paper except for the SS which were checked for the unfiltered effluent.

(a) Tous les paramètres ont été déterminés pour l'effluent filtré à travers du papier filtre Whatman 91, à l'exception des matières en suspension déterminées pour l'effluent non filtré.

(b) From PISTOL, 1981.

(c) Electrical conductivity.

(d) Sodium adsorption ratio.

(e) Chemical oxygen demand.

ned in 1 cm³ portions collected with a fraction collector at the bottom of the column. Bound and free forms appeared as different peaks on the chromatogram.

2. Cation chemistry and exchangeable sodium percentage (ESP)

The effect of equilibration of soils and clay with the effluents on the composition of the exchange complex was compared to the effect of equilibration with model solutions of the same Ca²⁺, Mg²⁺ and Na⁺ content. The exchangeable cations in soils and in homoionic Na and Ca montmorillonite (prepared from Fisher bentonite), after contact with the effluents and the model solution were measured by ammonium acetate extraction. The exchangeable cations were determined in soil columns after 10 pore volumes had been applied to the soils. It was ascertained that a steady-state was achieved by then. In the case of the pure clays batch experiments were done. A Perkin Elmer 460 atomic absorption spectrophotometer was used for the determination of Ca²⁺ and Mg²⁺.

3. Colloidal plugging

Measurements assessing the importance of suspended colloids in altering the K_{sat} were made by comparing the effluent movement through soil columns after different degrees of filtration. Unfiltered effluents as well as effluents filtered through Whatman 91 or through millipore 0.45 μ filters were investigated. In table 3, the suspended solids contents and associated characteristics of Eilat effluents after the different filtration procedures are presented.

4. Hydraulic conductivity

Soil columns 12 cm long and 5 cm in diameter were mechanically packed to uniform densities (Netanya soil 1.45 g/cm³; Bet Dagan soil 1.35 g/cm³ — table 1), using a device described by YARON *et al.* (1965). Columns were presaturated with the effluent by upward wetting. Effluent was run through the columns under a constant head of 1 cm of water. A fraction collector was used to follow the flow rate as a function of the leachate volume until a steady-state was achieved (less than 4 hours). Immediately afterwards the column was eluted with distilled water and the flow rate was again followed. The K_{sat} was determined from the flow rate using Darcy's law.

III. RESULTS AND DISCUSSION

A. Ca²⁺ and Mg²⁺ binding

In conventional irrigation water the SAR-ESP (sodium adsorption ratio-exchangeable sodium percentage) relations are a well-known tool for estimating the effect of water quality on the soil K_{sat} (e.g. QUIRK & SCHOFIELD, 1955; FRENKEL *et al.*, 1978). If organic solutes in the added effluents have a binding capacity for polyvalent metals, it is instructive to estimate the effect of such binding on the resulting K_{sat} . Table 4 presents the binding capacity of the effluents studied. It may be observed that the binding capacity is between 8-26 % of the soluble Ca²⁺ + Mg²⁺ content.

Adsorption and desorption, precipitation and biological reaction may cause a reequilibration between the bound and unbound cations in the effluent after it is added to the soil. However, after that steady state is achieved, the effect of the equilibrium binding capacity on the soil's exchange complex may be defined in many cases by the relation :

$$\text{SAR}_E = \frac{\text{Na}^+}{\left[\frac{\text{Ca}_F^{2+} + \text{Mg}_F^{2+}}{2} \right]^{1/2}} \quad (1)$$

where Ca_F^{2+} and Mg_F^{2+} are the unbound cations concentrations (meq/l) in the equilibrium soil solution, Na^+ is the sodium concentration (meq/l) and SAR_E is the effective SAR which determines the ESP in the soil according to the modified Gapon equation :

$$\text{ESP} = \frac{K_G \text{SAR}_E}{1 + K_G \text{SAR}_E} \quad (2)$$

where ESP is the exchangeable sodium percentage and K_G is the Gapon coefficient.

The actual steady state ESP will be strongly dependent on the soil and effluent properties such as the presence of CaCO₃ in soil, or the pH and CO₃²⁻/HCO₃⁻ contents of the effluent. These effects are known (BOWER *et al.*, 1968) and will not be further discussed here. It may be expected, for example, that CaCO₃ containing soils in which free Ca²⁺ is controlled by equilibrium with the solid CaCO₃ will be less affected by the binding of divalent ions.

TABLE 3

Eilat effluents after various degrees of filtration : some properties and effects on the K_{sat} of 2 soils.
Effluents d'Eilat après divers degrés de filtration : quelques propriétés et effets sur la conductivité hydraulique de 2 sols.

