Annual Meeting

NAICC

2002 *ANNUAL MEETING* in Albuquerque, New Mexico

Presentations: [*in progress*]

- The 4th OECD Consensus Workshop. Horley, U.K..June,2001
- NAICC 2002 Fred Rice, ABC Laboratories, Inc.
- Syngenta
- Syngenta posters ... [PDF; 3MB]
- Structuring Payments for Contract Research. The Carringers, Inc.
- Painting a New Tomorrow With DNA and Genetic Engineering Paint Brushes. DuPont Crop Protection
- 2002 NAICC Presidential Platform

2001 *ANNUAL MEETING*

Presentations:

- The use of PAM: a linear polyacrylamide for use in irrigation water
- Technology Farming - Randy, Bruce and Jerry Brightbill; Cotton Center, Texas
- Surprise, Surprise, Surprise!!
- ASSESSING THE SPATIAL REPRESENTATIVENESS OF AIR TEMPERATURE RECORDS
- Availability and Accessibility of Historical and Near-Real Time Weather Data
- ALABAMA & GEORGIA ASSOCIATION OF PROFESSIONAL AGRICULTURALCONSULTANTS ANNUAL MEETING
- Biotechnology: What lies ahead for Agriculture and Consultants
- Efficacy Data Uniformity
- EPA AND OECD
- Regulatory Update Cross-Media Electronic Reporting & Recordkeeping Rule

---

Proceedings from the Annual 2000 Meeting.

The use of PAM -- a linear polyacrylamide for use in irrigation water

R.E. Sojka[1]

[1]Soil Scientist, USDA-Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793N-3600E Kimberly, Idaho 83341, USA <sojka@kimberly.ars.pn.usbr.gov>

Abstract

This overview will be familiar to anyone who has visited the "PAM page" of the Northwest Irrigation and Soils Research Laboratory's web site. The reader is encouraged to visit that web site, <http://kimberly.ars.usda.gov/pampage.shtml>, for graphics and photos that were used in this NAICC presentation in Orlando in January, 2001, as well as for other more detailed technical information.

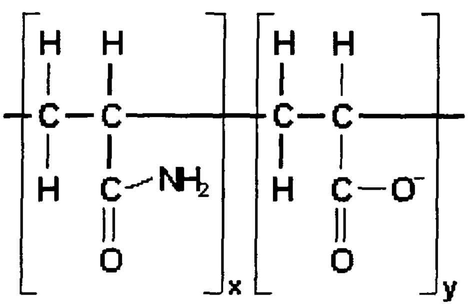
PAM has been sold in the United States since 1995 for reducing irrigation-induced erosion and enhancing infiltration. Its soil stabilizing and flocculating properties have also substantially improved runoff water quality by reducing sediments, N, ortho and total P, COD, pesticides, weed seeds, and microorganisms in runoff. The first series of practical field tests of PAM for irrigation erosion control was conducted in the U.S. in 1991. PAM used for erosion control is a large (12-15 megagrams per mole) water soluble (non-crosslinked) anionic molecule, containing <0.05% acrylamide monomer. In a series of field studies, PAM eliminated an average 94% (80-99% range) of sediment loss in field runoff from furrow irrigation, with 15-50% relative infiltration increases compared to untreated controls on medium to fine textured soils. Similar but less dramatic results have been seen with sprinkler irrigation. In sandy soils infiltration is often unchanged by PAM or can even be slightly reduced. Results are achieved with per irrigation field PAM application rates of about 1 kg ha-1 for furrow irrigation and about 4 kg ha-1 for sprinkler irrigation. Often only fractions of these rates are required on subsequent irrigations (if the ground has not been disturbed between irrigations) to maintain efficacy. Typical seasonal application totals vary from 3 to 7 kg per hectare. Farmer field sediment control has generally been about 80% or more of test plot results.

