Control with anionic polyacrylamide of runoff and erosion induced by irrigation on Alentejo soils: surface and sprinkler irrigation (center pivot)

Controlo do escorrimento e da erosão em solos do Alentejo com poliacrilamidas aniónicas: rega de superfície e por aspersão (rampas rotativas)

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ABSTRACT

Most of the Mediterranean soils in Southern Portugal, now being converted to irrigation, were under rain-fed agriculture, in areas of sensitive soils, eroded or with high potential for erosion. The particular characteristic of these soils is its rapidly permeable A-horizon overlaying a B-horizon of very low permeability. Such fact leads to low infiltration of the applied irrigation water and, consequently high limitations to irrigation. Therefore for these soils to be under irrigation it is important to adopt soil and water conservation practices and correctly manage the irrigation systems, hoping that these practices will favour agriculture yields and preserve the environment by reducing runoff, preventing soil loss and enhancing the infiltration of applied water. One of the strategies that can be used to achieve such goals and also help to improve the soil physical properties is the use of soil conditioners, particularly the anionic polyacrylamide (PAM). Encouraging results have been obtained in the irrigated soils of Southern Portugal with their use being able to stabilize soil surface structure and curb irrigation-induced erosion in surface irrigation as well as in sprinkler irrigated fields. Since 1997, studies of anionic polyacrylamide (PAM) application have been conducted on field experiments, under surface irrigation and on contour and slopping furrows, and also with pressurized irrigation (center pivot and sprinkler simulators), as well as in more controlled laboratory studies, to test the PAM usefulness in controlling erosion and enhancing infiltration of irrigated soils. Several methodologies of applying PAM have been tested (direct application to the soil surface, in water suspension and later applied to furrows and pressurized systems through the irrigation water, and in multiple and/or single applications) as well as several application rates and timing. The results have been conclusive and in most of the studied soils PAM application has been positive in reducing runoff and sediment loss, enhancing also infiltration rates. The paper summarizes these studies, presents

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the state of the art, the methodologies used and the main results and conclusions.

RESUMO

Os solos Mediterrâneos do sul de Portugal encontram-se na sua maioria sob agricultura de sequeiro, que circunscreve zonas de solos sensíveis, erodidos ou com um elevado potencial para a erosão. A principal característica destes solos é possuir um horizonte A de rápida permeabilidade seguido de um horizonte B de muito baixa permeabilidade. Este facto, induz a baixa infiltração da água de rega e, consequentemente, a elevadas limitações para a rega. Assim, para estes solos serem regados é importante que sejam adoptadas práticas de conservação do solo e da água, bem como a adequação do sistema de rega e sua correcta gestão. Estas práticas conservativas ajudam na obtenção de bons níveis de produtividade na agricultura e na preservação do ambiente, através da redução do escorrimento, da prevenção da perda de solo e no aumento da infiltração. Para tal, uma das estratégias que pode ser usada é a aplicação de condicionadores de solo que ajudam na melhoria das propriedades físicas, em particular as poliacrilamidas aniónicas (PAM). Têm-se obtido resultados bastante satisfatórios nos solos regados do Alentejo na estabilização da estrutura da superfície do solo e no controlo da erosão induzida pelas regas, quer de superfície, quer por rampas rotativas (center-pivot). Desde 1997 que são desenvolvidos estudos de aplicação de poliacrilamida aniónica (PAM) na rega de superfície, em terraços de contorno e em sulcos declivosos, bem como na rega por aspersão e ensaios em laboratório. Foram testadas várias metodologias de aplicação do condicionador (aplicação directa no solo, dissolução na água de rega e posterior aplicação em sulcos de rega e em sistemas sobre pressão, aplicações únicas e fraccionadas) bem como, variadas dosagens. Os resultados obtidos têm sido conclusivos quanto ao efeito benéfico da aplicação das PAM, mostrando reduções do escorrimento e da perda de solo e aumentos na infiltração. Esses estudos são resumidos neste trabalho, sendo também apresentado um estado da arte, as metodologias usadas e os principais resultados e conclusões.

INTRODUCTION

Irrigated crop production is critical to global agricultural output. The total irrigated cropland accounts for only 18% of the total Earth's cropland and surface irrigation, mostly furrow irrigation, accounts for 60% of this area (Sojka *et al.* 1996). Most of the irrigated agriculture is done in highly erodible soils. In Portugal, according to Raposo (1996), 85% of the 720 000 irrigated hectares are under surface irrigation, primarily furrow-irrigated (that represents 74% of the total irrigated area). Ideally, runoff should not occur from properly designed and managed furrow and sprinkler irrigation systems. However in non-uniform slopes, characteristic of the irrigated landscape in southern Portugal, where center pivot irrigation systems dominate, the water is applied faster than it can infiltrate, often causing runoff and non-uniform irrigation (Santos *et al.*, 2001a).

Another way of controlling irrigation-induced erosion is the use of soil conditioners that enhance soil physical structure, diminishing their susceptibility to erode. Anionic polyacrylamide with high molecular weight and negative charged has been advocated as a valid soil conditioner to use in irrigation, in complement of other conservation practices. It is used mainly in two forms: dry or granular and as an oil emulsion, being this form the ideal to inject in sprinkler irrigation. According to Sojka & Lentz (1996), treatment of the irrigation water with polyacrylamide may be the fastest growing conservation technology in irrigated agriculture in the USA. Environmental and safety concerns of applying anionic PAM to the irrigation water have been thoroughly reviewed by several authors. For furrow irrigation, polyacrilamide applications are recommended in the first irrigation and in small amounts such as 1 or 2 kg ha^{-1} mixed with irrigation water (Sojka *et al.*, 1998). The PAM effects on reducing seal formation and improving soil permeability of furrow irrigation were studied by several authors, namely Lentz & Sojka, 1994; Santos & Serralheiro (2000), whose data show that polyacrylamide is highly efficient in stabilizing soil structure, reducing crusting and soil seal of furrow irrigated soils. "Water-soluble" polyacrylamide, made up of many repeating subunits, binds to clay particles through divalent calcium or sodium present in the irrigation water and helps stabilize soil aggregates (through a network formation) or binds soil particles detached by the irrigation stream.