Degree of filtration	COD mg . l ⁻¹	Optical density ($\lambda = 400$ nm)	Suspended solids mg . l ⁻¹	K_{sat} decrease (°) (% initial K_{sat})	
				Bet Dagan soil	Netanya soil
No filtration	n.d.	0.33	50	53	65
Whatman 91 filter paper	170	0.22	7	20	22
Millipore filter	120	0.05	0	15	8
0.45 μ Pore diameter					
Model solution (°)	0	0	0	10	0

(°) After 10 pore volumes application of effluent.

(°) The model solution has the same Ca²⁺, Mg²⁺ and Na⁺ contents as the effluent.

TABLE 4

Binding capacity of some effluents.
Capacité de complexation de quelques effluents.

Source of the effluent	Binding capacity meq/l ⁻¹	Bound to total Ca + Mg in filtered effluent (%)
Eilat	5.6	25
Gan Raveh	1.1	14
Ramat Hasharon Oxidation pond	0.4	8
Ramat Hasharon Clarification pond	1.0	26

The effect of this binding on the ESP of the studied soils and of a standard clay is presented in table 5. Ramat Hasharon and Gan Raveh effluents raised the ESP of Fisher bentonite and the Netanya soil, respectively, above the ESP level reached upon contact with a model solution of the same SAR. Eilat effluent, on the other hand, brought the ESP of both Netanya and Bet Dagan soils to a level below that of the appropriate model solution. In this case, the factors mentioned above apparently overrode the effect of the binding capacity of the effluent on the ESP of the soil at steady state.

A model solution in which the SAR is equal to SAR_E of the effluent before it is added to the soils was prepared. Its effect on the ESP of the Netanya soil is given in table 5. In the case of both Eilat and Gan Raveh effluents, that ESP was larger than that resulting from elution with the effluent. This is a measure of the importance of different interactions of the effluent with the soil in reducing the effect of the binding of polyvalent cations in the effluent on the ESP of the soil.

In equations (1) and (2) it is assumed that exchangeable Ca and Mg behave in similar ways. This assumption holds only when the exchangeable Mg content is small as

compared to the exchangeable Ca content. A high percentage of exchangeable Mg in the exchange complex may have deleterious effects on soil-water relations (ROWELL & SHAINBERG, 1979 ; ALPEROVITCH *et al.*, 1981).

A comparative kinetics study of Ca²⁺, Na⁺ and Mg²⁺ exchange in two soils — Netanya and Bet Dagan — was carried out using the Eilat effluent. Figure 1 presents the exchange occurring in soil columns during leaching with ten pore volumes of Eilat effluent and of a model solution. In both soils there is an accumulation of Mg during leaching with this effluent. The concentrations of the three cations in the leachate as a function of the leachate volume (fig. 1a-f) show that during leaching, Na⁺ and Mg²⁺ replace Ca²⁺ in the soil. This is in agreement with the observed increase in the ESP after effluent irrigation.

B. Colloidal plugging

The decrease in soil K_{sat} due to plugging by suspended solids was determined by leaching the soil columns with unfiltered Eilat effluent and with that effluent after different degrees of filtration (fig. 2). Some properties of the effluents after filtration and the relative decrease in soil K_{sat} as a function of effluent quality are presented in table 3. It is clear that the suspended solids have a major effect on the K_{sat} as the decrease in K_{sat} is correlated strongly with the amount of suspended solids in the effluent. The binding of bivalent cations has only a small effect on soil K_{sat} (not more than a 10 % decrease). Filtering the effluent through Whatman 91 filter paper excludes the coarse suspended solids but not the finer colloidal fraction. Passing through the soil column ten pore volumes of the effluent filtered through Whatman 91 filter paper led to a 20 % decrease in the K_{sat} of the investigated soils as compared to more than 50 % decrease when unfiltered effluent was applied to the soils.

The rate of decrease of the K_{sat} of the Netanya and Bet Dagan soils when leached with the Eilat effluent after various filtrations is shown in figure 2. The effect of the model solution is also presented. When the unfiltered effluent is applied to the soil, the rate of decrease is high.

TABLE 5

The effect of irrigation with effluents on the ESP of 2 soils and a standard clay.
Effet de l'irrigation avec des effluents sur le pourcentage de sodium échangeable de 2 sols et d'une argile standard.

Solid medium	Source of the effluent	ESP	Method
Bentonite	Ramat Hasharon	12.9	Batch runs repeated until steady state was achieved
	Oxidation Pond	10.4	
	Model Solution (SAR _T)		
Bet Dagan soil	Eilat	10.7	Columns at steady state
	Model solution (SAR _T)	11.9	
Netanya soil	Gan Raveh	7.0	Columns at steady state
	Model solution (SAR _T)	6.0	
	Model solution (SAR _E)	8.5	
	Eilat	14.5	
	Model solution (SAR _T)	16.1	
	Model solution (SAR _E)	18.0	

SAR_T calculated with total divalent cation concentrations.

