PN-ACP-708
114854

FINAL REPORT

For the period: April 1997 - December 2000

Submitted to the office of the Science Adviser
U.S. Agency for International Development

PROJECT TITLE: **IMPROVING IRRIGATION MANAGEMENT IN THE SYR-DARYA DELTA.**

Project Identification no. CA16-016
Grant no. TA-MOU-96-CA16-016

Principal nvestigator: **I. Shainberg**
Inst. of Soil, Water and Environ. Sci. ARO, The Volcani Center, Bet Dagan, Israel
Co-Principal Investigator: **J.U. Akhanov**
Soil Science Inst., Academy of sciences of Kazakhstan, Almaty, Kazakhstan.
Co-Investigators: **G.J. Levy and D. Goldstein**
Inst. of Soils, water and Environ. Sciences, The Volcani Center, Bet Dagan, Israel.
K. Zh. Karazhanov and A. Otarov
Soil Science Institute, Academy of Sciences of Kazakhstan, Almaty, Kazakhstan.

A. I. D. Grant Project Officer: David Mulenex, American Embassy, Tel Aviv, Israel

November/ 2001

Table of Contents

1) Cover page 1

2) Table of Contents 2

3) Executive Summary 3

4) Research Objectives 4

5) Methods and Results 4

6) Impact Relevance and Technology Transfer 14

7) Project Activities/outputs 15

8) Project Productivity. 15

9) Future Work. 16

10) Literature Cited. 16

11) Appendices

Appendices A, B, C, D, E and F.

3. Executive Summary

Surface irrigation is the most widely used irrigation method in the Syr-Daria river basin, and in the world. However, surface irrigation systems are relatively inefficient and only about 60% of the applied water is consumed by the crops. As a result of inefficient irrigation, water table in the basin is rising and secondary salinization occurred. Also, the soils in the region are susceptible to furrow erosion. The general objective of this study was to improve the efficiency of surface irrigation and to prevent furrow erosion by the use of surge and polymers technologies.

In laboratory experiments in Israel the following studies were completed and published in international journals: 1) Flow interruption effects on intake rate and rill erosion. 2) Hydraulic gradients, aging, and water quality effects on the hydraulic properties of soils. 3) Polyacrylamide, sediments, and interrupted flow effects on rill erosion and intake rate. 4) Hydraulic gradient and wetting rate effects on the hydraulic conductivity of soils. In these studies, the interaction between soil properties, surge flow and polymers were evaluated and recommendations for the field studies in Kazakhstan were outlined.

The effect of surge irrigation and PAM in field studies (200m long furrows and inflow rates of 30-50 L/min) was determined in Kazakhstan. Surge irrigation was very effective in reducing furrow erosion and infiltration rate. Similarly, PAM was also most effective in preventing furrow erosion. In soils with poor structure that were very susceptible to furrow erosion, combination of surge irrigation with PAM application ($10g/m^3$) was most effective in preventing furrow erosion, decreasing water intake rate, improving irrigation efficiency and preventing water table rise and secondary salinization.

Prof. Akhanov visited in Israel in March 1997 and Dr Shainberg and Dr Levy visited in Kazakhstan in June 1998. The cooperation between the two teams was productive and an extension of the cooperation is proposed.

4) Research Objectives

The overall objective of this proposal was to develop irrigation management that enables uniform water distribution, minimizes runoff and erosion and minimizes rising water table and secondary salinization. Specific objectives were:

1) To study the effect of surge irrigation on the intake rate and furrow erosion of silty loam to clay soils (laboratory and field studies).
2) To study the effect of soil properties and water quality on water intake and sediment concentration in furrow irrigation (laboratory and field studies).
3) To study the effect of wetting rate, initial moisture content and aging on intake rate and furrow erosion (laboratory studies).
4) To study the effect polymers (Polyacrylamide) on soil erosion and intake rate in furrow irrigation (laboratory and field studies).

5) Methods and Results

In Israel

5.1. The effect of soil texture on the efficiency of interrupted (surge) flow in reducing infiltration rate and rill erosion. (Appendix A. Published in Soil Science Society of America Journal 65:828-834, 2001).

Effects of interrupted flow on rill erosion and infiltration rate of a silt loam and a clay soil were studied in the laboratory using miniflumes. Interrupted flow reduced the infiltration rate in both soils compared with continuous flow. The reduction in infiltration rate by surge flow was more effective in the silt loam because of its unstable structure, than in the stabled structured clay soil. Interrupted flow consolidated the soil surface and reduced its hydraulic conductivity. Conversely, interrupted flow reduced furrow erosion in both soils in a similar

way. The results suggested that surge flow might be an effective management tool in surface irrigation to enhance infiltration uniformity and for the control of furrow erosion.

5.2. The effect of aging and hydraulic gradient on the hydraulic properties of soils (Appendix B. Published in Soil Science Society of America Journal 62: 1488-1496, 1998).

Aggregate stability in a moist soil increases with aging time due to the formation of cohesive forces between soil particles. Aging also increases the hydraulic conductivity of soils and decreases soil's erodibility. The rate of cohesive bond formation increased with increasing hydraulic gradient (and compression of the clay fabric) and decreased with a decrease in water quality. Aging and hydraulic gradient effects contribute to the explanation of the effect of interrupted flow on furrow erosion and intake rate in furrow irrigation.

5.3. PAM, Sediments, and interrupted flow effects on rill erosion and intake rate (Appendix C. Published in Soil Science Society of America Journal 64:1487-1495, 2000).

The effect of PAM and sediment concentration in irrigation water on infiltration rate and rill erosion in silty loam and clay soil was studied using laboratory miniflumes. Rill erosion in both soils was eliminated by the PAM treatment (10g m^{-3}) in both continuous and interrupted flow. The PAM treatment reduced infiltration rate in the silty loam and increased it in the clay soil. The contradictory effect of PAM on infiltration rate was explained by two opposing mechanisms: (I) enhancement of infiltration rate by prevention of erosion and of depositional seal formation and (ii) reduction of infiltration rate because of partial blocking of the conducting pores by the tails of adsorbed polymers molecules. Interrupted flow reduced infiltration rate in the silty loam by 18-37% and had an insignificant effect in the clay soil. Sediments in irrigation water reduced cumulative infiltration by 22% and 59 % in the clay and silty loam, respectively. These reductions were attributed to depositional seal formation.

Sediments in irrigation water also reduced rill erosion. These results indicated that the potential benefits of interrupted flow as a means of improving surface irrigation efficiency and controlling furrow erosion would be manifested in soils with weak structure like the soils in the Syr-Daria basin. Addition of polymer to the irrigation water enhances the effect of interrupted flow in these soils.

5.4. Hydraulic gradient and wetting rate effects on the hydraulic conductivity of clay soils. (Appendix D. Published in Soil Science society of America Journal 64: 1211-1219, 2000).

Understanding the combined role of intrinsic (e.g. clay content) and extrinsic soil conditions (prewetting rate and hydraulic gradient) in determining the hydraulic conductivity of soils is a key factor in improving soil and irrigation management. Under conditions of limited aggregation (fast prewetting), development of cohesive forces between structural units explained the increase in hydraulic conductivity and the rate of increase in hydraulic conductivity increased with increase in hydraulic gradient. Conversely, when a stable aggregation was maintained (e.g. slow wetting rate), the development of cohesion bonds was of minor importance in increasing the hydraulic conductivity.

In Kazakhstan

Field experiments were carried out in Kazakhstan. The methods and results of the field experiments are presented in detail in Appendix E. A detailed description of the furrow irrigation experiments as outlined by Dr Shainberg and Dr Levy in their visit to Kazakhstan is given in Appendix F. Since the results have not been published in international journals, a short description of the methods and results (from Appendix E) is presented here.

5.5. The climate, geography, vegetation and soils in the Syr Darya delta (Appendix E, Chapter 1). The climate in the Syr-Daria basin is highly continental with dry hot summer, cold winter,

100 mm percipitation and strong winds. Silty loams and sandy loams are the dominant soils. The silty loams contain 20% clay and 70% silt. The cation exchange capacity of the soil was 20 meq/100 g, exchangeable sodium percentage was low (<2%) and exchangeable Magnesium reached 30-50 %. Detailed description of the soils is given in Tables 1-4 in Appendix E. Ground water table in the region is high and depends on irrigation regimes. Because of inefficient irrigation water table is rising and secondary salinization prevail.

5.6. Effect of PAM on soil structure, evaporation rate and furrow erosion (laboratory studies) (Appendix E. Chapter 2).

PAM was mixed with the soil surface at rates of 1.0, 4.0, 10.0 and 40.0 kg/ha. Following drying in the field, dry and wet aggregate sieving analysis was done in the laboratory. The results are presented in Table 5 (from Appendix E). PAM at all treatments increased the percentage of meso-aggregates and the rate of 10 kg/ha was most beneficial in improving soil structure. The improved soil structure decreased evaporation from the soil surface (Table 7, Appendix E). Stabilization of aggregates at the soil surface prevented capillary rise of water and decreased evaporation (Table 7, Appendix E).

Table 5. Influence of different dozes of PAM on structure-aggregate composition

Vari-ants	Size of aggregates, mm										Coef of struc-ture
	Macro aggregates >10	Mezo-aggregates								Micro aggregates <0,25	
		10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25	Sum		
Control	44,06 broken	20,4 br.	6,26 br.	9,04 br.	5,1 0,19	3,8 0,25	0,5 1,95	2,1 7,92	47,2 10,3	8,74	0,9
1 kg\ha	38,78 br.	10,2 br.	9,0 0,86	18,5 1,81	9,04 1,59	8,2 1,92	2,78 3,38	0,98 7,05	58,8 16,6	2,42	1,4
4 kg\ha	34,38 br.	13,8 br.	11,7 0,28	15,0 1,04	8,24 0,73	7,2 0,94	3,08 4,7	1,46 9,03	60,5 16,2	5,06	1,5
10 kg\ha	32,68 3,18	19,9 1,34	17,4 0,73	17,7 1,69	6,0 1,57	3,7 2,0	0,87 6,4	0,14 9,6	65,7 25,9	1,55	1,9
40 kg\ha	41,98 br..	9,1 br..	11,3 br..	12,4 2,02	7,3 1,73	6,8 1,93	2,3 4,02	1,1 8,81	50,3 20,9	7,68	1,0

Table 7. Changes in moisture content as a function of evaporation days and PAM treatment

Variants	Evaporation days					
	1	2	3	4	5	6
Control	35,9	25,2	17,6	9,8	9,2	7,8
PAM1kg/ha	34,9	25,4	17,4	10,0	9,2	8,7
PAM4kg/ha	36,4	26,1	20,9	12,2	11,2	9,7
PAM10kg/ha	36,2	26,1	21,2	12,4	11,2	9,9
PAM40kg/ha	35,8	25,9	20,0	10,5	9,7	8,7

The susceptibility of the soil to furrow erosion was determined in the laboratory using specially prepared hydroflumes (Chapter 2.3, Appendix E). The effect of slope (0.002, 0.004 and 0.02), continued and surge flow, and PAM were studied. The results are summarized in Table 10 from Appendix E.

Table 10. Pliability of swamp-meadow soils to water erosion.

Variants	Outflow of soil particles under inigiation, g\l		
	0.002	0.004	0.02
Continued flow	0.69	0.85	1.1
Surge	0.47	0.61	0.62
Continued flow with application of different PAM doses			
40 kg\ha	0.0	0.0	0.0
10kg\ha	0.0	0.0	0.0
4kg\ha	0.0	0.0	0.0
1kg\ha	0.0	0.0	0.06

It is evident that surge flow was effective in decreasing furrow erosion and that PAM treatments prevented furrow erosion completely.

5.7. A field study of the effect of surge flow and PAM on furrow irrigation (Appendix E Chapter 3.2)

The experiment was performed according to the scheme proposed by Shainberg and Levy (Appendix F). Furrows of 200m were constructed in a maize field with 0.02 slope, on sierozemic-meadow loam of Tasotkel massif. Four treatments were applied: 1) Continues flow of 30L/min. 2) Surge flow of 30L/min and ratio of on/off flow of 1:1. 3) Continues flow with PAM (10g/m^3) and 4) Surge flow with PAM (10g/m^3). Inflow rate during the advancement stage and during 30 min after the flow reached the end of the furrow was maintained at 30 L/min. Thereafter the flow rate was diminished to 15 l/min. During the 30-min flow, samples of furrow water were taken at distances of 20, 100 and 180 m from the inflow side and sediment concentration were determined. Each treatment was replicated three times.

The effect of the surge and PAM treatments on furrow erosion are presented in Table 11 (Appendix e)

Table 11. Intensity of solid discharge formation in furrow water, g/l

Variants	Time of water sampling after the beginning of experiment, min	Distance from the beginning of furrow, m		
		20	100	180
Constant flow	10	0,22	0,34	0,74
	20	0,08	0,27	0,45
	30	0,09	0,19	0,37
Surge flow	10	0,11	0,07	0,08
	20	0,08	0,11	0,1
	30	0,04	0,07	0,08
Constant flow + PAM	10	0,1	0,08	0,07
	20	0,08	0,08	0,02
	30	0,03	0,03	0,5
Surge flow + PAM	10	0,07	0,05	0,05
	20	0,05	0,04	0,05
	30	0,03	0,03	0,01

It should be noted that 1) surge flow reduced furrow erosion to about 20% of that in continuous flow and that 2) PAM at the rate of 10 g/m^3 reduced furrow erosion to values <10% of the control. It was concluded that both methods, surge and PAM, are very effective in preventing furrow erosion.

When irrigation was completed the water content in the soil profile was determined and is presented in Table 12 (Appendix E).

Table 12. Influence of surge method of irrigation and PAM on the depth of wetting and soil humidity after irrigation.

Depth, cm	Moisture content of soil (%) from the beginning of the furrow (m)		
	20	100	180
		Constant flow	
0-20	23,9	24,3	25,1
20-40	26,1	24,1	24,6
40-60	23,2	23,6	23,8
60-80	20,1	20,5	19,7
		Surge flow	
0-20	23,7	24.0	24,1
20-40	20,1	19.1	19,7
40-60	17,3	18,7	18,2
60-80	17,1	18,0	17,3
		Constant flow+PAM	
0-20	24,1	22,3	20,0
20-40	23,3	23,8	21,0
40-60	23,5	21,0	20,6
60-80	22,8	22,5	20,5
		Surge flow+PAM	
0-20	26,5	24,4	19,9
20-40	22,8	24,1	19,5
40-60	23,0	23,6	20,4
60-80	23,5	22,2	22,1

It should be noted that surge flow reduced the moisture content in the soil profile. Whereas the moisture content in the 20-80 cm depth of the continuous flow ranged between 19.7 and 26.1 percent, the moisture content in the surge treatment ranged between 17.1 and 20.1 percent. These moisture content values indicate that surge irrigation reduced the rate of infiltration of

irrigation water into the soil. Consolidation of the depositional seal at the soil surface by the the flow interruption reduced the hydraulic conductivity of the seal and the infiltration rate (see appendix 1).

The moisture content in the PAM treatments was similar to those in the control (Table 12). PAM treatments prevented furrow erosion and depositional seal formation. When seal are not formed, surge flow had no effect on the infiltration rate.

Based on the above experimental results it was concluded that in regions with "unfavorable soil amelioration conditions", i.e. delta plains of Syr Daria and Shu, surge irrigation and application of PAM are most effective for stabilization of ground water level and prevention of furrow erosion.

5.8. A field study on the effects of irrigation method (surge vs. continuous flow), furrow length and inflow rate on soil loss and soil moisture (Appendix E Chapter 3.3).

The experiment was conducted in piedmont desert zone in South-East Kazakhstan. The soil consists of coarse alluvial deposits with sandy loam texture. 300,000 ha of these soils are spread at South-East Kazakhstan where sufficient supply of glaciers water from the mountains is available. The experiment was performed according to the method proposed by Shainberg and Levy (Appendix F):

Variants	Irrigation stream (Q) l/min	Length of a furrow (L) m
Surge flow	30	100
		150
	50	100
		150
Constant flow	30	**100(control)**
		150
	50	100
		150

The experiment was done in a sunflowers field with 3 furrows per treatment and 3 repetitions per treatment. The furrow erosion results are presented in Table 14 (Appendix E)

Table 14. Intensity of solid discharge formation, g/l

Variants	Irrigation water discharge l/min	Furrow length, m	Distance from the beginning of a furrow, m	Time for selection of irrigation water samples after beginning of the experiment, min		
				10	20	30
Surge flow	30	100	10	0,23±0,033	0,05±0,003	0,03±0,009
			50	0,27±0,017	0,28±0,017	0,15±0,05
			90	0,91±0,044	0,3±0,115	0,22±0,142
		150	10	0,4±0,05	0,43±0,192	0,18±0,018
			75	0,55±0,304	0,4±0,05	0,23±0,088
			140	0,63±0,127	0,55±0,12	0,52±0,231
	50	100	10	0,37±0,06	0,15±0,05	0,06±0,006
			50	0,45±0,058	0,35±0,05	0,13±0,033
			90	0,97±0,249	0,58±0,117	0,49±0,249
		150	10	0,55±0,029	0,33±0,033	0,07±0,015
			75	0,76±0,044	0,38±0,06	0,09±0,009
			140	1,28±0,334	0,37±0,101	0,32±0,136
Constant flow	30	100	10	0,46±0,033	0,2±0,076	0,11±0,006
			50	0,93±0,088	0,81±0,295	0,25±0,029
			90	1,32±0,044	0,82±0,289	0,45±0,029
		150	10	0,56±0,061	0,51±0,231	0,23±0,017
			75	0,88±0,016	0,57±0,088	0,28±0,117
			140	1,28±0,334	0,85±0,18	0,53±0,044
	50	100	10	0,55±0,104	0,33±0,014	0,15±0,05
			50	0,77±0,117	0,5±0,104	0,25±0,104
			90	1,38±0,017	0,97±0,12	0,55±0,029
		150	10	0,56±0,06	0,51±0,231	0,12±0,017
			75	0,88±0,016	0,57±0,088	0,18±0,133
			140	1,35±0,029	0,85±0,18	0,83±0,044

Based on the results presented in Table 14 it is concluded that surge irrigation was very effective in controlling furrow erosion. These results are expected from the laboratory experiments in Israel (Appendix A) but similar field data were not reported in the scientific literature. A more careful examination of the experimental results in Kazakhstan and more field experiments are needed to generalize these conclusions and to develop a recommendation on the use of surge irrigation to prevent furrow erosion.

The effect of surge irrigation on the efficiency of furrow irrigation on the piedmont soil is presented in Table 16 (Appendix E)

Table 16. Comparative efficiency of surge irrigation.

Variants	Volume of irrigation stream	Furrow length, m	Time of irrigation, min	During irrigation		Irrigation rate, m^3/ha	Balance	
				Delivered to a furrow, m^3/ha	Down throw at the end of a furrow, m3/ha		m^3/ha	%
Surge flow	30	100	360	900	82	818	-82	9.1
		150	375	642	332	310	-590	65,5
	50	100	350	1428	81	1347	447	49,6
		150	357	985	316	669	-231	23,6
Constant flow	30	**100 (control)**	**380**	**985**	**85**	**900**	**-**	**100**
		150	390	685	345	340	-560	62,2
	50	100	355	1464	81	1383	482	53,5
		150	365	1023	322	701	-149	22,1

The data in Table 16 suggest the following: 1) Time of irrigation in surge irrigation is shorter than the corresponding time in continuous flow. For example: whereas in the control (furrow length of 100 m and inflow rate of 30 L/min, time of irrigation was 380 min, in the corresponding surge flow the time of irrigation was 360 minutes. Surge irrigation decrease the infiltration rate of the soil and decrease the advancement time (Appendix A), thus it decrease the total irrigation time. 2) The volume of water that infiltrated the soil in surge irrigation was less than the volume in continuous flow. This suggest that surge irrigation was more efficient in water use.

Conclusions

Laboratory experiments demonstrated that surge irrigation improved the efficiency of furrow irrigation and decreased furrow erosion. Similarly laboratory experiments demonstrated that mixing PAM with irrigation water (10 g/m^3) reduced dramatically furrow erosion. Other laboratory experiments demonstrated the effect of aging and hydraulic gradients in stabilizing soil aggregates and increasing the cohesion forces between soil particles. These laboratory conclusions were tested in Kazakhstan in laboratory and field experiments. Based on field experiments it was concluded that surge flow decreased furrow erosion, decreased advancement time in furrow irrigation and increased irrigation efficiency.

6. Impact Relevance and Technology Transfer

Surface irrigation is the most widely used irrigation method in the Syr-Daria river basin in Kazakhstan. Because of inefficient irrigation, water table in the region is rising and secondary salinization prevails. Soils in this region have unstable structure and are very susceptible to erosion. Introducing an irrigation management that improve irrigation efficiency and prevent erosion will be very useful in the region. Surge irrigation and the addition of PAM to irrigation water are cost effective technologies that improve irrigation efficiency and prevent soil erosion. These two technologies were studied in this research project and both were found to be very effective in the Syr Daria basin.

A large group of both scientists and technical staff of the Institute of Soil Science in Almaty Kazakhstan and in the extension service were involved in this project and were exposed to the Israeli experience and expertise in the management of soils and irrigation water. The investigators in Kazakhstan were very enthused with the experimental results (See their report in Appendix E) and it is likely that the results of this project will be applied in Kazakhstan. It is hoped that both technologies (Surge irrigation and PAM) will be used in Kazakhstan and that

the investigators involved directly with this program will be able to run independent research and extension work in other regions in the country.

7. Project Activities/outputs.

Prof. Akhanov visited in Israel in 1997 and Prof. Shainberg and Dr Levy visited in Kazakhstan in june 1998. During these visits the applied and basic aspects of surge irrigation and polymers effects were discussed with Soil and Water scientists. During the visit of Drs Shainberg and Levy, detailed field experiments were outlined. Scientists in the Institute of Soils in Kazakhstan are now familiar with the surge and polymers technologies.

The following project funded publications were published:

1) Moutier M, I. Shainberg and G.J. Levy. 1998. Hydraulic gradient, aging, and water quality effects on hydraulic conductivity of a vertisol. Soil Sci. Soc. Am. J. 62:1488-1496.
2) Moutier M, I. Shainberg and G. J. Levy. 2000. Hydraulic gradient and wetting rate effects on the hydraulic conductivity of two Calcium vertisols. Soil Sci. Soc. Am. J. 64:1211-1219.
3) Sirjacobs D, I. Shainberg, I. Rapp and G. J. Levy. 2000. Polyacrylamide, sediments and interrupted flow effects on rill erosion and intake rate. Soil Sci. Soc. Am. J. 64:1487-1495.
4) Sirjacobs D, I. Shainberg, I. Rapp and G. J. Levy. 2001. Flow interruption effects on intake rate and rill erosion in two soils. Soil Sci. Soc. Am. J. 65: 828-834.

It is hoped that the results of the field experiments in Kazakhstan (Appendix E) will be published in both, international and national journals.

8) Project Productivity

The project accomplished all the proposed goals.

9) Future work

The PI of this proposal thinks that extension of this project for 2 more years is needed. The objectives of this extension are:

1) To publish in international journals the results of the field experiments as described in Appendix E. The effect of surge irrigation on furrow erosion have not been documented in the literature.
2) The results of the field experiment described in Appendix E are the result of only one-year. The experiments should be repeated two more years.
3) The field experiments described in Appendix E were performed in one region and in one-soil types. More field experiments in different regions and on different soils must be done.

10.Literature Cited

1. Alekhsandrova L.N. and et al. Laboratory-practical studies on soil science. "Kolos"Leningrad, 1967, p.152-154.
2. Akhanov J.U., Korobkin V.A. Regulation of water-salt regime in soils of Tas-Utkul massif. "Nauka"Alma-Ata, 1982. 200 p.
3. Akhanov J.U. Pecularities of soil formation processes in delta plains of the South Kazakhstan. Natural conditions and resources of deserts in the USSR, their rational use. Ylym Ashkhabad, 1984. P.183-191.
4. Akhanov J.U. Soil formation in delta plains of the South Kazakhstan. "Nauka"Alma-Ata, 1987.
5. Akhmedsafin U.M. Method for compiling of prognozing maps and observation of artesian basins of Kazakhstan. Alma-Ata, 1962.
6. Borovskiy V.M., Pogrebinskiy M.A. Ancient delta of SyDarya and northern Kyzylkums. Publishing house of AS KazSSR, Alma-Ata 1958, T.1.
7. Borovskiy V.M. Investigation of Chiili oasis. Vestnik AS KazSSR. 1956, N1.
8. Borovskiy V.M. New method in rice agrotechnique. Publishing house of AS KazSSR. Alma-Ata 1950.
9. Borovskiy V.M. Geochemistry of saline soils in Kazakhstan. Moscow "Nauka"1978.
10. Borovskiy V.M. Formation of saline soils and galogeochemical provinces of Kazakhstan. "Nauka"Alma-Ata 1982.
11. Dolgov S.I. Investigation of soil moisture mobility and it's availability to plants. Moscow. Publishing house of AS SSSR. 1948. 20 p.

12. Egorichev G.A. Transformation of soil cover of Chiili oasis under the influence of irrigation. In: Ecologo-geographic and amelioration soil investigations in Kazakhstan. Publishing house of AS KazSSR. Alma-Ata, 1961. P.189-204.
13. Egorichev G.A. Transformation of soil-ameliorative conditions of Chiili oasis under the influence of irrigation. Synopsis of thesis. Alma-Ata, 1962.
14. Egorov V.V. Soil formation under irrigative amelioration in delta of Aralo-Caspian lowland. Publishing house of AS SSSR. Moscow, 1959.
15. Zhapbasbaev M. Agroclimatic conditions of rice growing in Kazakhstan and microclimate of rice field. Synopsis of thesis. Leningrad, 1965.
16. Kovda V.A. Land aridization and control for drought. Moscow. Nauka, 1977.
17. Kovda V.A. Soil cover, it's improvement, use and protection. Moscow. Nauka, 1981.
18. Mozhaitseva N.P. The role of vegetation in some soil processes of Syr-Darya delta. Synopsis od thesis, Alma-Ata, 1973.
19. Mikhailov V.D. New abilities for moisture conservation in soil. Jornal of Uzbekistan", 1961. N1, p.89-90.
20. Noskova L/V. Soils of the South-East part of Kzyl-Orda oblast. Synopsis of thesis. Khazan, 1964.
21. Rubtsov N.I. Vegetation cover of Kazakhstan. Essays on physical geography of Kazakhstan. Alma-Ata, 1952.
22. Ryzhov S.N., Bogomolov V.Z. Evaporation from structural and dispersed soil. Jornal "Pochvovedeniye", 1934, N1, p.61-72.
23. Eshanov I.E. Influence of polimer conditioners on soil fertility and yieldimg ability of cotton. Jornal "Chemistry in agriculture". N9. p.69-73.

Reprinted from the *Soil Science Society of America Journal*
Volume 65, no. 3, May–June 2001
677 South Segoe Rd., Madison, WI 53711 USA

Appendix A

Flow Interruption Effects on Intake Rate and Rill Erosion in Two Soils

D. Sirjacobs, I. Shainberg, I. Rapp, and G. J. Levy*

ABSTRACT

Efficiency of surface irrigation is often low because of poor infiltration uniformity, resulting from relatively long periods of infiltration at the upstream end and short periods of infiltration at the downstream end of the field. Surge irrigation, the intermittent supply of water to furrows, generally reduces soil intake rate (IR) and improves moisture uniformity over the entire field. However, IR reduction varies from one irrigation scheme to another, depends on soil and water properties, and is difficult to predict. A laboratory study using *miniflumes* was designed to investigate the effect of interrupted flow on IR and soil loss from short rills. Two soils differing in their textures, a silt loam (Calcic Haploxeralf) derived from loess and a clay soil (Typic Haploxerert), were studied. Intake rate in the clay soil was greater than that in the silt loam. Therefore, different inflow rates were applied to the two soils to achieve similar runoff flow rates from the two soils. Cumulative infiltration decreased from 646 mL in continuous flow to 539 mL in interrupted flow for the silt loam and from 1142 to 1068 mL in the clay soil. Interrupted flow also reduced cumulative soil loss by 84% in the clay soil but had only a small effect on soil loss from the silt loam. However, when flow rate was increased from 80 to 320 mL min^{-1}, interrupted flow reduced soil loss in the silt loam as much as in the clay soil. Consolidation of the soil surface and formation of cohesive forces between soil particles of the silt loam with unstable structure during flow interruption was suggested as the explanation for the effect of flow interruption on intake rate and soil detachment. These results need to be verified in field experiments.

SURFACE IRRIGATION is the most used irrigation practice worldwide. However, water application efficiency of surface irrigation is low, typically ≈45% (Wolters, 1992). Surge irrigation is the intermittent application of surface irrigation water (Stringham, 1988). It has the potential to increase infiltration uniformity of surface irrigation application by (i) increasing the advance rate, which decreases cross-field differences in infiltration opportunity time, and (ii) decreasing the IR at the upstream end of the furrows to compensate for the longer infiltration opportunity times at these locations (Kemper et al., 1988).

The infiltration decrease caused by surge flow is highly variable, is not fully understood, and is difficult to predict (Izuno et al., 1985; Kemper et al., 1988; Trout, 1991; Samani et al., 1985). Many studies have been conducted to determine the mechanisms taking place during the intermittent off period of surge flow irrigation. Several basic phenomena have been recognized:

1. Moisture Redistribution in the Soil Profile. During the interruption of water application, moisture redistribution is caused by the unbalanced capillary and gravitational forces acting on the water that has infiltrated. The redistribution process results in development of negative capillary pressure below the soil surface and a greater hydraulic gradient that increases water infiltration during the succeeding water application in surge flow irrigation (Samani et al., 1985). However, Izadi et al. (1990) demonstrated that this effect is short lived and that the net effect over a practical period of off time is negligible.

2. Consolidation of the Soil near the Furrow Perimeter. Development of negative pressure at the soil surface during flow interruptions leads to consolidation of the soil near the furrow perimeter. Kemper et al. (1988) measured negative pressures of up to 500 cm H_2O in a Portneuf soil (20% clay and 40% silt). The consolidated soil surface has a greater bulk density, lower porosity, and a lower HC; thus, even a thin consolidated layer can have a significant effect on reducing infiltration (Samani et al., 1985).

3. Surface Seal Formation. Furrow erosion, and particle transport, and subsequent deposition and rearrangement also significantly reduce infiltration by decreasing the permeability of the surface layer (seal formation). During surface irrigation, soil aggregates are weakened or partially broken by wetting (Kemper and Koch, 1966). Fast wetting disintegrates large aggregates into small aggregates, which then can be detached from the soil bed by the shear force of water and can be easily rolled along the bed of a furrow by moving water until deposition (Kemper et al., 1988). Trout (1991) observed a 50% reduction of infiltration because of surface seal formation on the Portneuf silt loam soil. Shainberg and Singer (1985) observed that depositional crusts (formed when turbid water infiltrates into soil) reduced the rate of water penetration by one to two orders of magnitude, and the magnitude of this decrease depended on soil properties and water quality.

In addition, other mechanisms related mainly to bed load have been proposed to explain the effects of surge irrigation on furrow IR: (i) filling of cracks that develop during flow interruption with bed load during the following surge (Kemper et al., 1988); (ii) greater sediment detachment and movement caused by more rapid advance of the surge stream front (Kemper et al., 1985; Trout, 1991); (iii) forced deposition (and consolidation) of suspended sediment on the furrow perimeter when the water supply is interrupted (Kemper et al., 1985); and (iv) air entrapment (Seymour, 1990) and its expansion upon rewetting (Jalali-Farahani et al., 1993).

Miniflumes have been used to evaluate the interactive effects of flow characteristics, soil properties and water quality on rill erosion in the laboratory (Shainberg et

D. Sirjacobs, I. Shainberg, I. Rapp, and G.J. Levy, Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet Dagan 50250, Israel. Contribution from the Agricultural Research Organization, The Volcani Center, P.O. Box 6, Bet Dagan 50-250, Israel. no. 625/98 series. Received 21 Sept. 1998. *Corresponding author (vwguy@volcani.agri.gov.il).

Published in Soil Sci. Soc. Am. J. 65:828–834 (2001).

Abbreviations: HC, hydraulic conductivity; IR, intake rate.

18

al., 1994, 1996). Rill erodibility data obtained with miniflumes agreed well with field data (Shainberg et al., 1994). Miniflume studies were also found to simulate well the effect of polyacrylamide (PAM) on furrow erosion in the field (Lentz et al., 1992; Shainberg et al., 1994). Miniflumes were used by Shainberg et al. (1996) to study rill erosion in a loess and a clay soil; it was found that (i) rill erosion decreased with aging of several hours, (ii) the decease in erosion was more pronounced in the clay soil, and (iii) erosion depended on water content in the soil. These researchers postulated that aging and water tension enhanced clay to clay contacts and increased cohesive forces between soil particles, thus leading to the observed reduction in erosion. Application of these mechanisms to surge irrigation suggests that the water tension that builds up during the off period of the surge may cause an enhanced reduction in erosion.

It is hypothesized that interrupted flow will affect both soil IR and rill erosion, and that it can be evaluated from laboratory miniflume studies. Thus, the objectives of our study were (i) to study the effects of continuous and interrupted flow on the IR and on rill erosion in a silt loam and a clay soil and (ii) to improve the understanding of the mechanisms that cause interrupted flow to reduce rill erosion and IR in the two soils. It was assumed that the erodibilities of the two different soils could be compared, provided similar runoff rates are maintained.

MATERIALS AND METHODS

Two calcareous soils were chosen for this study: a silty loam (Calcic Haploxeralf) from Nevatim, northern Negev, and a clay soil (Typic Chromoxerert) from Hafetz-Haim, the Pleshet plains, Israel. Samples of the cultivated layer (0–250 mm) of each soil type were brought to the laboratory, air-dried, and crushed to pass through a 4-mm sieve. Selected physical and chemical properties of the soils are given in Table 1. Smectite was the dominant clay type in the soils (≈60%), with kaolinite, illite, and calcite also present (Banin and Amiel, 1970). The fact that the clay content and cation-exchange capacity in the clay soil were twice that in the silt loam indicated that the clay mineralogy in the two soils was similar.

The experiments were carried out with a 0.5-m-long, 0.047-m-wide, and 0.12-m-deep flume; two 0.1-m-long V-shaped metallic rills were connected on both ends of each flume. The flume was placed at a 10% slope in order to maintain high flow shear force, high soil detachment, and high rill erosion. Water used in the experiments was laboratory tap water (electrical conductivity = 0.95 dS m^{-1}; Na adsorption ratio = 2.5 $(mmol_c\ L^{-1})^{0.5}$; Ca + Mg = 5 $mmol_c\ L^{-1}$; Na = 4 $mmol_c\ L^{-1}$; Cl = 6.2 $mmol_c\ L^{-1}$).

Air-dried soil was slightly compacted in the flumes to field densities of 1390 kg m^{-3} for the silt loam and of 1280 kg m^{-3} for the clay soil. When dry, the volume of the clay soil was intentionally kept smaller than that of the silt loam. However, upon wetting and subsequent swelling, the final volume of the wet clay soil in the flume was similar to that of the silt loam, and the wet bulk density of the silt loam and clay soil was 1390 and 1200 kg m^{-3}, respectively. A V-shaped rill (44 mm wide and 22 mm deep) with a 90° angle between its sides was formed in the soil surface. Water was applied with a peristaltic pump to the upstream metallic rill, and runoff water containing sediment was collected in beakers from the downstream metallic rill. Runoff volume was measured by weighing the beakers and sediment content in the outflow was determined by drying. Inflow and outflow rates were continuously recorded and average IR for each minute of flow time was calculated from the difference. Similarly rill erosion as a function of flow time was calculated.