The effects of PAM application to soil through irrigation water via sprinkler droplets have been studied in laboratories, using rainfall simulators, with few field studies reporting on the phenomena. In large soil box laboratory studies, single application of PAM at a rate of 2 kg ha^{-1} to an Idaho coarse silty soil reduced runoff 70% compared to control (Aase *et al.*, 1998). Reducing runoff also reduced soil loss by 75% compared to control. Similarly, Bjorneberg & Aase (2000) reported for the same soil and laboratory experiments that applying PAM at a rate of 3 kg ha^{-1} in a single irrigation reduced cumulative soil loss by 60% compared to control, but applying PAM at the same rate in three consecutive irrigations reduced cumulative soil loss by 80%. They concluded that both single and multiple PAM applications reduced runoff and soil loss, with multiple applications effectively controlling runoff longer than the single application. The effectiveness of sprinkler-applied polyacrylamide is less evident and more variable than in furrow irrigation because of spatial variations in water drop energy (in the extremities of center-pivots, for example, the intensity of water application can be as high as 100 mm h^{-1}), rate of water application, PAM application efficiency, and water/PAM application timing scenarios inherent to sprinkler systems (Aase *et al.*, 1998).

Since 1997, experimental field and laboratory work with anionic polyacrylamide (PAM) have been conducted with the aim of associating the use of "water-soluble" PAM with other conservation practices, to improve soil characteristics under irrigation and reduce its susceptibility to erosion. In general, studies comparing sloping and contour furrows (orientation of furrows following contour lines in angles such that maximum slopes are avoided), and the effects of water-added polyacrylamide on erosion and infiltration control of highly erodible Luvisols (Mediterranean soil) are described by Santos & Serralheiro (2000) and Martins *et al.* (2000). Application of PAM in sprinkler irrigation were studied and documented by Santos *et al.* (2001a) and Bjorneberg *et al.* (2003). Laboratory tests to assess the degree of effectiveness of polyacrylamide on promoting aggregate stability, flocculation and infiltration rates of several Mediterranean soil-units were documented by Santos *et al.* (2001b). Key aspects and conclusions of this work to preserve the irrigated Mediterranean soils in Southern Portugal are revisited here and presented below.

MATERIALS AND METHODS

Surface Irrigation

The polyacrylamide applied to irrigation water was a dry granular form with high molecular weight, manufactured and marketed under the trade name of Superfloc A836 by Cytec Industries. The experimental fields were prepared in 3 plots of different slopes and irrigation inflows, and different methods of PAM application were also used. Furrows were selected and monitored, having PAM as a treatment and also a control, without PAM application. Irrigation and runoff times were monitored on all furrows, and runoff volumes were also measured every 20 min, using calibrated V-notch flumes. One-litre runoff samples were collected every 20 min during each irrigation event, and the settled volume per litter of sediment collected in the Imhoff cones were evaluated and measured. The weight of sediment per litter of runoff was obtained from the settled volume of sediment in the cone, according to the methodology proposed by Sojka *et al.* (1992). To collect infiltration data net furrow infiltration was obtained from differences between inflow and runoff volumes.

PAM was applied on experimental fields with slopping furrows that were organised and prepared, as follows:

Plot A – slopping furrows organised with slopes of 1.4% and 140 m in length. The total application depth was 102 l m^{-1}. PAM was applied only on the advancing phase of the irrigation event (1997) at a rate of 10 ppm (1 kg ha^{-1}).

Plot B – slopping furrows organised with slopes of 2% and 140 m in length. In this plot different methods of PAM application were tested, as presented in Table 1.

The field (plot C) was organised in contour, with furrows placed in uniform slopes of 0.2% and 180 to 300 m of length. The total intake depths of 102 l m^{-1} were also used. PAM application rates of 10 ppm (1 kg ha^{-1}) were applied as follows: year 1997- during the entire irrigation period (1997) and only in the first irrigation; year 1999- only during the advance time that water takes to get to the end of the furrow. Re-application of PAM in some furrows was done in the 22nd irrigation.

Sprinkler Irrigation

The polyacrylamide applied with the irrigation water was a dry granular and an oil emulsion form with high molecular weight, marketed under the trade name Superfloc A836 and Superfloc A-1883 RS, respectively, by Cytec Industries Inc. The dry granular was dissolved with water, to constitute a solution stock used *a posteriori* to spray the dry soil surface, or to inject into the main line of a center pivot. Similar procedure was done with the oil emulsion form that was injected, as is, by a small pump and into the main line of the center pivot (2000-2004) and a sprinkler simulator (2001-2004) used in the laboratory tests. The experimental field tests were done under corn, to test different methods and amounts of PAM application. Small rectangular erosion plots of 2.56 by 1.0 m were installed in the experimental fields, with one of the two smaller sides of the rectangle in a V shape to collect runoff and deliver it trough a plastic tube to a recipient container. A similar device, a small ring of

TABLE 1 - **Methods of applying PAM in Plot B**

Method	Application	PAM rate (kg ha^{-1})	Inflow rate (l m^{-1})	Number of application
PAM 1	Advance time of irrigation	1	30	1st irrigation
PAM 2	Advancing (1st hour) and 3rd hour	1	30	1st irrigation
PAM 2^{A}	Advance time of irrigation	1	30	1st and 5th irrigation
PAM 3	Advance time of irrigation	1	30	Every irrigation

470 mm in diameter, hammered into the soil to a depth of 100 mm and connected by a small hole of 7.5 mm to a recipient container by a small plastic tube, was also used to collect runoff. The study of polyacrylamide effects on infiltration and sediment loss under the sprinkler irrigation systems was done by delimiting areas irrigated with PAM plus irrigation water and areas in the field irrigated only with water, without PAM treatment. Both areas had the small rectangular erosion plots and rings to collect runoff volumes and sediment losses.