SAR_E calculated with unbound divalent cation concentration.

Figure 1

Changes in the concentrations of Ca^{2+} , Mg^{2+} and Na^{+} in the leachate during the leaching of 2 soils with Eilat effluents: a, b, c Bet Dagan soil; d, e, f Netanya soil.

The full curves correspond to leaching with a model solution having the same cation concentrations as the effluent; horizontal lines represent the concentrations in the incoming effluents.

Evolution des concentrations en Ca^{2+} , Mg^{2+} et Na^{+} dans le lessivat durant le lessivage de 2 sols avec les effluents d'Eilat: a, b, c sol de Bet Dagan; d, e, f sol de Netanya.

Les courbes continues correspondent au lessivage avec une solution modèle ayant les mêmes concentrations en cations que l'effluent; les lignes horizontales représentent les concentrations dans les effluents avant leur pénétration dans le sol.

Figure 2

The effect of leaching with Eilat effluent after different degrees of filtration on the hydraulic conductivity of 2 soils: I, Netanya soil; II, Bet Dagan soil.

a. Model solution; b. Effluent filtered through 0.45 μ millipore filter; c. Effluent filtered through Whatman 91 filter paper; d. Unfiltered effluent.

Effet du lessivage avec des effluents d'Eilat soumis à différents degrés de filtration, sur la conductivité hydraulique de 2 sols: I, sol de Netanya; II, sol de Bet Dagan.

a. Solution modèle, b. Effluent filtré à travers un filtre millipore de 0,45 μ , c. Effluent filtré à travers du papier filtre Whatman 91, d. Effluent non filtré.

Figure 3

The effect of leaching with distilled water on the K_{sat} of soils previously leached with Eilat effluents (see fig. 2 legend; the arrow indicates the beginning of the application of distilled water).

Effet du lessivage avec de l'eau distillée sur la conductivité hydraulique des sols lessivés préalablement avec les effluents d'Eilat (cf. légende fig. 2; la flèche indique le début de l'application d'eau distillée).

When the coarse suspended solids were removed by filtration with Whatman 91 filter paper, the rate of decrease was similar to that caused by the unfiltered effluent, until approximately two pore volumes of effluent passed through the column. The rate of plugging diminished greatly afterwards. The rate of reduction of the K_{sat} by the effluent filtered through millipore paper was yet slower and more similar to the rate observed for the model solution.

After the soil columns were leached with effluent or with model solution, they were eluted with distilled water (mimicking rain). As a result, the K_{sat} of the finer textured Bet Dagan soil decreased appreciably for the model solution and the effluents regardless of the extent of filtration (fig. 3-II). When soil is percolated with water of low electrical conductivity (such as rain), clay swelling and dispersion are strong above a given ESP. Thus, while suspended solids affect the immediate K_{sat} , the effective SAR (namely the binding of polyvalent cations) may affect the K_{sat} during subsequent rain or irrigation with high quality water. Another difference between the long-term effects on K_{sat} of the cationic composition and of the suspended solids is that the first will cause a new equilibrium ESP in the soil, which will not change further upon addition of effluent of similar quality, while the latter causes a gradual plugging, which may increase for a long time as long as elution with the effluent continues (fig. 2).

In the Netanya soil, which has a coarser texture than Bet Dagan soil (see table 1), eluting with distilled water follo-

wing effluent irrigation reduced the K_{sat} to a small extent (fig. 3-I). When elution with distilled water followed the unfiltered effluent, an interesting change of the K_{sat} with time was observed. Adding water of low electrical conductivity to this sandy soil apparently causes dispersion and downward movement of the colloids. This phenomenon was observed in the Netanya soil for the native colloids (PUPISKY & SHAINBERG, 1979). This will reduce the K_{sat} during the dispersion stage, followed by an increase in the K_{sat} as part of the plug is descending with the effluent. At the point where the moving colloids were flushed out (which should have occurred after more than one pore volume of distilled water passed — fig. 3-I), the K_{sat} stabilizes again.

Among the properties of sewage effluents applied to soils, which affect the K_{sat} , two might have not received their due consideration. The distribution in soil of the incoming suspended solids may reduce the K_{sat} significantly. The binding of polyvalent cations by polyelectrolytes or by ligands in the effluent is another factor which may affect the K_{sat} , but its immediate effect is usually less pronounced. During subsequent rain, or irrigation with high quality water, the effect of this binding on the K_{sat} through its influence on the ESP of the soil may in some cases be of some importance.

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