Each individual experiment was divided into two stages. In the first stage either continuous (control) or interrupted flow was applied. The control treatment consisted of 4 min of flow; the interrupted flow treatment consisted of four cycles of 1 min of flow and 10 min of interruption. Preliminary studies on the effect of off time on rill erosion and IR in the miniflumes indicated that most of the changes in IR and erosion were obtained in off periods of <5 min. Thus it was assumed that an off time of 10 min would be sufficient for the changes in rill erosion and IR caused by flow interruption to be completed. In order to obtain a measurable outflow during the first minute and to obtain similar runoff during the consecutive 3 min, the inflows applied to the clay soil and the silt loam were 320 and 240 mL min^{-1}, respectively. Because the IR in the clay soil was higher than that in the silt loam, it took 57 s for the first surge to reach the end of the rill in the clay soil, and only 17 s in the silt loam. However, during the second, third, and fourth surges, the outflow rates were similar in both soils because of the higher IR in the clay soil. Thus, the shear stress of flowing water on the rill perimeter and stream transport capacity were similar for both soils.

The second stage of the experiment started immediately at the end of the 4-min flow in the control or after completion of the four cycles of interrupted flow in the interrupted flow treatment. At this stage, the inflow was reduced to allow more precise measurements of IR and was applied continuously to simulate field conditions. A continuous inflow of 100 mL min^{-1} for 10 min was applied to the clay soil, and a continuous inflow of 80 mL min^{-1} for 10 min was applied to the silt loam. Total inflow, outflow, and soil loss were recorded every minute for both soils. The second stage was terminated when the moisture front reached a depth of ≈100 mm, and the soil layer at the bottom of the miniflume remained dry. The length of the

Table 1. Physical and chemical properties of the soils used.

Soil	Classification	Particle-size distribution			$CaCO_3$	CEC†	ESP‡	EPP§	OM¶
		Sand	Silt	Clay					
		g kg^{-1}			g kg^{-1}	cmol$_c$ kg^{-1}	%		g kg^{-1}
Silt loam	Calcic Haploxeralf	413	362	225	180	17.7	2.1	9.1	21
Clay soil	Typic Chromoxerert	438	156	406	107	34.2	2.3	2.9	34

† Cation-exchange capacity.
‡ Exchangeable Na percentage.
§ Exchangeable K percentage.
¶ Organic matter content.

19

second stage was estimated from preliminary experiments done on the same miniflumes packed with the same soils. The dry layer of soil at the bottom of the flume assured the presence of the suction needed to consolidate the soil surface. The suction was maintained at the bottom of the soil in the flume to simulated the moisture profile prevailing under field conditions.

Three replicates were performed for each of the soils and the two flow patterns. Each replicate consisted of a miniflume packed with a fresh dry soil sample. For each soil, the Honestly Significant Difference test (Tukey–Kramer, $\alpha = 0.05$) was used to compare the means of the IR and rill erosion between the two flow patterns studied. Differences in the IR and rill erosion between the two soils could not be statistically analyzed because inflow rates differed between the soils. However, because the outflow in the two soils were similar, the flow shear force and the stream transport capacity at the down stream end of the rill were similar and rill erodibility of the two soils could be compared and discussed.

RESULTS AND DISCUSSION

Effects of Flow Type on Infiltration Rate in the Two Soils

The effects of interrupted flow on IR (obtained from the difference between the inflow and the outflow rate) in the silt loam and the clay soil are presented in Fig. 1. Intake rate in the clay soil was significantly greater

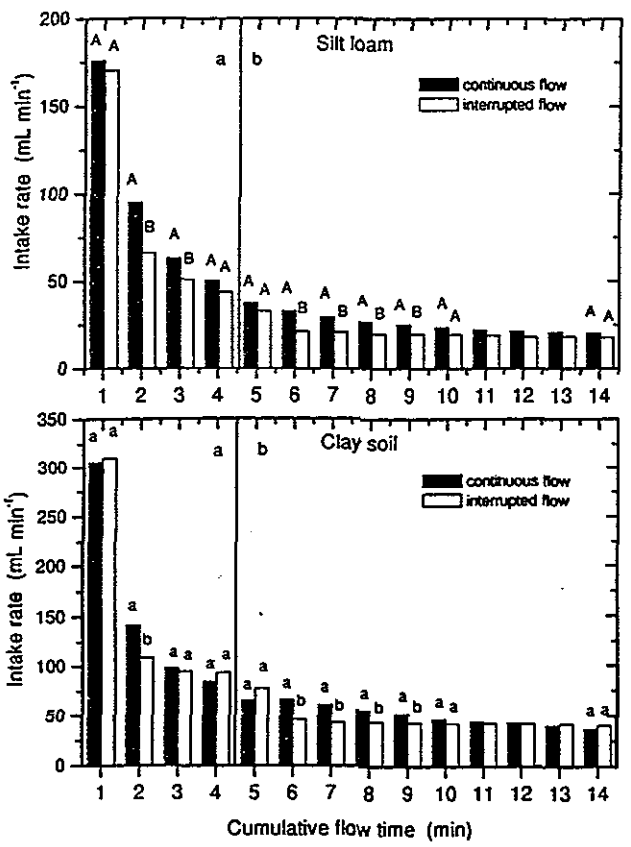


Fig. 1. Intake rate as a function of cumulative flow time for the clay soil and silt loam at Stage 1 (a) and Stage 2 (b) of the experiment. For a given cumulative flow time, and within a soil, bars labeled by the same letter (lower case for the clay soil and upper case for the silt loam) do not differ significantly at the 0.05 level.

than that in the silt loam. The high IR in the clay soil (both the initial and the steady state values) was ascribed to its aggregated structure and stable aggregates. Aggregate stability of soils from semiarid regions generally increases with increasing clay content, since the clay acts as a cementing material, enhancing the formation and stabilization of aggregates (Kemper and Koch, 1966). Stable aggregates lead to stable interaggregate macropores, which are responsible for the high IR (Rengasamy et al., 1984; Kay and Angers, 1999). Conversely, in the silt loam the low IR values (Fig. 1) were ascribed to its medium clay and high silt content (Table 1), which resulted in a markedly less aggregated structure than that of the clay soil (Kemper and Koch, 1966; Rengasamy et al., 1984). Thus, difference in texture between the two soils was considered as the main reason for the large difference in IR between the two soils.

The IR decreased with increasing cumulative flow time (Fig. 1). With increasing depth of water penetration in the soil profile, the hydraulic gradient, which provided the main driving force for water movement into the soil, decreased and IR also decreased. Reduction of IR between the first and the second minute in the continuous flow was more pronounced in the clay soil than in the silt loam (Fig. 1). This was probably due to (i) more water penetrating into the clay soil during the first minute, leading to a lower hydraulic gradient and lower infiltration rate of water, and (ii) more clay swelling and aggregate breakdown occurring in the clay soil, which resulted in a decrease in the size of the interaggregate macropores (Rengasamy et al., 1984; Kay and Angers, 1999).

In the interrupted flow treatment, the first flow interruption (i.e., off period) was effective in reducing the IR with the effect being similar (in relative terms) in both soils (Fig. 1, second minute). The second off period was effective only in the silt loam in reducing the IR compared with that of continuous flow. The effect of interrupted flow disappeared in the fourth and fifth minute measurements (Fig. 1). With the introduction of continuous low-rate inflow in the second stage of the experiment, the effect of interrupted flow in reducing IR became evident again (Fig. 1). Four cycles of interrupted flow reduced the final cumulative intake of the silt loam by 19% and that of the clay soil by 6% (Fig. 1). The effect of interrupted flow on intake rate was significant in both soils, but its effect was more pronounced in the silt loam.

During the period of flow interruption, compaction and consolidation of the soil surface caused by the soil water tension most likely occurred, and the hydraulic conductivity of the soil surface is thus reduced (Kemper et al., 1988; Samani et al., 1985). More surface consolidation and a decrease in infiltration is expected in soils with weak structure such as the silt loam (Mullins, 1999). This conclusion was verified by a complementary experiment similar to the one described by Samani et al. (1985). In those experiments disturbed dry soil samples (100 g) of the silt loam or the clay soil were placed inside a funnel with a fritted disc (40–60 μm pores) in the bottom. The internal diameter of the funnel was 65

20

mm and the thickness of the soil samples was ≈22 mm. The funnel was connected to a plastic tube filled with water. The soil sample was saturated from the bottom by raising the plastic tube. After saturation, the saturated hydraulic conductivity of the soil sample was measured by applying water to the top of the soil sample in the funnel and collecting the outflow from the end of plastic tube. After measuring the saturated hydraulic conductivity, the same soil was drained to a tension of 20 cm by lowering the plastic tube. At the end of the draining process, the soil sample was saturated again by raising the plastic tube and new saturated hydraulic conductivity of the soil samples was measured. Finally, a tension of 50 cm water was applied, the soil sample was saturated, and saturated hydraulic conductivity following 50-cm tension was measured. Under no tension the hydraulic conductivities of the silt loam and clay soil were 11.8 and 55.6 mm h^{-1}, respectively. When a tension of 20 cm H_2O was applied, the hydraulic conductivities of the silt loam and the clay soils dropped to 0.69 and 0.94 of the reference values. When the silt loam and clay soils were exposed to 50 cm suction, the hydraulic conductivity dropped to 0.5 and 0.73 of the values at no tension, respectively. The silt loam hydraulic conductivity was more susceptible to the effect of water tension than the clay soil.

The low IR (Fig. 1) and low hydraulic conductivity of the silt loam suggests that its fraction of water-conducting pores was small and a higher soil water tension could develop before air penetrated the soil surface (Kemper et al., 1988). Thus, the more pronounced effects of interrupted flow in the silt loam, compared with the clay soil, is explained by both a greater consolidation of the soil surface and a greater tension that can develop during the off period.

Aggregate disintegration by fast wetting may have also contributed to the beneficial effect of interrupted flow in the silt loam. Rapid advance of the stream front increases aggregate disintegration and seal formation. Conversely, when soils are wetted slowly, entrapment and subsequent explosion of entrapped air is limited, and soil structure is maintained (Kemper et al., 1985, 1988). Fast prewetting predominated in the silt loam, where the 0.5-m-long furrow was wetted in 17 s, compared with 51 s for the clay soil.

Opposing Effects of Interrupted Flow

Applying flow in surges should have two opposing effects on IR: (i) water tension that is developed during the off period consolidates the soil surface and reduces the IR; and (ii) reduced intake leads to an increase in the hydraulic gradient in the soil profile, which in turn increases the IR (Izadi et al., 1990; Izuno et al., 1985). In our study the effects of interrupted flow on reducing the IR decreased with flow time (Fig. 1). Similar observations were made by Izuno et al. (1985), who concluded from field data that the infiltration decrease with surge irrigation occurred in the first cycle only. No further reduction in infiltration rate was observed in subsequent surges of a given irrigation (Izuno et al., 1985). The disappearance of the effect of flow interruption on IR with flow time is explained by the fact that less water infiltrated during subsequent interrupted flow. This is demonstrated in Fig. 2, where IR is presented as a function of cumulative intake for both continuous and interrupted flow. Comparing IRs of continuous and interrupted flow for both soils at identical cumulative intakes (e.g., during the second minute of water application; Fig. 2) revealed that the intake rate in the interrupted flow treatment was smaller than in the continuous flow treatment. Conversely, in the third minute of water application, less water penetrated the soil in the interrupted flow treatment, and the effect of interrupted flow on intake rate became less pronounced in both soils (Fig. 2). The suction that developed in the interrupted flow treatment (due to the smaller cumulative intake) was high enough to cause an increase in the IR. Conse-

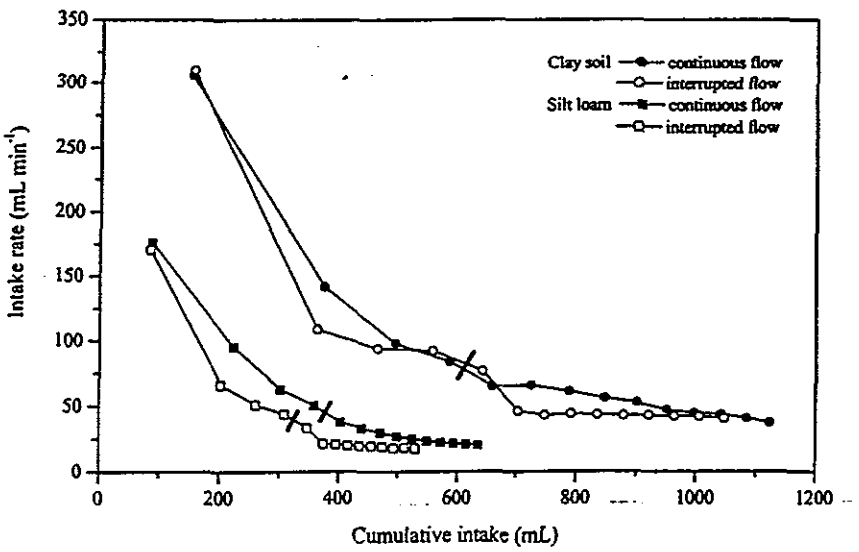


Fig. 2. Intake rate as a function of cumulative intake for the silt loam and clay soil. The "/" on each curve indicates transition from Stage 1 to Stage 2 of the experiment.

21

quently, the IR in the interrupted flow treatment increased to a level similar to that in the continuous flow treatment.

The favorable effect of interrupted flow in reducing the IR reappeared for both soils when flow rate was reduced (Fig. 2). During the continuous low flow (80 and 100 mL min^{-1} for the silt loam and the clay soil, respectively), flow was limited to the bottom of the rills as predicted by the Manning equation (e.g., Shainberg et al., 1994). This part of the rill perimeter was more affected by particle deposition and soil consolidation caused by the interrupted flow, and had a lower HC than the upper part of the wetted perimeter. Thus, concentrating the flow in the bottom of the rill, where the effect of interrupted flow is more pronounced, caused the reappearance of the interrupted flow effect (Fig. 2).

Effects of Soil and Flow Type on the Erosion Process

Effects of continuous and interrupted flow on rill erosion rate for the silt loam and the clay soil are presented in Fig. 3. For both soils, most of the erosion took place during the first 4 min (Stage 1 of the experiment), when high flow rates (240 and 320 mL min^{-1} for the silt loam and clay soils, respectively) exerting high shear stresses (Shainberg et al., 1994) were used. In the control

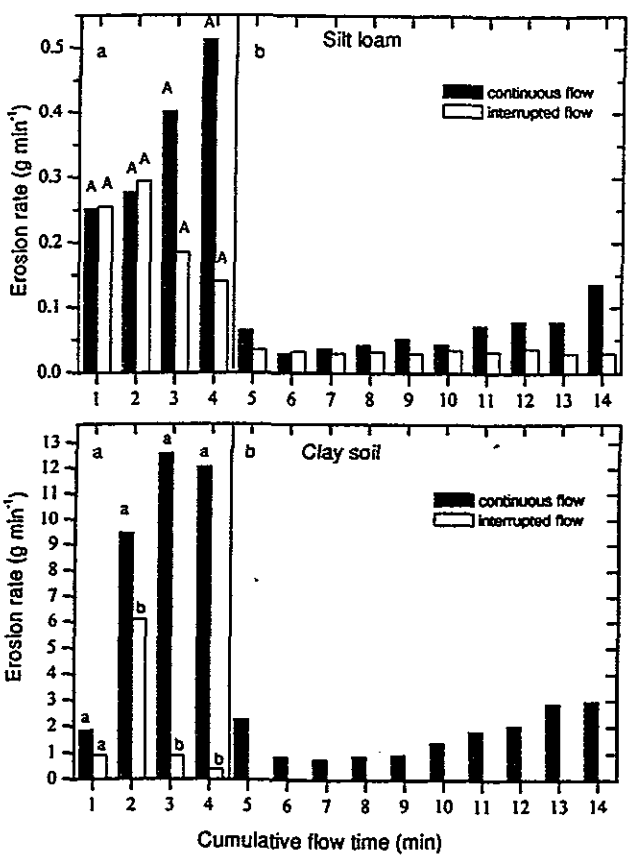


Fig. 3. Erosion rate as a function of cumulative flow time for the clay soil and silt loam at Stage 1 (a) and Stage 2 (b) of the experiment. For a given cumulative flow time, and within a soil, bars labeled by the same letter (lower case for the clay soil and upper case for the loess) do not differ significantly at the 0.05 level.

treatment (i.e., continuous flow), rill erosion in the clay soil was one to two orders of magnitude greater than that in the silt loam (Fig. 3).

The rill erosion in the two soils can be compared, despite the difference in inflow rate (240 and 320 mL min^{-1}), because runoff flows in the two soils were similar. The IRs in the clay soil exposed to continuous flow during the second, third, and fourth minute of Stage 1 were 145, 105, and 90 mL min^{-1} (Fig. 1), which resulted in respective runoff flow of 175, 215, and 230 mL min^{-1}. Similarly, for the silt loam the IRs were 90, 65, and 55 mL min^{-1} for the second, third, and fourth minute of the first stage (Fig. 1), and the corresponding runoff flows were 150, 175, and 185 mL min^{-1}. Runoff in the clay soil were only slightly higher than runoff from the silt loam, and a comparison between the rill erodibilities of the two soils was possible. The fact that under these conditions inflow rate and shear stress at the upper end of the flume were higher in the clay soil than in the silt loam cannot explain the observed differences in rill erosion between the two soils. Shainberg et al. (1996) used similar inflow rates and observed greater rill erosion in the clay soil than in the silt loam.

The differences in runoff between the two soils could not explain in full the differences in rill erodibility of the two soils (Fig. 3). Thus, the higher erodibility of the clay soil was ascribed to the weak cohesive forces that existed between the aggregates (Shainberg et al, 1996). Aggregate stability increases with increase in clay content (Kemper and Koch, 1966). Soils with high clay content, such as the one used in our study (Table 1), have stable aggregates and high interaggregate macroporosity (Rengasamy et al., 1984; Kay and Angers, 1999) leading to greater distance and fewer contacts between adjacent aggregates. The larger distance between aggregates contributes to weak cohesive forces among the aggregates, which in turn makes the aggregates more susceptible to detachment from the soil surface. This may explain the higher erodibility of the clay soil compared with the silt loam. Our results seem not to agree with many observations suggesting that clay soils are less erodible than silt loams (e.g., Laflen et al., 1991; Ben-Hur et al., 1985). Studying the effect of clay content on crusting, runoff, and erosion in soils exposed to simulated rain, Ben-Hur et al. (1985) found that soils with 20% clay were susceptible to crusting and that soils with higher clay content had more stable aggregates and less runoff and erosion. The low erosion in clay soils was because of low runoff. When soil erosion from two soils with similar runoff is compared, as in the conditions of this study, erosion from the clay soil may exceed erosion from the silt loam.

The first flow interruption of 10 min significantly reduced the erosion rate of the clay soil compared with that obtained in continuous flow (second minute, Fig. 3). This decrease in erodibility of the clay soil during the first flow interruption became even more pronounced during the subsequent surge cycles (Minutes 3–5, Fig. 3). Four flow interruptions, each of 10 min, had a lasting effect on the rill erosion of the clay soil during the following 10 min of continuous flow (Fig. 3). In the

22

clay soil interrupted flow reduced cumulative erosion by 84% (Fig. 3).

Rill erosion in the silt loam exposed to inflow of 240 and 80 mL min^{-1} was too small for accurate measurement, and for evaluation of the effects of interrupted flow on erosion (Fig. 3). Thus, a complementary experiment was performed. Following the continuous and interrupted flow in Stages 1 and 2, the miniflumes with the silt loam were exposed to an additional 3 min of continuous inflow of 320 mL min^{-1}. Amount of erosion obtained in these last 3 min in the silt loam decreased from 42.6 g in the continuous flow to 7.6 g in the interrupted flow treatment. Evidently, the silt loam was less erodible than the clay soil, but when the silt loam was exposed to high flow rate, interrupted flow reduced rill erosion to 18% of the erosion in continuous flow. Interrupted flow in the silt loam was as effective in reducing rill erosion as in the clay soil.

The observed effects of interrupted flow on rill erosion can be attributed to two mechanisms that are active during flow interruption. First, the suction developed at the soil surface during the off period pulled the soil particles closer together and increased the cohesive forces between the surface particles and reduced erosion rate (Kemper and Roseneau, 1984; Shainberg et al., 1996). Second, aging (four periods of 10 min) increased the cohesive forces between soil particles (Kemper and Roseneau, 1984). These authors postulated that slightly soluble components diffusing to and cementing points of contact between particles were responsible for the bonding mechanism of the cohesive forces. Realizing, that net attractive forces acted between clay edges and clay surfaces, and also between clay surfaces with high charge densities, Shainberg et al. (1996) suggested that under conditions of high water content supplemented by an adequate aging period, clay to clay contacts occur, and clay cementing was responsible for the development of a cohesive structure that resisted rill erosion.

Interrupted flow reduced cumulative erosion in the two soils to <20% of the erosion in continuous flow. These results suggested that surge irrigation can be considered as an effective management tool for the control of furrow erosion problems in surface irrigation.

SUMMARY AND CONCLUSIONS

Effects of interrupted flow on rill erosion and IR of a silt loam and a clay soil were studied. Interrupted flow reduced the IR in both soils compared with that obtained with continuous flow. This reduction in IR was more effective in the silt loam because of its unstable structure than in the stable structured clay soil. The effect of interrupted flow in reducing the IR decreased with increase in the number of flow cycles and depended on soil type. Interrupted flow consolidated the soil surface and reduced the depth of water that infiltrated. Eventually, the higher hydraulic gradient created by the interrupted flow (due to the reduced depth of infiltrating water) compensated for the consolidation of the soil surface, and the favorable effect of interrupted flow on decreasing IR vanished.

Rill erosion in the clay soil was higher than rill erosion in the silt loam. However, interrupted flow reduced rill erosion in both soils and to a similar degree. Flow interruption reduced rill erosion to 16 and 18% of the rill erosion in continuous flow for the clay soil and silt loam, respectively.

Our results show that, unlike many studies have shown for interrill erosion, rill erosion is higher in clay soil than in silt loam. However, the results also suggest that interruption of flow might be considered as an effective management tool in surface irrigation to enhance infiltration uniformity and for the control of furrow erosion in the two soil types.

ACKNOWLEDGMENTS

D. Sirjacobs is grateful to the Agricultural Research Organization, Bet Dagan, Israel, in providing him with a grant which made the realization of this work possible. This study was supported by grants TA-MOU-96-CA16-016 and TA-MOU-97-CA17-008 from the US-Israel Cooperative Development Research (CDR) Program, Office of Science Advisor, U.S. Agency for International Development (AID). The support of the CDR is gratefully acknowledged.

REFERENCES

Banin, A., and A. Amiel. 1970. A correlative study of the chemical and physical properties of a group of natural soils of Israel. Geoderma 3:185–198.

Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soils as related to water salinity. Irrig. Sci. 6:281–294.

Izadi Bahzad, D.F. Heerman, and A. Klute. 1990. Soil water redistribution and hysteresis in surge irrigation. Trans. ASAE 33:799–806.

Izuno, F.T., T.H. Podmore, and R.H. Duke, 1985. Infiltration under surge irrigation. Trans. ASAE 28:517–521.

Jalali-Farahani, H.R., H.R. Duke, and D.F. Heermann. 1993. Physics of surge irrigation. I. Quantifying soil physical parameters. Trans. ASAE 36:37–44.

Kay, B.D., and D.A. Angers. 1999. Soil structure. p. A229–A276. *In* M.E. Sumner (ed.). Handbook of soil science. CRC Press, Boca Raton, FL.

Kemper, W.D., and E.J. Koch. 1966. Aggregate stability of soils from western U.S. and Canada. Tech. Bull. 1355. USDA-ARS. U.S. Gov. Print. Office, Washington, DC.

Kemper, W.D., and R.C. Roseneau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., R.C. Roseneau, and S. Nelson. 1985. Gas displacement and aggregate stability of soils. Soil Sci. Soc. Am. J. 49:25–28.

Kemper, W.D., T.J. Trout, and A.S. Humphreys. 1988. Mechanisms by which surge irrigation reduces furrow infiltration rates in a silty loam soil. Trans. ASAE 31:821–829.

Laflen, J.M., W.J. Elliot, J.R. Simanton, C.S. Holzhey, and K.D. Kohl. 1991. WEPP soil erodibility experiments for rangeland and cropland soils. J. Soil Water Conserv. 46:39–44.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow erosion with small application of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Mullins, C.E. 1999. Hardsetting soils. p. G65–G88. *In* M.E. Sumner (ed.) Handbook of soil science. CRC Press, Boca Raton, FL.

Rengasamy, P., R.S.B. Green, and G.W. Ford. 1984. The role of clay fraction in the particle arrangement and stability of soil aggregates—A review. Clay Res. 3:53–67.

Samani, Z.A., W.R. Walker, and L.S. Willardson. 1985. Infiltration under surge flow irrigation. Trans. ASAE 28:1539–1542.

Seymour, R.M. 1990. Air entrapment and consolidation as mechanisms in infiltration with surge irrigation. Ph.D thesis. Colorado State Univ., Fort Collins.

Shainberg, I., and M.J. Singer. 1985. Effect of electrolyte concentration on the hydraulic properties of depositional crusts. Soil Sci. Soc. Am. J. 49:1260–1263.

Shainberg, I., J.M. Laften, J.M. Bradford, and L.D. Norton. 1994.

23

Hydraulic flow and water quality characteristics in rill erosion. Soil Sci. Soc. Am. J. 58:1007–1012.
Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging, and temperature. Soil Sci. Soc. Am. J. 60:916–922.
Stringham, G.E. 1988. Surge flow irrigation. Final report of the Western Regional Research Project W-163. Res. Bull. 515. Utah Agric. Exp. Stn., Utah State Univ., Logan.
Trout, T.J. 1991. Surface seal influence on surge flow furrow infiltration. Trans. ASAE 34:66–72.
Wolters, W. 1992. Influences on the efficiency of irrigation water use. Publ. 51. ILRI, Wageningen, the Netherlands.

Reprinted from the *Soil Science Society of America Journal*
Volume 62, no. 6, Nov.–Dec. 1998
677 South Segoe Rd., Madison, WI 53711 USA

Appendix B

Hydraulic Gradient, Aging, and Water Quality Effects on Hydraulic Conductivity of a Vertisol

M. Moutier,* I. Shainberg, and G. J. Levy

ABSTRACT

Aging, manifested by an increase with time of the aggregate mechanical strength, has been reported recently to affect the response of a soil to water quality. However, experimental evidence demonstrating its effect on the hydraulic conductivity is lacking. We present the results of aging, hydraulic gradient, and water quality effects on the saturated hydraulic conductivity of disturbed smectitic soil samples (A horizon, Chromic Haploxerert). The effects of two hydraulic gradients (2.9 and 12) and two leaching durations (3–4 and 20 h) were tested. Soil consecutively leached with 0.5, 0.05, 0.01, and 0.003 *M* Cl^- solutions (Na adsorption ratio, SAR = 10) or 0.5, 0.01 *M* Cl^- solutions and deionized water (SAR = 0). The saturated hydraulic conductivity of the soil decreased with an increase in soil exchangeable Na percentage and a decrease in total electrolyte concentration. Also, the relative hydraulic conductivity of the soil decreased from 1.1 to 0.94 when subjected to a high-hydraulic gradient treatment, and subsequently increased to 2.32 under prolonged leaching with 0.01 *M* Cl^- solution of SAR = 0. This decrease was attributed to the compression of clay particles at the column outlet. The subsequent increase in hydraulic conductivity was ascribed to thixotropic stabilization of the clay fabric and cohesive bond development. The effects of hydraulic gradient and aging were less pronounced in soil in equilibrium with solution of SAR = 10 because the higher sodicity increased the repulsion forces between clay particles, thus reducing clay-to-clay contact. Some practical consequences were postulated concerning aging effect under field conditions.

Hydraulic conductivity of soils is related to the composition and concentration of exchangeable cations and soluble electrolytes (Quirk and Schofield, 1955). The hydraulic conductivity of soils decreases with an increase in soil exchangeable Na percentage (ESP) and a decrease in the total electrolyte concentration of the soil solution. Two main mechanisms have been proposed to explain the reduction in hydraulic conductivity, namely clay swelling and clay dispersion (Quirk and Schofield, 1955).

Clay swelling is essentially a reversible process and may lead to a significant narrowing of the conducting (effective) pores. It is not greatly affected by low ESP values (<10–15), but it increases with an increase in ESP or a decrease of the total electrolyte concentration of the interclay solution (Oster et al., 1980).

Clay dispersion takes place throughout the entire Na adsorption ratio (SAR) range provided the total electrolyte concentration is below the critical flocculation concentration (Oster et al., 1980). The critical flocculation concentration is defined as the minimum electrolyte concentration necessary to flocculate a given colloidal suspension in a given time (van Olphen, 1977). Clay dispersion increases with (i) increasing soil ESP and soil pH (Suarez et al., 1984) and (ii) decreasing oxides or hydroxides content (Alperovitch et al., 1985) and organic matter content (Gupta et al., 1984). Clay mineralogy, nature of the exchangeable cations other than Na, and the presence of organic or inorganic anions (Frenkel et al., 1992) also affect clay dispersion.

Recently, several authors have reported that the response of a soil to water quality was also affected by time-dependent variables. The effects of aging duration, water content, and temperature during aging on aggregate stability, infiltration rate, and erosion have been discussed by Blake and Gilman (1970), Kemper and Rosenau (1984), Le Bissonnais and Singer (1992), Shainberg et al. (1996), and Levy et al. (1997). It has been suggested (i) that the binding of soil particles is independent of organic matter content and of the activity of a viable microbial population (Blake and Gilman, 1970; Kemper et al., 1987); (ii) that chemical processes involving precipitation of $CaCO_3$ and silica might be responsible for particle binding (Kemper et al., 1987); (iii) that physicochemical forces between clay platelets, such as face-to-face and edge-to-face forces, might be responsible for the development of cohesion forces (Shainberg et al., 1996); (iv) that clay movement and reorientation, which increases with an increase in water content, Brownian motion (aging temperature), and clay content, might control the rate of cohesive forces development (Shainberg et al., 1996). These significant thixotropic changes were observed within 20 to 30 h for artificial aggregates made from Webster clay loam (34.9%) (Blake and Gilman, 1970) and in aggregates of a vertisol (46.5%) following 24 h of aging (Shainberg et al., 1996). In addition, a positive correlation has been demonstrated between clay content (number of clay-to-clay contacts) and aggregate stability in arid and semi-arid soils where clay plays a major role in the cohesion of larger particles (Kemper and Koch, 1966). A similar conclusion was drawn by Singer et al. (1992) concerning the strong dependence of aggregate stability on the clay mineralogy and clay content; an increase in clay content (especially kaolinite or smectite) resulted in an increased aggregate stability.

An increase with time of the aggregate mechanical

M. Moutier, Université Catholique de Louvain, Unité de Genie Rural, Place Croix du Sud 2, Bte 2, B-1348 Louvain-la-Neuve, Belgium. I. Shainberg and G.J. Levy, Institute of Soils and Water, Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet-Dagan 50-250, Israel. Contribution from Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet-Dagan 50-250, Israel. no 2257 - E 1997 series. Received 6 Aug. 1997. *Corresponding author (moutier@geru.ucl.ac.be).

Published in Soil Sci. Soc. Am. J. 62:1488–1496 (1998).

Abbreviations: EC, electrical conductivity; ESP, exchangeable Na percentage; SAR, Na adsorption ratio.

25

strength (aging) will affect the hydraulic conductivity; however, experimental evidence demonstrating its effect on the hydraulic conductivity is lacking. It is also hypothesized that an interaction might exist between aging and the conditions that could be applied for the hydraulic conductivity measurement. Thus, the following study was designed to establish and define the effects of the hydraulic gradient, leaching duration, and water quality on the hydraulic conductivity of a disturbed smectitic vertisol.

THEORETICAL BACKGROUND

Particle Arrangement and Microstructure in Smectitic Soils

Sodium-smectite particles in dilute solutions occur as single platelets with mutual repulsion forces predicted by the diffuse double-layer theory (van Olphen, 1977). Smectite clay particles saturated with Ca^{2+} and Mg^{2+} form tactoids (Blackmore and Miller, 1961) or quasi-crystals (Quirk and Aylmore, 1971) even in dilute salt solutions. Quasi-crystals are packets of 5 to 10 platelets arranged in a more or less parallel alignment (face-to-face arrangement). The number of platelets per quasi-crystal depends on the clay ESP, the total electrolyte concentration, the layer charge, the clay concentration, and the consolidation or air drying pressure applied to the system.

An association of several quasi-crystals is referred to as a *domain* (Aylmore and Quirk, 1959), and is considered in our study as the structural unit of the clay fabric (Fig. 1). A domain consists of overlapping or interleaving quasi-crystals. This overlapping generates an assembly of slits and of wedge-shaped voids, with widths in the range of 2 to 5 nm, referred to as the intercrystal or intradomain porosity (Murray and Quirk, 1990).

The domains can be held together by various cementing materials, e.g., sesquioxides, organic matter, or carbonates (Emerson and Greenland, 1990) and by domain bridging, which generates an open microstructure enclosing 1- to 2-μm pores. These pores constitute the interdomain porosity. Such microstructures were examined by Tessier (1984) using electron microscopy.

In soils, these microstructures are associated to form micro- (<250 μm) or macro- (>250 μm) aggregates (Fig. 1). Coarse pores, i.e., transmission pores (>50 μm) and storage pores (500 nm to 50 μm), occur in macroaggregates and, in particular, in sections where microaggregates join. Transmission pores differ from storage pores in the capability of the latter to retain water against gravity. Because of the small sizes of the intercrystalline (2–5 nm) and interdomain (1–2 μm) pores in comparison with that of the transmission pores, it is assumed that most of the water flow in soils takes place in these transmission pores.

Effect of the Hydraulic Gradient on the Hydraulic Conductivity of a Compressible Porous Medium

When a pressure difference, i.e., a hydraulic gradient, is applied across a compressible clay medium, the pressure difference will push the quasi-crystals toward the low-pressure side (Kemper et al., 1972) (Fig. 2b). However, the forces tending to concentrate the clay particles on the outflow side are opposed by the electric double-layer repulsion force, also called the swelling pressure of the particles, which increases as the quasi-crystals are pushed closer together. At a steady state, the applied hydraulic gradient is balanced by the swelling pressure gradient and the steady-state solution flow is explained in terms of an electro-osmotic gradient (Kemper et al., 1972). In an incompressible porous medium exposed to a hydraulic gradient, the particles are held in place by solid-to-solid contact, and all particles remain in their initial positions (Fig. 2a). The pores at the outflow side remain essentially the same size as those at the inflow side, and solution flow is determined by the hydraulic gradient. However, in an expandable clay soil (e.g., vertisol), which is not considered an ideal compressible medium, the application of a hydraulic gradient can lead to a physical compression of the clay fabric. This, in turn, will result in the narrowing of all pores at the outlet of the column, including the water transmitting ones, whereas the pores at the inflow side will remain largely unaffected.