The objective of the center pivot field experiments was to test if PAM-treatment would increase aggregate stability, help to reduce runoff and erosion, and enhance infiltration. Experiments were carried out in 1999 on two Dystric Fluvisols with high sand and silt content in the upper horizons of the profile, and in 2000 in a Haplic Luvisol, a Mediterranean soil with an A-horizon with low aggregate stability. In the 1999 experiment, two PAM treatments were carried out on both soils: in treatment I the application of PAM was studied at a rate of 10 mg l^{-1} sprayed to dry soil surface prior to irrigation; treatment II was used as control. A total of 23 irrigations were monitored. The collected runoff was weighted and later filtered to determine sediment loss. To study infiltration, data was collected and the infiltration calculated by difference between the volume of water applied and the collected runoff. In 2000 experiment, two treatments were also tested: treatment I applied PAM at a rate of 10 mg l^{-1} delivered to the main line of the pivot and to the soil with the first irrigation water, by injection with a small pump; and treatment II was used as control. A total of 21 irrigation events were monitored. The collected runoff was quantified and sediment loss was measured using Imhoff cones.

To define whether single or multiple applications of PAM would improve infiltration and better control erosion under field conditions, tests were conducted in 2001 on the same Dystric Fluvisols (A1 and A2) as in 1999, on fields irrigated with center pivot on uniform slopes of less than 1%. The three studied treatments were: control, single PAM applications (in the first irrigation event) and multiple PAM applications (in the three first consecutive irrigation events) at the rate shown in Table 2, using an oil emulsion (Superfloc A-1883 RS from Cytec Industries Inc.) injected into the main line of the center pivot. PAM injection was stopped after the pivot travelled to pass the PAM plots.

TABLE 2 - **PAM application rates (kg ha^{-1} active ingredient) for field studies in Fluvisols dystric (2001)**

Irrigation	Single	Multiple
1	0.3	0.1
2	0.0	0.1
3	0.0	0.1
Total	0.3	0.3

Laboratory tests

To evaluate the degree of effectiveness of polyacrylamide on promoting aggregate stability, flocculation and infiltration rates on the soils, laboratory tests were also conducted on several Mediterranean soil-units that are classified in Table 3. Equipment and procedures used during these tests were the wet sieving technique and the sedimentation rate, similar to those described by Roa-Espinosa (1996).

TABLE 3 - **Soil classification of the 10 soil families used in the laboratory sprinkler simulator tests**

Portuguese soil classification	International (FAO) soil classification
Bvc	Vertisol calcic
Bpc	Vertisol calcic
Bp	Vertisol eutric
Cb	Vertisol eutric
Pmg	Luvisol
A1	Dystric Fluvisol
A2	Dystric Fluvisol
Pg	Dystric Cambisol
Ppg	Dystric Cambisol
Vt	Dystric Cambisol

FAO, Food and Agriculture Organisation.

RESULTS AND DISCUSSION

Surface Irrigation

Table 4 shows sediment loss data collected from the first four irrigation carried on plot C (contour furrows) and plot A (slopping furrows) with no PAM treatment (control furrows). Comparing the sediment loss values it is conspicuous that slope is a very important factor inducing erosion in surface irrigation. Field plot organised on contour (plot C) helped to halt erosion, with reductions on average of 96%. The first irrigation is very erosive, with severe soil losses in the slopping furrows of more than 15 tons.

TABLE 4 - **Soil loss (kg ha^{-1}) on tail end of the contour and slopping furrows, with no PAM applied**

Irrigation No.	Contour furrows (plot C)	Slopping furrows (plot A)	Reduction (%)
1	377.42	15 931.72	97.6
2	229.01	8 196.40	97.1
3	161.48	2 458.90	93.4
4	222.60	*	*
Total	990.51	26 587.02	96.3

* Values unavailable

The influence of PAM and its number of applications on soil loss is shown in Table 5. In general, the use of polyacrylamide in irrigation water of slopping furrows considerably reduced soil loss. In the first irrigation, sediment loss for untreated plot (control) is significantly higher than in those treated with PAM.