Research has shown no adverse effects on soil microbial populations. PAM effects on crop yields have only been sparsely documented. Initial studies, focused mostly on erosion and runoff water quality effects, conducted largely in field beans or maize, showed little effect on yields, probably because all treatments were supplied adequate water. Some evidence exists for PAM-related yield increases where infiltration was crop-limiting, especially in field portions having irregular slopes, where erosion prevention eliminated deep furrow cutting that deprives shallow roots of adequate water delivery. PAM's ability to increase lateral spread of water during infiltration is useful for early season water conservation. Only small amounts of water are needed to germinate seed or sustain small seedlings shortly after planting. Water conservation is accomplished by not needing to completely fill the soil profile because wetting patterns of PAM-treated furrows spread further laterally for a given volume of water applied. High effectiveness and low cost of PAM for erosion control and infiltration management, coupled with relative ease of application compared to traditional conservation measures, has resulted in rapid technology acceptance in the US, with about 400,000 ha of irrigated land currently employing PAM for erosion and/or infiltration management.

Water soluble anionic high-purity PAM is a safe environmentally friendly soil conditioner, that when delivered via irrigation, reduces erosion, prevents sediment and chemical and biological pollutants from entering runoff and greatly expands management options for all forms of irrigated agriculture because of its soil stabilizing effects and direct effects on water properties influencing field water management. PAM is economical, typically $4.50 to $12 per kilogram of active ingredient, effective at low rates (1 to 5 kg per hectare per season) and relatively easy to use.

Keywords. *Irrigation, Water quality, Erosion, Polymer, Pollution, Surface seal, Infiltration*

1 PAM Copolymer



PAM, Definition and Use: The term polyacrylamide and the acronym "PAM" are generic chemistry vocabulary, referring to a broad class of compounds. There are hundreds of specific PAM formulations, varying in polymer chain length and number and kinds of functional group substitutions. In erosion polyacrylamides, the PAM homopolymer is copolymerized. Some of the spliced chain segments replace PAM amide functional groups with groups containing sodium ions or protons. They freely dissociate in water, providing negative charge sites (fig. 1). Typically one in five chain segments provide a charged site in this manner. PAM formulations for irrigated agriculture are water soluble (linear, not gel-forming, not cross-linked super water absorbent) anionic polymers with typical molecular weights of 12 to 15 Mg mole-1 (over 150,000 monomer units per molecule). These PAMs are "off the shelf" industrial flocculent polymers used extensively to accelerate separation of solids from aqueous suspensions in sewage sludge dewatering, mining, paper manufacture, clarification of refined sugar and fruit juices and as a thickening agent in animal feed preparations.

Coulombic and Van der Waals forces attract soil particles to PAM (Orts et al., 1999, 2000). These surface attractions stabilize soil structure by enhancing particle cohesion, thus increasing resistance to shear-induced detachment and preventing transport in runoff. The few particles that detach, are quickly flocculated by PAM, settling them out of the transport stream. Minute amounts of Ca++ in the water shrink the electrical double layer surrounding soil particles and bridge the anionic surfaces of soil particles and PAM molecules, enabling flocculation (Wallace and Wallace, 1996).

Soil stabilizing polymers were used in World War II to aid road and runway construction (Wilson and Crisp, 1975). Uses were adapted for agriculture in the early 1950s (Weeks and Colter, 1952). PAM and other conditioners improved plant growth by reducing soil physical problems by stabilizing aggregates in the entire 30 to 40 cm tilled soil depth. This approach applied hundreds of kilograms per hectare of PAM via multiple spray and tillage operations. Material and application costs limited PAM-use to high value crops, nursery operations, etc. By the 1980s polymer costs, formulations and purity improved. Paganyas (1975) and Mitchell (1986) noticed reduced sediment in runoff when irrigating furrows after pretreatment with PAM. Lentz et al. (1992) reported a practical economical low-rate strategy for PAM-use to control furrow irrigation erosion. Malik et al. (1991b) found that PAM applied via infiltrating water is irreversibly adsorbed in the top few millimeters of soil once dry. PAM delivery via furrow streams is very efficient, because it needs only stabilize the thin veneer of soil directly active in the erosion process. In furrow irrigation PAM treats only about 25% of the field surface area to a few millimeters depth, requiring only 1-2 kg ha-1 of PAM per irrigation.