These changes affect the hydraulic conductivity across the soil column: as the hydraulic gradient across the soil

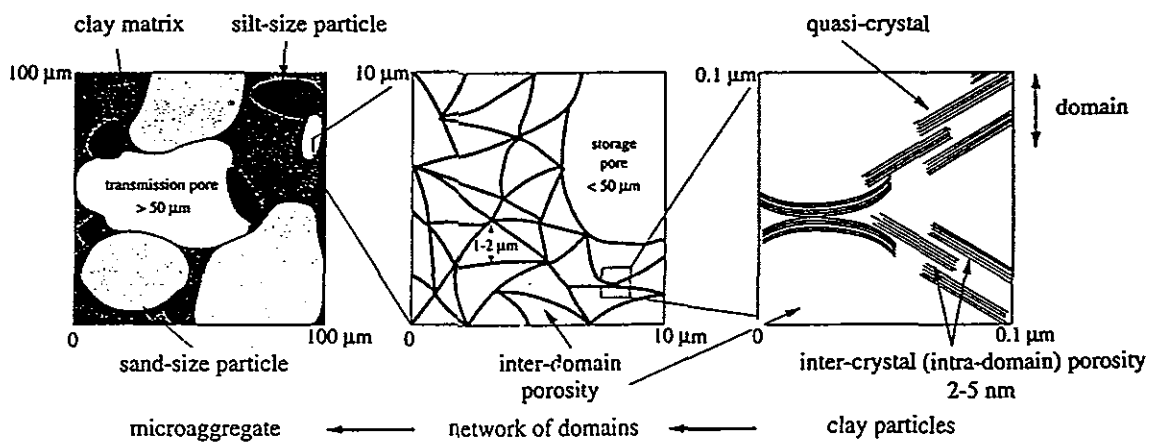


Fig. 1. Schematic representation of particle arrangement and microstructure in smectitic soils.

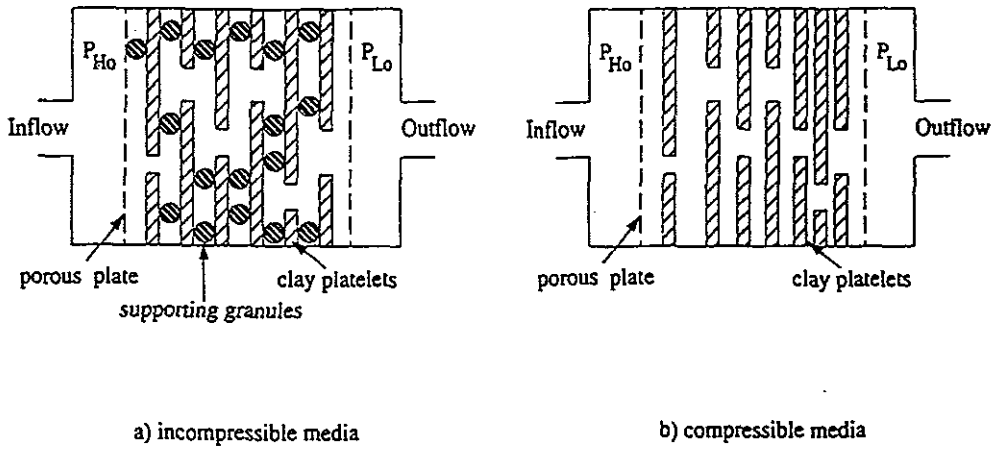


Fig. 2. Effect of a pressure differential (initial $P_{high\text{-}pressure\ side}$ − initial $P_{low\text{-}pressure\ side}$) applied across (a) an incompressible and (b) an idealized compressible porous medium during pressure-induced hydraulic flow (from Kemper et al., 1972).

column increases, so does the compression at the lower end of the column. The hydraulic conductivity in this region decreases and, subsequently, so does the average hydraulic conductivity of the soil column (Kemper et al., 1972).

MATERIALS AND METHODS

The effects of hydraulic gradient, leaching duration, and water quality on the hydraulic conductivity (K) were studied at constant room temperature on disturbed, air-dried, and sieved soil (<2 mm). These experimental conditions were a reasonable compromise between the use of artificial aggregates reconstituted from completely disintegrated soil samples (Kemper et al., 1987) and larger aggregates generally used in infiltration studies (Levy et al., 1997). Disturbed samples of a smectitic soil (Chromic Haploxerert) were taken from the A horizon (0–25 cm) of a cultivated field in the Yizreel Valley, Israel. Samples were characterized using standard methods (Klute, 1986; Page et al., 1986). The clay and silt contents of this soil were 70.3 and 14.3%, respectively; its cation exchange capacity was 55.5 cmole kg^{-1} dry soil; and it contained 12.3% $CaCO_3$. Organic matter content (4.5%) was determined by the "loss on ignition" method (Ben-Dor and Banin, 1989).

Soil columns were prepared by packing 120 g of sieved, air-dried soil into small cylinders (5.4 cm in diameter) resulting in an average dry bulk density of $1.34 \pm 1.79 \times 10^{-2}$ Mg m^{-3} (±1 standard deviation). The soil columns were covered with a filter paper to minimize surface disturbance when solutions were applied. Basal support of the column consisted of a rubber stopper with a hole to accommodate an outflow tube and a screen covered with acid-washed sand (35 g). Prewetting was done by saturating the soil column using a Mariotte bottle placed at the bottom of the dry soil. Solutions of 0.5 M Cl^-, containing NaCl and $CaCl_2$, of predetermined SAR (0 or 10) were used for prewetting. Upon wetting, the clay soil swelled to an average wet bulk density of $0.997 \pm 4.42 \times 10^{-2}$ Mg m^{-3}. During the prewetting procedure, the length of the soil column increased from an average of $3.9 \pm 5.06 \times 10^{-2}$ cm in the dry state to $5.3 \pm 1.69 \times 10^{-1}$ cm in the wet state. During the experiment, the soil length was regularly measured.

Following saturation, the flow direction was reversed and the column was leached using a constant-head device. Two hydraulic heads were applied: low (≈15.3 cm) and high (≈63.8 cm) hydraulic head. These heads corresponded with hydraulic gradients of 2.9 and 12.3, respectively. Columns were first leached with the 0.5 M Cl^- solution of SAR = 0 or 10. Approximately 10 to 20 pore volumes were passed through the column in order to equilibrate the exchange phase of the soil with the composition of the solution. Pore volume was calculated by subtracting the volume of solid M/ρ_s from the total bulk volume AL, where M is the mass of air-dried soil, ρ_s density of solid particles (2.65 Mg m^{-3}), A the cross-sectional area of the soil column (m^2), and L the length of the soil column.

Following this conditioning, the flow rate was measured and the saturated hydraulic conductivity was calculated using Darcy's law:

$$K = -v/\nabla H \qquad [1]$$

where v is the water flux, i.e., the volume of solution passing through unit cross-sectional area of soil per unit time [m^3 m^{-2} s^{-1}]; and ∇H the hydraulic gradient [−], which is constant throughout the experiment. Saturated hydraulic conductivities calculated at the end of the conditioning (0.5 M Cl^-) were taken as reference values ($K_{0.5}$). Thereafter, the soil columns were successively leached with 0.05, 0.01, and 0.003 M Cl^- for SAR = 10 and solutions of 0.01 M Cl^- and deionized water for SAR = 0. The effect of leaching duration, allowing aging to take place, was evaluated by comparing short leaching (3–4 h) with long leaching (20 h). This experimental choice was based on previously published data (Kemper and Koch, 1966; Blake and Gilman, 1970; Shainberg et al., 1996).

During leaching, the effluent was collected continuously with a fraction collector. The volumes of the leachates and their EC were measured. Each treatment was duplicated except one that was triplicated (high hydraulic gradient, long leaching, SAR = 0). Results were analyzed by one-way analysis of variance using paired Student t-test (comparison of two means with unknown but equal variance). Since $K_{0.5}$ varied between treatments, the hydraulic conductivity for a given treatment was expressed in terms of relative hydraulic conductivity K_r, given by the ratio of saturated hydraulic conductivity calculated for a given solution to the respective $K_{0.5}$ calculated for the 0.5 M Cl^- solution of identical SAR.

RESULTS AND DISCUSSION

Vertisol in Equilibrium with Sodium Adsorption Ratio = 0 Solutions

The effects of the total electrolyte concentration (0.01 M Cl^- and deionized water) on the relative hydraulic conductivity in the SAR = 0 treatment are presented in Fig. 3. The final corresponding absolute values of K

27

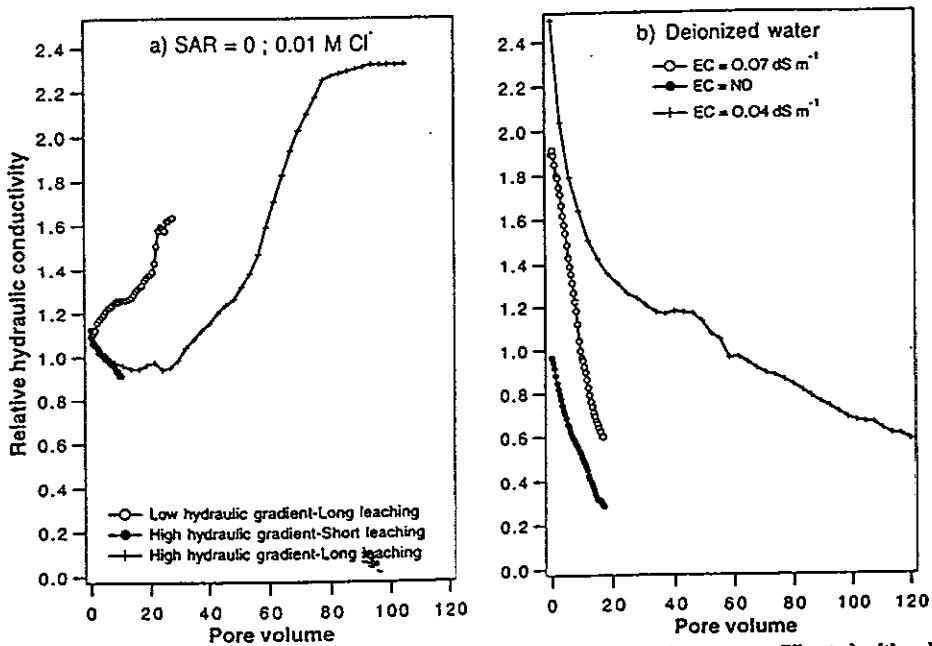


Fig. 3. Relative hydraulic conductivities as a function of pore volume for the Chromic Haploxerert equilibrated with solutions of SAR = 0, consecutively leached with (a) 0.01 *M* Cl^- and (b) deionized water. Three combinations were tested: high hydraulic gradient–long leaching; low hydraulic gradient–long leaching; low hydraulic gradient–short leaching.

and their standard deviations are summarized in Table 1. The response of the soil to changes in solution concentration depended on the hydraulic gradient, but there was no effect of the hydraulic gradient on $K_{0.5}$. When a high hydraulic gradient was applied, K decreased during the passage of the first 20 pore volumes (Fig. 3a, short and long leaching treatments). A similar decrease in K_r, for a vertisol, has been reported in the literature and ascribed to the existence of a rather labile structure (McNeal and Coleman, 1966). The decrease in K_r was explained in terms of two mechanisms: (i) swelling at the external surfaces of the quasi-crystals (Blackmore and Miller, 1961), which leads to increased volume of the quasi-crystals at the expense of the transmission pores (>50 μm) (Fig. 1); and (ii) under exposure to a high hydraulic gradient, extensive compression of the clay matrix at the outflow side of the soil column (Fig. 2b), leading to narrower pores and lower K values. This was not accompanied by a reduction in the soil column length. In most previous studies, leaching with the 0.01 *M* Cl^- solution was stopped when <20 pore volumes had passed and only a decrease in K_r was observed (Fig. 3a, short leaching). However, when leaching was continued for 20 h (40–100 pore volumes), an increase in K_r was observed (Fig. 3a). This unexpected increase in K_r was attributed to the development of cohesive forces between clay fabric structural units, which, in our case, were mainly clay domains (Kemper and Rosenau, 1984; Shainberg et al., 1996). These forces would cause reorientation and reorganization of domains and microaggregates in the soil fabric, leading to an increase in the average size of the transmission pores (Fig. 1) and, hence, to an increase in K. It was assumed that this phenomenon was not due to the high degree of disturbance of the soil samples (sieved and air dried). Increases with time of aggregate stability were demonstrated in synthetic aggregates reconstituted from disintegrated soil samples (Singer et al., 1992) as well as in soil aggregates (Chromic Haploxerert with 46.5% clay) during 24 h of aging (Shainberg et al., 1996).

Table 1. Absolute values of the hydraulic conductivity (K) and its standard deviation (σ) calculated at the end of leaching with solutions of Na adsorption ratio (SAR) = 0 (0.5, 0.01 *M* Cl^- and deionized water) or with solutions of SAR = 10 (0.5, 0.05, 0.01, and 0.003 *M* Cl^-). The subscript refers to the corresponding solution.

	SAR = 0						SAR = 10					
	Low gradient, long leaching		High gradient, long leaching		High gradient, short leaching		Low gradient, long leaching		High gradient, long leaching		High gradient, short leaching	
	K	σ	K	σ	K	σ	K	σ	K	σ	K	σ
	[cm h⁻¹]											
$K_{0.5}$	1.01	3.05×10^{-1}	1.26	1.85×10^{-1}	1.02	2×10^{-1}	1.59*	2.62×10^{-1}	1.14	1.28×10^{-1}	0.92	6.89×10^{-3}
$K_{0.05}$							1.97	8.24×10^{-2}	1.54	8.90×10^{-2}	0.70	5.39×10^{-2}
$K_{0.01}$	1.65	4.40×10^{-1}	2.90	7.73×10^{-1}	0.93	1.44×10^{-1}	1.22	1.54×10^{-1}	0.99	6.41×10^{-1}	0.49	4.70×10^{-2}
$K_{0.003}$							0.24	3.84×10^{-2}	0.28	2.37×10^{-1}	0.14	5.97×10^{-3}
K_{DW}†	0.61	2.29×10^{-1}	0.77	4.79×10^{-1}	0.29	3.75×10^{-2}						

* Significant at the 0.05 probability level.
† DW, deionized water.

28

The effect of leaching duration on the K was further demonstrated when the vertisol was exposed to a low hydraulic gradient (Fig. 3a). Leaching the soil with 0.5 M Cl^- solution was continued for 20 h (10–20 pore volumes), during which the K of the soil increased slightly (data not presented), suggesting that some stabilization of the soil structure had already occurred at the conditioning stage. When the 0.5 M Cl^- solution was replaced with a 0.01 M Cl^- solution at a slow flow rate, K_r increased from the very beginning, indicating that stabilization of the soil structure continued (Fig. 3a). This phenomenon was contrary to the commonly observed trend: a decrease in K (due to swelling of quasicrystals) has been noted on replacement of a concentrated solution with a more dilute one (Quirk and Schofield, 1955; McNeal and Coleman, 1966). It should be clear that under the low hydraulic gradient, as with the high hydraulic gradient, swelling and physical compression of the soil at the bottom of the soil column took place, but their adverse effects were outweighed by the favorable effect of the development of cohesion forces in increasing K.

The rate of increase in K_r under the low hydraulic gradient seemed similar to that observed with the high hydraulic gradient except for the fact that the ascending part was displaced by 30 pore volumes (Fig. 3a). In the low-hydraulic gradient treatment the soil column was leached with only 30 pore volumes of 0.01 M Cl^- solution compared with 110 pore volumes in the high-hydraulic gradient treatment because of the lower rate of water flow in the low-hydraulic gradient treatment. Plotting the hydraulic conductivity as a function of cumulative time, for the two treatments, indicated that the rate of increase in K_r was lower in the low-hydraulic gradient treatment than in the high-hydraulic gradient treatment (Fig. 4a). The high rate of hydraulic conductivity increase in the high-hydraulic gradient treatment was attributed to the close packing of the clay fabric structural units at the outflow end of the soil column, and would accelerate the formation of clay-to-clay contacts and bonds.

When the 0.01 M Cl^- solution of SAR = 0 was replaced with deionized water, K_r decreased, irrespective of the hydraulic gradient and the duration of leaching (Fig. 3b and Table 1). In deionized water, either clay dispersion or swelling could be responsible for the changes in the K. However, clay was not observed in the leachate, and since the EC of the leachate (0.04–0.07 dS m^{-1}) was above the critical flocculation concentration of Ca-montmorillonite (0.25 mol_c m^{-3}) (van Olphen, 1977) and that of Ca-soil (Goldberg and Forster, 1990), no macromovement of dispersed clay was likely (Fig. 3b). Thus, swelling was considered to be the main mechanism responsible for the decrease in K_r. Since steady-state EC values were obtained during the passage of the first two pore volumes and the decrease in K_r continued during the passage of 20 to 120 pore volumes (Fig. 3b) or 8 to 24 h (Fig. 4b), it is evident that clay swelling is a slow process (Keren and Singer, 1988).

Figure 3b suggests that the rate of decrease in K in the soil columns exposed to high hydraulic gradient was slow compared with that in the low-hydraulic gradient treatment. However, when K_r was plotted as a function of time (Fig. 4b), all treatments showed a similar rate of decrease in K_r. This similarity supports the conclusion that swelling was the governing mechanism responsible for hydraulic conductivity decrease.

A comparison between the hydraulic conductivity curves for short and long leaching treatments with deionized water (Fig. 3b and 4b) supports our conclusion that aging stabilized soil fabric and reduced the susceptibility of soil upon leaching with deionized water. After

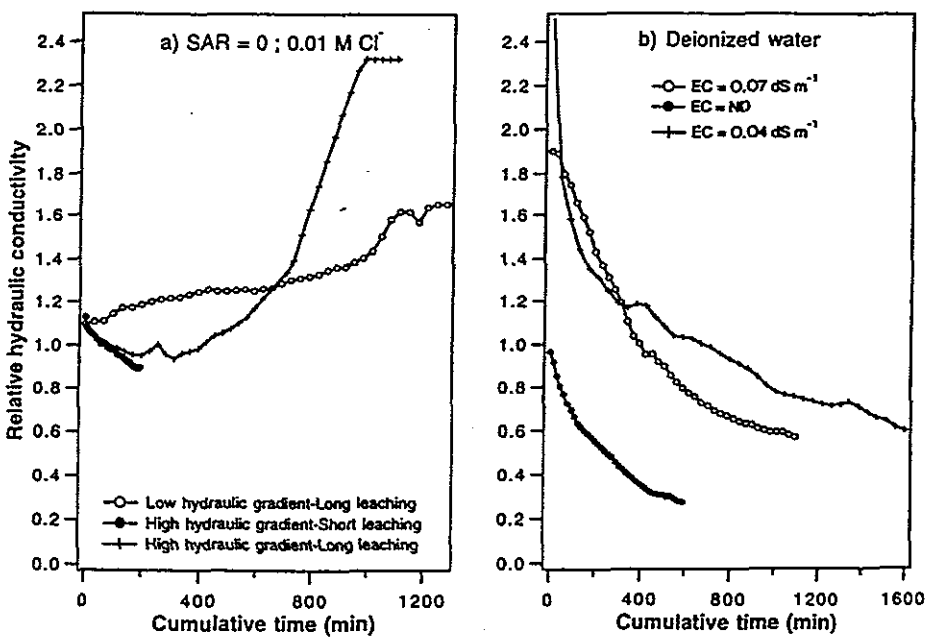


Fig. 4. Relative hydraulic conductivities as a function of cumulative time for the Chromic Haploxerert equilibrated with solutions of SAR = 0, consecutively leached with (a) 0.01 M Cl^- and (b) deionized water. Three combinations were tested: high hydraulic gradient–long leaching; low hydraulic gradient–long leaching; low hydraulic gradient–short leaching.

short leaching, K_r in deionized water decreased to 0.3 in 600 min. Despite the quick drop in K_r in soil columns under exposure of a high-hydraulic gradient treatment, K_r was maintained at 0.6 (Fig. 4b). In addition, the long-leaching with a solution of 0.01 M Cl^- stabilized the soil structure so much that the response of the Chromic Haploxerert (A horizon) to leaching with deionized water was independent of the hydraulic gradient (Fig. 4b).

The hydraulic conductivity at the beginning of leaching with deionized water was somewhat higher than that at the end of leaching with the 0.01 M Cl^- solution, especially in the long-leaching treatments (Fig. 3 and 4). Many experiments showed that stopping the flow for a short time resulted in a jump in K_r. Changing solutions necessitates stopping the solution flow for short periods, which releases the pressure difference across the soil column (Fig. 2b), and causes a more uniform distribution of soil particles, which, in turn, leads to an increase in K. The magnitude of the increase in K depends on the hydraulic gradient: the higher the hydraulic gradient, the more pronounced is the increase in K of the soil when the flow is stopped. Indeed, in our studies (Fig. 3 and 4), stopping the flow and releasing the pressure in the high-hydraulic gradient treatment had a greater effect on the increase of K than stopping the flow in the low-hydraulic gradient treatment.

Vertisol in Equilibrium with Sodium Adsorption Ratio = 10 Solutions

In a soil equilibrated with a solution of SAR = 10, the ESP of the soil is approximately 10 (U.S. Salinity Laboratory, 1954). At this ESP level, Ca and Na cations adsorbed on the clay are not randomly distributed on the quasi-crystal; demixing of cations occurs, whereby Ca cations mainly neutralize the charges on the internal surfaces and the Na cations concentrate on the external surfaces of the quasi-crystals (Glaeser and Mering, 1954). Introduction of Na ions on the external surfaces of the quasi-crystals induces swelling of the quasi-crystals and the domains, at the expense of the conducting pores (Fig. 1). In addition, the high swelling pressure between quasi-crystals in SAR = 10 solution opposes the hydraulic gradient forces tending to push the clay particles closer together (Fig. 2b); therefore, the decrease in hydraulic conductivity due to hydraulic gradient should be less pronounced in SAR = 10 solutions.

The effects of the total electrolyte concentration (0.05, 0.01, and 0.003 M Cl^-) on K_r in the SAR = 10 solutions are presented in Fig. 5. The corresponding absolute values of K calculated at the end of each leaching period and their standard deviations are summarized in Table 1. The $K_{0.5}$ values in soil columns subjected to low hydraulic gradient were significantly higher (0.05 level) than in those soils subjected to high hydraulic gradient (Table 1). This was attributed to two mechanisms. First, under low hydraulic gradient, leaching with the 0.5 M Cl^- solution (conditioning) was slow and the development of cohesion forces was pronounced; thus, K increased in the 0.5 M Cl^- solution (data not presented) and the final hydraulic conductivity ($K_{0.5}$) was higher; conversely, under high hydraulic gradient, leaching with the 0.5 M Cl^- solution was fast and there was not enough time for cohesive forces to develop. Second, under high hydraulic gradient, there was more severe physical compression at the outflow end of the column than with low hydraulic gradient, and a lower $K_{0.5}$ was obtained.

The effect of replacing the 0.5 M Cl^- solution (SAR = 10) with 0.05 M Cl^- solution on the hydraulic conductivity of the Chromic Haploxerert (A horizon) depended on the hydraulic gradient (Fig. 5a). When high hydraulic gradient was applied, K_r first decreased, and then, with further leaching, increased (long-leaching treatment).

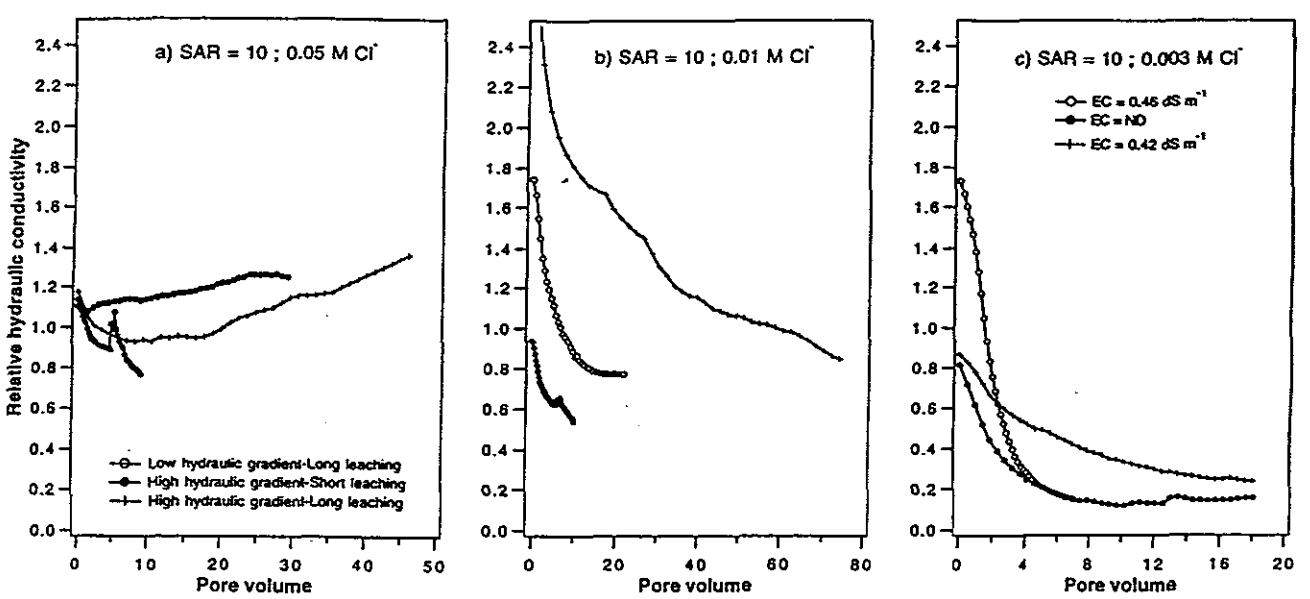


Fig. 5. Relative hydraulic conductivities as a function of pore volume for the Chromic Haploxerert equilibrated with a solution of SAR = 10, consecutively leached with (a) 0.05 M Cl^-, (b) 0.01 M Cl^-, and (c) 0.003 M Cl^-. Two hydraulic gradients were tested: high and low hydraulic gradient under prolonged leaching.

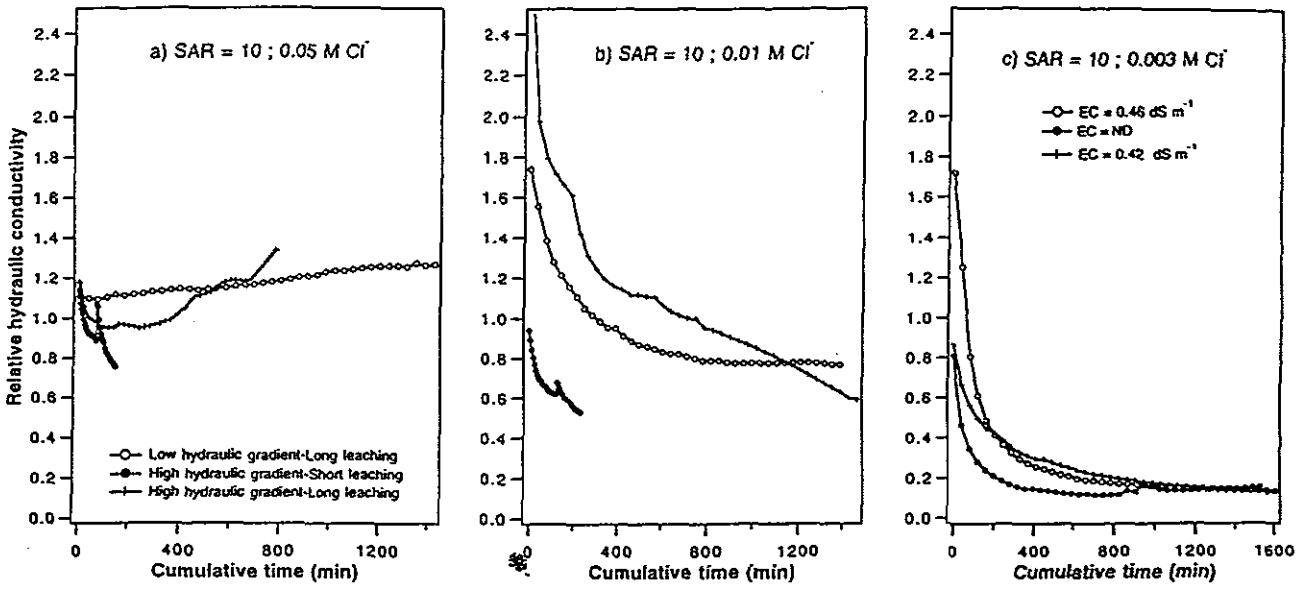


Fig. 6. Relative hydraulic conductivities as a function of cumulative time for the Chromic Haploxerert equilibrated with a solution of SAR = 10, consecutively leached with (a) 0.05 *M* Cl^-, (b) 0.01 *M* Cl^-, and (c) 0.003 *M* Cl^-. Two hydraulic gradients were tested: high and low hydraulic gradient under prolonged leaching.

This trend was similar to that observed when the soil columns were leached with the 0.01 *M* Cl^- solution of SAR = 0 (Fig. 3a) and a similar explanation, involving three processes, is proposed: (i) decrease in K_r because of swelling of the quasi-crystals; (ii) decrease in K_r because of compression of the clay fabric at the outflow side of the soil column; and (iii) increase in K_r because of the development of cohesive bonds between domains and microaggregates. In the initial stages of leaching, the first two processes dominated and K_r decreased, but after long leaching, the first two processes reached a steadystate and only the aging mechanism continued, leading to an increase in K_r (Fig. 5a).

When the soil was leached with 0.05 *M* Cl^- solution under low hydraulic gradient, K_r increased gradually almost from the very beginning. Similar observations were obtained in the Chromic Haploxerert (A horizon) leached with 0.01 *M* Cl^- solution of SAR = 0. Under low hydraulic gradient, only slight compression of the clay fabric was induced and the resulting decrease in K_r was small. Also, swelling was more pronounced with solutions of SAR = 10 and K_r decreased slightly during the passage of the first 3 pore volumes. As the leaching proceeded, the development of cohesive bonds led to the increase in K_r as the leaching volume and leaching time increased.

The rate of increase in K_r in 0.05 *M* Cl^- solution was higher under high hydraulic gradient than under low hydraulic gradient (Fig. 5a and 6a, respectively). Again, similar observations were made for the vertisol leached with 0.01 *M* Cl^- solutions of SAR = 0, in which close contacts between clay particles are prevented by water layers surrounding them (Blake and Gilman, 1970; Shainberg et al., 1996). When high hydraulic gradient is applied, the soil particles are closer together and the rate of cohesive bond formation is higher. It should also be noted that the rate of hydraulic conductivity increase in solutions of SAR = 10 was slower than that in solutions of SAR = 0 (Fig. 3a) because the expanded diffuse double layer between quasi-crystals and domains inhibited the development of cohesive forces.

When the 0.05 *M* Cl^- solution was replaced by the 0.01 *M* Cl^- solution, K_r decreased in all treatments (Fig. 5b). Similar decreases in the hydraulic conductivity of vertisols in equilibrium with SAR = 10 were reported by Curtin et al. (1994), who leached with solutions of TEC lower than 20 $mol_c\ m^{-3}$. Clay dispersion was not likely to occur at a concentration of 0.01 *M* Cl^-, which is above the critical flocculation concentration of smectite with ESP = 10 (Oster et al., 1980). Thus, the decrease in K_r was probably due to the combined effects of clay fabric compression and swelling. Compression for soil columns exposed to low hydraulic gradient would be limited, and the increase in compression in soil columns leached with solutions of SAR = 10 and exposed to high hydraulic gradient would be also limited, because of high swelling compared with solutions of SAR = 0. Thus, swelling was probably the main mechanism responsible for the decrease in K_r in both high and low hydraulic gradient, and the rates of decrease in hydraulic conductivity were similar in both treatments (Fig. 6b).

When a solution of 0.003 *M* Cl^- replaced the 0.01 *M* Cl^- solution, K_r decreased sharply. The decrease was very steep even in soil with the stable structure generated by the development of cohesive forces (long leaching, high hydraulic gradient). The sharp decrease in K_r was due to the combined effects of swelling and dispersion (Fig. 5c). Dispersion became possible because the EC of the leachates (0.4–0.5 dS m^{-1}) (Fig. 5c) was close to the critical flocculation concentration of smectites (5 $mol_c\ m^{-3}$ for SAR = 10) (Oster et al., 1980). However, no clay appeared in the leachates, suggesting that macroscopic movement of clay within the heavy soil was limited by the small size of the pores. The very

steep decrease in K_r in all treatments is demonstrated by plotting K_r as a function of leaching time (Fig. 6c). In all three treatments only 100 min of leaching were needed to replace two pore volumes and to reach a chemical equilibrium of the soil with the soil solution. The processes responsible for the hydraulic conductivity decrease in soil with ESP = 10 and leached with very dilute solutions are much faster compared with soil equilibrated with solutions of SAR = 0. Dispersion of quasi-crystals and their deposition in conducting pores is a fast process compared with swelling.

SUMMARY AND CONCLUSION

We demonstrated that in addition to water quality and soil ESP, the saturated hydraulic conductivity of disturbed soil samples (Chromic Haploxerert - A horizon) depended on the hydraulic gradient applied to the soil column and duration of leaching. Three mechanisms were offered to explain the changes in hydraulic conductivity of the soil. First, swelling of the clay fabric (i.e., quasi-crystals and domains) at the expense of the transmission pores led to a reduction in hydraulic conductivity. Swelling increased with a decrease in the total electrolyte concentration and an increase in SAR. Second, the physical compression of the clay fabric in the lower part of the soil column, which led to narrower pores and lower hydraulic conductivity. The degree of compression increased with increasing hydraulic gradient. However, with high SAR, the compression was not as pronounced, because of the extensive swelling. These two mechanisms, which resulted in a decrease of the hydraulic conductivity, were balanced by the third mechanism, i.e., development of cohesion forces with time (aging) between clay fabric structural units (domains) and microaggregates, which resulted in an increase in the soil hydraulic conductivity. Reorientation and reorganization of the structural units led to an increase in the average size of the transmission pores and to an increase of the hydraulic conductivity. The rate of the development of interparticle forces also depended on the hydraulic gradient and on water quality. The rate of cohesive bond formation increased with increasing hydraulic gradient (and compression of the clay fabric) and decreased with increasing SAR. Our results suggest that hydraulic gradient and leaching duration play a predominant role in determining the hydraulic conductivity of a highly smectitic clay soil. Their importance of controlling hydraulic conductivity as a function of additional time-dependent variables, e.g., the rate of prewetting, or of controlling the hydraulic conductivity of soils with a lighter texture needs further investigation.

It should be mentioned that the results and conclusions are limited to the experimental choices. This is not to say that aging does not play a role. Under field conditions, soil structure undergoes frequent changes. Small soil masses are frequently broken down by the impact of rain drops, rapid (pre)wetting rate, the use of tillage tools, and shrinking and swelling mechanisms, creating a system where stabilization through aging can take place. Following, e.g., irrigation and tillage of a vertisol, the soil consists in more or less severely destructed aggregates. In soils close to saturation, the rate of development of cohesive forces is slow (e.g., Levy et al., 1997). As the soil dries, the increasing tension pulls the soil particles closer together, increasing the number of clay-to-clay contacts at which bonding forces can develop. A similar mechanism occurs with the application of a high hydraulic gradient in hydraulic conductivity measurements. The development of cohesive bonds will further increase with an increase in aging time (Levy et al., 1997). Aggregate strength will be maintained until soil particles are again disrupted.