TABLE 5 - **Soil loss (kg ha^{-1}) on tail end of the slopping furrows where PAM was applied (1999)**

Irrigation Number	Control	PAM1	Reduction (%)	PAM2A	Reduction (%)	PAM3	Reduction (%)
1	301.3	29.0	90.4	32.9	89.1	35.0	88.4
2	270.6	84.1	68.9	73.9	72.7	34.2	87.4
3	238.2	108.4	54.5	100.7	57.7	34.2	85.7
4	224.1	149.0	33.5	150.7	32.8	33.3	85.1
5	253.5	201.5	20.5	34.6	86.4	32.5	87.2
6	231.1	233.1	-0.9	115.7	49.9	35.4	84.7
7	247.6	257.4	-4.0	163.9	33.8	38.9	84.3
8	235.6	271.5	-15.2	190.0	19.4	39.3	83.3
Total	2 002.0	1 334.0	33.4	862.4	56.9	282.8	85.9

TABLE 6 - **Soil loss (kg ha^{-1}) measured on tail end of the contour furrows**

Irrigation	Control	PAM		Reduction (%)	
			1997		
1	377.42	49.72		86.8	
2	229.01	46.79		79.6	
3	161.48	32.98		79.6	
4	222.6	34.19		84.6	
Total	990.51	163.68		83.5	
			1999		
Irrigation	Control	PAM1	Reduction (%)	PAM2	Reduction (%)
1	38.42	0.00	100.0	0.00	100.0
2	32.02	3.84	88.0	4.69	85.3
3	28.17	8.53	69.7	13.66	51.5
22	18.35	15.37	16.3	2.99	83.7
Total	116.96	27.74	76.3	21.34	81.8

Concerning PAM application strategies, the best one in this case of slopping furrows is its application in all irrigations. The application of PAM in the treatment PAM2A (during 1st and 5th irrigation) revealed inadequate in halting erosion since loss curbing with the two treatments were not obtained for the remaining of the season, as obtained with treatment PAM3 (application in every irrigation). The fact confirms the influence of slope on soil loss, and it is highly recommended that PAM be applied with the first irrigation of the season that proved to be the most erosive. The use of PAM applied with treatment 2A would probably be adequate in more moderate slopes. Despite the soil loss reduction obtained with contour furrows, shown in Table 4, that curbed soil loss to as much as 96 % when compared with slopping furrows, the use of PAM still had a remarkable influence on the tail end soil loss on contour furrows, as shown in Table 6.

The use of PAM induced average soil loss reductions of 84%. The fact suggests that the use of polyacrylamide should be adopted even with contour furrows that are also designed to protect soil from erosion. Application of PAM should be done only during the advance phase of the first irrigation.

Concerning infiltration, data gathered on the monitored fields - contour and slopping furrows - in the 1997 experiments are presented in Table 7 and 8, where significant differences and high variability among tests within the same treatment were observed.

TABLE 7 - **Average intake rates and cumulative infiltration for four monitored polyacrylamide (PAM) treated and control irrigation on contour furrows**

Monitored	**Infiltration rate**			**Cumulative infiltration**		
Irrigation	*Control*	*PAM-treated*	*Increase*	*Control*	*PAM-treated*	*Increase*
	l/m min	*l/m min*	*%*	*l/m*	*l/m*	*%*
1st	0.51	0.59	13.3	46.0	78.8	41.6
2nd	0.27	0.34	20.5	31.9	43.8	27.2
3rd	0.16	0.33	52.7	36.3	43.8	16.9
4th	0.11	0.24	52.7	12.8	31.8	59.7

TABLE 8 - **Average intake rates and cumulative infiltration for four monitored polyacrylamide (PAM) treated and control irrigation on slopping furrows**

Monitored Irrigation	**Infiltration rate**			**Cumulative infiltration**		
	Control l/m min	*PAM-treated l/m min*	*Increase %*	*Control l/m*	*PAM-treated l/m*	*Increase %*
1st	0.05	0.17	70.6	4.0	20.4	80.3
2nd	0.13	0.31	58.0	7.4	50.0	85.2
3rd	0.05	0.24	79.2	3.4	11.3	70.0

As shown in Table 7, for PAM treated furrows intake rates and cumulative infiltration were higher than the control, and its benefits were more relevant after the second irrigation. These facts can be explained by the higher stability of the wetted perimeter and reductions in seal formation induced by PAM use.

The average infiltration rates and cumulative infiltration of the tests carried out in slopping furrows show significant differences between PAM treated furrows and control. PAM effects were noticed since the first irrigation, with percent increases of 58-85%, probably due to furrow shape stability throughout irrigations, greater lateral flow and less seal formation.

Sprinkler Irrigation

The Dystric Fluvisols (soil A1 and A2) experimental field tests carried out in 1999 with a center pivot and data gathered from the 23 monitored irrigation events show that it is significant the influence of PAM in controlling sediment losses throughout the irrigation period. Figure 1 shows sediment loss per unit area on both Fluvisols (soil A1 and A2).

Soil loss for Fluvisol A1 increases in the control treatment after the first irrigation, remaining relatively high until the 10th irrigation and progressively decreases with time. Within the first 10 irrigations sediment loss considerably varied with each irrigation event, particularly in the control treatment. The largest reductions in sediment losses, with values between 84 to 100%, occurred where PAM was applied. Effectively, for the 23 monitored irrigations an average total of 2285.9 kg ha^{-1} of sediment lost from PAM treated soil in contrast to the 8614.1 kg ha^{-1} from the control treatments. For Fluvisol A2, the amounts of sediment loss for each of the 23 monitored irrigation events indicate that the influence of polyacrylamide in preserving aggregate stability and controlling sediment losses per unit area of the fallow plots was quite notorious. As shown in Figure 1 an average total of 204.6 kg ha^{-1} sediment loss was observed in the PAM treated plots and 18106.3 kg ha^{-1} in the control ones, which represents a PAM reduction in soil loss of 98%.

Concerning infiltration, values obtained in the experimental field tests in 1997 are shown in figure 2 for the fallow plots. The average distribution and the amounts recorded per monitored irrigation are depicted.