Water soluble polyacrylamide (PAM) was identified in the 1990s as a highly effective erosion-preventing and infiltration-enhancing polymer, when applied at rates of 1 to 10 kg ML-1 (10 ppm or 10 g m-1) in furrow irrigation water (Lentz et al., 1992; Lentz and Sojka, 1994; McCutchan et al., 1994; Trout et al., 1995; Sojka and Lentz, 1997; Sojka et al., 1998a,b). PAM achieves this result by stabilizing soil surface structure and pore continuity. In 1995 the United States Natural Resource Conservation Service (NRCS) published a PAM-use conservation practice standard (Anonymous, 1995) revised in 2000. The standard gives considerations and methodologies for PAM-use. PAMs were first sold commercially for erosion control in the US in 1995. By 1999 about 400,000 ha were PAM-treated in the U.S. The U.S. market is expected to continue to grow as water quality improvements are mandated by new Federal legislation and court action, and since PAM use is one of the most effective and economical technologies recently identified that accomplishes the needed water quality improvement. PAM-use has also branched into soil stabilization of construction sites and road cuts, with statewide standards for these uses having been formalized in Wisconsin and several southern states. Interest in PAM has also occurred outside the U.S., in places as diverse as Australia, Canada, Central America, Africa, Spain, Portugal, France, and Israel.

Erosion Control: PAM, used following NRCS guidelines (Anonymous, 1995), reduced sediment in runoff 94% in three years of furrow irrigation studies in Idaho (Lentz and Sojka, 1994). The 1995 NRCS standard calls for dissolving 10 kg ML-1 (10 ppm or 10 g m-3) PAM in furrow inflow water as it first crosses a field (water advance -- typically the first 10 to 25% of an irrigation duration). PAM dosing is halted when runoff begins. The PAM applied during advance generally prevents erosion throughout a 24 hr irrigation. Application amounts under the NRCS standard are 1-2 kg ha-1. For freshly formed furrows, Lentz and Sojka (1999) reported that effectiveness of applying PAM at a uniformly dosed inflow concentration varied with inflow-rate, PAM concentration, duration of furrow exposure, and amount of PAM applied. Erosion control with PAM on 1 to 2% slopes was similar for three application methods: 1) the NRCS 10 kg ML-1 standard, 2) application of 5 kg ML-1 during advance, followed by 5 to 10 minutes of 5 kg ML-1 re-application every few hours, or 3) continuous application of 1 to 2 kg ML-1. Constant application of 0.25 kg ML-1 controlled erosion about one third less effectively.

PAM treatment is recommended whenever soil is disturbed (loose and highly erodible) before an irrigation. When dosing the advance flow as prescribed by the NRCS standard, erosion control typically drops by half if soil is undisturbed between irrigations and PAM is not re-applied. Following initial PAM-treatment, erosion in subsequent irrigations can usually be controlled with only 1 to 5 kg ML-1 PAM if the soil has not been disturbed between irrigations.