ACKNOWLEDGMENTS

The first author is grateful to the Agricultural Research Organization, Bet-Dagan, Israel, the Catholic University of Louvain, Louvain-la-Neuve, Belgium and the Rotary Club of Wavre-Europe, Belgium, in providing her with grants enabling the realization of this work. This study was supported by grant No. TA-MOU-96-CA-16-016 US–Israel Cooperative Development Research Program, Office of the Science Advisor, U.S. Agency for International Development (USAID).

REFERENCES

Alperovitch, N., I. Shainberg, R. Keren, and M.J. Singer. 1985. Effect of clay mineralogy and aluminium and iron oxides on the hydraulic conductivity of clay-sand mixtures. Clays Clay Min. 33:443–450.

Aylmore, L.A.G., and J.P. Quirk. 1959. Swelling of clay-water systems. Nature (London). 183:1752–1753.

Ben-Dor, E., and A. Banin. 1989. Determination of organic content in arid-zone soils using a simple "loss on ignition" method. Soil Sci. Plant Anal. 20:1675–1695.

Blackmore, A.V., and R.D. Miller. 1961. Tactoid size and osmotic swelling in calcium montmorillonite. Soil Sci. Soc. Am. J. 25:169–173.

Blake, G.R, and R.D. Gilman. 1970. Thixotropic changes with aging of synthetic soil aggregates. Soil Sci. Soc. Am. Proc. 34:561–564.

Curtin, D., H. Steppuhn, and F. Selles. 1994. Structural stability of Chernozemic soils as affected by exchangeable sodium and electrolyte concentration. Can. J. Soil Sci. 74:157–164.

Emerson, W.W., and D.J. Greenland. 1990. Soil aggregates — Formation and stability. p. 485–511. *In* M.F. De Boodt et al. (ed.) Soil colloids and their associations in aggregates. Plenum Press, New York.

Frenkel, H., M.V. Fey, and G.J. Levy. 1992. Organic and inorganic anion effects on reference and soil clay critical flocculation concentration. Soil Sci. Soc. Am. J. 56:1762–1766.

Glaeser, R., and J. Mering. 1954. Isothermes d'hydratation des montmorillonites bi-ioniques (Na, Ca). Clay Miner. Bull. 2:188–193. (Hydration isotherms of binary (Na,Ca) montmorillonites)

Goldberg, S., and H.S. Forster. 1990. Flocculation of reference clays and arid-zone soil clays. Soil Sci. Soc. Am. J. 54:714–718.

Gupta, R.K., D.K. Bhumbla, and I.P. Abrol. 1984. Effect of sodicity, pH, organic matter and calcium carbonate on the dispersion behavior of soils. Soil Sci. 137:245–251.

Kemper, W.D., and E.J. Koch. 1966. Aggregate stability of soils from western U.S. and Canada. USDA Tech. Bull. 1355. U.S. Gov. Print. Office, Washington, DC.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., and R.C. Rosenau, and A.R. Dexter. 1987. Cohesion development in disrupted soils as affected by clay and organic matter content and temperature. Soil Sci. Soc. Am. J. 51:860–867.

Kemper, W.D, I. Shainberg, and J.P. Quirk. 1972. Swelling pressures, electric potentials and ion concentrations: Their role in hydraulic and osmotic flow through clays. Soil Sci. Soc. Am. J. 36:229–236.

Keren, R., and M.J. Singer. 1988. Effect of low electrolyte concentration on hydraulic conductivity of sodium/calcium montmorillonite-sand system. Soil Sci. Soc. Am. J. 52:368–373.

32

Klute, A. (ed.) 1986. Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9, ASA and SSSA, Madison, WI.

Le Bissonnais, Y., and M.J. Singer. 1992. Crusting, runoff and erosion response to soil water content and successive rainfalls. Soil Sci. Soc. Am. J. 56:1898–1903.

Levy, G.J., J. Levin, and I. Shainberg. 1997. Prewetting rate and aging effects on seal formation and interrill soil erosion. Soil Sci. 162: 131–139.

McNeal, B.L., and N.T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Sci. Soc. Am. Proc. 30:308–312.

Murray, R.S., and J.P. Quirk. 1990. Interparticle forces in relation to the stability of soil aggregates. p. 439–461. *In* M.F. De Boodt et al. (ed.) Soil colloids and their associations in aggregates. Plenum Press, New York.

Oster, J.D., I. Shainberg, and J.D. Wood. 1980. Flocculation value and gel structure of sodium/calcium montmorillonite and illite suspensions. Soil Sci. Soc. Am. J. 44:955–959.

Page, A.L., R.H. Miller, and D.R. Keeney (ed.) 1986. Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Quirk, J.P., and L.A.G. Aylmore. 1971. Domains and quasi-crystalline regions in clay systems. Soil Sci. Soc. Am. Proc. 35:652–654.

Quirk, J.P., and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163–178.

Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging, and temperature. Soil Sci. Soc. Am. J. 60:916–922.

Singer, M.J., R.J. Southard, D.N. Warrington, and P. Janitzky. 1992. Stability of synthetic sand-clay aggregates after wetting and drying cycles. Soil Sci. Soc. Am. J. 56:1843–1848.

Suarez, D.L., J.D. Rhoades, R. Lavado, and C.M. Grieve. 1984. Effect of pH on saturated hydraulic conductivity and soil dispersion. Soil Sci. Soc. Am. J. 44:3–7.

Tessier, D. 1984. Etude expérimentale de l'organisation des matériaux argileux. Hydratation, gonflement et structuration au cours de la dessication et de la réhumectation. Thèse, Univ. Paris VII, UER des Sciences Physiques de la Terre, 361 pp. (Experimental study on particle arrangement in clayey materials. Hydration, swelling and structuration during drying and rewetting).

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and sodic soils. USDA Handb. 60.

van Olphen, H. 1977. An introduction to clay colloid chemistry. 2nd ed. John Wiley & Sons, New York.

Appendix C

Reprinted from the *Soil Science Society of America Journal*
Volume 64, no. 4, July–Aug. 2000
677 South Segoe Rd., Madison, WI 53711 USA

Polyacrylamide, Sediments, and Interrupted Flow Effects on Rill Erosion and Intake Rate

D. Sirjacobs, I. Shainberg, I. Rapp, and G. J. Levy*

ABSTRACT

The reduction in the intake rate (IR) during interrupted irrigation is difficult to predict. Sediments in irrigation water decrease the effect of interrupted irrigation on IR. Polyacrylamide (PAM) reduces rill erosion, but its effect on IR is controversial. The effects of water quality (tap water, tap water containing sediments, and 10 g m^{-3} PAM solution) and interrupted flow on IR and rill erosion in an Alfisol (Calcic Haploxeralf) and a Vertisol (Typic Chromoxerert) were studied using laboratory miniflumes. Rill erosion in both soils was eliminated by the PAM treatment in both continuous and interrupted flow. The PAM application reduced IR in the Alfisol and increased it in the Vertisol. In the Alfisol, interrupted flow reduced IR of the PAM solution by 37% compared with only 18% for tap water. In the Vertisol, interrupted flow reduced IR only slightly and the decrease was not affected by the polymer. When the water contained sediments, cumulative infiltration was reduced by 22% for the Vertisol and 59% for the Alfisol in comparison with tap water. These reductions were attributed to depositional seal formation. The IR of the Alfisol was more susceptible to depositional seal formation than the Vertisol. The presence of sediments in water was effective in reducing rill erosion. The effects of interrupted flow with PAM on reducing IR were explained by partial blocking of the conducting pores leading to greater suction and compaction of the soil surface. For sediment-laden irrigation water, interrupted flow had no advantage over continuous flow in reducing IR because of depositional seal formation associated with the sediments in the water.

SURFACE IRRIGATION is the most used irrigation practice worldwide, but its water use efficiency is low (Wolters, 1992). Interrupted irrigation, which is the intermittent application of irrigation water during the advancement stage of furrow irrigation (Stringham, 1988), has the potential to reduce IR and improve the efficiency of surface irrigation by increasing field water application uniformity. In spite of much research (Izuno et al., 1985; Jalali-Farahani et al., 1993; Kemper et al., 1988; Samani et al., 1985; Trout, 1991), the process is still not fully understood and its effects on IR are difficult to predict.

Two basic phenomena have been identified during interruption of flow: (i) moisture redistribution in the soil profile and (ii) consolidation of the soil near the rill surface. During the interruption of water application, water drainage into the underlying dry soil and moisture redistribution result in the development of negative pressure suction near the soil surface. This negative pressure increases the forces that pull water into the soil during the next flow period (Samani et al., 1985), and should increase the IR. However, the development of negative pressure in the soil surface during flow interruptions consolidates the soil near the rill surface, increases surface bulk density, and reduces the hydraulic conductivity (HC) of this surface layer. Thus, this thin layer can have a significant effect of reducing water infiltration in succeeding irrigation events (Izuno et al., 1985; Jalali-Farahani et al., 1993; Samani et al., 1985).

An additional important mechanism controlling IR in furrow irrigation, which is not necessarily related to interrupted irrigation, is the formation of a depositional seal at the furrow perimeter. The HC of depositional seals has been reported to be two to three orders of magnitude lower than that of the underlying soil (Shainberg and Singer, 1985). Trout (1991) observed a 50% reduction in infiltration in the Portneuf (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) silt loam during interrupted irrigation, and ascribed it to surface seal formation. The HC of the depositional seal depends on the size and mineralogy of the sediment particles, and on the electrolyte concentration of the water (Shainberg and Singer, 1985). Thus, the effect of sediment concentration on the IR varies from one irrigation scheme to another.

Soil erosion can be prevented by amending the soil with organic polymers, such as PAM, with high molecular weight and moderate negative charge density (e.g., Lentz et al., 1992; Shainberg et al., 1990; Sojka et al., 1998a, 1998b). If rill erosion is prevented, no depositional seal is formed and the rill IR increases (Lentz et al., 1992; Sojka et al., 1998b). Thus, an indirect effect of the PAM treatment is the increase in IR. However, Malik and Letey (1992) and Letey (1996) found that the addition of 10 g m^{-3} of PAM to water decreased the HC of fine porous media to 50% of that obtained when salt solutions were used. They suggested that the effective viscosity of polymer solutions in porous media was higher than would be anticipated according to standard viscosity measurements, and that the relative viscosity depended on the pore-size distribution of the soil. The effect of PAM in reducing the HC of porous media could also be explained in terms of partial blocking of conducting pores by the tails of the macromolecules that were adsorbed on soil particles. This partial blocking would probably become more pronounced in soils with narrow pores. Letey (1996) proposed that in furrow irrigation PAM treatment will reduce IR and increase the advancement rate of water in the furrows. It is possible therefore that the effect of PAM on IR in

D. Sirjacobs, I. Shainberg, I. Rapp, and G.J. Levy, Institute of Soils, Water and Environmental Sciences, Agricultural Research Organization (ARO), the Volcani Center, P.O. Box 6, Bet Dagan 50250, Israel. Contribution from the Agricultural Research Organization, the Volcani Center, P.O. Box 6, Bet Dagan 50250, Israel, no. 629/98 series. Received 24 Aug. 1999. *Corresponding author (vwguy@volcani.agri.gov.il).

Published in Soil Sci. Soc. Am. J. 64:1487–1495 (2000).

Abbreviations: HC, hydraulic conductivity; IR, intake rate; PAM, polyacrylamide.

34

Table 1. Some basic physical and chemical properties of the soils used.

Soil	Classification	Particle-size distribution			$CaCO_3$	CEC†	ESP‡	EPP§	OM¶
		Sand	Silt	Clay					
		g kg^{-1}				cmol$_c$ kg^{-1}	%		g kg^{-1}
Alfisol	Calcic Haploxeralf	413	362	225	180	17.7	2.1	9.1	21
Vertisol	Typic Chromoxerert	438	156	406	107	34.2	2.3	2.9	34

† CEC = Cation-exchange capacity.
‡ ESP = Exchangeable sodium percentage
§ EPP = Exchangeable potassium percentage.
¶ OM = Organic matter content.

furrow irrigation depends on soil properties, a topic to be clarified in this study.

The effects of interrupted irrigation in reducing IR depend on sediment concentration (Trout, 1991). As sediment concentration increases, IR decreases and the beneficial effect of interrupted irrigation for reducing the IR is reduced (Trout, 1991). It could be argued therefore, that PAM treatments will magnify interruption-induced effects on IR reduction. On the other hand, since PAM also stabilizes the structure at the soil surface (Sojka et al., 1998b), PAM may prevent the consolidation of the surface by the interrupted flow and the net effect of interrupted flow on IR in PAM treatments will be negligible. Hence it is difficult to assess the effects of PAM on the IR in interrupted flow.

Miniflumes have been used to evaluate the interaction between flow characteristics, soil properties, and water quality on rill erosion in the laboratory (Shainberg et al., 1994, 1996). The rill erodibility data obtained with the miniflumes agreed well with field data (Shainberg et al., 1994). Miniflume studies were also found to simulate well the effect of PAM on rill erosion in the field (Lentz et al., 1992; Shainberg et al., 1994). Using miniflumes, Shainberg et al. (1996) studied rill erosion in an Alfisol and a Vertisol and found that rill erosion decreased with aging of several hours and that it depended on water content in the soil. These researchers postulated that aging and water tension enhanced clay to clay contacts, increased the cohesive forces between soil particles, and led to reduction in rill erosion. We hypothesized that miniflumes may also be used to study the processes that operate in interrupted irrigation.

Interrupted flow reduced erosion in irrigated furrows (Yonts et al., 1998). In miniflumes, the same effect has been observed and was attributed to consolidation of the soil surface (Sirjacobs, 1999, unpublished data). If rill erosion and depositional seal formation are reduced, a high IR should be maintained. Interrupted flow may therefore have two opposing effects on IR; that is, it may reduce IR by consolidating the soil surface or increase IR by reducing rill erosion and seal formation. The net effect of interrupted flow on IR may be evaluated either by preventing rill erosion (e.g., by irrigation with water containing PAM) or by increasing the sediment content of the irrigation water. When rill erosion is prevented, no depositional seal is formed and the effect of interrupted flow in consolidating the rill surface and reducing IR is predominant. Conversely, sediment deposition and seal formation may be enhanced by the use of sediment-laden water (Shainberg and Singer, 1985). Applying water containing sediments will, therefore, decrease IR in both continuous and interrupted flow applications. However, the relative effects of water containing sediments on the IR in continuous and interrupted flow effect are not clear and will be studied.

The objective of our study was to investigate the effects of PAM- and sediment-containing inflow on IR and rill erosion under continuous and interrupted flow conditions in two soil types. The interaction between sediments, PAM, and soil properties on the effect of interrupted flow on IR and rill erosion were evaluated by comparing the results obtained with clear tap water with those obtained with PAM solutions and sediment-laden inflow water.

MATERIALS AND METHODS

Two arable soils of differing texture were chosen for this study: a silty loam Alfisol (Calcic Haploxeralf) from Nevatim, northern Negev, and a clay Vertisol (Typic Chromoxerert) from Hafetz-Haim, Pleshet Plains, Israel. Some basic physical and chemical properties of the soils are given in Table 1.

The experiments were carried out with a 0.5-m-long, 0.047-m-wide, 0.12-m-deep flume. Two 0.2-m-long "V"-shaped metallic rills were connected on both of its sides. The miniflumes were placed at a 10% slope in order to maintain high flow shear force, high soil detachment, and high rill erosion.

Air-dried soils, crushed to pass through a 4.0-mm sieve, were slightly compacted in the flume to densities of 1390 kg m^{-3} for the Alfisol and 1200 kg m^{-3} for the Vertisol. The dry volume of the Vertisol was slightly smaller than that of the Alfisol. However, upon wetting and subsequent swelling, the final volume of the wet Vertisol in the flume was similar to that of the Alfisol. A "V"-shaped rill (44 mm wide and 22 mm deep) with a 90° angle between its sides was formed in the soil surface. Water was applied with a peristaltic pump to the upstream metallic rill, and the runoff containing sediments was collected from the downstream metallic rill in beakers.

Three water types were studied in the experiments: (i) laboratory tap water (electrical conductivity = 0.95 dS m^{-1}; Na adsorption ratio = 2.5 [mmol$_c$ L^{-1}]$^{0.5}$; Ca + Mg = 5 mmol$_c$ L^{-1}; Na = 4 mmol$_c$ L^{-1}; Cl = 6.2 mmol$_c$ L^{-1}); (ii) tap water containing 10 g m^{-3} PAM; and (iii) tap water containing 7.5 g L^{-1} of suspended sediments. The PAM solution was prepared from a concentrated polymer solution that contained 1 g L^{-1} high molecular weight (2×10^7 Da) anionic PAM with a moderate negative charge (20% hydrolysis). Suspensions of each soil were prepared by shaking 300 g of soil with 3 L of tap water for 1 h. After shaking, the coarse particles were allowed to settle out of the suspension for 3 min. Sediment content of the suspensions was 7.5 g L^{-1} for each soil. During each miniflume run, the suspension was stirred continuously in order to ensure its homogeneity. Samples of the suspension were taken periodically during the run and the sediment content of the suspension was recorded.

Each individual experiment was divided into two stages. In the first stage either continuous (control) or interrupted flow was applied, and the three water qualities were used. The

35

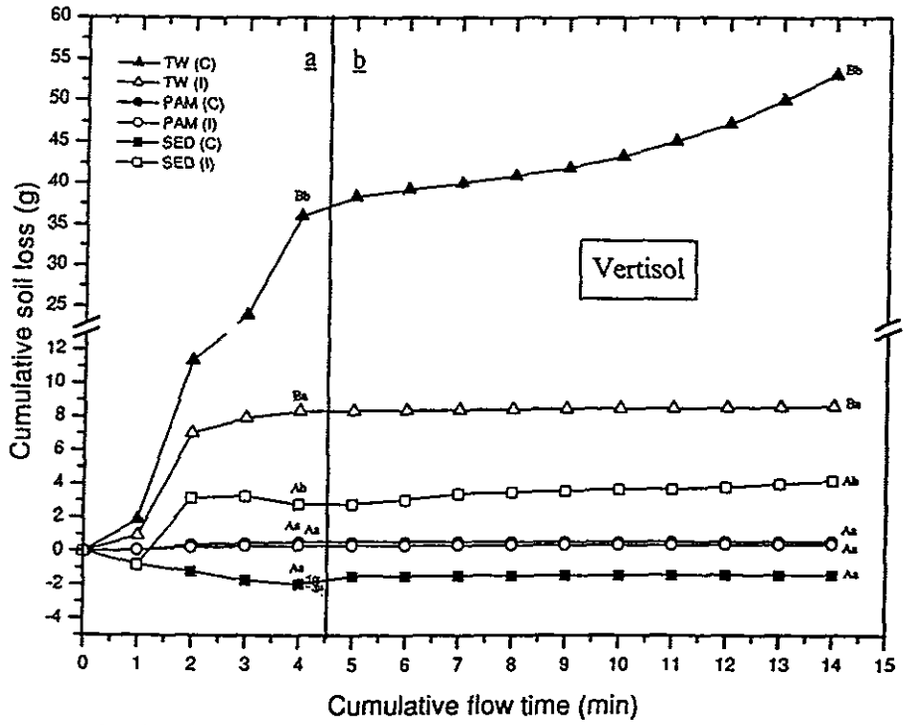


Fig. 1. Cumulative soil loss as a function of cumulative flow time for the Vertisol during (a) Stage 1 and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

control treatment consisted of 4 min of flow; the interrupted flow treatment consisted of four cycles of 1 min of flow and 10 min of interruption. Preliminary studies on the effect of interruption time on rill erosion and IR indicated that for an interruption time of <5 min, changes in interruption time affected IR and rill erosion, but choosing interruption times longer than 5 min did not affect the IR and rill erosion. Inflows applied to the Vertisol (320 mL min^{-1}) and the Alfisol (240 mL min^{-1}) were chosen in order to obtain a measurable outflow during the first minute and to obtain a similar flow rate and runoff during the consecutive 3 min. Because the IR in the Vertisol was higher than the IR in the Alfisol, it took 51 s for the clear water to wet the soil and reach the end of the rill in the Vertisol and 17 s in the Alfisol. However, during the second, third, and fourth pulses of flow, the average outflow rates in the two soils were similar (Fig. 3 and 5). Total inflow, outflow, and soil loss were recorded for every minute of flow.

The second stage of the experiment started immediately at the end of the 4-min flow in the control or after completion of the four cycles of interrupted flow treatment. At this stage, only clear tap water was used and inflow rate was reduced in order to allow more precise measurements of IR, and it was applied continuously to simulate field conditions. Again, in order to maintain similar flow and shear force in the rills, a continuous 100 mL min^{-1} inflow was applied to the Vertisol and 80 mL min^{-1} was applied to the Alfisol. The second stage was terminated when the moisture content front reached a depth of ≈100 mm and the soil layer at the bottom of the miniflume remained dry (i.e., after 10 min for the Vertisol and 20 min for the Alfisol). The dry layer of soil at the bottom of the flume assured the presence of the suction needed to consolidate the soil surface. Total inflow, outflow, and soil loss were recorded every minute for both soils.

Three replicates were performed for each of the twelve combinations tested (two soils, interrupted and continuous flow, and three types of irrigation waters). The effect of water type on interrupted flow was analyzed separately for the Alfisol and for the Vertisol. For each soil, the effects of two factors (water type and flow type) on rill erosion and IR were considered. Our experiments involved three levels of water type (tap water, tap water with PAM, and tap water with sediments) and two levels of flow type (continuous and interrupted flow). For each minute and for each variable measured, a full factorial analysis of variance, based on the Standard Least Squares test ($\alpha = 0.05$), was applied. When an interaction between the two factors was found, the different levels of water type were compared within each level of flow type and vice versa. When no interaction was detected, each factor was studied individually, without distinction between the levels of the other factor.

RESULTS AND DISCUSSION

Because the effects of interrupted flow on IR depend on rill erosion and depositional seal formation (Kemper et al., 1988; Trout, 1991), the effects of water type on rill erosion in continuous and interrupted flow are discussed first.

Water Type Effects on Rill Erosion

Polyacrylamide

Rill erosion in the Vertisol exposed to a continuous flow of tap water was high (Fig. 1), and that in the Alfisol was low (Fig. 2). Application of interrupted flow caused a significant reduction in rill erosion only in the Vertisol. Most of the rill erosion in the two soils occurred during the first 4 min, when the flow rate was high

36

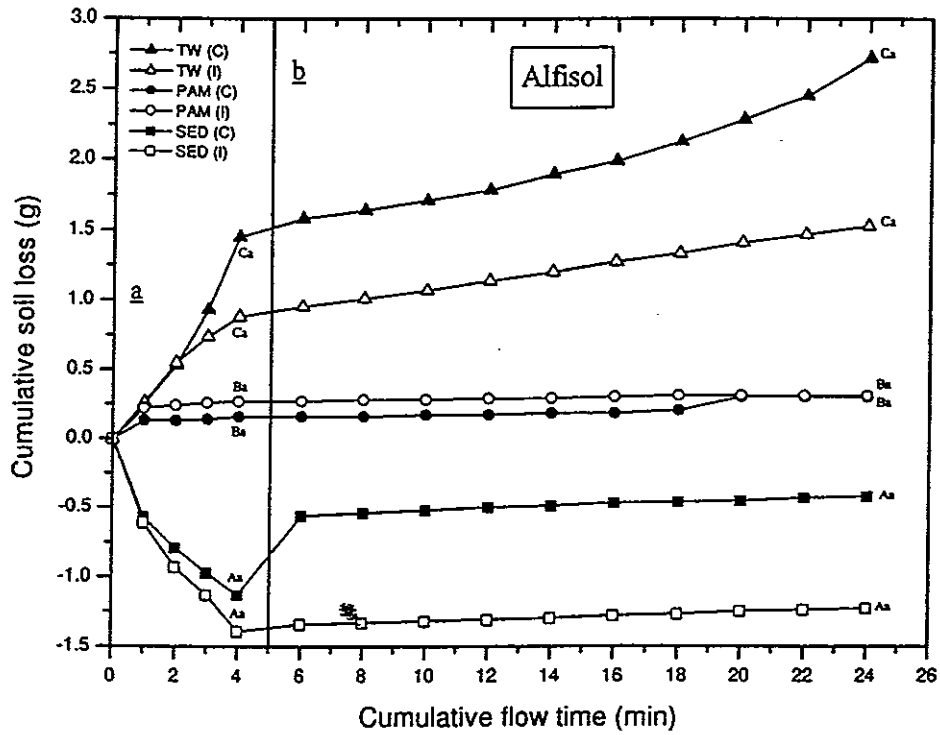


Fig. 2. Cumulative soil loss as a function of cumulative flow time for the Alfisol during (a) Stage 1, and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

(320 and 240 mL min^{-1} for the Vertisol and Alfisol, respectively) and the flow shear force was high. In the second stage of the experiment, when a continuous low-rate flow was used, erosion was low (Fig. 1 and 2). In the Vertisol, intraaggregate stability is greater than that in the Alfisol (Shainberg et al., 1992). However, interaggregate cohesive forces in the Vertisol are weaker than in the Alfisol (Shainberg et al., 1996), thus detachment of aggregates by the flowing water could possibly be easier in the Vertisol than in the Alfisol. At the same time, it is expected that detached particles in the Vertisol are larger than those in the Alfisol, because of the better aggregation of the Vertisol, and would thus be less available for transportation by the flowing water. Our results showed more erosion in the Vertisol, suggesting that under our experimental conditions the size of the detached particles in the Vertisol did not affect their transportability. Therefore, Vertisols, owing to their high clay content (Table 1), have a stable aggregated structure with weak cohesive forces among soil particles, which in turn, made them more susceptible to detachment and subsequently to transportation than the aggregates of the Alfisol.

Polyacrylamide addition to the inflow water during the first stage of the experiment essentially eliminated rill erosion in both continuous and interrupted flow. The effect of PAM on soil loss was already evident from the first minute of inflow. Its favorable effect was especially impressive in the Vertisol, where with continuous flow, the PAM treatment reduced cumulative soil loss to 1% of the erosion obtained in tap water (Fig. 1). In the Alfisol, PAM application reduced soil loss from 2.7 g per flume to only 0.3 g per flume in continuous flow (Fig. 2). The PAM efficacy resulted from the fact that the polymer adsorbed on the external surfaces of the aggregates (Lentz et al., 1992) cemented the aggregates together and prevented their detachment.

In the PAM treatment, erosion in both soils was very low under continuous flow, and no further decrease in erosion because of interrupted flow was possible (Fig. 1 and 2). As the binding between soil particles in the presence of PAM was already strong enough to prevent erosion, further strengthening of interparticle cohesive forces by aging and compaction during flow interruptions caused no further reduction of rill erosion.

Sediments

In the Vertisol, the use of sediment-loaded water led to the formation of a visible and homogeneous seal at the rill perimeter. This depositional seal dramatically reduced rill erosion compared with inflow of tap water (Fig. 1). For continuous flow, the presence of sediments in the irrigation water was as effective as the presence of PAM in preventing rill erosion. When interrupted flow was applied, PAM was more effective than sediments in preventing rill erosion (Fig. 1). The difference in cumulative erosion between interrupted and continuous flow appeared from the second minute (Fig. 1). The higher erosion under interrupted flow was attributed to

37

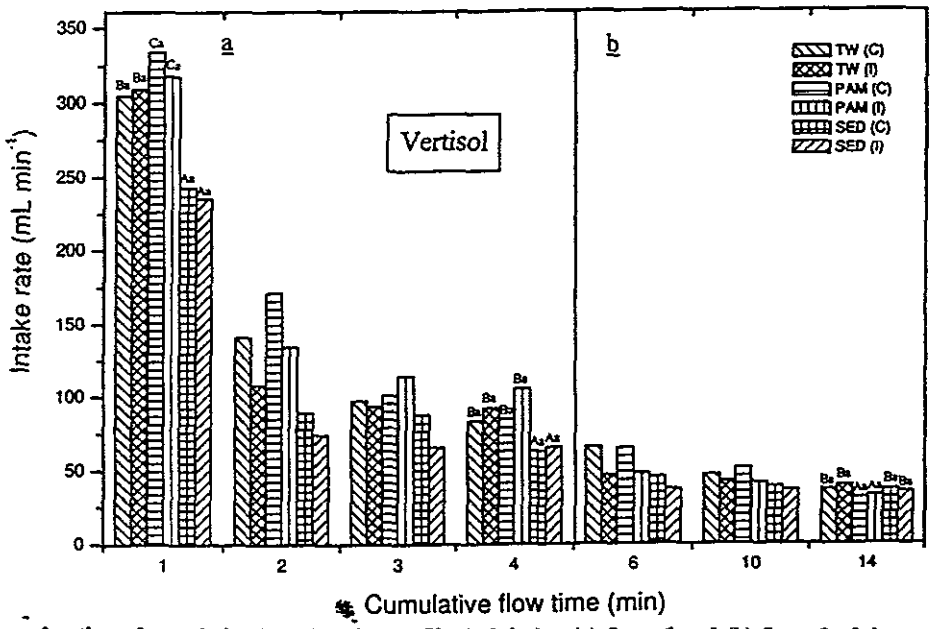


Fig. 3. Intake rate as a function of cumulative flow time for the Vertisol during (a) Stage 1 and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

lower intake rate in the interrupted flow (see below), which resulted in higher flow velocity and greater shear force (Kemper et al., 1988). In our study, rill erosion was high only in the second minute of inflow. Thereafter, hardly any additional difference in soil loss between the interrupted and continuous flow treatments was observed. Apparently, aging and compaction mechanisms that acted during the flow interruption created a sufficient increase in soil cohesive forces that could resist the high shear force and thus limit soil loss.

Unlike the case of the Vertisol, a net deposition of sediments was observed in the Alfisol under both interrupted and continuous flow during the 4 min of application of water containing sediments. This is represented in Fig. 2 by the negative values of cumulative soil loss, which demonstrate that ≈20% of the sediments flowing into the flume were deposited on the rill perimeter. In the second stage of the experiment when a continuous low flow rate of tap water was used for 20 min (as opposed to only 10 min in the Vertisol), a small amount of soil erosion was observed in the continuous flow treatment. Conversely, in the interrupted flow treatment, no sediments were measured in the tap water runoff and no increase in cumulative erosion was demonstrated (Fig. 2).

Deposition of sediments at the soil surface filled the pores and created a depositional seal with a smooth surface on the rill perimeter. The fine particles within the pores acted as a cementing material between soil particles, and the sealed rill surface became more resistant to erosion then the original soil surface. Similar findings were reported by Brown et al. (1988), who studied the effects of sediment-laden water on IR and furrow erosion in the field. These researchers concluded that deposition of the fine sediments on the perimeter decreased IR and thus increased soil water tension, consequently leading to an increase in the forces that hold the sediments at the perimeter, and to a decrease in erosion. The presence of sediments in the inflow water was effective in preventing net soil loss erosion in both soils. The presence of sediments in the water in continuous flow was more effective in decreasing rill erosion than interrupted flow or the addition of PAM to the inflow water. The beneficial effect of sediments in the inflow water suggest that sediments in irrigation water should not be removed prior to irrigation. This conclusion corroborates the findings of Brown et al. (1988) obtained in short furrows in the field.

Water Type Effects on Intake Rate

Polyacrylamide

In the first stage of the experiment (i.e., first 4 min) for both flow types in the Vertisol, addition of PAM to the inflow water resulted in IRs that were higher than, or similar to, those for tap water. Considering the effect of PAM on advancement time, a similar conclusion is derived. Whereas the time needed for the first pulse of tap water to reach the end of the 0.5-m rill was 51 ± 2 s, it took 57 ± 3s with the PAM solutions. Prevention of rill erosion and depositional seal formation prevented the decrease in IR during the first minute, and the advance time for the PAM solution was longer than that for tap water. Similar findings were reported by Lentz at al. (1992) and Lentz and Sojka (1994) who observed, in field experiments, that PAM reduced furrow erosion and increased furrow IR.

The effects of PAM on the cumulative intake of the

38

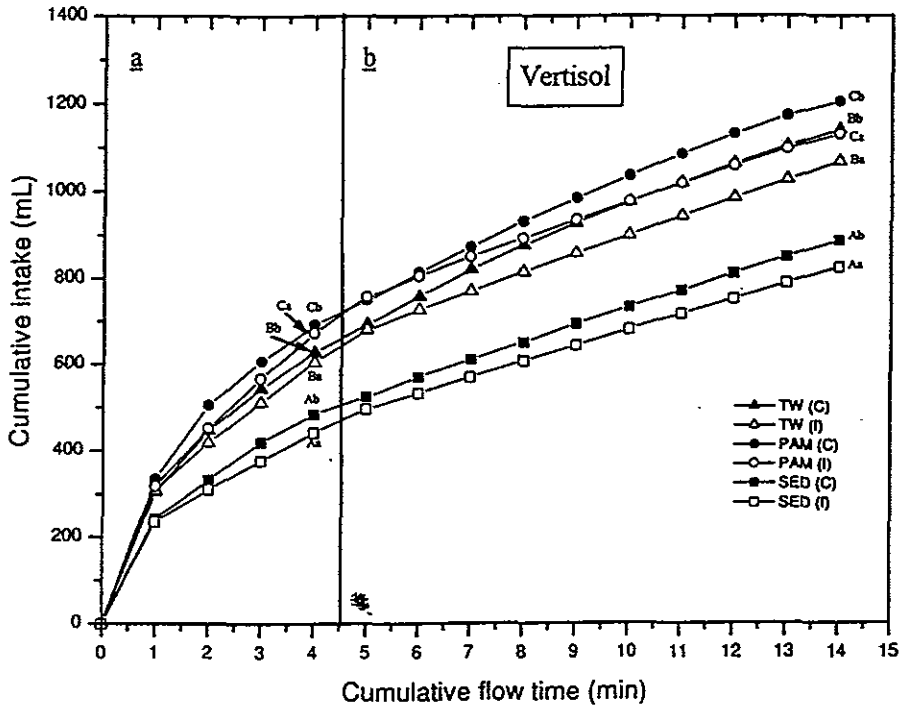


Fig. 4. Cumulative intake as a function of cumulative flow time for the Vertisol during (a) Stage 1 and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

Vertisol exposed to continuous and interrupted flow are presented in Fig. 3. The PAM treatment increased the cumulative intakes under both continuous and interrupted flow by 6%. This increase in IR and cumulative intake was contrary to the predictions of Letey (1996) and Malik and Letey (1992), who suggested that PAM increased the apparent viscosity of the solution within the soil pores, and therefore, that soil IR should decrease. The PAM-related IR increase observed in the Vertisol was attributed to two possible mechanisms: (i) PAM prevented rill erosion and the formation of depositional seal (Lentz et al., 1992; Sojka et al., 1998a) and (ii) PAM stabilized the soil structure and prevented deterioration of the soil surface HC (Shainberg et al., 1990). The effects of interrupted flow on IR in the PAM and the tap water treatments were similar (Fig. 3); interrupted inflow in the Vertisol decreased both cumulative intakes by 6% (Fig. 4). Interrupted flow was as effective in decreasing IR in tap water and the accompanying high erosion as it was when PAM was used and only a small amount of sediments was present in the water. The similarity in the decrease in IR for the tap water and PAM treatments is suggested to be related to the structure of the seal formed. When sediments were deposited from a solution that had an electrolyte concentration exceeding the flocculation value of the soil clay (i.e., tap water), the seal formed had an open structure (Shainberg and Singer, 1985) that was susceptible to compaction and consolidation when exposed to suction, in a way similar to that of an unsealed soil surface.