Infiltration values in Fluvisol A1 are similar in the first irrigation event for both treatments. In all other monitored irrigations, PAM treated plots show better intake rates and enhanced infiltration. An average total of 241.4 mm infiltrated in contrast to the 162.8 mm infiltrated from

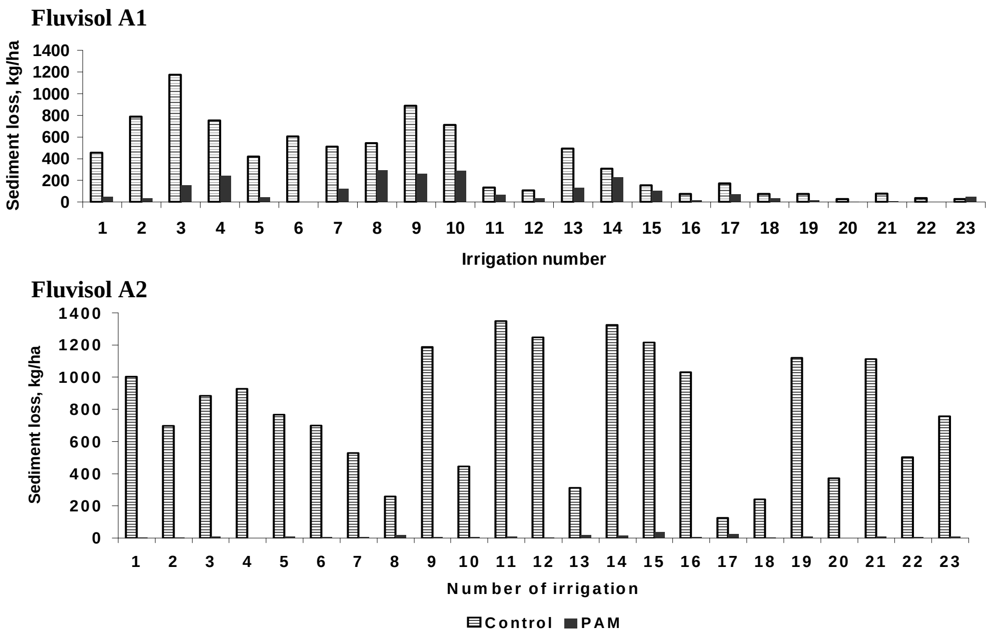

Figure 1 - Average sediment loss per unit area observed for each irrigation in fallow plots of Fluvisols (A1 and A2).

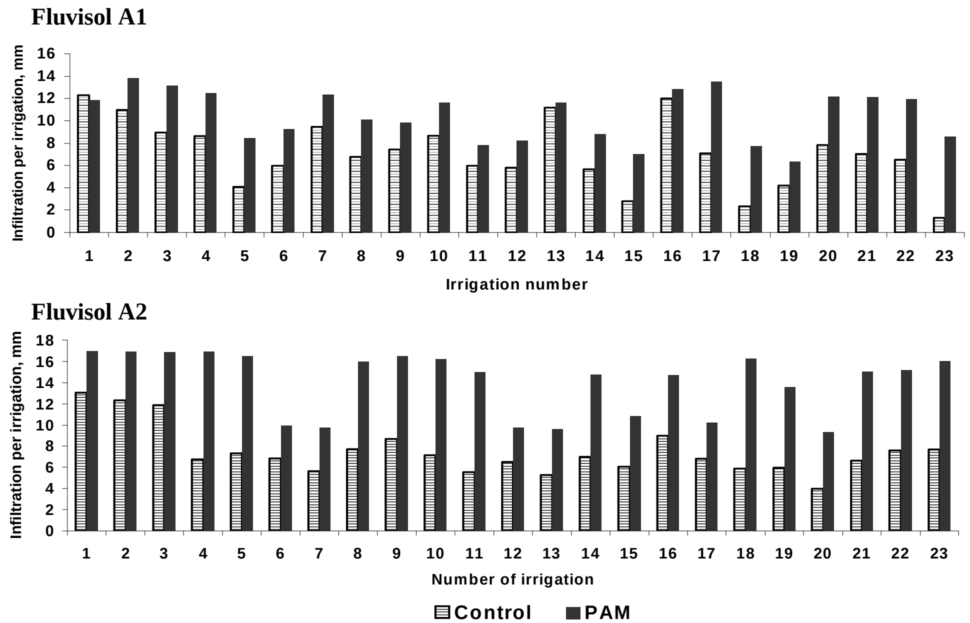

Figure 2 - Average infiltration observed per irrigation in the fallow plots of Fluvisol A1 and A2.

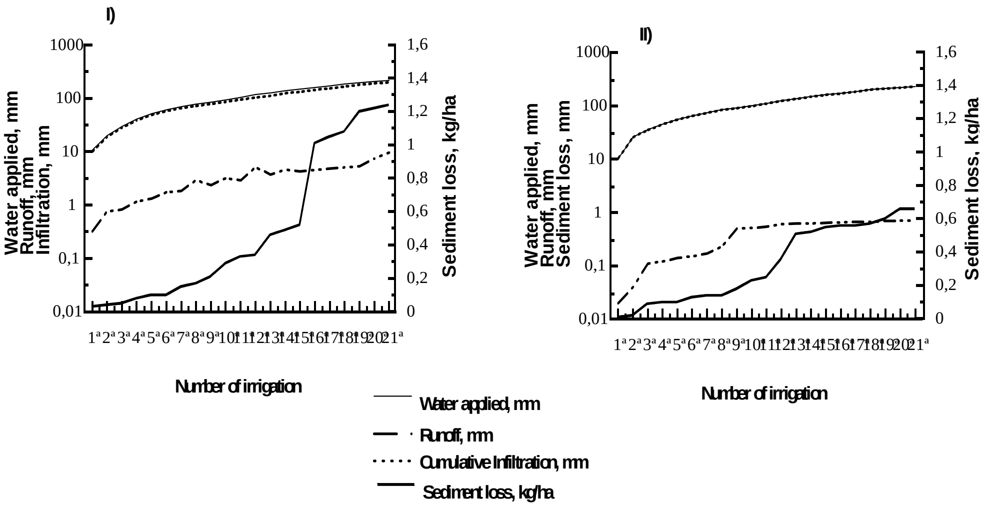

Figure 3 - Average cumulative water applied, runoff, infiltration and soil loss observed for control (I) and PAM applied (II) treatment plots of the fallow sub-treatment.

the control treatment, which represents a 34% PAM increase in infiltration. The Fluvisol A2 also revealed significant infiltration increment in the fallow plots treated with PAM. Those plots had developed less surface seal from irrigations, with consequently more unblocked pores available for infiltrate irrigation water. An average total of 322.7 mm infiltrated for the irrigation season in PAM treated plots, contrasting with the 171.1 mm of the control ones, representing a relative PAM increase in infiltration of 89%.

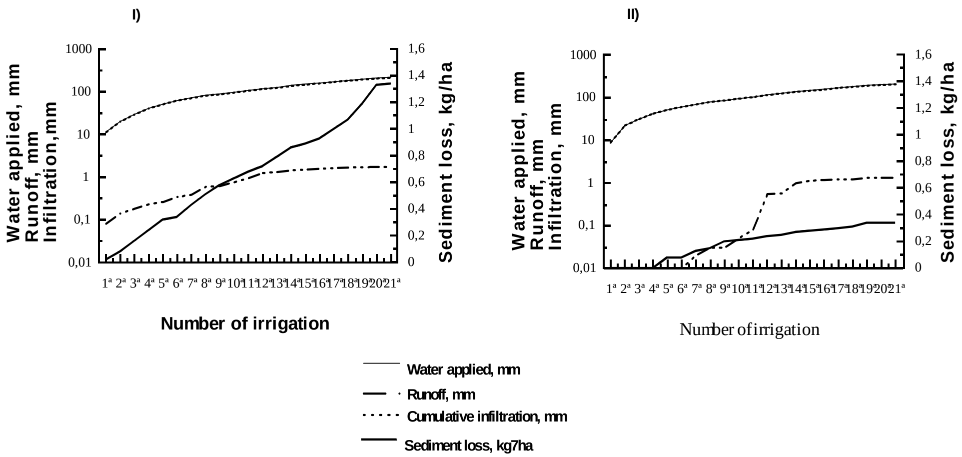

Figure 4 - Average cumulative water applied, runoff, infiltration and soil loss observed for control (I) and PAM applied (II) treatment plots of the corn growing sub-treatment

In the 2000 experimental field tests on a Haplic Fluvisol where 21 irrigations events were monitored in control and PAM treatments in fallow and corn growing plots, the amounts of sediments loss, runoff and infiltration rates were determined and presented in Figure 3 as occurred cumulative changes.

The single injection of PAM at a concentration of 10 mgl^{-1} into the center pivot main line during the first irrigation significantly reduced runoff and sediment losses from the fallow plots, totalling an average of 93% decrease in runoff, 15% increase in average cumulative infiltration and 46% reduction in sediment losses. For the corn growing plots, Figure 4 shows that PAM treatment had also an important impact on sediment loss, runoff and infiltration control.

Tests carried out in 2001 in a corn field irrigated with center pivot to study the strategy of applying PAM as a single application or as multiple applications of the same total amount are presented in Table 9.

TABLE 9 - **Measured runoff from silty-loam plots during 2001 growing season in Monte dos Alhos, Portugal (Table 2)**

Irrigation			Runoff			ANOVA
No.	**Date**	**Irrigation depth**	**Control**	**Single#**	**multiple***	**Probability**
		---------- mm ----------				
1	6/21/01	10	0.02	0.00	0.00	0.46
2	6/22/01	10	1.17	0.15	0.15	0.55
3	6/27/01	17	7.88 a	1.78 b	0.06 b	**<0.01**
8	7/10/01	23	13.57	3.76	10.25	0.16
10	7/17/01	23	13.68	7.42	13.26	0.19
12	7/24/01	23	13.77 a	3.24 b	13.43 a	**0.02**
14	7/31/01	23	13.74 a	9.61 b	13.87 a	**0.03**
15	8/2/01	23	12.45 a	5.57 b	2.22 b	**<0.01**
16	8/7/01	10	1.20	0.27	0.27	0.14
17	8/9/01	23	7.77	4.90	1.44	0.28
20	8/17/01	14	2.44	0.83	0.74	0.33
21	8/18/01	14	5.57 a	0.98 b	1.56 b	**0.05**
22	8/19/01	14	6.72 a	1.25 b	0.39 b	**0.04**
24	8/24/01	11.5	3.82	0.98	3.05	0.60
25	8/27/01	10	0.88	0.19	0.98	0.63
26	8/29/01	10	0.68	0.29	1.17	0.70
27	8/30/01	10	0.82	0.23	0.78	0.78
28	9/4/01	10	1.56	0.34	0.51	0.67
29	9/7/01	10	1.11	0.37	0.49	0.76
30	9/13/01	14	1.71	1.02	0.45	0.71
Total		291.0	110.58 a	43.18 b	65.06 c	**<0.01**

Applied a total of 1.0 kg PAM ha^{-1} with irrigation 1. * Applied 1.0 kg PAM ha^{-1} with irrigations 1-3. † Values in a row with similar letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