The effect of PAM on IR in the Alfisol was the opposite of that in the Vertisol. In the Alfisol, PAM decreased IR significantly, both in continuous and in interrupted flow, during the first and the second stages of the experiment (Fig. 5). The same conclusion is derived from consideration of advancement time. Advancement times in the first minute in the Alfisol were 7 ± 2 s with PAM solution and 17 ± 3 s with tap water. The high advance rate of the PAM solution in the Alfisol suggested that 10 g m^{-3} of PAM in the inflow water reduced IR. When rill erosion is low, as was the case in the Alfisol, depositional seal effect on IR is minimal, and the effect of PAM in reducing the HC (Letey, 1996) predominates. The effect of PAM on HC is further demonstrated from the consideration of the cumulative intake in the Alfisol (Fig. 6). Final cumulative intakes obtained in continuous and interrupted flows with PAM solution were lower by 37 and 51%, respectively, than those obtained with tap water for the respective flows (Fig. 6). Only little erosion and clay deposition took place in the Alfisol with either tap water or PAM solution; therefore, the effect of PAM in reducing IR was probably because of its effect on the HC of the soil (Malik and Letey, 1992; Letey, 1996). Malik and Letey (1992) suggested that the effective viscosity of polymer solutions in porous media was higher than would be anticipated according to standard viscosity measurements and that the relative viscosity depended on the pore-size distribution of the soil. The effect of PAM in reducing the HC of porous media could also be explained in terms of partial blocking of conducting pores by the tails of the macromolecules that were adsorbed

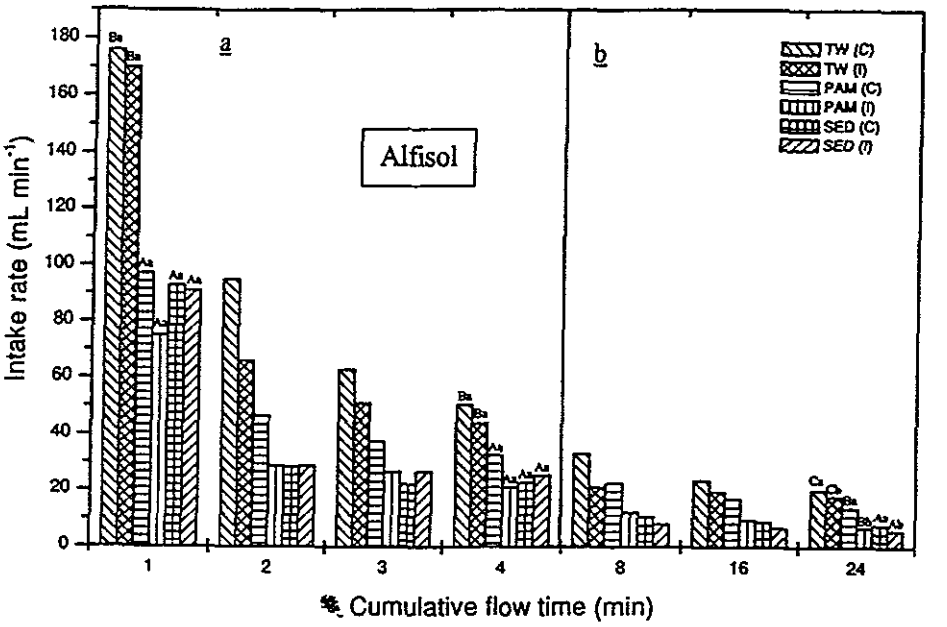


Fig. 5. Intake rate as a function of cumulative flow time for the Alfisol during (a) Stage 1 and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

on soil particles. This partial blocking would probably become more pronounced in soils with narrow pores. Thus, it is to be expected that in the Alfisol, with its unstable structure, low HC, and fine conducting pores, PAM would be effective in reducing IR; conversely, in the Vertisol, with its large conducting pores and high HC, the effect of PAM on IR should be small. Our data (Fig. 3–6) support this hypothesis. The PAM solutions of 10 g m^{-3} had a negligible effect on IR in the Vertisol (Fig. 3 and 4) and a marked effect on IR in the Alfisol (Fig. 5 and 6).

It is postulated that the effects of PAM on infiltration depend on two opposing mechanisms: (i) enhancement of IR by prevention of erosion and seal formation and (ii) reduction of IR because of increased apparent viscosity of the solution, or partial blocking of conducting pores by the tails of the macromolecules adsorbed on soil particles. The relative weight of each of these two opposing mechanisms, which determines the actual effect on IR, depends on soil type. Thus, PAM increased IR in the Vertisol by preventing seal formation and erosion, but decreased IR in the Alfisol by decreasing the HC, either by increasing the apparent viscosity of the soil solution or by clogging the conducting pores.

Addition of PAM to the inflow water did not alter the interrupted flow effect on IR in the Vertisol. Interrupted flow decreased the final cumulative intake by 6% in both the PAM and tap water treatments; however, in the Alfisol, interrupted flow was more effective in decreasing the IR with PAM than with tap water. In the latter case, it reduced cumulative intake by 18% compared with continuous flow, whereas in the PAM solution it reduced cumulative intake by 38% (Fig. 6). The beneficial effect of interrupted flow with PAM solutions in the Alfisol can be explained as follows: PAM decreased the HC of the soil surface by partial blocking of the conducting pores, thus also reducing air penetration into the soil surface. Consequently PAM increased the soil water tension that developed during the flow interruptions (Kemper et al., 1988) and in turn caused enhanced compaction and consolidation of the wetted perimeter, thus reducing the infiltration rate. It is hypothesized that a similar phenomenon occurs in surge irrigation and that the surge effect on irrigation efficiency is improved in PAM treatments in silty loam soils like the Alfisol.

Sediments

The effects of sediments in inflow water on IR in the Vertisol and the Alfisol are presented in Fig. 3 and 5, respectively. In both soils, IR was significantly lower from the very first minute of flow with water containing sediments than with tap water (Fig. 3 and 5). This decrease in IR led to total reductions in cumulative intake of 22% in the Vertisol (Fig. 4) and 59% in the Alfisol (Fig. 6), compared with that obtained when tap water was used. The reduction in IR was related to sediment deposition and the formation of a seal at the rill perimeter (Trout, 1991). The reduction in IR was more pronounced in the Alfisol than in the Vertisol because the Alfisol was more susceptible to seal formation (Ben-Hur et al., 1985). The Alfisol, with its poor structure, was more easily clogged with suspended clay particles than the Vertisol, with its developed structure and large water conducting pores. As a result of the low IR, this treatment also increased the advancement rates on both soils; the advancement times for irrigation with water containing sediments and with tap water were 10 and 17 s, respectively, on the Alfisol and 36 and 51 s, respec-

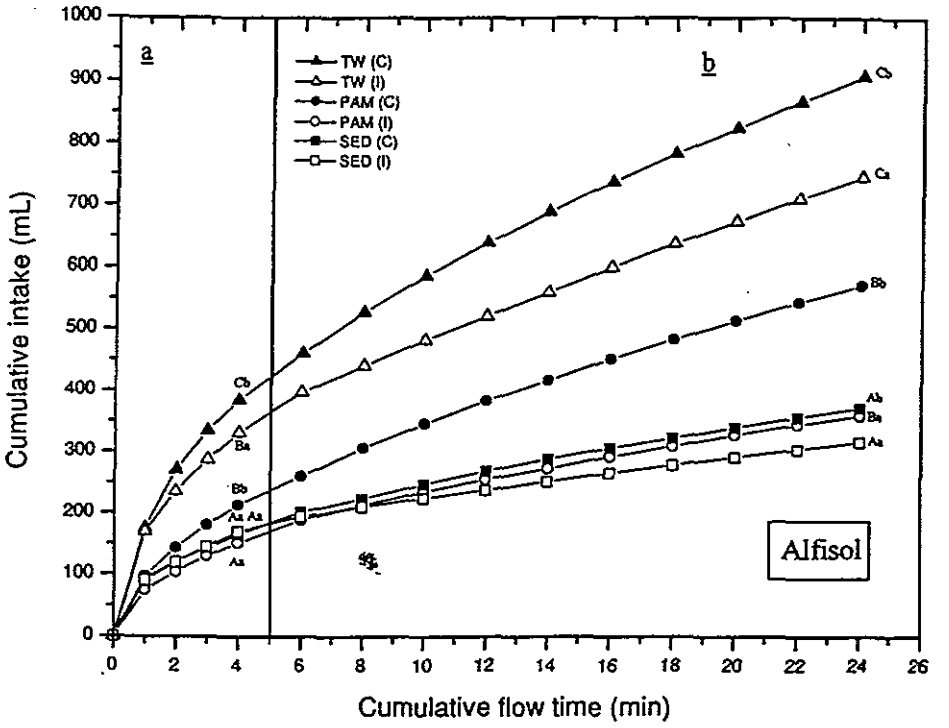


Fig. 6. Cumulative intake as a function of cumulative flow time for the Alfisol during (a) Stage 1 and (b) Stage 2 of the experiment. Significant differences between water types for a given cumulative flow time and flow type are indicated by upper-case letters ($P < 0.05$). Significant differences between flow types for a given cumulative flow time and water type are indicated by lower-case letters ($P < 0.05$). TW is tap water, PAM is polyacrylamide-containing water, and SED is sediment-containing water. (C) and (I) denote continuous and interrupted flow, respectively.

tively, on the Vertisol. Sediments decreased the advancement times in the Alfisol by 41% and in the Vertisol by 29%. The effect of sediments in irrigation water in increasing the advance rate in furrow irrigation may be included in consideration of the efficiency of surface irrigation.

In the Vertisol, the use of interrupted flow caused a significant decrease in cumulative intake for both tap water and sediment-laden water (Fig. 4). However, the use of sediment-laden water did not have a greater beneficial effect (in relative terms) in decreasing cumulative intake than interrupted flow with tap water. Interrupted flow decreased the final cumulative intake in the Vertisol by 7% with water containing sediments and by 6% with tap water (Fig. 4). In the Alfisol too, the use of interrupted flow caused a significant decrease in cumulative intake for both tap water and sediment-laden water (Fig. 6). However, in the Alfisol a trend was noted whereby interrupted flow was more effective in decreasing cumulative intake with tap water (18%) compared with sediment-containing water (15%) (Fig. 6). This trend may be explained by the greater IR reduction by the formation of a depositional seal in the Alfisol than in the Vertisol (Fig. 3 and 5). When a seal with a low HC is formed, the seal controls the IR and the effects on IR of interrupted flow and the suction that develops during the off time are negligible. Similar observations were made by Trout (1991), who observed that infiltration was reduced by 50% (because of surface seal formation) when sediments were present in irrigation water and that the interrupted flow effect was less pronounced when a depositional seal of low HC was present.

SUMMARY AND CONCLUSIONS

The effects of PAM and sediment concentration in inflow water on the effect of interrupted flow on infiltration rate and rill erosion was studied in a silty loam Alfisol and a clay Vertisol, using miniflumes. In both soils, rill erosion was dramatically reduced by the PAM treatment. Polyacrylamide increased the IR in the Vertisol and decreased IR in the Alfisol. The contradictory effect of PAM on rill IR was explained by two opposing mechanisms: (i) enhancement of IR by prevention of erosion and of a depositional seal formation (Lentz et al., 1992; Trout, 1991) and (ii) reduction of IR because of increased apparent viscosity of the solution in the soil pores or by clogging of the conducting pores by the tails of adsorbed polymer molecules (Letey, 1996). The second mechanism dominates in the Alfisol with little rill erosion and no depositional seal formation. The polymer did not influence the interrupted flow effect on IR in the Vertisol. In the Alfisol, interrupted flow reduced the final cumulative intake by 37% in the PAM treatment and by 18% with tap water. The effect of interrupted flow with PAM solutions in the Alfisol was explained by the partial blocking of the conducting pores, which increased the suction and compaction of the soil surface, and so reduced the IR.

When applying sediment-containing water, deposi-

tional seal formation markedly decreased the IR of both soils. The reduction of final cumulative infiltration was more pronounced in the Alfisol (59%) than in the Vertisol (22%). The Alfisol, with its unstable structure and narrow conducting pores, was more easily clogged by sediments than the Vertisol, with its stable structure and large pores. When the inflows contained sediments, the interrupted flow effect on IR was limited. Continuous irrigation with water containing sediments increased the advancement rate and reduced rill erosion more effectively than interrupted flow or PAM treatment. This effect should be considered when water containing sediments is used in surface irrigation.

Our results indicate that the potential benefits of interrupted flow as a means of improving surface irrigation efficiency and controlling rill erosion will be gained mainly in weakly structured soils. Addition of polymer to the irrigation water may enhance interrupted flow effects in these soils. When irrigation water contain sediments, interrupted flow has no advantage over continuous flow.

ACKNOWLEDGMENTS

D. Sirjacobs is grateful to the Agricultural Research Organization, Bet Dagan, Israel, for providing him with a grant that made the realization of this work possible. This study was supported by grants TA-MOU-96-CA16-016 and TA-MOU-97-CA17-008, from the U.S.-Israel Cooperative Development Research (CDR) Program, Office of Science Advisor, U.S. Agency for International Development (AID). The support of the CDR is gratefully acknowledged.

REFERENCES

Ben-Hur, M., I. Shainberg, D. Bakker, and R. Keren. 1985. Effect of soil texture and $CaCO_3$ content on water infiltration in crusted soils as related to water salinity. Irrig. Sci. 6:281–284.

Brown, M.J., W.D. Kemper, T.J. Trout, and A.S. Humphreys. 1988. Sediment, erosion and water intake in furrows. Irrig. Sci. 9:445–55.

Izuno, F.T., T.H. Podmore, and R.H. Duke.1985. Infiltration under surge irrigation. Trans. ASAE. 28:517–521.

Jalali-Farahani, H.R, H.R. Duke, and D.F. Heermann. 1993. Physics of surge irrigation. I. Quantifying soil physical parameters. Trans. ASAE 36:37–44.

Kemper, W.D., T.J. Trout, and A.S. Humphreys. 1988. Mechanisms by which interrupted irrigation reduces rill infiltration rates in a silty loam soil. Trans. ASAE 31:821–829.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation rill erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Lentz, R.D., and R.E Sojka. 1994. Field results using polyacrylamide to manage furrow erosion. Soil Sci. 158:274–282.

Letey, J. 1996. Effective viscosity of PAM solutions through porous media. p. 44–96. *In* R.E. Sojka and R.D. Lentz (ed.) Proc. Conf. on managing irrigation-induced erosion and infiltration with PAM. Publ. no. 101. Univ. of Idaho, Twin Falls, ID, 6–8 May. Univ. of Idaho, Twin Falls.

Malik, M., and J. Letey. 1992. Pore size dependent apparent viscosity for organic solutes in saturated porous media. Soil Sci. Soc. Am. J. 56:1032–1035.

Samani, Z.A., W.R. Walker, and L.S. Willardson. 1985. Infiltration under interrupted flow irrigation. Trans. ASAE 28:1539–1542.

Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging, and temperature. Soil Sci. Soc. Am. J. 60:916–922.

Shainberg, I., J.M. Laflen, J.M. Bradford, and L.D. Norton. 1994. Hydraulic flow and water quality characteristics in rill erosion. Soil Sci. Soc. Am. J. 58:1007–1012.

Shainberg, I., G.J. Levy, P. Rengasamy, and H. Frenkel. 1992. Aggregate stability and seal formation as affected by drops impact energy and soil amendments. Soil Sci. 154:113–119.

Shainberg, I., and M.J. Singer. 1985. Effect of electrolyte concentration on the hydraulic properties of depositional crust. Soil Sci. Soc. Am. J. 49:1260–1263.

Shainberg, I., D. Warrington, and P. Rengasamy. 1990. Effect of soil conditioner and gypsum application on rain infiltration and erosion. J. Soil. Sci. 149:301–307.

Sojka, R.E., R.D Lentz, C.W. Rose, T.J. Trout, D.L. Bjorneberg, and J.K. Aase. 1998b. PAM effect on infiltration in irrigated agriculture. Soil Water Conserv. 53:325–331.

Sojka, R.E., R.D Lentz, and D.T. Westerman. 1998a. Water and erosion management with multiple application of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J. 62:1672–1680.

Stringham, G.E. 1988. Interrupted flow irrigation. Final report of the Western Regional Research Project W-163. Research Bull. 515. Utah Agric. Exp. Stn., Utah State Univ., Logan.

Trout, T.J. 1991. Surface seal influence on interrupted flow rill infiltration. Trans. ASAE 34:66–72.

Wolters, W. 1992. Influences on the efficiency of irrigation water use. ILRI, Publ. 51, Wageningen, the Netherlands.

Yonts, C.D., B.L. Benham, K.L. Palm, and D.L. Reichert. 1998. Influence of PAM used in combination with surge irrigation, on irrigation performance and soil erosion. ASAE paper no. 982171. ASAE, St. Joseph, MI.

ERRATUM

Timing Effects of Deep Tillage on Penetration Resistance and Wheat and Soybean Yield

W. J. Busscher, J. R. Frederick, and P. J. Bauer
Soil Sci. Soc. Am. J. 64:999–1003 (May–June 2000).

On p. 999, the division heading is incorrect. It should have read "Division S-6—Soil & Water Management & Conservation" (rather than "Division S-6—Forest & Range Soils").

APPENDIX D

Hydraulic Gradient and Wetting Rate Effects on the Hydraulic Conductivity of Two Calcium Vertisols

M. Moutier,* I. Shainberg, and G. J. Levy

ABSTRACT

Understanding the combined role of intrinsic (e.g., clay content) and extrinsic soil conditions in determining the saturated hydraulic conductivity (K) is a key factor in improving soil and irrigation management. Hydraulic gradient effects on K have been investigated on two Ca vertisols (Chromic Haploxerert) from Yizreel and Kedma, Israel. Samples were packed in columns and subjected to two prewetting rates (4.5 and 70 mm h^{-1}) and two hydraulic gradients (2.8 and 11.6 for Yizreel; 3.1 and 13.6 for Kedma). Saturated K was determined during leaching with $CaCl_2$ solutions having total electrolyte concentrations (TEC) of 0.5, 0.01 M Cl^-, and deionized water (DW). The average hydraulic conductivity at the end of the leaching with the 0.5 M solution ($\overline{K}_{0.5}$) of the two vertisols increased with a decrease in prewetting rate. The effect of prewetting rate was more pronounced in Yizreel, where the high clay content (70.3% clay) resulted in a more stable structure. Upon leaching with the 0.01 M solution, $\overline{K}_{0.01}$ first decreased and then increased. This increase in $\overline{K}_{0.01}$ was explained by cohesive bond formation, which increased with an increase in soil clay content and with increased proximity between the clay particles. High hydraulic gradient enhanced clay to clay contacts, and a steep increase in $\overline{K}_{0.01}$. Following fast prewetting, the effect of the hydraulic gradient on cohesive bond formation was more pronounced in Yizreel than in Kedma (46.5% clay). Leaching with DW decreased the $\overline{K}_{DW}$, regardless of the prewetting treatment or soil clay content, suggesting that swelling was the governing mechanism in the reduction of $\overline{K}_{DW}$.

THE SATURATED HYDRAULIC CONDUCTIVITY (K) of soils depends on soil permanent properties (e.g., soil texture, clay mineralogy), soil structure, presence of entrapped air (e.g., Christiansen, 1944; De Backer, 1967; Constantz et al., 1988; Faybishenko, 1995), type of exchangeable cations, and salt concentration of the leaching solution. Saturated hydraulic conductivity tends to decrease with increasing exchangeable Na percentage and decreasing TEC (Quirk and Schofield, 1955). Recently, aggregate stability, infiltration rate, and erosion studies demonstrated that soil structure and its hydraulic properties depended on, in addition to sodicity and water quality, the antecedent water content, aging, and prewetting rate (Kemper and Rosenau, 1984; Shainberg et al., 1996; Levy et al., 1997).

The prewetting rate influences aggregate stability (Le Bissonnais, 1988, 1989; Levy et al., 1997) and, hence, K. Whereas slow prewetting minimizes degradation of the original structure of the soil, fast prewetting disintegrates the aggregates and deteriorates the hydraulic properties of soils (Kemper and Koch, 1966). Aggregate breakdown (slaking) results from the development of internal pressures that cause them to explode (Kemper and Rosenau, 1984). These pressures can arise from a differential hydration and swelling of the clay fraction (Le Bissonnais, 1989) or the compression of occluded air in the capillary pores (Panabokke and Quirk, 1957; Boiffin, 1984). Murray and Quirk (1990) suggested that aggregate slaking was due to both the weakening of the cohesive interparticle binding forces by wetting and the appearance of repulsive interparticle forces. The presence of organic matter and inorganic cementing agents such as Fe oxides will contribute to the stability of aggregates. The extent of slaking and the relative importance of each process controlling it were found to depend on TEC, Na adsorption ratio (SAR) (Abu-Sharar et al., 1987), and clay content (Le Bissonnais, 1988).

Hydraulic properties are also affected by the presence of entrapped air, the amount of which depends on the method used for the initial saturation (Faybishenko, 1995). Following an upward initial saturation, which occurs in soils during the rise of the groundwater table, the volume of entrapped air is <5% and mobile air is almost absent. Upon wetting a dry soil from the top, the volume of entrapped air is large and it blocks a significant volume of the water-conducting pores. As entrapped air dissolves, K increases. Increases of K by a factor of 5 to 10 were reported by Constantz et al. (1988), whereas Christiansen (1944) determined that the relative permeability increased by 2 to 40 times. It should be noted that when soil columns are wetted from below, the volume of entrapped air is small and most of it is immobile; changes in K upon air dissolution are therefore insignificant (Faybishenko, 1995).

An increase of aggregate mechanical strength with time has been reported by several authors (e.g., Blake and Gilman, 1970; Singer et al., 1992; Shainberg et al., 1996). Blake and Gilman (1970) observed significant thixotropic changes in artificial aggregates (Webster clay loam [fine-loamy, mixed, superactive, mesic Typic Endoaquoll] with 34.9% clay) within 20 to 30 h. Significant development of cohesive forces in aggregates of a vertisol (46.5% clay) were reported during 24 h of aging (Shainberg et al., 1996). The development of cohesive bonds has been recently inferred from K measurements in a smectitic vertisol (Moutier et al., 1998).

The hydraulic conductivity of a disturbed vertisol (A horizon, Chromic Haploxerert) wetted by capillary rise was shown to be affected by aging and by the hydraulic gradient applied to the soil column (Moutier et al.,

M. Moutier, Université catholique de Louvain, Unité de Génie Rural, Place Croix du Sud 2, bte 2, B-1348 Louvain-la-Neuve, Belgium; I. Shainberg and G.J. Levy, Inst. of Soils, Water, and Environmental Sciences, Agricultural Research Organization (ARO), The Volcani Center, P.O. Box 6, Bet Dagan 50-250, Israel. Contribution from the Agricultural Research Organization, The Volcani Center, P.O. Box 6, Bet Dagan 50-250, Israel. no 604/99 series. Received 8 Dec. 1998. *Corresponding author (marylene.moutier@skynet.be).

Published in Soil Sci. Soc. Am. J. 64:1211–1219 (2000).

Abbreviations: DW, deionized water; EC, electrical conductivity; SAR, Na adsorption ratio; TEC, total electrolyte concentration.

43

1998). The relative hydraulic conductivity (K_r) initially decreased before increasing as a function of leaching volume or time. A combination of three mechanisms was suggested to explain the observed changes in saturated K_r (Moutier et al., 1998):

Swelling. Swelling of the quasi-crystals (reduction in the intraaggregate porosity) was offered to explain the decrease of K (Blackmore and Miller, 1961) when a more dilute solution replaced a more concentrated one.

Physical Compression of the Clay Fabric. Kemper et al. (1972) observed the physical compression of the clay fabric at the outflow side of a clay column. This compression of clay resulted in lower K values in the outflow side of the column, and thus, lower average K values for the whole column. A similar observation was made in our laboratory in a leaching experiment on Ca-saturated Yizreel soil samples packed in columns equipped with piezometers (I. Shainberg, 1997, unpublished data). It was noted that with leaching, the hydraulic gradient in the lower part of the column increased (i.e., a decrease of K). Because water flow in such a column is controlled by the layer with the lowest K (i.e., a bottleneck for the water flow), the average K decreased. It should be noted that the decrease in K was not accompanied by a measurable change in the soil column length. The degree of compression increased with increasing hydraulic gradient and decreasing SARs (Moutier et al., 1998), as greater repulsion forces develop with higher SAR values (Kemper et al., 1972).

Development of Cohesive Bonds. The development of cohesive bonds between clay fabric structural units and microaggregates in close contact (Kemper and Rosenau, 1984; Bresson and Boffin, 1990; Shainberg et al., 1996; Levy et al., 1997), unlike the former two mechanisms, leads to an increase in the average size of transmission pores, and hence an increase in K_r (Moutier et al., 1998). This concept of "reaggregation" is similar to the "coalescence" idea presented by Bresson and Boiffin (1990). Coalescence is regarded as the welding of initially loose aggregates into larger, stronger structural units by plastic deformation that is induced by the prewetting procedure. Such structural changes in seedbeds of a red-brown earth wetted by capillary rise were also observed by Bresson and Moran (1995).

The rate of cohesive bonds development, as inferred from the increase of K_r with time, was also shown to depend on the hydraulic gradient applied and water quality (Moutier et al., 1998). The higher the hydraulic gradient and the lower the SAR of the leaching solution, the steeper the increase of K_r with time of aging. This suggested that the proximity of the clay particles was essential for the formation of the cohesive forces at the aggregate level (Zubkova, 1998). The "proximity" consideration explains some conflicting results related to cohesive bond development under saturated conditions where water layers surrounding the clay particles may prevent close contacts (Blake and Gilman, 1970; Kemper and Rosenau, 1984; Shainberg et al., 1996).

The combined effect of intrinsic soil properties and extrinsic conditions in the measurement of saturated K should be studied in greater detail. We hypothesize that the hydraulic gradient effect on controlling the saturated hydraulic conductivity might be affected by the initial structural state of the soil sample. Thus, this study aims to investigate the effect of a hydrostatically induced pressure on saturated K, as measured with the constant head method, for two Ca-saturated vertisols of differing clay contents. The contrasting initial structure was achieved by varying the prewetting treatment prior to the K measurements.

Table 1. Some physical and chemical properties of the soils studied.

Soil	Particle-size distribution			CEC†	OM‡	$CaCO_3$
	Sand	Silt	Clay			
	g kg^{-1}			cmol kg^{-1}	g kg^{-1}	
Yizreel§	154	143	703	55.5	45	123
Kedma¶	310	225	465	39.8	21	151

† CEC, cation-exchange capacity.
‡ OM, organic matter content determined by the loss on ignition method (Ben-Dor and Banin, 1989).
§ From Moutier et al. (1998).
¶ From Levy et al. (1997).

MATERIALS AND METHODS

Disturbed samples of two smectitic soils (Chromic Haploxerert) were taken from the A horizon (0–250 mm) of two cultivated fields from the Yizreel Valley and the Pleshet Plains (Kedma), Israel. Soil samples were physically and chemically characterized by standard methods (Klute, 1986; Page et al., 1986) (Table 1). The clay fraction of these soils contained ≈64% smectite, 13% kaolinite, 4% illite, 12% calcite, and 7% sesquioxides (Banin and Amiel, 1970).

Soil columns were prepared by packing 120 g of sieved (<2 mm) and air-dried soil into small cylinders (5.4 cm in diameter by ≈4 to 5 cm long with a metal screen covered with sand at the bottom). The dry bulk densities of Yizreel and Kedma soils were 1.33 ± 0.02 (one standard deviation) and 1.46 ± 0.04 Mg m^{-3}, respectively. A filter paper covered the surface of the soil to minimize soil disturbance when replacing solutions. After packing, the soil columns were prewetted from below, either quickly (20 min, fast prewetting treatment) or slowly (8 h, slow prewetting treatment), with a $CaCl_2$ solution (0.5 M Cl^-). Calcium systems were studied because the effects of hydraulic gradient and aging were reported to be more pronounced in Ca-saturated soil samples (Moutier et al., 1998). The prewetting treatments were chosen to simulate likely field conditions. The fast prewetting was achieved by using a Mariotte bottle with zero water pressure head set at the bottom of the dry soil column. Once the water level reached the top of the sample, the pressure head was increased to expose the samples to an hydraulic gradient of approximately 1.2. Prewetting rate was quantified by weighting the Mariotte bottle during capillary rise. This prewetting resulted in an average rate of 160 mL h^{-1} (equivalent to 70 mm h^{-1}). The slow prewetting was achieved by saturating the soil column from below using a peristaltic pump at an average flow rate of 10.2 mL h^{-1} (equivalent to 4.5 mm h^{-1}) until a ponded water level of 1 cm above the soil surface was attained. During prewetting and saturation of the soil columns, the Yizreel and Kedma soils swelled from an initial dry soil column length of 3.94 ± 0.07 and 3.58 ± 0.10 cm, respectively, to 5.26 ± 0.16 and 4.44 ± 0.06 cm at the wet state. Swelling was more pronounced in Yizreel soil because of its higher clay content. The flow was then reversed and the columns were leached with a constant head device. Two hydraulic gradients (2.8 and 11.6 for Yizreel; 3.1 and 13.6 for Kedma) were applied, corresponding with hydrostatically induced pressures of 145 and 625 kg m^{-2} for the low and high hydraulic gradient treatment, respectively.

44

Table 2. Mean absolute ($\overline{K}_{0.5}$) and relative hydraulic conductivities ($\overline{K}_{r\,0.01}$, $\overline{K}_{rDW}$) with their standard deviations (σ) calculated at the end of leaching with $CaCl_2$ solutions (0.5, 0.01 *M* Cl^-) and deionized water. For a given treatment, mean absolute and relative hydraulic conductivities of replicates were calculated at the same pore volume.

	Yizreel				Kedma			
	Fast Prewetting†		Slow Prewetting		Fast Prewetting		Slow Prewetting	
	High gradient	Low gradient	High gradient	Low gradient	High gradient	Low gradient	High gradient	Low gradient
	cm h^{-1}							
$\overline{K}_{0.5} \pm \sigma$	1.26 ± 0.18	1.01 ± 0.30	7.80 ± 1.71	4.96 ± 1.75	1.07 ± 0.84	2.11 ± 1.20	4.36 ± 0.05	3.25 ± 1.73
$\overline{K}_{r\,0.01} \pm \sigma$	2.32 ± 0.65	1.66 ± 0.02	2.07 ± 0.23	1.15 ± 0.18	1.79 ± 0.43	1.55 ± 0.67	1.36 ± 0.02	2.40 ± 0.93
$\overline{K}_{rDW} \pm \sigma$‡	0.54 ± 0.29	0.57 ± 0.05	2.18 ± 0.62	0.61 ± 0.17	0.42 ± 0.37	0.14 ± 0.02	0.85 ± 0.07	0.58 ± 0.21

† From Moutier et al. (1998).
‡ DW, deionized water.

In order to ensure saturation of the soil samples with exchangeable Ca, the soil columns were leached with 10 to 30 pore volumes of a $CaCl_2$ solution (0.5 *M* Cl^-), which took 1 to 4 h, depending on the prewetting treatment and the soil. However, the conditioning stage (leaching with the 0.5 *M* Cl^- solution) was much longer for Yizreel soil samples exposed to a fast prewetting and low hydraulic gradient since leaching with 10 to 20 pore volumes took ≈22 h (Moutier et al., 1998). The hydraulic conductivity measured at the end of the conditioning stage was taken as reference hydraulic conductivity ($K_{0.5}$).

Following leaching with the 0.5 *M* Cl^- solution, the soil columns were leached with ≈80 pore volumes (≈5 L) of dilute $CaCl_2$ solution (0.01 *M* Cl^-) or DW. The 0.01 *M* Cl^- solution was chosen in order to induce some swelling (but no clay dispersion), whereas DW was used to simulate rainwater infiltration. As development of cohesive forces were reported to be time dependent (e.g., Blake and Gilman, 1970; Shainberg et al., 1996), leaching duration was limited to 20 h. However, the treatment was much shorter for soil columns exposed to a high hydraulic gradient and slow prewetting rate as it only took 200 min to infiltrate 80 pore volumes through these columns. In the few cases where steady-state hydraulic conductivities were not maintained, the experimental results were extrapolated to steady-state values, which are presented in Table 2.

The hydraulic gradient was maintained constant during leaching for a given solution (0.5 *M* Cl^-, 0.01 *M* Cl^-, or DW) except for short periods (5–10 min) when flow was stopped to change the leaching solution. The 5-L Mariotte bottle with the original solution was first disconnected and the Mariotte bottle with the new solution then reconnected and the hydraulic gradient reestablished. This procedure minimized mixing of the two leaching solutions (Moutier et al., 1998).

The column leachates were collected in tubes with a fraction collector and electrical conductivity (EC), pH, and volume of leachate were measured. Results for both vertisols were compared in terms of relative hydraulic conductivity, K_r, defined as the ratio of the saturated hydraulic conductivity calculated for a given solution ($K_{0.01}$ or K_{DW}) to the reference hydraulic conductivity calculated at the end of the conditioning stage ($K_{0.5}$). Up to five replicates were carried out and the results were analyzed by one-way analysis of variance using paired Student *t* test (comparison of two means with unknown but equal variance). A significance level of 0.05 was chosen for the tests.

RESULTS AND DISCUSSION

Effects of Prewetting Rate

Mean reference hydraulic conductivities ($\overline{K}_{0.5}$), mean relative hydraulic conductivities ($\overline{K}_{r0.01}$ or $\overline{K}_{rDW}$) measured at the end of the corresponding leaching period, and their standard deviations are summarized in Table 2. Hydraulic conductivities ($\overline{K}_{0.5}$, $\overline{K}_{r0.01}$, or $\overline{K}_{rDW}$) for the fast prewetting treatment of the Yizreel vertisol were not affected significantly by the hydraulic gradient. As expected, the slow prewetting treatment minimized structure degradation and led to significantly higher values when compared with the fast prewetting treatment. Relative hydraulic conductivities for the slow prewetting treatment for the Yizreel soil samples exposed to a high hydraulic gradient were significantly higher $\overline{K}_{0.5}$, than those exposed to a low hydraulic gradient for both leaching solutions.