TABLE 10 - **Measured soil loss from silty-loam plots during 2001 growing season in Monte dos Alhos, Portugal**

Irrigation			Soil Loss			ANOVA
No.	Date	Irrigation depth	Control	Single#	Multiple*	Probability
		---------------------------- mm ----------------------------				
1	6/21/01	10	4.43	0.00	0.00	0.47
2	6/22/01	10	2.58	4.43	16.24	0.62
3	6/27/01	17	1.34	0.59	3.69	0.62
8	7/10/01	23	5.89	6.94	3.54	0.11
10	7/17/01	23	6.04 a	2.68 b	2.69 b	**0.01**
12	7/24/01	23	3.00	2.46	3.72	0.58
14	7/31/01	23	4.96	1.91	3.66	0.21
15	8/2/01	23	1.83	2.80	3.56	0.64
16	8/7/01	10	10.54	1.74	4.43	0.22
17	8/9/01	23	3.48	3.04	6.86	0.09
20	8/17/01	14	20.69	19.38	39.14	0.58
21	8/18/01	14	3.87	6.09	8.86	0.08
22	8/19/01	14	3.91	5.93	8.86	0.88
24	8/24/01	11.5	6.88	4.50	1.56	0.86
25	8/27/01	10	4.87	1.11	1.55	0.48
26	8/29/01	10	6.50	1.48	1.48	0.39
27	8/30/01	10	13.66	0.92	2.22	0.19
28	9/4/01	10	2.35	4.05	4.26	0.92
29	9/7/01	10	2.91a	19.67 b	3.10 a	**0.04**
30	9/13/01	14	3.16	6.00	3.37	0.73
Total		291.0	112.91	95.71	122.77	0.80

Applied a total of 1.0 kg PAM ha^{-1} with irrigation 1. * Applied 1.0 kg PAM ha^{-1} with irrigations 1-3. † Values in a row with similar letters are not significantly different based on LSD with P=0.05. Letters were not shown if ANOVA probability was >0.05.

According to the data shown, single PAM application had 67% less total runoff than the control treatment; the multiple PAM treatment had 41% less runoff the control. Comparing PAM treatments, the single application had 34% less runoff than the multiple treatments. Cumulative runoff for the irrigation season was 38%, 15% and 22% of the applied irrigation water for the control, single and multiple treatments, respectively. Concerning the soil losses, PAM treatments had little or no effect on measured soil loss from the silty loam plots. Among treatments only two out of the 20 irrigations were significantly different, as shown in Table 10.

Due to low amount of PAM applied with each multiple application the results presented in table 10 are not very conclusive and cannot be taken as final. Further tests should be done with multiple applications of PAM but at higher rates.

Laboratory Tests

Aggregate stability

Figure 5 shows the average percent difference in retention (aggregation) between control and PAM treated soils. The highest percent of retention occurred on 500 µm sieve opening. For the Vertisols, soil Bvc presented the highest difference between polymer application and control treatments, with a value of 23 percent, followed by the soils Bp (20%) and Cb (7%). It seems that the effect of PAM in promoting aggregation and stability is less evident, as silt and clay content increases in the upper horizon of soil profile. This finding seems to also hold for the Luvisols, where Pm and Pmg soils, with the highest values in sand content among the Luvisols, show the best performance for aggregation and stability increase under polymer application.

Sedimentation rate

Soils tested with the sedimentation method differ from one another in time and speed for aggregating the soil particles. Figure 6 shows for all settling times the percent difference concentration of particles obtained for the solution mix with polymer at a concentration of 10 mgl^{-1} and control treatments.

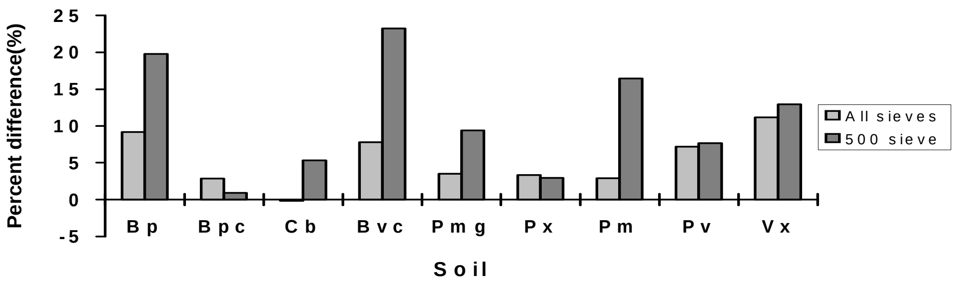

Figure 5 - Percent difference of Vertisols and Luvisols particles retained on all sieves of all size openings (500, 250 100 and 50 µm), and on 500 µm sieve, between PAM at concentration of 10 mgl^{-1} and control treatments.

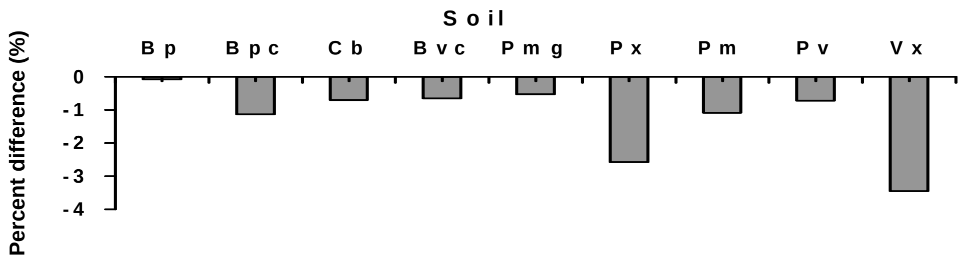

Figure 6 - Percent difference concentration of Vertisol and Luvisol particles obtained for all settling times between polymer solution application at a concentration of 10 mgl^{-1} and control treatments.

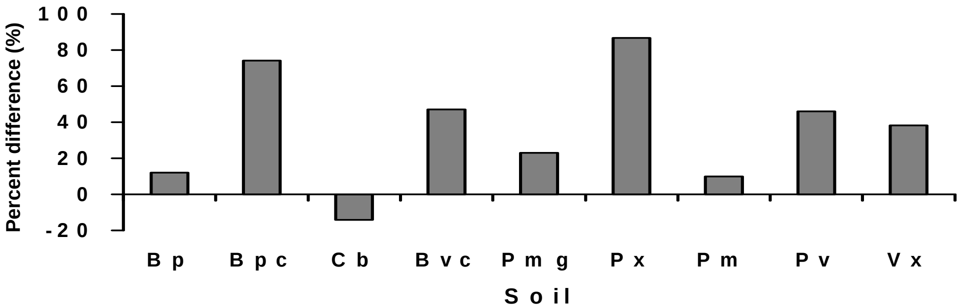

Figure 7 - Percent difference cumulative infiltration (mm) of Vertisol and Luvisol soils between polymer at a concentration of 10 mgl^{-1} and control treatments.

Infiltration

Figure 7 shows the percent difference values obtained between polymer application and control treatments. These results show that Vertisol Bpc soil has the highest cumulative infiltration response to polymer application, followed by soil Bvc. Figure 8 also suggests that the best responses to polymer are obtained for Luvisols, with polyacrylamide application at a concentration of 10 mg l^{-1} considerably increasing cumulative infiltration of Luvisols Px, Vx and Pv, soils who show low infiltration rates for the control treatments.

CONCLUSIONS

Surface Irrigation

Results of the three years study confirm that contour furrows are a valuable soil conservation technique under irrigation, responsible for sharp decline in soil loss and important infiltration increase. When compared to slopping furrows, the positive responses are more dramatic as slope increases. Polyacrylamide applications are, on their own right also an important instrument to counteract soil losses of furrow irrigated fields, even in the ones already under contour terraces. Adding PAM to irrigation water in a concentration of 10 mg l^{-1} on furrow irrigation produced highly visual results in the field, showing flowing and runoff water with a transparent or clear appearance. The recommended procedure is to apply PAM with the first irrigation and in the advance flow stream to preserve the pervious soil pore structure of the irrigated furrows. Further PAM applications are recommended as field slope increases. Observed cumulative infiltration increases are also considerably high with PAM applications, which add to the recommendation of using PAM in irrigated Mediterranean soils. Significant increases in infiltration were observed in both fields organisation, contour and slopping furrows, with percentages of 13-59% and 58-85%, respectively. Since slopping furrows are traditionally more susceptible to higher runoff and sediment losses due to the slope effect, the infiltration rates will be lower than in contour furrows were water tends to have more opportunity to infiltrate. Therefore, PAM treatment effects are more evident in sloping furrows than in contour furrows.

The increase in cumulative infiltration and hydraulic conductivity will allow for longer irrigation set times and higher inflow rates, enhancing actual management. As a consequence of PAM application, finer particles are less prone to desagregation by the inflow stream. When it happens, they are more readily flocculated by the presence of PAM in the flow stream. Both processes allow soil pores to stay unblocked by fine particles and the permeability of soil surface is better preserved.

Sprinkler Irrigation

PAM sprayed to the surface of Fluvisols effectively controlled sediment loss, erosion and infiltration, and also did so when applied to the soil through injection into the main line of center pivots. On the same soil, a single PAM application at the rate of 1 kg ha^{-1} was effective for at least 10 to 13 irrigations and proved to be beneficial throughout all monitored irrigations. In Luvisols the results of PAM application were less notorious than in Fluvisols, fact that might be due to soil clay content and to lesser amount of silt, which is known to induce dispersion and soil pore blockage. Current management of the center pivot systems in irrigated Fluvisols, with their high speed and short irrigation times to minimize runoff losses and increase efficiency, is time consuming, labour-intensive and non-economical, and the application of PAM at the first irrigation is probably a better management strategy to help preserve the initial soil conditions and to ensure that adequate crop water requirements are satisfied.

Some experimental field tests were however less conclusive concerning the best PAM application strategy to use with center pivot irrigated soils. However, applying PAM with multiple irrigations can result as good or better than applying the same amount of PAM with a single irrigation. Further tests are necessary to confirm such hypothesis. The application of PAM in multiple irrigations can reduce the chance of skips or poor coverage caused by application problems during a single irrigation.

Sprinkler irrigation simulation tests conducted in the laboratory showed that the intensive use of sprinklers in the rolling and fragile landscape may impose serious environmental risks to the irrigated soils. By controlling soil infiltration, runoff and sediment loss, small amounts of PAM seem to be able to moderate such risks in selected soils. Applying PAM with the first irrigation water and in a concentration of 10 mg l^{-1} minimised these shortcomings. Laboratory results also suggest that applications of polyacrylamide at a concentration of 10 mg l^{-1} to Bpc, Bvc, Px, Vx, Pv, Pmg and Pm soils can have a particularly beneficial effect on their conservation under irrigation, by maintaining and improving soil structure and allowing for higher infiltration capacity. This can translate into an increased aggregate resistance to disintegration and soil crust formation, reduction of erodibility, higher infiltration rates and longer soil moisture content retention in the soil profile for crop development.

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