A comparison of $\overline{K}_{r0.01}$ as a function of pore volume (Fig. 1a) and cumulative time (Fig. 1b) is given for Yizreel soils samples exposed to fast and slow prewetting and two different hydraulic gradients. When the 0.5 *M* Cl^- solution was replaced by the 0.01 *M* Cl^- solution $\overline{K}_{r0.01}$ decreased, and attained a minimum before increasing as a function of pore volume or time. However, the amplitude and the rate of increase of $\overline{K}_{r0.01}$ differed among the treatments. Results for Yizreel soil samples exposed to fast prewetting were discussed elsewhere (Moutier et al., 1998) and only the main conclusions are presented. The decrease in $\overline{K}_{r0.01}$ was attributed to the combination of two mechanisms, namely swelling upon dilution of the leaching solution and physical compression of the clay fabric at the outflow end of the soil column (Kemper et al., 1972; Moutier et al., 1998). Physical compression increases with an increase in the hydrostatically induced pressure, and hence, with an increase in hydraulic gradient. The initial decrease was followed by an increase in $\overline{K}_{r0.01}$. Increases of the hydraulic conductivities were reported by several authors (Christiansen, 1944; Constantz et al., 1988; Faybishenko, 1995). Faybishenko (1995) attributed his observations to air entrapment and its subsequent dissolution. Our soil samples were prewetted by capillary rise, and only immobile entrapped air remained in the column, representing probably <5% of the total porosity (Faybishenko, 1995). This was also confirmed by flushing soil columns with CO_2 prior to the prewetting treatment (data not presented). The small amount of entrapped CO_2 dissolved readily during the soil conditioning phase when the soil was leached with the 0.5 *M* solution. The trends exhibited by $\overline{K}_{r0.01}$ (Fig. 1) were similar for both air and CO_2 flushing prior to soil saturation, with no significant difference between the two treatments. The experiment with and without CO_2 flushing confirmed (i) that the effect of entrapped air following the fast

45

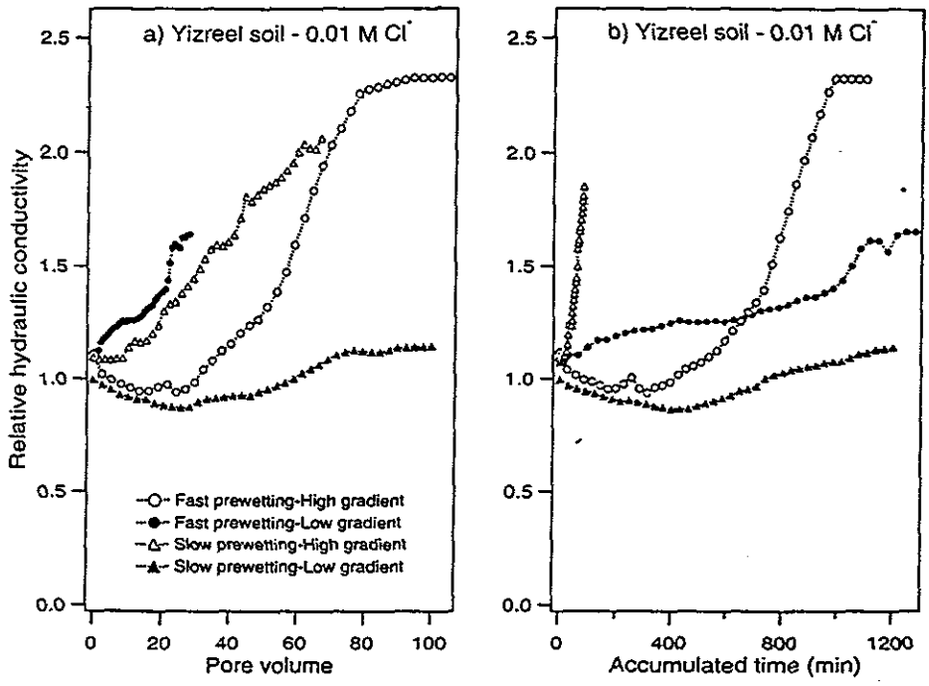


Fig. 1. Relative hydraulic conductivities as a function of (a) pore volume and (b) accumulated time for Yizreel leached with 0.01 *M* Cl^- solutions (data for the fast prewetting treatment were taken from Moutier et al., 1998).

prewetting procedure applied to the soil columns was minimal and (ii) that dissolution of entrapped air was not responsible for the increase in $\overline{K}_{r0.01}$. Thus, the development of cohesive bonds between clay fabric structural units and microaggregates in close contact has been proposed to explain the observed increase in $\overline{K}_{r0.01}$ (Kemper and Rosenau, 1984; Shainberg et al., 1996; Moutier et al., 1998).

The hydraulic conductivity of the slow prewetted Yizreel soil columns also depended on the hydraulic gradient (Fig. 1a). The higher the hydraulic gradient, the greater the increase in $\overline{K}_{r0.01}$. In the low hydraulic gradient treatment, the effect of aging time on the increase of $\overline{K}_{r0.01}$ was less pronounced in slow prewetted columns than in fast prewetted ones. When aggregate breakdown was reduced by slow prewetting, the efficacy of cohesive bond formation and reaggregation was also limited. In the high hydraulic gradient treatment, fast prewetting led to higher $\overline{K}_{r0.01}$ values than slow prewetting (Table 2), although absolute values were much lower with the former treatment. $K_{0.01}$ equaled 2.90 and 16.05 cm h^{-1} for the fast prewetting, high hydraulic gradient and slow prewetting, high hydraulic gradient treatments, respectively.

The rate of development of interparticle bonding forces, as expressed by the rate of increase in $\overline{K}_{r0.01}$, was evaluated by plotting $\overline{K}_{r0.01}$ as a function of cumulative time (Fig. 1b). The assumption that prolonged leaching was needed for cohesive forces to develop is not necessarily true (Moutier et al., 1998). A sharp increase in $\overline{K}_{r0.01}$ was observed for soil columns exposed to slow prewetting and high hydraulic gradient treatment in spite of the fact that leaching with the 0.01 *M* Cl^- solution lasted only 200 min (Fig. 1b). It is suggested therefore that the rate of development of bonds between clay particles in close proximity (e.g., when high hydraulic gradient is used) is very fast. Conversely, the formation of bonds in soils exposed to low hydraulic gradient is slow because of the relatively large distance between the clay particles.

The observed interaction between the rate of bond formation, as expressed by the increase in $\overline{K}_{r0.01}$, and the proximity of clay particles, as determined by the hydrostatically induced pressure, was verified by studying the effect of aging at zero hydraulic gradient. The experiment at zero gradient mimics experiments at zero compaction such as those recently published by Ben-Hur et al. (1998). Following leaching with a 0.01 *M* Cl^- solution (five pore volumes), the slow prewetting treatment for Yizreel soil samples were exposed to a zero gradient and allowed to age for 16 h (960 min). The flow was then reestablished and a high hydraulic gradient of 11.8 was applied (50 min). The rate of increase in $\overline{K}_{r0.01}$ in Yizreel soil samples exposed to a zero hydraulic gradient for 16 h was much lower than the subsequent rate of increase when high hydraulic gradient was applied (Fig. 2). $\overline{K}_{r0.01}$ increased from 1.14 to 1.6 within 16 h (equivalent to a rate of 0.03 h^{-1}) and from 1.6 to 2.2 within the subsequent 50 min (equivalent to a rate of 0.72 h^{-1}) when the high hydraulic gradient was applied. The latter was close to the rate of increase of $\overline{K}_{r0.01}$ observed in the slow prewetting, high hydraulic gradient treatment (0.54 h^{-1}) (Fig. 1b). This experiment supported the hypothesis that the rate of hydraulic conductivity increase and the formation of cohesive bonds strongly depended on the mutual proximity of the clay particles. This is also clearly demonstrated in Fig. 1b. For a given prewetting treatment, the rate of hydraulic conductivity increase was

46

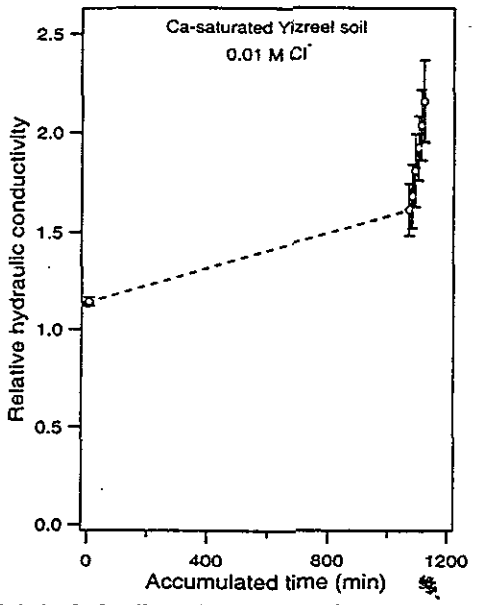


Fig. 2. Relative hydraulic conductivities as a function of accumulated time for Yizreel exposed to slow prewetting and high hydraulic gradient treatment (50 min) following a zero hydraulic gradient treatment (16 h).

higher in columns exposed to high hydraulic gradient than those exposed to low hydraulic gradient. This is in agreement with previously published data (Moutier et al., 1998) and confirms the fact that the rate of particle bond formation depends on the hydraulic gradient; the higher the hydraulic gradient, the closer the clay particles and the higher the rate of cohesive forces development. This confirms recently published findings that the "closeness" of clay particles is a prerequisite for the manifestation of these cohesive forces at the aggregate level (Zubkova, 1998). It also explains some conflicting evidence that cohesive interparticle bonds might develop under saturated conditions where water layers surrounding the clay particles impede close contacts (Blake and Gilman, 1970; Kemper and Rosenau, 1984; Shainberg et al., 1996).

Replacing the 0.01 *M* Cl^- solution with DW resulted in a decrease in $\overline{K}_{rDW}$ of Yizreel columns, irrespective of the prewetting rate or the hydraulic gradient applied to the soil columns (Fig. 3a and 3b). Also presented in Fig. 3b are the quasi-steady state EC values measured at the end of leaching with DW. In the calcareous Yizreel, EC values were affected by $CaCO_3$ dissolution that, in turn, depended on flow velocity. When a high hydraulic gradient was applied or when a high $\overline{K}_{rDW}$ was maintained because of slow prewetting, a high water flux through the column was maintained. Consequently there was less time for $CaCO_3$ to dissolve, and EC was low (0.035 dS m^{-1}). When the water flow was slowed by fast prewetting and a low hydraulic gradient, there was more time for $CaCO_3$ to dissolve and the EC was higher (0.07 dS m^{-1}). However, in both cases, the total electrolyte concentrations, inferred from the ECs of the leachates[1] (Fig. 3b) were higher than the critical flocculation value of Ca-saturated smectite (0.25 $mmol_c$ L^{-1}) (Oster et al., 1980), suggesting that swelling was the governing mechanism responsible for the decrease in $\overline{K}_{rDW}$. The long duration needed for the decrease in $\overline{K}_{rDW}$ (Fig. 3b), coupled with the fact that swelling is a slow process compared with clay dispersion (Keren and Singer, 1988), further supported the swelling mechanism.

After 1200 min of leaching, the Yizreel soil with deionized water, $\overline{K}_{rDW}$ was approaching a quasi-steady state value of ≈0.6, in three of the four treatments (Fig. 3b). The near steady state $\overline{K}_{rDW}$ indicated that the swelling in these columns was almost complete. Only in the soil columns subjected to a slow prewetting and high hydraulic gradient treatment, where the initial hydraulic conductivity was high ($K_{0.01}$ = 16.05 cm h^{-1}), the leaching period with DW was short (200 min) and $\overline{K}_{rDW}$ was maintained at 2.2. Slow prewetting prevented aggregate degradation and maintained large conducting pores between the aggregates, whereas a high hydraulic gradient resulted in a short leaching time. Evidently, that peculiar combination prevented swelling from reaching its full extent and resulted in a stable $\overline{K}_{rDW}$. The deleterious effect of DW on $\overline{K}_{rDW}$ in these slowly prewetted, highly smectitic soil samples was probably prevented by the development of inter- and intraaggregate cohesion forces resulting from the high hydraulic gradient, and limited swelling.

Effects of Clay Content

Mean reference hydraulic conductivities ($\overline{K}_{0.5}$), mean relative hydraulic conductivities ($\overline{K}_{r0.01}$ or $\overline{K}_{rDW}$) measured at the end of leaching and their standard deviations for the vertisol with a lower clay content (Kedma soil with 46.5% clay) are also summarized in Table 2. The reference values ($\overline{K}_{0.5}$) of the Kedma exposed to fast prewetting were 1.07 and 2.11 cm h^{-1} under high and low hydraulic gradient treatments, respectively, and were similar to those for Yizreel despite the difference between their clay contents. As expected, slow prewetting resulted in higher $\overline{K}_{0.5}$. However, this increase in $\overline{K}_{0.5}$ was lower than the corresponding increase for Yizreel (Table 2). The more pronounced effect of prewetting rate on $\overline{K}_{0.5}$ of Yizreel was attributed to the more stable structure that its higher clay content imparted to this soil (Kemper and Koch, 1966); the higher the clay content, the more stable the aggregates. Slow prewetting did not cause aggregate breakdown in the Yizreel soil; therefore $\overline{K}_{0.5}$ was high. Due to its lower clay content, Kedma soil aggregates were less stable and some slaking probably occurred during the slow prewetting treatment, resulting in the lower $\overline{K}_{0.5}$ values. When fast prewetting was applied, aggregate disintegration occurred in both soils, resulting in comparable $\overline{K}_{0.5}$ values.

As cohesive forces are more prone to develop in soils with higher clay contents (Singer et al., 1992), the impact of hydraulic gradient on hydraulic conductivity was expected to be less pronounced in Kedma soil samples. All treatments (Fig. 4a), with the exception of the slow prewetting, low hydraulic gradient treatment, resulted

[1] The total electrolyte concentration (TEC) can be inferred from the EC using the following approximation: TEC ($mmol_c$ L^{-1}) = 10 EC (dS m^{-1}).

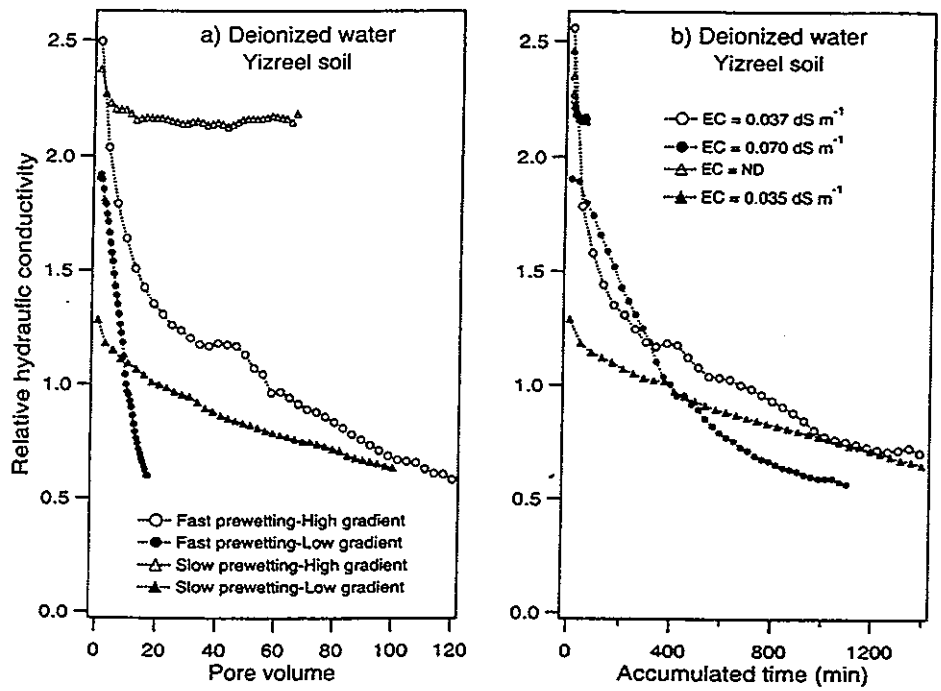


Fig. 3. Relative hydraulic conductivities as a function of (a) pore volume and (b) accumulated time for Yizreel leached with deionized water (data for the fast prewetting treatment were taken from Moutier et al., 1998).

in trends similar to those of Yizreel (Fig. 1a) but were less pronounced. For the Kedma vertisol, both prewetting treatments resulted in final $\overline{K}_{r0.01}$ values that were not significantly affected by the hydraulic gradient.

When a high hydraulic gradient was applied following fast prewetting, $\overline{K}_{r0.01}$ first decreased. However, the duration of the hydraulic conductivity decrease was shorter in the Kedma than in the Yizreel (10 pore volumes for Kedma compared with 30 pore volumes for Yizreel). This difference was probably due to the more limited swelling in the Kedma with its low clay content. Having a lower clay content (number of clay to clay contacts), the rate of cohesive bond formation was lower for Kedma than for Yizreel. As a result, the initial decrease in $\overline{K}_{r0.01}$ was followed by a more gradual increase in the Kedma vertisol (Fig. 4) than the corresponding increase in the Yizreel vertisol (Fig. 1).

Data in Fig. 4a support our hypothesis that the initial

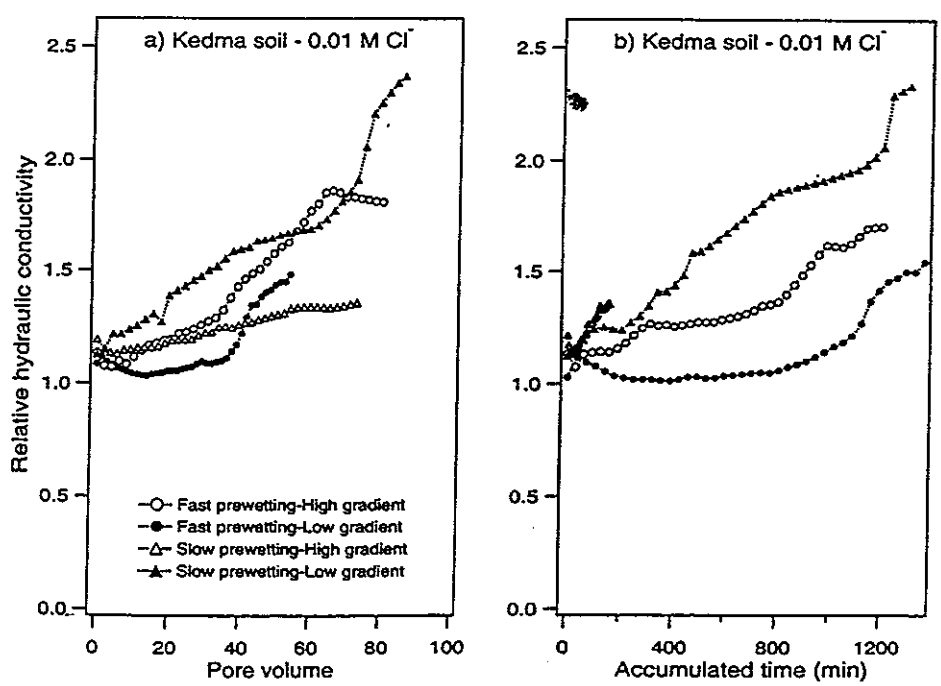


Fig. 4. Relative hydraulic conductivities as a function of (a) pore volume and (b) accumulated time for Kedma leached with 0.01 *M* Cl^- solutions.

48

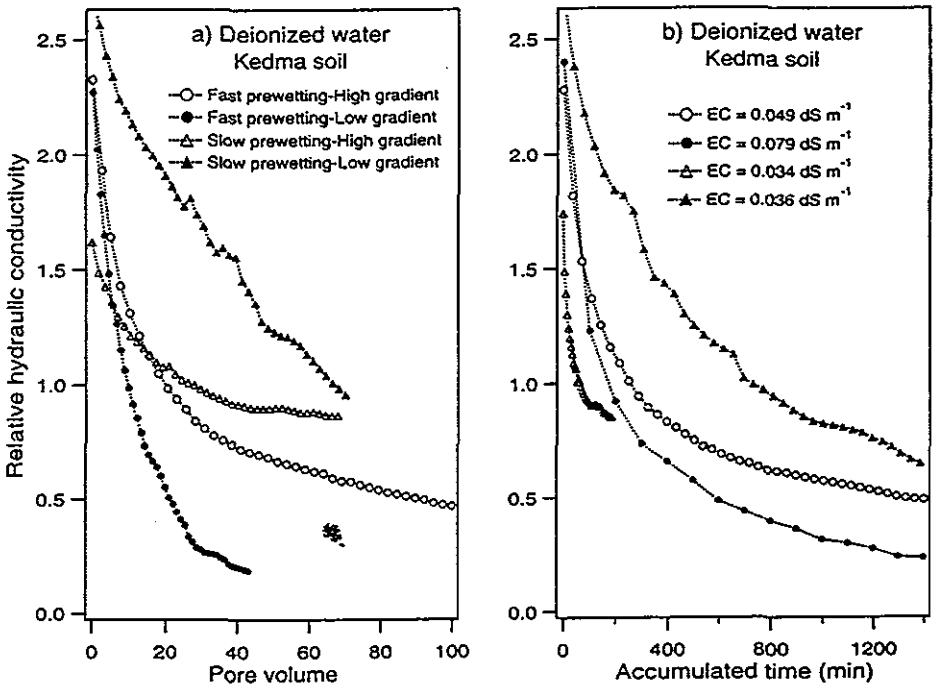


Fig. 5. Relative hydraulic conductivities as a function of (a) pore volume and (b) accumulated time for Kedma leached with deionized water.

structural state of Kedma affects the impact of hydraulic gradient on relative hydraulic conductivity. The increase in $\overline{K}_{r0.01}$ for Kedma soil columns exposed to a low hydraulic gradient was more pronounced following a slow prewetting than following a fast prewetting treatment (Fig. 4a). Due to the lower clay content in Kedma soil samples, fast prewetting resulted in a more extensive breakdown of soil aggregates, and the effects of aging and the increase in $\overline{K}_{r0.01}$ were less pronounced. Conversely, under slow prewetting, the increase in $\overline{K}_{r0.01}$ was more pronounced because aging was more extensive in partially broken aggregates. These results (Fig. 4a) supported a previously published assumption (Levy et al., 1997) that aging is more effective in partially disintegrated aggregates than in aggregates where extensive slaking has taken place. Thus, the increase of $\overline{K}_{r0.01}$ was greatest when Kedma columns were exposed to slow prewetting and a low hydraulic gradient. Unlike the other three treatments, this treatment seemed to be more effective in improving $\overline{K}_{r0.01}$ in the Kedma than in the Yizreel soil.

The change in $\overline{K}_{r0.01}$ with time for Kedma soil is shown in Fig. 4b. The results confirmed the strong dependence between the rate of development of interparticle binding forces, as inferred from the rate of increase in $\overline{K}_{r0.01}$, and the mutual proximity of clay particles within the clay fabric, as determined by the hydraulic gradient applied to the soil column for a given treatment. The rate of bond formation increased with increasing hydraulic gradient. Because of the more stable structure resulting from slow prewetting, a similar hydraulic gradient treatment resulted in a higher rate of cohesive bond development than that which followed fast prewetting.

The effect of clay content on the rate of increase in $\overline{K}_{r0.01}$ is demonstrated by comparing the results shown in Fig. 1b and 4b. Following slow prewetting, the rate of development of interparticle binding forces increased in the following order: low hydraulic gradient (Yizreel) < low hydraulic gradient (Kedma) < high hydraulic gradient (Kedma) < high hydraulic gradient (Yizreel). The lowest and the highest rates were both ascribed to the high clay content of Yizreel. High clay content contributed to two opposing tendencies: (i) a limited effect of aging because of the more stable clay fabric and (ii) an enhanced number of potential clay to clay contacts, which increases with increasing hydraulic gradient. Because of its lower clay content, Kedma exhibited intermediate rates of bond formation for similar hydraulic gradient treatments. Following fast prewetting, the effect of hydraulic gradient on the rate of cohesive bond formation was more pronounced in Yizreel (Fig. 1b) than in Kedma because fast prewetting resulted in extensive slaking, which affected the Kedma to a greater extent, and the rate of cohesive bond formation was lower in the latter (Fig. 4b).

When the 0.01 M Cl^- solution was replaced with DW, $\overline{K}_{rDW}$ of the Kedma decreased irrespective of the prewetting rate or the hydraulic gradient applied to the soil columns (Fig. 5). The quasi-steady state ECs of the effluent are presented in Fig. 5b. As in the case of the Yizreel soil, the high EC in the Kedma was due to $CaCO_3$ dissolution and depended on flow rates. Despite similarities in the ECs of the effluents when the two soils were leached with deionized water, the following should be noted:

1. The fast prewetting and high hydraulic gradient treatment resulted in comparable relative hydraulic conductivity values in the two soils (Table 2). Evidently, swelling affected both soils in a similar

way. Because conditions for cohesive forces development were not favorable when Kedma was subjected to the fast prewetting, low hydraulic gradient treatment, $\overline{K}_{rDW}$ decreased to 0.14.

2. In the slow prewetting, high hydraulic gradient treatment, the hydraulic conductivity of the Yizreel soil at the end of the leaching with DW was similar to that at the end of the leaching with the 0.01 M Cl^- solution, and more than twice the initial value (Table 2). In the Kedma, $\overline{K}_{rDW}$ decreased to 0.85. Following the slow prewetting treatment, aggregate breakdown in Yizreel was much less pronounced than in Kedma. During leaching with DW the adverse effect of swelling in this soil was probably offset by the development of cohesive forces, and the net effect was that the size of the water-conducting pores was not affected. Conversely, in the Kedma, in which some aggregate slaking took place during the slow prewetting, swelling of the microaggregates probably reduced the size of the conducting pores, and $\overline{K}_{rDW}$ decreased.
3. In the slow prewetting, low hydraulic gradient treatment, the $\overline{K}_{rDW}$ of the Yizreel soil decreased to 0.61 (Table 2). Under a low hydraulic gradient, formation of cohesive bonds between clay particles is not as effective; therefore, because of swelling, $\overline{K}_{rDW}$ decreased. Similar conditions prevailed in the Kedma, and the final $\overline{K}_{rDW}$ in the two soils reached similar values.

SUMMARY AND CONCLUSIONS

We investigated the effect of hydrostatical pressure on K for two Ca-saturated vertisols of contrasting initial structure. Under conditions that led to limited aggregate breakdown (i.e., low clay content and slow prewetting, or high clay content and fast prewetting) development of cohesive forces between structural units was suggested to explain the increase in hydraulic conductivity. The rate of increase in K also depended on the hydraulic gradient. Under greater hydraulic gradient, the structural units of the soils moved closer together, leading to greater number of clay to clay contacts and to a faster increase in the hydraulic conductivity. Conversely, when a stable soil structure was maintained (i.e., high clay content and slow prewetting), the development of cohesive bonds was of minor importance in increasing K. Understanding the combined role of intrinsic (e.g., clay content) and extrinsic (e.g., prewetting rate and hydraulic gradient) soil conditions on K will allow development of better soil and irrigation strategies for sustaining soil hydraulic properties. Maintaining a stable structure is essential for ensuring high K in vertisols. This can be obtained by prevention of soil structure degradation or enhancing structural stability. Structure degradation can be reduced by using a combination of zero-tillage and irrigation methods that cause slow prewetting (e.g., microdrippers, microsprinklers). Structural stability can be augmented by enabling conditions favorable for the development of cohesive forces (zero tillage). Extrinsic factors, such as hydrostatic or mechanical pressure or partial drying, decrease the distance among soil particles and enhance the development of cohesive bonds that stabilize soil structure.

ACKNOWLEDGMENTS

The first author is grateful to the Agricultural Research Organization, Bet Dagan, Israel; the Catholic University of Louvain, Louvain-la-Neuve, Belgium; and the Rotary Club of Wavre-Europe, Belgium, in providing her with grants enabling the realization of this work. This study was supported by grant no. TA-MOU-96-CA-16-016 U.S.-Israel Cooperative Development Research Program, Office of the Science Advisor, U.S. Agency for International Development (AID).

REFERENCES

Abu-Sharar, T.M., F.T. Bingham, and J.D Rhoades. 1987. Reduction in the hydraulic conductivity in relation to clay dispersion and disaggregation. Soil Sci. Soc. Am. J. 51:342–346.

Banin and Amiel. 1970. A correlative study of the chemical and physical properties of a group of natural soils of Israel. Geoderma 3:185–198.

Ben-Dor, E., and A. Banin. 1989. Determination of organic content in arid-zone soils using a simple "loss on ignition" method. Soil Sci. Plant Anal. 20:1675–1695.

Ben-Hur, M., M. Agassi, R. Keren, and J. Zhang. 1998. Compaction, aging, and raindrop-impact effects on hydraulic properties of saline and sodic vertisols. Soil Sci. Soc. Am. J. 62:1377–1383.

Blackmore, A.V., and R.D. Miller. 1961. Tactoid size and osmotic swelling in calcium montmorillonite. Soil Sci. Soc. Am. J. 25:169–173.

Blake, G.R., and R.D. Gilman. 1970. Thixotropic changes with aging of synthetic soil aggregates. Soil Sci. Soc. Am. Proc. 34:561–564.

Boiffin, J. 1984. La dégradation structurale des couches superficielles du sol sous l'action des pluies. Thèse de Docteur-Ingénieur. Institut National Agronomique, Paris, Grignon.

Bresson, L.M., and J. Boiffin. 1990. Morphological characterization of soil crust development stages on an experimental field. Geoderma 47:301–325.

Bresson, L.M., and C.J. Moran. 1995. Structural change induced by wetting and drying in seedbeds of hardsetting soil with contrasting aggregate size distribution. Eur. J. Soil Sci. 46:205–214.

Christiansen, J.O. 1944. Effect of entrapped air upon the permeability of soils. Soil Sci. 58:355–365.

Constantz, J., W.N. Herkelrath, and F. Murphy. 1988. Air encapsulation during infiltration. Soil Sci. Soc. Am. J. 52:10–16.

De Backer, L.W. 1967. The measurement of entrapped gas in the study of unsaturated flow phenomena. Water Resour. Res. 3:245–249.

Faybishenko, B.A. 1995. Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments. Water Resour. Res. 31:2421–2435.

Kemper, W.D., and E.J. Koch. 1966. Aggregate stability of soils from western U.S. and Canada. USDA Tech. Bull. 1355. U.S. Gov. Print. Office, Washington, DC.

Kemper, W.D., I. Shainberg, and J.P. Quirk. 1972. Swelling pressures, electric potentials and ion concentrations: Their role in hydraulic and osmotic flow through clays. Soil Sci. Soc. Am. J. 36:229–236.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Keren, R., and M.J. Singer. 1988. Effect of low electrolyte concentration on hydraulic conductivity of sodium/calcium montmorillonite–sand system. Soil Sci. Soc. Am. J. 52:368–373.

Klute, A. (ed.) 1986. Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Le Bissonnais, Y. 1988. Analyse des mécanismes de désagrégation et de la mobilisation des particules de terre sous l'action des pluies. Thèse de doctorat, Univ. d'Orleans, France.

Le Bissonnais, Y. 1989. Contribution à l'étude de la dégradation structurale superficielle: analyse des processus de microfissuration des agrégats par l'eau. Sci. Sol. 27:187–199.

Levy, G.J., J. Levin, and I. Shainberg. 1997. Prewetting rate and aging

50

effects on seal formation and interrill soil erosion. Soil Sci. 162:131–139.
Moutier, M., I. Shainberg, and G.J. Levy. 1998. Hydraulic gradient, aging and water quality effects on the hydraulic conductivity of a vertisol. Soil Sci. Soc. Am. J. 62:1488–1496.
Murray, R.S., and J.P. Quirk. 1990. Interparticle forces in relation to the stability of soil aggregates. p. 439–461. *In* M.F. De Boodt et al. (ed.) Soil colloids and their associations in aggregates. Plenum Press, New York.
Oster, J.D., I. Shainberg, and J.D. Wood. 1980. Flocculation value and gel structure of sodium/calcium montmorillonite and illite suspensions. Soil Sci. Soc. Am. J. 44:955–959.
Page, A.L., R.H. Miller, and D.R. Keeney (ed.) 1986. Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.
Panabokke, C.R., and J.P. Quirk. 1957. Effect of initial water content on stability of soil aggregates in water. Soil Sci. 83:185–195.
Quirk, J.P., and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163–178.
Shainberg, I., D. Goldstein, and G.J. Levy. 1996. Rill erosion dependence on soil water content, aging and temperature. Soil Sci. Soc. Am. J. 60:916–922.
Singer, M.J., R.J. Southard, D.N. Warrington, and P. Janitzky. 1992. Stability of synthetic sand–clay aggregates after wetting and drying cycles. Soil Sci. Soc. Am. J. 56:1843–1848.
Zubkova, T.A. 1998. The nature of mechanical strength of oven-dry aggregates of soil. Eurasian Soil Sci. 31:254–262.

A Thermal Wave Approach for Heat Transfer in a Nonuniform Soil

Mostafa A. Karam*

ABSTRACT

A novel thermal wave model is developed for studying heat transfer in nonuniform soils. The model, which is based on the wave-like characteristics of periodic heat flow, discretizes the soil into sublayers. The total thermal reflection and transmission coefficients at the interfaces of those sublayers are formulated and then employed to construct the soil temperature and heat flux profiles from their values at the air–soil interface. Numerical simulations showed that the thermal wave model could predict the predictions of two exact analytic models for the temperature profiles and their derivatives.

It has been shown that periodic heat flow in a medium can be described by the propagation of thermal waves in such a medium. Those thermal waves have characteristics similar to the characteristics of other types of waves (e.g., electromagnetic waves and acoustic waves). Among these characteristics are the reflection and transmission at interfaces separating two media, scattering from thermal anomalies, and interference. There has been considerable interest in exploiting the characteristics of thermal waves in detecting, analyzing, and imaging thermal and nonthermal features in a variety of materials (Bennet and Patty, 1982; Rosencwaig et al., 1985; Tang and Araki, 1996). In this study, two characteristics of thermal waves in layered media are explored and then used to study heat transfer in nonuniform soils. This study is the first step in our attempt to answer the following questions: can we apply techniques developed for studying wave propagation to study heat transfer, and how accurate are the results stemming from applying those techniques? Answering these questions may lead to an alternative efficient technique for studying heat transfer in soils, or it may enhance some of the existing techniques for studying heat transfer.

To achieve the objective of this study, the thermal reflection and transmission coefficients characterizing thermal waves at the interfaces of layered soils are formulated and then used to create a thermal wave model for constructing temperature profiles in nonuniform soils. The model is tested and validated using the predictions of two exact analytic models. One of those models has been developed for soils having thermal properties described by exponential profiles (Massman, 1993), and the other model has been developed for soils having thermal properties described by linear profiles (Nerpin and Chudnovskii, 1984). The mathematical formulations describing those two analytic models are usually given in terms of Kelvin's functions of different orders. To ensure that those formulations are correct and their predictions are exact, they are rederived, and programmed on a digital computer using FORTRAN language.

M.A. Karam, GenCorp Aerojet, 1100 W. Hollyvale St., Azusa, CA 91702. Received 3 May 1999. *Corresponding author (mostafa.karam@aerojet.com).

Published in Soil Sci. Soc. Am. J. 64:1219–1225 (2000).

THEORY AND METHODS

Thermal Wave Characteristics in Layered Soils

Let us explore the thermal wave characteristics of periodic heat transfer in layered soils and derive two of those characteristics that will be used to study heat transfer in nonuniform soils. To do so, we consider a layered soil occupying the lower-half space and having $(N + 1)$ layers (Fig. 1). Any arbitrary layer n ($n = 1, \ldots, N + 1$) within the layered soil has thermal properties (e.g., thermal conductivity κ_n, and heat capacity c_n) that are taken to be uniform, time independent, and different from the corresponding properties of other layers. The one-dimensional equation governing the temperature $T_n(z,t)$ within the arbitrary layer n can be written as ($-d_n < z < -d_{n+1}$, $d_1 = 0$),

$$c_n \frac{\partial T_n(z,t)}{\partial t} = \kappa_n \frac{\partial^2 T_n(z,t)}{\partial z^2} \quad [1]$$

where T is temperature (°C), t is time (s), z is an arbitrary depth below the surface within a layer, and d is a depth below the surface at a layer interface.

In the quasi steady-state portion of the solution of

51

App. E

Ministry of Science - Academy of Sciences of the Republic Kazakhstan
Institute of Soil Science after U.Uspanov

Director of the Soil Science Institute
---------- J.U.Akhanov
"_____"----------1999

REPORT
on research work
for grant
TA-MOU-96-CA, 16-016
"Improving irrigation management in the Syr-Darya delta"
(final)

Principal investigators:
Associate Member of NAS RK, Dr.Agr.Sci
Professor Akhanov
J.U.

(Kazakhstan)

Professor
Shainberg I.

(Israel)

Almaty,1999

List of co-investigators:

1. Dr Levy
(Israel)
2. Dr.Karazhanov K Zh.
3. Senior scientific worker Otarov A.
(Kazakhstan)
4. Leading scientific worker Ibraeva M.
(Kazakhstan)

Content

Introduction

1. Natural conditions of the investigated object
1.1. Conditions of soil formation
1.2 Soil cover
2. Optimization of water regime in hydromophic soils of delta alluvial plains of Syr-Darya with the help of artificial conditioning.
2.1. Influence of PAM on structural pecularities of soils.
2.2. Influence of artificially formed structure on moisture evaporation from the soil surface.
2.3. Experimental study of the ways on decrease of irrigation erosion under furrow irrigation.
3. Soil protection from irrigation erosion and selection of the optimal methods of irrigation.
3.1. Natural conditions of the investigated objects.
3.2. Influence of surge irrigation and PAM on irrigation erosion and water properties of soil.
3.3. Intensity of irrigation erosion under differtent methods of irrigation, length of furrows and debit of irrigation stream.
Conclusion
Reference

Introduction

Development of irrigation accompanied by discharge improvement of Syr-Darya, increase of water intake and irrevocable water consumption at the upper and middle stream has led to extreme deficiency of water resources, anthropogenic aridization and transformation of soil cover at the low reaches of the river. The most valuable for agriculture hydromorphic soils of delta-alluvial Syr-Darya plain (prodelta - Chiili massif, ancient delta - Kzylorda massif, current delta - Kazalinsk massif) have been mostly transformed. Desertification process is going on out of irrigation zone, secondary salinization is observed at irrigation massifs.

Less favourable salt regime of seasonal-reversible nature arises in conditions of Chiili massif, where soil testing was held, and rice, demanding the long-term flooding, is cultivated together with crops of interrupted irrigation. Irrigation by overstating rates under surface furrow irrigation and weak outflow of ground water cause gradual lifting of ground water leading to secondary salinization and soil swamping. Besides, irrigation erosion takes place under furrow irrigation. Sediments formation at the bottom of furrow deteriorates conditions of moisture absorbtion by soil.

Proceed from these facts the problem of an alternative method (to the furrow one) of irrigation is very actual in practice and for ecologic optimization of soil resources in the region.

The project stipulates study of irrigation methods that don't cause aftereffects.

The work is fulfilled jointly with the Institute of Soil and Water, Israel, beginning from the first of April, 1997 to December 1999, on finansial means of the Grant TA-MOU-96-CA16-016 "Improving irrigation management in the Syr-Darya delta".

The main field and laboratory experiments were performed in Kazakhstan at the Institute of Soil Science, final results are represented in this report.

1. Natural conditions of the object subjected to study

1.1. Conditions of soil formation

Chiili massif of irrigation occupies the major part of Syr-Darya prodelta. It is a part of Chiili region, Kzyl-Orda oblast.

Natural conditions of the prodelta are shown in works of many investigators (Borovskiy, 1956, 1958; Egorichev, 1961, 1963; Noskova, 1964; Akhmedsafin, 1961; Rubtsov, 1962; Zhakbaspaev, 1952, Mozhaytseva 1973).

As far as geomorphology is concerned, prodelta is represented by alluvial plain stretching as a band along the river between Karatau and Kzylkum plateau. V.M.Borovskiy distinguished in 1958 the Syr-Darya valley in prodelta region characterized as weakly inclined from the river and piedmont alluvial-proalluvial plain with inclination to the river.

Except these two elements of macrorelief, elements of mezorelief typical for deltas of the southern Kazakhstan develop on alluvial plain namely natural levees and flat ouvals bordering depressions on interriver bed inclinations.

Definite types of sediments correspond to the mentioned above elements of accumulative relief, depositing of which takes place in some hydrodynamic conditions, i.e. the process of litho-morpho-genesis unity is going on.

Syr-Darya, being the main supplier of ancient and current alluvial, regularly distributes it during floods.

Silty loamies and light loams prevail in the structure of natural levees. Depressions of natural inclinations mainly consist of clays and loams. Rocks with prevalence of silty loams and loamies, being more diverse by granulometric composition, take place in the structure of flat water shed ouvals.

Geologic structure of the prodelta is presented by complex of Quarternary alluvial deposits mainly of light granulometric composition with thickness up to 50 m, layered by saline clays of Palaeogene-Neogene age.

Ground waters of the massif are located in loose clastic deposits of Quarternary age. Chalk-Palaeogene clays serve as impermeable layer for them, the surface of which has got a basin nature and doesn't have general slope to the Aral sea because of tectonics, destruction and accumulation. (Borovskiy, Pogrebinskiy, 1958).

Ground waters of the massif are enclosed and they are subjected to transpiration and evaporation leading to constant accumulation of salts which are delivered there with the surface discharge. Now the regime of ground waters is subjected mainly to irrigational factor, hydrogeologic type of the regime is transformed to irrigational one. Irrigation by overstating rates in conditions of the territory weak drainage causes progressive elevating of the ground waters' level, providing secondary salinization and soil swamping. (Egorov,1959; Kovda, 1977, 1981; Borovskiy, 1958, 1978, 1982,; Akhanov, 1982).

By climatic indices the territory of Chiili massif refers to the northern desert. The climate is highly continental with dry hot summer, cold winter with rare snow, strong winds, sand storms. The total sum of positive temperatures is higher than 15° C and reaches 3464°, it permits to cultivate different crops within the irrigated territories. (Zhapbasbaev, 1965).

Average annual amount of precipitation don't exceed 100 mm/year. The major part of precipitation falls in cold period of the year. The sum of precipitation in the long-term cycle is considerably less than the deficit of air humidity. Extreme increase of air

humidity deficit is observed in spring and decreases in autumn causing intensive moisture evaporation from the soil surface and drying of the profile upper part up to air-dry condition.

Vegetation of the massif depends on hydrologic regime, soil salinization and other conditions. Gallery tugai forests,typical for the Central Asia, grow on natural levees of functioning river beds. Reeds grow on interriver bed inclinations which are becoming dry now everywhere. Holophites are located on flat water sheds and on slopes of natural levees. The main vegetation on takyr-like soils is represented by Haloxylon aphyllum, Salsola rigida, Anabasis salsa.

1.2. Soil cover

The significance of a relief as a differentiator of soil cover is well known. But in deltas this factor is realised vividly because hydrologic factor is connected with it and plays a decisive role in delta soil formation. (Egorov, 1959; Borovskiy, 1958; Akhanov, 1987).

Alluvial-meadow soils are forming on natural levees of the river and it's delta channels, composed by layered alluvial of light mechanical composition with weakly mineralized ground waters.

Soils of the swamp series are forming in flat wide depressions of interriver bed inclinations composed by heavy grounds with enclosed ground waters dynamic either by the depth or by mineralization. Holomorphic soils are located on undulate water sheds of the second order with mineralized ground waters.

Arid climate in combination with enclosed territories impart unique zonal-provincial characters to hydromorphic process of soil formation in delta, displaying in wide spreading of soils with different level and nature of salinization.

Alluvial-meadow soils of natural levees are forming on layered structural grounds of light mechanic composition under Elaeagnus oxycarpa, Salix wilhelmsiana,
with herbs. These soils are characterized by weak surface salinization of chloride-sulphate type. Ground waters are located at the depth of 1.3-3 m, they are mainly fresh, sometimes weakly saltish with weak outflow aside from the river bed.

Intensive dark-gray colour of the humus horizon caused by organic matter and humus content of 0.7-2% are typical for alluvial-meadow soils.

Upper humus horizon with loam mechanic composition has a clearly displayed clotted, clotted-graining structure and becomes structureless or vague-clotted with loamy composition. Modifying of carbonates' content along the profile is connected with composition transformation of alluvial layers. Absorbing capacity of the upper horizons - 7.7-10.0 mg-equ per 100g of soil, calcium prevails in composition of the absorbed bases.

Swamp-meadow soils of the massif are considerably spread, occupying the slopes of natural levees and elevated water sheds. They are formed under herb-reed vegetation (on fallow soils under weeds-reed vegetation) with close location (2 m) of ground waters and difficult conditions of local undersurface flow. The soils are formed by layered alluvium, mainly of loam composition.

Humus horizon with thickness 20-30 cm is rather strongly pronounced. Humus level in upper horizons ranges within 2-3%. The sum of the absorbed bases is 16-20 mg-equ per 100 g of soil with prevalence of the exchangeable calcium.

Meadow-swamp soils are also widely spread at the massif. They occupy wide flat depressions formed by ground of heavy mechanic composition. Vegetation cover of

them is homogeneous and consists of reed (Phragmites communis). Saltish ground waters are located at the depth 2-3 m, they are salinized from the surface. Virgin lands are met rarely, mainly they are cultivated and included into agrucultural fund of the most suitable soils for rice growing. Meadow-swamp soils have dark humus horizon with 2-4% of humus level. The sum of the absorbed bases in arable horizon makes up 12-25 mg-equ. Calcium plays the main role in soil absorbing complex.

Meadow-swamp soils are transforming into dry and desert variants with decrease of prodelta watering and change of hydrologic regime.

Swamp soils occupy flat depressions of interriver bed basins with typical Typha angustifolia-phragmites communis vegetation group. The swamp soils in natural conditions after inundation by flooding or waste waters exist not so long. As they become dry and the level of the ground waters decreases they transform into meadow-swamp soils.

Irrigated (paddy) swamp soils are the most interesting for agriculture. Pecularities of rice cultivation (the long-term flooding) causes series of qualitative changes in soil. During the whole vegetation period, anaerobic conditions are forming in soil, causing hydrogen sulphide, methane formation, which are harmful for plants and accumulation of FeO, manganese and other elements with variable valency. And the heavier mechanic composition the greater these processes are expressed. Rice cultivation on soils with light granulometric composition leads to freshening of soils and ground waters. Salt regime has a season-reversible nature.

Solonchacks occupy mainly flat water shed ouvals of interriver bed depressions, they are characterized by high surface and deep profile salinization 2-6%, mainly of chloride-sulphate type. Mineralized ground waters occure at the depth of 3-7 m with chlorides prevalence. Natural thinning is typical for the plant cover consisting of separate bushes such as Tamarix gracilis, Halocnemum strobilaceum and other typical Salsolas.

Takyr-like soils located in peripheral part of prodelta occupy the upland elements of the relief - flat ouvals. Ground waters occure deeply (6-12 m), they have a layered structure mainly of light mechanical composition and develop under Haloxylon aphyllum, Artemisia panciflora, Anabadis salsa, Salsolas and ephemers.

Thus it is difficult to achieve full regulation of water-salt regime in delta soils under irrigation. Excessive irrigation in some cases and insufficient irrigation in other cases, caused by imperfect irrigation and drainage net in conditions of weak natural outflow of ground waters, make furrow irrigation low effective and productivity of soil becomes very low. The necessity of looking for new ways of irrigation management, improving at the low reaches of Syr-Darya is obvious.

2. Optimization of water regime in hydromorphic soils of delta-alluvial plains of Syr-Darya with the help of artificial conditioning.

Swamp-meadow soils of Chiili massif of irrigation were the object of investigation. It is located at the right bank of Syr-Darya prodelta part.

A site, where soil pit was established for characteristic of soil, had been chosen on the territory of the joint stock company "Gigant" for field experimental work. The site is located on the flat ouval scarcely visible. Vegetation cover consists of reeds, Aeluropus litoralis (Gouan Parl.) and weed herbs.

0-20 cm. Dark-gray, of coarse clottered structure heavy loam, compacted, dry to the top and wet to the bottom with rare vertical fissures, thickly trancpierced by plant roots.

20-33 cm. Light-gray, structureless, compacted heavy loam. Humid with humus streaks in the form of pockets.

33-53 cm. Buried horison with interlayer of carbon substances - traces of former sites of a fire, heavy loamy, humid.

53-103 cm. Light-gray with bluish-like and ochre-like veins and interlayers, moderately loamy, structureless, humid - at the top, wet - at the bottom. Ground water is at the depth of 103 cm.

Humus horizon of small thickness (20-25 cm) has mottles typical for arable soils - a result of layers mixing under tillage.

Humus distribution has a regresive-accumulative type with maximum at the top horizon. Relative poorness of humus by nitrogen is typical - relation C:N is equal to 11.9-13.5 (table 1).

Table 1. Chemical and water-physical properties of swamp-meadow soils.

Depth, cm	Humus, %	Nitrogen		C:N	CO_2,%	pH	Bulk density, g\cm^3	Natural humidity, m^3\ha	The least humidity, m^3\ha	Deficite of moisture, m^3\ha
		Total, %	Easy hydrolised, mg\kg							
0-20	1.79	0.084	42.0	11.9	9.5	8.3	1.10	371.1	543.0	-171
20-33	1.76	0.074	39.2	13.5	9.5	8.5	1.41	707.0	584.0	+122
33-53	0.87	-	-	-	4.2	7.8	-	-	-	-
53-103	-	-	-	-	12.2	8.7	-	-	-	-

Soil humidity, located lower than 29 cm, exceeds the least water capacity in the profile of the given soils with the depth of ground waters 1.0-1.5 m.

In arable horizon water deficit makes up 171.6 m^3/ha. Soil gleization - rusty and bluish-like mottles and pockets are visible at the lowest horizon in connection with high soil moisture.

By mechanical composition the soil is distinguished by a rather homogenious profile with some prevalence of heavy loams. The soil consists of silt particles by 75-80%, the fraction of coarse silt prevails.

Comparison of results of mechanic and microaggregate composition shows that soil comprises a considerable amount of waterstable microaggregates damaged only under mechanic tillage.

The factor of dispersity (K), showing the level of microaggregates' damage in water (water stability of microaggregates) is rather low and equal to 12.9 (table 2).

The overwhelming part of microaggregates at the upper layers of soil refers to fractions of fine sand and coarse silt (up to 75%). Therefore this soil inspite of heavy loam mechanic composition, and because of microaggregation will have higher water and air permeability.

Table 2. Mechanic and microaggregate composition of swamp-meadow soils.

Depth, cm	Content of fractions, %						Physic. clay,%	K
	Size of fractions, mm							
	Sand		Silt			Clay	<0.01	
	1.0-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	<0.001		
Mechanic composition								
0-20	0.01	2.3	39.3	14.7	21.9	21.7	58.3	12.9
20-33	0.1	5.7	38.5	17.1	21.2	20.4	55.7	27.9
33-53	0.3	3.4	36.9	5.8	26.2	17.4	59.4	-
53-103	-	2.6	55.8	11.1	17.6	12.9	41.6	-
Microaggregate composition								
0-20	3.0	35.2	40.7	6.8	8.5	2.8	-	-
20-33	2.5	42.1	33.3	11.6	4.8	5.7	-	-

According to morphologic signs and results of chemical analysis the signs of alkalinity haven't been found in this soil. Absorbing capacity in the upper humus horizon is 21.1 mg-equ per 100 g of soil. The content of exchange sodium is very low and doesn't exceed 0.9% from the sum, the content of calcium and magnesium is rather high (table 3).

Table 3. Composition of the absorbed bases in swamp-meadow soil.

Depth, cm	Absorbed bases *mg-egu* pcr 100g of soil				Sum	From the sum			
	Ca	Mg	K	Na		Ca	Mg	K	Na
0-20	12.0	8.5	0.376	0.188	21.1	56.9	40.3	1.9	0.9
20-33	10.5	8.0	0.283	0.697	19.5	53.9	41.1	1.5	3.5

Analyses of water extraction (table 4) show, that the soil is surface-medium salanised with chloride-sulphate type of chemism. Ca, Mg and Na are in equal amount in cation composition.

Table 4. Composition of swamp-meadow soils' water extraction, %/mg-equ.

Depth,cm	HCO_3	Cl	SO_4	Ca	Mg	Na	K	Sum of salts	Tupe of salini-zatcon	Leve ltun of salin isa
1	2	3	4	5	6	7	8	9	10	11
0-20	0.026 0.43	0.04 1.13	0.327 6.81	0.055 2.75	0.034 2.8	0.058 2.54	0.011 0.28	0.551	Ch-s Ca-Mg	Mea n sa-line
20-33	0.033 0.54	0.033 0.93	0.136 2.84	0.025 1.25	0.017 1.36	0.037 1.63	0.003 0.07	0.284	Ch-s Ca-Mg	Non sa-line
1	2	3	4	5	6	7	8	9	10	11

33-53	0.058 0.95	0.063 1.72	0.306 6.38	0.052 2.6	0.031 2.55	0.087 3.8	0.004 0.1	0.599	Ch-s Mg-Ca	Mean saline
53-104	0.024 0.39	0.018 0.51	0.094 1.97	0.02 1.0	0.01 0.82	0.023 1.0	0.002 0.05	0.191	Ch-s Ca-Mg	Non saline

Salt distribution along the profile greatly modifies. Salts are absolutely absent in underarable firm horizon, soil is fresh. The buried horizon is analogous to arable horizon by salinization, the sum of salts is 0.599%. According to the type of salinization it is also a chloride-sulphate one, sodium ions prevail in composition of cations. Demineralized horizon is located lower and contacts with ground waters directly.

Alkalinity from the normal carbonates in CO_3 is absent along the whole profile and alkalinity in HCO_3 achieves the threshold of toxicity and makes up 0.95 mg-equ per 100 g of soil only in buried horizon. Apparently, it is connected with ash composition of buried coal matters of the former tugai vegetation.

Washing regime of irrigation with rates exceeding water retaining ability of soil by 20-30% is practised under exploitation of such soils for cultivation of interrupted irrigation crops at the massif. Such practice has a negative side consisting in constant elevating of ground waters' level up to the critical one. Irrigation erosion is observed under furrow irrigation caused by fractions of silt particles prevailing in the ground composition.

2.1. Influence of PAM on structural pecularities of soils.

Soil structure is indispensable consequence of soil formation process and it regulates the main processes going on in soil. It plays a diverse but always protective role for life of plants from unfavourable conditions and it is a powerful means for regulation of soil conditions and soil protection from water and wind erosion. All of it put soil structure at one of the first places among the elements of soil fertility.

It should be noted here that the soil structure from agronomic and morpho-genetic points of view - different notions. From morphologic point of view, soil structure is, first of all, a form of it's physical manifistation, i.e. it is a diagnostic sign on the basis of which and in combination with other signs under field researches, soil can be refered to a corresponding place in soil classification.

From astronomic point of view, structural soils are those soils where mezoaggregates prevail, i.e. aggregates are of 0.25 - 10 mm, which promote soil fertility in the long run. All other soils under such conditions are considered to be structureless. Further only agronomic structure, it's influence on water regime and components of soil water balance will be considered.

Soil structure has a great amelioration significance in conditions of Chiili massive of irrigation in Syr-Darya prodelta, where investigations were carried out. It is well known that rice (Oriza sativa) is cultivated with other cultures of surge irrigation at the mentioned above massif and other massifs of the region (Kzylorda and Kazalinsk) and requires a long-term water inundation which promotes a gradual lifting of mineralized ground waters' level causing a threat of secondary soil salinization.

In these cases it is necessary to lead arable horison to a condition of clottered structure which will break an ascending cappilar water current and decrease a danger of salinization.

One of the main characteristics of structural soil is water stability of it's aggregates - stability to destroying action of water, determined by aggregate analysis.

Analysis of soil water stability together with diagnostic aims can be considered as a peculiar model for influence of irrigation water on concrete soil. Resistance to water diffusion or water stability of aggregates is different in any separate case and depends on mechanic composition of soil, amount of cementing substances, type and dose of artificial conditioners and other factors of biologic and abiotic nature.

In connection with the stated above there have been conducted laboratory and field experiments on soils of Chiili massif. Polyacrilimid was used as an artificial conditioner. It was given by our colleagues - co-investigators of the project, Institute of Soils and Water (Israel).

Method of experiment conduction is as follows:

Soil lot of arable horizon was treated by polyacrilomid in the corresponing doses: 1.0; 4.0; 10.0; 40.0 kg/ha after drying to air-dry condition and reducing to fragments. After the long-term drying during 30 days the soils were subjected to structural and aggregate analysis according to Savinov's method.

The essence of the method is in the following: soil samples after drying up to air-dry condition disperse on the column of soil sieves with the holes from 0.25 to 10 mm. After dispersion, the weight of aggregates left on each sieve is determined. Then, percentage content of each aggrigate fraction was determined by weighing on balance. So soil structural analysis finishes.

Further, from each structural fraction a half doze of it's percentage content (expressed in grammes) is selected and combined together, it makes up a lot for aggregate analysis. The lot, received by this way, is wet by water and "wet sieving" in water with the same set of sieves is performed as it had been made in case of structural analysis. Percentage of water stable aggregates is calculated by weighing of fractions left at each sieve.

Results of the performed experiment on influence of different dozes of polyacryloamide on structure-aggregate composition of swamp-meadow soil show that all the tested dozes positively influence on the given property of soil (table 5).

Increase of agronomically valuable aggregates' amount (0.25-10 mm) is observed in all variants in comparison with control. Factor of dispersion (K), showing the relations between mezoaggregates and the sum of macro- and microaggregates, increased in comparison with control by 1.1-2.1 times.

Table 5. Influence of different dozes of PAM on structure-aggregate composition of swamp-meadow soil, % .

structural aggregate

Vari-ants	Size of aggregates, mm										Coef ficie nt of struc -ture
	Macro aggreg ates >10	Mezoaggregates								Micr oagg regat es <0,2 5	
		10-7	7-5	5-3	3-2	2-1	1-0,5	0,5-0,25	0,5-0,25		
Contro l	44,06 broken	20,4 br.	6,26 br.	9,04 br.	5,1 0,19	3,8 0,25	0,5 1,95	2,1 7,92	47,2 10,3	8,74	0,9
1 kg\ha	38,78 br.	10,2 br.	9,0 0,86	18,5 1,81	9,04 1,59	8,2 1,92	2,78 3,38	0,98 7,05	58,8 16,6	2,42	1,4
4 kg\ha	34,38 br.	13,8 br.	11,7 0,28	15,0 1,04	8,24 0,73	7,2 0,94	3,08 4,7	1,46 9,03	60,5 16,2	5,06	1,5
10 kg\ha	32,68 3,18	19,9 1,34	17,4 0,73	17,7 1,69	6,0 1,57	3,7 2,0	0,87 6,4	0,14 9,6	65,7 25,9	1,55	1,9
40 kg\ha	41,98 br..	9,1 br..	11,3 br..	12,4 2,02	7,3 1,73	6,8 1,93	2,3 4,02	1,1 8,81	50,3 20,9	7,68	1,0

Optimal doze, providing a well structured layer of swamp-meadow soil is the doze - 10 kg/ha.

Thus, the received data permit to make a conclusion that PAM in doze 10 kg/ha promotes formation of a rather large amount of water stable aggregates together with increase of dispersion factor of swamp-meadow soils and it is a means for conservation of favourable soil structure, means for crust formation control, compactness and irrigation erosion.

Microstructure under it's porosity and water stability favourably influences on agronomic properties of soil. Microaggregates of 0.25-0.05 and 0.05-0.01 mm are the best ones. Microaggregates with the size of medium silt (0.01-0.005 mm) impede water- and airexchange, promote increase of evaporation ability of soils. Comparison of data received after mechanical and microaggregate analyses, made simultaneously, is one of the methods that helps to learn the level of microaggregates water stability.

Coming from the given above statement, soil samples from the first experiment were subjected to microaggregate analysis and the initial (control) soil - to mechanic analysis in order to learn influence of PAM on the amount and water stability of microaggregates.

Results of microaggregate analysis of soil, treated by different dozes of PAM show that in a whole a tendency to increase of microaggregates size is observed, i. e. such method promotes an increase of water stable microaggregates' amount (table 6).

Table 6. Transformation of microaggregate composition of soil under the influence of PAM.

Variants	Content of fractions,%						Factor of Dispersion, %
	Sizes of fractions,mm						
	Sand		silt			clay	
	1-0.25	0.25-0.05	0.05-0.01	0.01-0.005	0.005-0.001	less 0.001	
Microaggregate composition							
Control	0,7	22,4	33,5	19,0	17,6	6,8	32,5
PAM1kg/ha	4,1	29,1	42,9	5,4	12,6	5,9	28,2
PAM4kg/ha	1,6	28,9	34,2	15,1	13,2	7,0	33,5
PAM10kg/ha	3,9	29,8	32,1	16,4	14,5	3,3	15,8
PAM40kg/ha	2,9	23,5	36,4	6,0	26,9	4,3	20,5
Mechanical composition of initial soil							
Control	0,2	8,4	31,3	13,8	25,4	20,9	-

The factor of microaggregate enlargement as a result of soil tillage by PAM is obviously visible if we compare microaggregate composition with the mechanical one. The factor of dispersion, that characterizes the level of microaggregates distruction in water and expressed by correlation of microaggregates with the size of clay fraction and clay content according to the data of mechanic analysis show that the most optimal doze of PAM, when factor of dispersion has the lowest value (15.8%), is 10 kg/ha.

Therefore, coming from the amount and quality (sizes) of microaggregates under PAM 10 kg/ha, it is possible to make a conclusion that the given doze promotes the formation of the more structural upper layer of soil and it will decrease physical evaporation of water from the soil surface.

It should be noted that improvemwnt of macro- and microaggregate soil composition is a direct argument for decrease of soil evaporation ability. Thus a laboratory experiment was carried out for examination of the given statement with a direct determination of evaporation intensity from the soil surface, treated by PAM.

2.2 Influence of artificially formed structure on water evaporation from the soil surface.

Unproductive part of soils' water balance is physical evaporation of water from the soil surface. Physical evaporation leads to fatal aftereffects for yields of crops under insufficient amount of water.

Structural pecularities of soil surface layer - velocity of water lifting to evaporating surface, is one of the causes that influences on the rate of water evaporation from the soil surface.

As the essential factor of water delivering to evaporating surface from deeper soil layers is capillar lifting of water, so changes in structure of the soil surface layer, conditioned by application of chemical materials, must transform regime of evaporation.

Evaporation decreases owing to formation of structural condition to the upper soil layer. Formation of the set of non-capillar intervals abruptly retards capillar elivating,

decreases the rate of evaporation and conserves water. It is especially valuable in irrigation agriculture with deficite of water resources in such regions as Aralsk one.

B.D.Mikhailov (1961) showed that after PAM application in doze 0.0005% from weight of soil in the layer of 5 cm after each irrigation, 120 m^3 /ha of water are conserved in it.

N.I.Eshanov (1965), investigating evaporation in field experiments on sierozems under their conditioning by the polymer K-4 in doze from300 to 1000 kg/ha notes that humidity in control variant was by 2-3% less than in experimental one.

Thus, even simple enlargement of aggregates forms necessary preconditions for evaporation decrease.

S.N.Dolgov (1948), investigating the rates of capillar water lifting to evaporating surface in soil aggregates of different diameters showed that the hight of capillar lifting is more in microaggregates < 0.25 mm than in macroaggregate soils.

S.N.Ryzhov and V.Z.Bogomolov (1934), learning dependence of evaporation from the soil surface on the structure of the upper layer, came to the conclusion that more amount of water is lost during the first period of drying from the aggregate layer under rather high humidity, and during the further periods microaggregate, dispersed soil becomes dry very quickly.

Experiments were carried out in vessels with swamp-meadow soil sifted through a sieve of 2 mm. PAM was applied in the upper layer of soil as a solution. Soil humidity was under observation during 6 days, by weighing the soil on balance.

The results of observation show that difference in water loss in different variants wasn't essential (table 7) when the soils had a rather high humidity.

Table 7. Dynamics of humidity depending on PAM dozes, %.

Variants	Time of observation,days					
	1	2	3	4	5	6
Control	35,9	25,2	17,6	9,8	9,2	7,8
PAM1kg/ha	34,9	25,4	17,4	10,0	9,2	8,7
PAM4kg/ha	36,4	26,1	20,9	12,2	11,2	9,7
PAM10kg/ha	36,2	26,1	21,2	12,4	11,2	9,9
PAM40kg/ha	35,8	25,9	20,0	10,5	9,7	8,7

Further as humidity decreased, PAM begins it's activity, so the dozes of 10 and 4 kg/ha appeared to be the most effective for decrease of physical evaporation. The variants with these dozes in comparison with control comprize more water, correspondingly by 2.1 and 1.9%.

Efficiency of 10 kg/ha PAM doze for decrease of soil evaporating ability was tested in conditions of field experiment at Chiili massif of irrigation. The sizes of experimental plots are 100 m^2. A thrice-repeated experiment was performed. PAM was applied by a knapsack sprayer. Maize (Sea mais) was used as an experimental culture. The width between the raws is 70 cm. 3 irrigations were made along the furrows with the constant water flow during vegetation period.

The results of soil humidity observations show that water intensively evaporated from the soil surface in control variant (table 8) practically in all periods of observation.

Table 8. Dynamics of soil humidity in field experiment,%.

Variants	Time of observation, dates							
	5.06	15.06	25.06	5.07	15.07	25.07	5.08	15.08
Contro	20.6	19.2	17.0	20.2	21.4	20.6	19.9	17.8
PAMkg/ha	21.0	19.4	18.7	20.8	22.6	21.6	21.2	20.1

The following regularity is observed. At the stage of constantly water decrease (from the beginning of the experiment till the first irrigation and from the last irrigation till the end of the experiment, the more visible difference in variants' humidity is observed than during interirrigation periods. Irrigations were performed on 29 July, 8 and 16 July.

The results of the given before experiments show that physical evaporation of water from the soil surface essentially influences on artificial structure formation. Thus, changing structural composition of soil surface layer with the help of PAM, it is possible to regulate the elements of soil water balance.

The data on positive influence of PAM on structural condition of soil, decrease of physical evaporation from the soil surface show that the investigated soil saves loose condition, higher humidity, optimal water permeability, aeration during the whole vegetation period. It means that more favourable complex of conditions for growing and development are observed in it, it is prooved by the data of miize grain yielding ability in field experiment (table 9).

Table 9. Structural analysis of maize grain yielding ability.

Variants	Yielding ability of grain, c/ha	Increase c/ha	Hight of stem, cm	Weight of1000 grains, g
Control	58.3	-	230	230
PAM 10kg/ha	63.4	5.1	230	238

2.3. Experimental study of ways for decrease of irrigation erosion under furrow irrigation.

Soil pliability to water erosion was studied in laboratory experiments using specially prepared hydroflumes for it and imitating different inclinations of irrigation furrows. Hydroflume was made according to the requirements formulated by V.B.Gusak (1950).

A section of a furrow was made by means of a flume 1 m length and 0.15 m width from the dry and reduced to fragments soil. Inclination was regulated by a special screw. Water discharge was measured with the help of stationary established three-cornered Thompson weir.

Experiment was carried out with three inclinations: small - 0.002; moderate - 0.004; and large - 0.02. Two variants of irrigation were imitated:

1. Usual furrow with the constant portion of water.
2. Furrow surge.

Irrigation rate was determined by calculations of humidity deficit. It made up 15 l for conventional flume. Soil amount in grammes, washed out by one litre of water (Lysenko, 1984), was selected as a criterion of soil pliability to erosion. This criterion simplifies analytic process and gives a chance to conduct a comparative assessment of soil pliability to water erosion. Different dozes of PAM were tested as conditioners.

Below we give the results of the experiment with different inclinations under application of different PAM dozes.

Table 10 shows that surge irrigation in comparison with usual furrow one, under other things being equal, occured to be more effective for irrigation erosion control. Besides this method of irrigation promotes reduction of irrigation rate owing to decrease of unproductive expenditure.

Table 10. Pliability of swamp-meadow soils to water erosion.

Variants	Outflow of soil particles under inigiation, g\l		
	0.002	0.004	0.02
Usual furrow	0.69	0.85	1.1
Surge	0.47	0.61	0.62
Usual furrow method with application of different PAM doses			
40 kg\ha	0.0	0.0	0.0
10kg\ha	0.0	0.0	0.0
4kg\ha	0.0	0.0	0.0
1kg\ha	0.0	0.0	0.06

Application of PAM only on soil surface proposed by Shainberg (1985) for swamp-meadow silt soils turned out more effective. Erosion of these soils under usual furrow irrigation begins with the PAM dose 4 kg/ha and inclination 0.02.

3. Soil protection from irrigation erosion and selection of optimal methods of irrigation

Discharge of irrigation waters causing soil washing and remove of it's most fertile part is called as irrigation erosion. Damage caused by irrigation erosion for agriculture is enormous. Areas of valuable agricultural lands are subjected to distruction, common hydrologic regime and vegetation water supply become worse as a result of irrigation erosion.

Soil protection from irrigation erosion is carried out on the basis of complex measures including selection irrigation method, length and direction of furrows, irrigation stream discharge and etc. But water absorbtion ability of soils is very often insufficient due to low water stability of soil aggregates after application of the proposed measures.

As it was marked, application of artificial polymers is one of the methods for increase of water stability of aggregates. The results of investigations on irrigation methods and PAM influence upon irrigation erosion and water regime of sierosemic-meadow soils of Tasotkel massif will be considered below.

3.1 Natural conditions of the investigation object.

Tasotkel massif, located in the terraced part of the middle stream of the river Shu (Dzhambyl oblast), was selected as an object for investigations because irrigation erosion has only a local significance within the crop rotation field in conditions of alluvial-delta plains of the river Syr-Darya basin.

The direct object of investigations - sierozemic-meadow soils within the massif are located on the second fluvial terrace above flood-plain with a gentle inclination from the South to the North. The width of the terrace is 15-20 km. The surface of it is complicated by different forms of mezorelief. Twisting hollow-like depressions are inherited from wanering currents of the river Shu under overflow here and there. Microrelief of the second fluvial terrace above flood-plain is caused mainly by human economic activity and represents irrigation landscape of old and new irrigation.

Sierozemic-meadow soils, as a rule, are formed in weakly expressed flat padings with comparatively close (up to 1.5 m) position of mainly mineralized ground waters (Akhanov 1982).

Humus level in the upper 0-30 cm horizon reaches 1.52%. Carbonates are from the surface, pH of soil solution is alkaline. Absorbing capacity is small - 6-13 mg-equ per 100 g of soil. Magnesium takes a great part in composition of exchangeable bases. It's content in upper horizons is 25-40% and 50 % from the sum of the absorbed bases in the horizon located lower than 50 cm. Probably, it exactly gives compactness and morphologic alkalinity to soils.

The main part of soils (about 65%) is salinized. Non-saline soils are met in the form of separate mottles under irrigation cultures and middle depth of ground waters 1.8 m and mineralization 1.2-1.9 g/l. Sodium sulpfates and soda dominate in salt composition, chlorine is accumulated at the surface.

Lifting of ground waters was caused by worsening of natural outflow now and the problems of overmoistening, secondary salinization, mainly of alkaline and soda composition appeared. It naturally greatly decreases soil fertility. Introduction of non-traditional methods of irrigation, promoting decrease of irrigation water loss for infiltration and decrease of irrigation negative aftereffects is one of the measures for improvement of amelioration situation at the massif under the conditions when transformation of the soil cover caused prevalence of low productive soils. Application of artificial conditioners, permitting to prevent evaporation concentration of salts at the upper soil horizon and to decrease possible irrigation erosion, can play a very valuable role.

3.2.Influence of surge irrigation and PAM on irrigation erosion and water properties of soils.

Surge irrigation - a periodical delivering of irrigation stream into furrow, i.e. impulse delivering of water. This type of irrigation initially was used for decrease of irrigation erosion intensity (Atringham, 1979). Later Shainberg (1979) found out that this method of irrigation decreases water capacity and the time of water saturation, it permits to decrease an irrigation rate.

The experiment was performed according to the method proposed by Shainberg and Levy (1977) on sierozemic-meadow soil of Tasotkel massif according to the following scheme.

1. Constant flow
2. Surge flow
3. Constant flow + PAM

4. Surge flow + PAM

A three-fold repetition in three furrows of 200 m length were performed on industrial sowings of maize. A furrow inclination is 2^0. PAM of 10 g/m^3 doze was applied in irrigation water during furrow wetting (the time when the water reaches the end of a furrow). For calculation of irrigation water disharge at the beginning of a furrow there were used a siphon with 15 l/min discharge and Thomson's overfalls at the end of a furrow. The content of suspended particles in furrow water is determined by weighing, soil humidity - by weight method.

The following regularity is observed during analysis of the solid discharge in furrow irrigation for both types of flow (table II). Increase of solid discharge amount in furrow water is observed along the furrow from the beginning to the end, and with the time increase from the beginning of irrigation it's decrease is observed along the furrow.

Table 11. Intensity of solid discharge formation in furrow water, g/l

Variants	Time of water sampling after the beginning of experiment, min	Distance from the beginning of furrow, m		
		20	100	180
Constant flow	10	0,22	0,34	0,74
	20	0,08	0,27	0,45
	30	0,09	0,19	0,37
Surge flow	10	0,11	0,07	0,08
	20	0,08	0,11	0,1
	30	0,04	0,07	0,08
Constant flow + PAM	10	0,1	0,08	0,07
	20	0,08	0,08	0,02
	30	0,03	0,03	0,5
Surge flow + PAM	10	0,07	0,05	0,05
	20	0,05	0,04	0,05
	30	0,03	0,03	0,01

It should be noted that intensity of irrigation erosion under surge flow application is low in comparison with the constant flow. PAM application in irrigation water practically prevents occurence of irrigation erosion.

Therefore, surge irrigation is an effective method for soil protection from irrigation erosion on soils of lightened soil texture.

Analysis of surge nethod of irrigation and PAM influence on the depth of wetting and soil humidity after irrigation show that surge flow significantly decreases infiltration rate along the furrow length (table 12).

Mechanizm of infiltration rate decrease we can explain in the following way. Intensive irrigation erosion occures in a furrow during the first surge with a rather high discharge of irrigation water (30 l/min), i.e. the content of clay particlies and particles less than 0.002 mm increases in furrow water which have to deposite on the bottom at the moment of surge flow breaking and they don't reach the end of a furrow. Thus, the amount of deposits in a furrow increases with each surge flow and decreases the rate of water infiltration into the horozons located lower.

So we came to a very useful conclusion here, that we can stabilize the level of ground waters with the help of surge method of irrigation, protecting the soils from the damage of the secondary salinization.

Table 12. Influence of surge method of irrigation and PAM on the depth of wetting and soil humidity after irrigation.

Depth, cm	Moisture content of soil (%) from the beginning of the furrow (m)		
	20	100	180
Constant flow			
0-20	23,9	24,3	25,1
20-40	26,1	24,1	24,6
40-60	23,2	23,6	23,8
60-80	20,1	20,5	19,7
Surge flow			
0-20	23,7	24,0	24,1
20-40	20,1	19,1	19,7
40-60	17,3	18,7	18,2
60-80	17,1	18,0	17,3
Constant flow+PAM			
0-20	24,1	22,3	20,0
20-40	23,3	23,8	21,0
40-60	23,5	21,0	20,6
60-80	22,8	22,5	20,5
Surge flow+PAM			
0-20	26,5	24,4	19,9
20-40	22,8	24,1	19,5
40-60	23,0	23,6	20,4
60-80	23,5	22,2	22,1

Intensity of soil wetting in variants with application of PAM in irrigation water is practically at the level of control. As far as uniformity of wetting is concerned, either constant or surge flows without PAM distribute water along the furrow rather evenly. In variants with PAM, soil humidity decreases at the end of the furrow to some extend, but it is apparently connected with technical execution of PAM mixing with irrigation water, namely with uneven delivering of PAM solution.

From the data of table 13 it is evident that surge flow and two variants with PAM application decrease the time of irrigation and discharge of irrigation water.

The variants with surge flow and it's combination with PAM occured to be the most effective, they permit to save irrigation water, correspondingly by 29 and 36% in comparison with usual furrow method of irrigation (control).

Table 13. Efficiency of surge method and PAM in irrigation

Variants	Time for irrigation,min	Irrigation rate, m^3/ha	Balance	
			m^3/ha	%

Constant flow	870	1514	-	100
Surge flow	650	1071	443	29
Constant flow + PAM	580	1343	171	11
Surge flow + PAM	440	971	543	36

The following conclusions can be made on the basis of experimentally received results. In the regions with unfavourable soil-ameliorative conditions, i.e. delta plains of Syr-Darya and Shu, surge irrigation and application of PAM on soil surface in doze 4-10 kg/ha are the most effective for stabilization of ground water level and amelioration condition as a whole. In the regions with satisfactory amelioration conditions surge irrigation with application of PAM in irrigation water in doze 10 g/m^3 is recommended.

3.3. Intensity of irrigation erosion under different methods of irrigation, furrow length and debit of irrigation stream.

Under selection of irrigation method and elements of irrigation technique, under large inclinations, the main attention should be paid to soil stability to erosion under the influence of irrigation stream. In connection with it, under large inclinations and furrow method of irrigation it is necessary to use small irrigations streams in furrows and it is desirable to decrease water discharge, delivered to open irrigation net. Decrease of irrigation stream volume and water discharge in channels causes increase of irrigation duration, delay of after irrigational tillage and as a result increase of water loss for evaporation and deep penetration. Unevenness of soil wetting along the furrow - at the beginning of the furrow - excessive, at the end - insufficient is a negative side of this method of irrigation.

The volume of irrigation stream, delivered to the furrow, also depends on the soil permeability capacity. The higher soil permeability, the larger is water discharge into the furrow.

In connection with the stated above, a comparative study of the furrow methods of irrigation with the constant and surge flow delivering of irrigation water into the furrow was performed.

The experiment was conducted in piedmont desert zone of the South-East Kazakhstan on the fields of soil stationary of the Soil Science Institute. The relief of the site is rather even with a significant inclination (0.05-0.07) to the North. The surface is covered by coarse and fine pebbles and rounded stones. Lithology of the site consists of middle Quarternary alluvial deposits represented by coarse- medium- and fine sands with lens of gravel. Alluvial-proalluvial deposits in the form of sand, shingle beds and rock debris are soil formation rocks.Vegetation cover at virgin sites is represented by Eurotia-Artemizia primitive plant aggregations with Stipa capillata, Kochia prostrata and Nanophyton erinaceum from place to place.

Ground waters are located deeply and don't influence on the process of soil formation.

Soil cover is represented mainly by non-complete- and poor - developed with weakly-, medium-, and high skeletal gray-brown soils. A disditctive pecularity of them is not-completely developed with strong rock debris profile with rock debris and shingle beds deposits laying under at the depth 25-50 cm. Pebbles and rock debris are usually well cemented by lime and covered by carbonate crust at the bottom surface.

Presence of weakly differentiated genetic horizons are typical for these soils: A-humous, B-transitional, C- pebbles and rock debris of different size. Gray-brown soils

are poor by the content of organic and mineral substances that are necessary for plants nutrition. Humus level ranges within 0.4-0.6%. Fulvo acids considerably exceed humine acids in humus composition.

Soil provision with easily assimilated forms of phosphorus is 1.37-3.27 mg per 100 g of soil. Mobile potassium is within 10.0-33.6 mg per 100 g of soil. The soils are non-saline and non-alkaline. Absorbing capacity doesn't exceed 10 mg-equ per 100 g of soil at the upper horizons. In composition of cation exchange capacity Ca prevails. Ph of water suspension is within 8.5-8.7.

By profile soil texture is homogeneous, but the content of sand fraction and skeletal particles sharply increases from the depth. By soil texture these soils are silt-sand, loamy, with strong rock debris.

Close bedding of alluvial-aggregation plain rock debris and shingle beds deposits with sand-loamy aggregate, presence of gravel, rock debris and pebbles in arable (upper) horizon greatly influence on water-physical properties that are important under agrotechnique and ameliorative measures.

Arable horizon of these soils has a good water permeability that exceeds 0.25 cm\min for 1 hour of observation. Besides low water capacity and therefore small water supply in soil are typical for these soils. Rock debris profile causes decrease of water supply in soil. The least water capacity ranges within 14.0-18.0%. The structure is not waterstable. It disintegrates and destroys under wetting and tillage of soils. Crust formation is expressed greatly.

Irrigation erosion is manifested in a considerable degree under the influence of irrigation waters and because of large slope (0.05-0.07) on the surface of irrigated fields under furrow method of irrigation.

As a result of erosion, leaching of soil silt fraction , transference of the main nutrition elements of plants take place. Sometimes after irrigation, erosion scars are formed on irrigated field, especially at the upper parts of irrigation furrows, which can be characterised by fine earth leaching to rock debris and shingle beds depth.

Thus testing and application of surge method of irrigation is very actual and cause theoretic and practical interest.

According to the data of the Soil Science Institute analogous soils are spread in piedmont zone of the South-East Kazakhstan and occupy 300 th.ha, where there is a sufficient supply of fresh water, streaming down from the mountains as a result of glaciers melting. The experiment was performed according to the method of Shainberg and Levy by the following scheme:

Variants	Irrigation stream (Q) l/min	Length of a furrow (L) m
Surge flow	30	100
		150
	50	100
		150
Constant flow	30	**100(control)**
		150
	50	100
		150

Experiment repetition - 3-fold one, 3 furrows per each variant on industrial sowings of sunflowers. Width of spaces between raws is 70 cm, depth of a furrow is 15 cm.

The following common but with different intensity regularity is observed under analysis of the solid discharge in irrigation water for all the variants. Solid discharge increases from the beginning to the end along the furrow length but it gradually decreases with the increase of irrigation time.(Table 14, pic.1,2). Intensity of solid discharge formation is lower by 2-5 times under the surge flow than under the constant flow.

Table 14. Intensity of solid discharge formation, g/l

Variants	Irrigation water discharge l/min	Furrow length, m	Distance from the beginning of a furrow, m	Time for selection of irrigation water samples after beginning of the experiment, min		
				10	20	30
Surge flow	30	100	10	0,23±0,033	0,05±0,003	0,03±0,009
			50	0,27±0,017	0,28±0,017	0,15±0,05
			90	0,91±0,044	0,3±0,115	0,22±0,142
		150	10	0,4±0,05	0,43±0,192	0,18±0,018
			75	0,55±0,304	0,4±0,05	0,23±0,088
			140	0,63±0,127	0,55±0,12	0,52±0,231
	50	100	10	0,37±0,06	0,15±0,05	0,06±0,006
			50	0,45±0,058	0,35±0,05	0,13±0,033
			90	0,97±0,249	0,58±0,117	0,49±0,249
		150	10	0,55±0,029	0,33±0,033	0,07±0,015
			75	0,76±0,044	0,38±0,06	0,09±0,009
			140	1,28±0,334	0,37±0,101	0,32±0,136
Constant flow	30	100	10	0,46±0,033	0,2±0,076	0,11±0,006
			50	0,93±0,088	0,81±0,295	0,25±0,029
			90	1,32±0,044	0,82±0,289	0,45±0,029
		150	10	0,56±0,061	0,51±0,231	0,23±0,017
			75	0,88±0,016	0,57±0,088	0,28±0,117
			140	1,28±0,334	0,85±0,18	0,53±0,044
	50	100	10	0,55±0,104	0,33±0,014	0,15±0,05
			50	0,77±0,117	0,5±0,104	0,25±0,104
			90	1,38±0,017	0,97±0,12	0,55±0,029
		150	10	0,56±0,06	0,51±0,231	0,12±0,017
			75	0,88±0,016	0,57±0,088	0,18±0,133
			140	1,35±0,029	0,85±0,18	0,83±0,044

The amount of solid discharge in irrigation water increases either with the increase of irrigation stream or a furrow length. The most optimal variant on decrease of negative influence if irrigation erosion on soil of irrigated site was the variant with surge flow and the length of a furrow 100 m and debit of irrigation stream - 30 l/min. As it followed, constant flow with the furrow length 150 m and debit of irrigation stream 50 l/min appeared to be the most intensive soil eroding variant. Therefore,

surge irrigation is one of the most effective methods of soil protection from irrigation erosion when there are large inclinations of surface.
Analysis of surge irrigation influence on evenness of moisture distribution along the furrow length shows that either surge or constant flow under all lengths of a furrow and debit of irrigation stream wet the furrow along the whole length excluding initial site, practically evenly. (Table 15, pic.3,4).

Table 15. Determination of soil humidity after experiment.

Vari-ants	Irrigation water dis-charge, l/min	Furrow depth, m	Distance from the beginning of a furrow, m	Depth, cm	
				0-10	10-20
Surge flow	30	100	20	12,7±0,152	14,3±0,425
			50	12,4±0,176	13,4±0,165
			80	12,1±0,351	13,40,296
		150	20	14,6±0,152	16,8±0,318
			75	13,8±0,176	16,0±0,284
			130	13,2±0,176	14,8±0,346
	50	100	20	13,1±0,176	15,5±0,318
			50	13,4±0,264	14,3±0,260
			80	12,2±0,208	13,4±0,167
		150	20	15,1	16,9±0,152
			75	15,6±0,167	17,1±0,067
			130	14,2±0,14	16,5±0,240
Con-stant flow •	30	100	20	13,1±0,145	14,5±0,384
			50	13,0±0,491	13,7±0,240
			80	13,0±0,338	13,9±0,305
		150	20	15,4±0,120	16,9±0,384
			75	15,4±0,554	17,1±0,517
			130	14,4±0,233	15,4±0,305
	50	100	20	14,2±0,346	15,0±0,410
			50	13,8±0,384	14,6±0,503
			80	13,8±0,152	13,9±0,208
		150	20	16,5±0,290	17,4±0,218
			75	16,0±0,475	16,0±0,202
			130	15,5±0,175	16,5±0,378

The course of heightened moistening (overirrigation) of the initial furrow sites can be explained as follows. Initial furrow site is subjected to destroying (eroding) influence equally either under the constant or surge flow of irrigation water, i.e. clay and silt particles from the initial furrow sites under both types of flow go away for ever though

the intensity is different. Thus this effect promotes increase of infiltration rate. As far as decrease of irrigation time and rational use of moisture (overirrigation and insufficient irrigation), it is evident that under other things being equal, surge flow occured to be more optimal, meeting the requirements of water regime of sunflower when the irrigation rate is closer to that one, calculated on deficit of moisture before irrigation (800 m^3) (Table 16).

Table 16. Comparative efficiency of surge irrigation.

Variants	Volume of irrigation stream	Furrow length, m	Time of irrigation, min	During irrigation		Irrigation rate, m^3/ha	Balance	
				Delivered to a furrow, m^3/ha	Down throw at the end of a furrow, m3/ha		m^3/ha	%
Surge flow	30	100	360	900	82	818	-82	9.1
		150	375	642	332	310	-590	65,5
	50	100	350	1428	81	1347	447	49,6
		150	357	985	316	669	-231	23,6
Constant flow	30	**100 (control)**	**380**	**985**	**85**	**900**	**-**	**100**
		150	390	685	345	340	-560	62,2
	50	100	355	1464	81	1383	482	53,5
		150	365	1023	322	701	-149	22,1

Therefore, application of surge method of irrigation for soils of light soil texture with high water permeability and large slope of irrigated site is one of the measures that decreases harmful influence of irrigation erosion. Besides this type of irrigation promotes decrease of irrigation time and irrigated rates to some extend.

Conclusion

Study of PAM interaction with different types of soils located in different unfavourable amelioration conditions permits to come to the conclusion that it's ability to improve aggregate-structural soil condition and connected with it positive changes of regimes and processes, taking place in soil, is it's multifunctional property.

Besides improvement of structure-aggregate condition of soils PAM in doze 10 kg/ha also promotes formation of rather large amounts of water stable aggregates and

it is a means for conservation of favourable soil structure, control of crust formation, compactness and irrigation erosion. Besides, PAM decreases water evaporation due to improvement of structural condition of the upper layer of soil.

We came to the conclusion that it is possible to regulate directly the processes of soil water evaporation owing to regulation of thickness and structure-aggregate condition of soil surface.

Comparative study of surge flow with constant one permits to make a conclusion that surge flow has two effects in improvement of irrigation soils management. First of all, it permits to decrease intensity of solid discharge formation in furrow water and it is one of effective measures for irrigation erosion. Secondary, it permits to stabilize the level of ground waters, not bringing to critical point, due to infiltration rate decrease of irrigation water. If the use of one surge irrigation promotes decrease of irrigation rate by 29%, their joint use - 36%.

It should be noted that joint use of PAM and surge flow intensifies their action. Irrigation erosion is practically prevented under their joint use within the moderate inclinations.

In connection with it we recommend to use surge flow plus application of PAM in doze 4-10 kg/ha in the regions with unfavourable soil-amelioration conditions for stabilization of ground water level and amelioration condition as a whole. And in the regions with satisfaxtory amelioration conditions we recommend PAM in doze 10 g/cm^3.

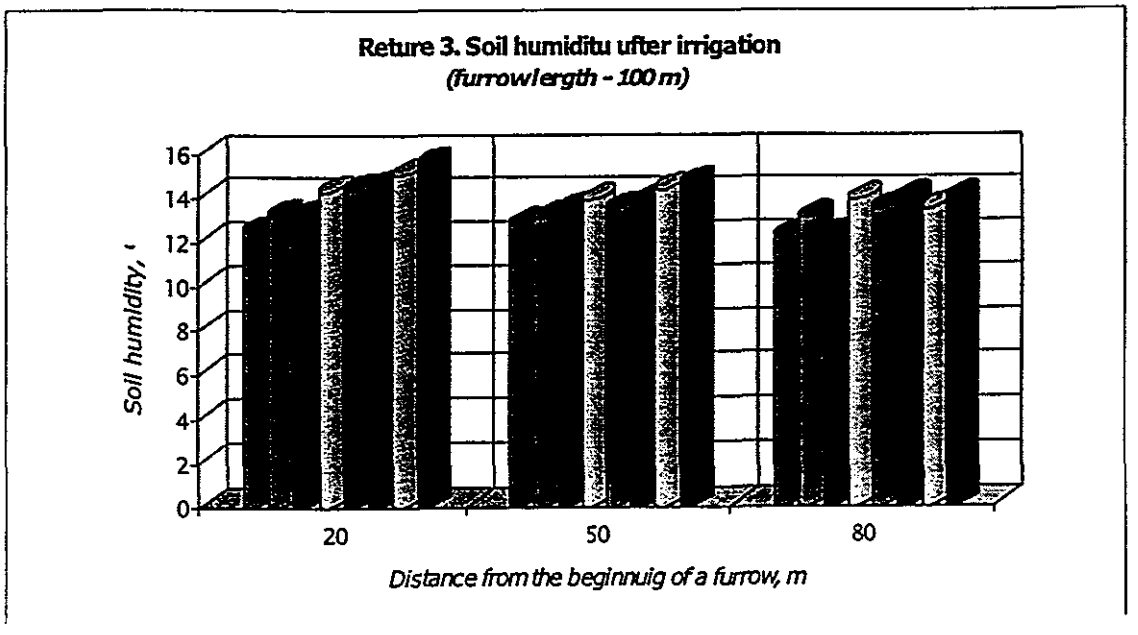
We recommend surge irrigation with debite of irrigation stream 30 l/min in piedmont regions with shallow rock debris and shingle beds lying under them. The length of a furrow isn't more 100 m.

The performed work has a definite theoretical and practical significance for improvement of irrigation water use, soil-amelioration conditions of delta plain Syr-Darya, Shu and piedmont territories with weakly- and not completely developed soils.

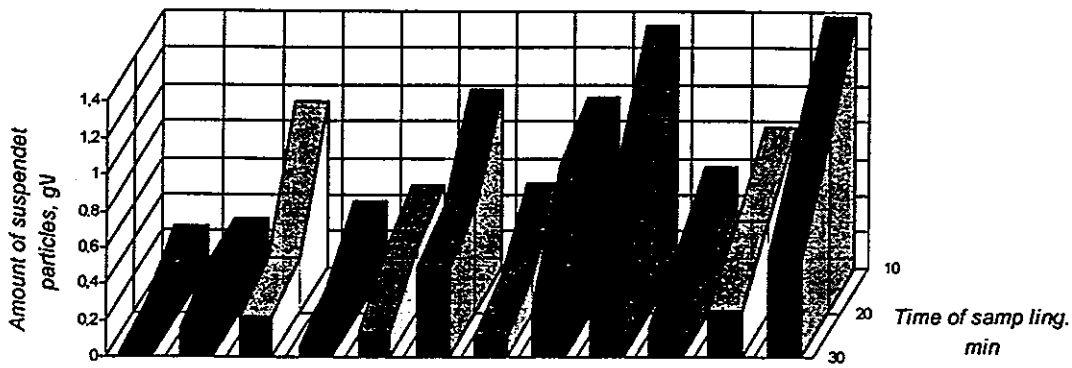
Reference

1. Alekhsandrova L.N. and et al. Laboratory-practical studies on soil science. "Kolos"Leningrad, 1967, p.152-154.
2. Akhanov J.U., Korobkin V.A. Regulation of water-salt regime in soils of Tas-Utkul massif. "Nauka"Alma-Ata, 1982. 200 p.
3. Akhanov J.U. Pecularities of soil formation processes in delta plains of the South Kazakhstan. Natural conditions and resources of deserts in the USSR, their rational use. Ylym Ashkhabad, 1984. P.183-191.
4. Akhanov J.U. Soil formation in delta plains of the South Kazakhstan. "Nauka"Alma-Ata, 1987.
5. Akhmedsafin U.M. Method for compiling of prognozing maps and observation of artesian basins of Kazakhstan. Alma-Ata, 1962.
6. Borovskiy V.M., Pogrebinskiy M.A. Ancient delta of SyDarya and northern Kyzylkums. Publishing house of AS KazSSR, Alma-Ata 1958, T.1.
7. Borovskiy V.M. Investigation of Chiili oasis. Vestnik AS KazSSR. 1956, N1.
8. Borovskiy V.M. New method in rice agrotechnique. Publishing house of AS KazSSR. Alma-Ata 1950.
9. Borovskiy V.M. Geochemistry of saline soils in Kazakhstan. Moscow "Nauka"1978.
10. Borovskiy V.M. Formation of saline soils and galogeochemical provinces of Kazakhstan. "Nauka"Alma-Ata 1982.

11. Dolgov S.I. Investigation of soil moisture mobility and it's availability to plants. Moscow. Publishing house of AS SSSR. 1948. 20 p.
12. Egorichev G.A. Transformation of soil cover of Chiili oasis under the influence of irrigation. In: Ecologo-geographic and amelioration soil investigations in Kazakhstan. Publishing house of AS KazSSR. Alma-Ata, 1961. P.189-204.
13. Egorichev G.A. Transformation of soil-ameliorative conditions of Chiili oasis under the influence of irrigation. Synopsis of thesis. Alma-Ata, 1962.
14. Egorov V.V. Soil formation under irrigative amelioration in delta of Aralo-Caspian lowland. Publishing house of AS SSSR. Moscow, 1959.
15. Zhapbasbaev M. Agroclimatic conditions of rice growing in Kazakhstan and microclimate of rice field. Synopsis of thesis. Leningrad, 1965.
16. Kovda V.A. Land aridization and control for drought. Moscow. Nauka, 1977.
17. Kovda V.A. Soil cover, it's improvement, use and protection. Moscow. Nauka, 1981.
18. Mozhaitseva N.P. The role of vegetation in some soil processes of Syr-Darya delta. Synopsis od thesis, Alma-Ata, 1973.
19. Mikhailov V.D. New abilities for moisture conservation in soil. Jornal • griculture of Uzbekistan", 1961. N1, p.89-90.
20. Noskova L/V. Soils of the South-East part of Kzyl-Orda oblast. Synopsis of thesis. Khazan, 1964.
21. Rubtsov N.I. Vegetation cover of Kazakhstan. Essays on physical geography of Kazakhstan. Alma-Ata, 1952.
22. Ryzhov S.N., Bogomolov V.Z. Evaporation from structural and dispersed soil. Jornal "Pochvovedeniye", 1934, N1, p.61-72.
23. Eshanov I.E. Influence of polimer conditioners on soil fertility and yieldimg ability of cotton. Jornal "Chemistry in agriculture". N9. p.69-73.

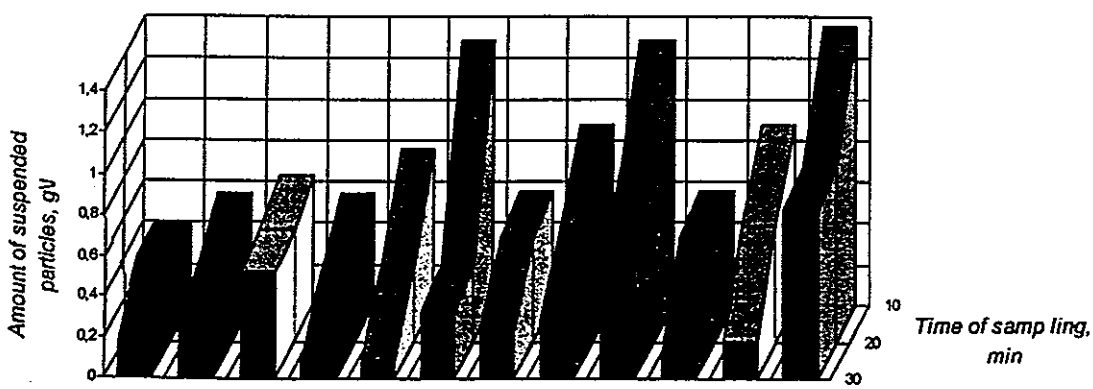


Reture 1. Intensitu of erosion irrigation
(furrow lergth - 100 m)



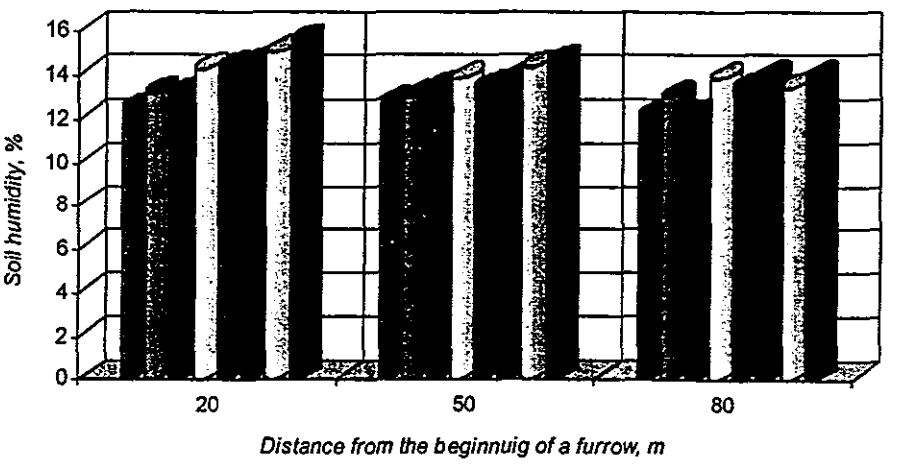
Surge flow 30 l/min 10 m	Surge flow 30 l/min 50 m	Surge flow 30 l/min 90 m
Surge flow 50 l/min 10 m	Surge flow 50 l/min 50 m	Surge flow 50 l/min 90 m
Constant flow 30 l/min 10 m	Constant flow 30 l/min 50 m	Constant flow 30 l/min 90 m
Constant flow 50 l/min 10 m	Constant flow 50 l/min 50 m	Constant flow 50 l/min 90 m

Reture 2. Intensitu of erosion irrigation
(furrow length-150 m)



Surge flow 30 l/min 10 m	Surge flow 30 l/min 75 m	Surge flow 30 l/min 140 m
Surge flow 30 l/min 10 m	Surge flow 50 l/min 75 m	Surge flow 50 l/min 140 m
Constant flow 30 l/min 10 m	Constant flow 30 l/min 75 m	Constant flow 30 l/min 140 m
Constant flow 50 l/min 10 m	Constant flow 50 l/min 75 m	Constant flow 50 l/min 140 m

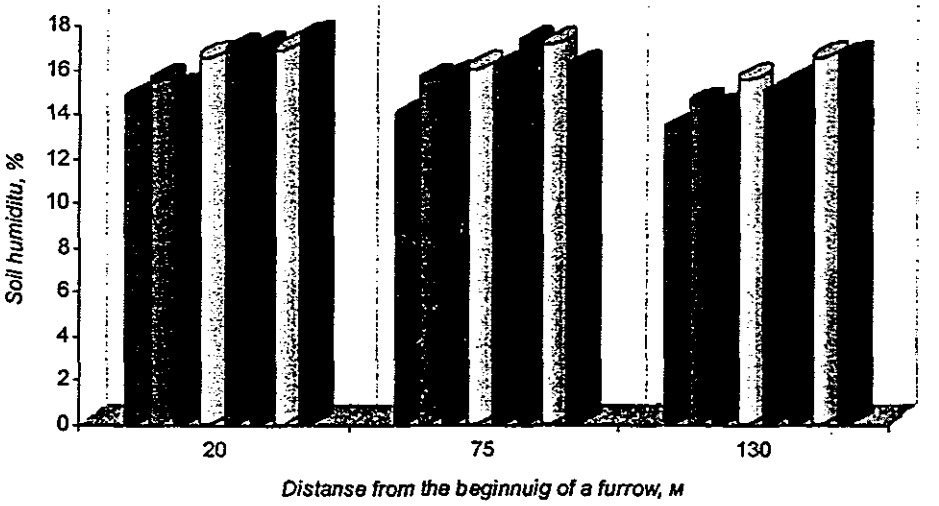
(furrow lergth - 100 m)



- Surge flow 30 l/min 0-10 cm
- Surge flow 50 l/min 0-10 cm
- Surge flow 30 l/min 10-20 cm
- Surge flow 50 l/min 10-20 cm
- Constant flow 30 l/min 0-10 cm
- Constant flow 50 l/min 0-10 cm
- Constant flow 30 l/min 10-20 cm
- Constant flow 50 l/min 10-20 cm

Reture 4. Soil humiditu ufter irrigation

(furrow lergth - 150 m)



- Surge flow 30 l/min 0-10 cm
- Surge flow 50 l/min 0-10 cm
- Surge flow 30 l/min 10-20 cm
- Surge flow 50 l/min 10-20 cm
- Constant flow 30 l/min 0-10 cm
- Constant flow 50 l/min 0-10 cm
- Constant flow 30 l/min 10-20 cm
- Constant flow 50 l/min 10-20 cm

Appendix E

Effect of surge irrigation and PAM on furrow erosion, infiltration rate (IR) and uniformity of water distribution

I. Shainberg and G.J. Levy

Introduction

Surge irrigation is the intermittent application of surface irrigation water. Under some conditions, the technique reduces the application time and volume required to advance flow across the field surface and thus improves irrigation water distribution uniformity.

The reduced advanced times are the result of reduced infiltration rates. teh most often cited mechanism for reduced soil permeability is the the consolidation of the wetted soil during flow interuption due to increased soil water tension (Trout and Kemper, 1983; Kemper et al., 1988).

Kemper et al. (1988) proposed that intermittent flow can increase aggregate breakdown and sediment erosion and deposition, thus the formation of depositional surface seals. When sediments are present in furrow water the IR is reduced by 50%(compared with water of no sediments)

Polyacrylamide (PAM) at concentration of 10 g/m3 in irrigation water was demonstrated to prevent furrow erosion and to increase IR (Lentz et al., 1992). Thus the objectives of this study are:

1. To study the effect of surge irrigation on furrow erosion and infiltration rates.
2. To study the effect of PAM on furrow erosion and IR.
3. To study the interaction between surge irrigation and PAM in their effects on erosion and IR.
4. To study the effects of the above treatments on irrigation water distribution uniformity.

It is hypothesized that:

1. Consolidation and aging of furrow surfaces during the off periods in surge irrigation reduces furrow erosion.Surge irrigation willl be as effective as PAM in preventing furrow erosion. and therefore more economically.
2. Consolidation of the depositional crust that is formed in the first surge is very effective in reducing IR; thus surge irrigation is effective in decreasing IR.
3. PAM, being effective in preventing furrow erosion and depositional crust formation will be effective in maintaining high IR.
4. Surge irrigation in PAM treatment will be effective in consolidation of soil surface and reducing IR. However, the effect of surge irrigation in PAM treatments will not be as effective as in conventional treatment (i.e., without

Procedure

1. Effect of surge flow on furrow erosion and intake rate.

A. Continous irrigation (Control). 0.5 l/sec.

a. Furrows of 200 m long. Water is applied at inflow rate of 30 L/min. Measure the time (Tc) for water to reach the end of the furrow.

b. Continue the flow at 30 L/min for additional 30 min, and take samples of water with sediments fom the furrows at distances of 20, 100 and 180 m. dry the water samples to measure sediment concentration. Repeat the measurement of sediment concentration (at the 3 locations) at 10, 20, and 30 min after the water reached the end of the furrow.

c. After measuring sediment concentration, reduce inflow to 15 L/min and continuous irrigation for 5 h. Measure inflow and outflow rates during these 5 h at 20 min intervals. Calculate the change in average IR with time and the total volume of water that infiltrated the furrows.

d. Repeat the above measurements in 5 furrows.

e. When irrigation is completed measure the water content in the profile (to the depth 150 cm) along the furrows at 10 , 100 and 180 m. Determine the unifomity of water distribution in the field.

B. Surge irrigation

a. Divide the time it took for continuous water flow (30 L/min) to reach the end of the furrow (Tc) into 4 equal time intervals (Tc/4). Apply surge irigation of Tc/4 ON, and Tc/4 OFF with inflow rate of 30 L/min until the surges reach the end of the furrow. Record the ON time it took to wet the entire furrow.

When the water reaches the end of the furrow continue with continuous flow of 30 L/min for additional 30 min and repeat steps "b" through "e" in the continuous flow procedure.

2. Effect of PAM on furrow erosion and IR.

A. Continuous irrigation

Mix PAM, 10 g/m3, with the irrigation water and follow step "a" in 1A, but the PAM is mixed with the irrigation water only until the entire furrow is wetted (i.e., the advancement stage is completed). Record the advancement time (Tcp). Then continue with steps "b" through "e" in 1A, using PAM-free irrigation water.

B. Surge flow with PAM application.

The same as 1B - surge irrigation in conventional water except that PAM in concentration of 10 g/m3 is mixed with irrigation water during the surges (i.e., the advancement stage) using Tcp/4 time intervals for the ON and OFF periods.