Furrow irrigators often use a simple application strategy which they call the "patch method." This involves spreading dry PAM granules into the furrow bottom of the first 1 to 2 m below the inflow point. The amount of granules can be accurately determined on an area-equivalent basis-- furrow spacing x length at a 1 kg ha-1 field application rate. Typical patch doses are 15 to 30 g/furrow (approximately half ounce to an ounce or teaspoon to tablespoon amounts). When water flows over this "patch" of dry granules, a thin slimy mat forms that slowly dissolves during the course of the irrigation. Erosion and infiltration effects of the patch method are comparable to dosing the inflow at 10 kg ML-1 (Sojka and Lentz, unpublished data). Erosion control in subsequent non-treated irrigations is often better with patch application than for dissolving PAM in the water supply. This is because bits of the patch are often still intact at the end of the treated irrigation, providing small amounts of PAM in later irrigations. Advantages and disadvantages of each application method depend on field conditions and system requirements (Sojka et al., 1998c). The patch method works well in most circumstances, but is less reliable on very steep slopes (greater than about 3%) or where inflow rates are very high (greater than about 50 L min-1). These conditions can cause breakup and transport of the patch down the furrow, or burying of the patch by the sediment scoured at or near the inflow point. PAM pre-dissolved in the advancing inflow performs more reliably at high water flow rates or on steep slopes. However, when soil is damp (from dew, or a light rainfall, or canopy shading) the patch method or use of a continuous low dosage seems to control erosion more reliably than the pre-dissolved dosing only during advancing inflow. The reason for this effect is not fully understood. A possible explanation is that the initial surface soil wetness may interfere with PAM adsorption. Wetter soil also infiltrates less PAM-bearing water. Thus, delivering a constant small dose of PAM is needed to compensate for weaker initial stabilization of the initially wetter soil.

In the US Pacific Northwest, on farm fields where irrigation of disturbed soil is PAM-treated at 10 kg ML-1 in the advance or using the patch method, followed by irrigations of undisturbed soil that are either untreated or treated at lower rates, farmers and NRCS report about 80% seasonal erosion control. Farmers typically use 3 to 5 kg ha-1 in a season depending on field conditions and crop (thus, number of cultivations and irrigations).

Infiltration: Furrow irrigation stream advance is usually slower when using PAM, especially for the first irrigation on newly formed or cultivated furrows (Sojka et al., 1998a,b). The reason is that the infiltration rate of PAM-treated furrows on medium to fine textured soil is usually faster than on untreated furrows. Surface seals form on untreated furrow bottoms due to the destruction of soil aggregates with rapid wetting, and the detachment, transport and redeposition of fine sediments in the furrow stream. This seal formation process blocks most of the pores at the soil surface, reducing the infiltration rate. For equal inflows, net infiltration on freshly formed PAM-treated furrows in silt loam soils is typically 15% more, compared to untreated water. On clay, infiltration can increase 50% compared to untreated water (Sojka et al., 1998a). Pore continuity is maintained when aggregates are stabilized by PAM. Sojka et al. (1998a) reported that infiltration at 40 mm tension varied among irrigations over the range 12.9 to 31.8 mm hr-1 for controls and 26.7 to 52.2 mm hr-1 for PAM-treated furrows and that infiltration at 100 mm tension varied from 12.3 to 29.1 mm hr-1 for controls and 22.3 to 42.4 mm hr-1 for PAM-treated furrows.

PAM infiltration effects are a balance between prevention of surface sealing and apparent viscosity increases in soil pores. Bjorneberg (1998) reported that in tube diameters >10 mm, PAM solution effects on viscosity are negligible at 15 and 30 C. Macropore viscosity rose sharply only after PAM exceeded 400 kg ML-1. In small soil pores, "apparent viscosity" increases greatly, however, even at the dilute PAM concentrations used for erosion control (Malik and Letey, 1992). The more significant effect in medium to fine textured soils, is the maintenance of pore continuity achieved by aggregate stabilization. In coarse textured soils (sands), where little pore continuity enhancement is achieved with PAM, there have been reports of no infiltration effect or even slight infiltration decreases, particularly at concentrations above 20 kg ML-1 (Sojka et al., 1998a).

For furrows formed on wheel-tracks, the increase of infiltration often seen with PAM does not last as long as on non-trafficked furrows (Sojka et al., 1998b). They postulated that reduced surface sealing with PAM improves infiltration only until repeated wetting and drying begins to disrupt subsurface aggregates and/or deliver enough surface-derived fines to seal the few remaining subsurface pores which have already been partially reduced by compaction. Because PAM prevents erosion of furrow bottoms and sealing of the wetted perimeter, lateral water movement increases about 25% in silt loam soils compared to non-treated furrows (Lentz et al., 1992; Lentz and Sojka, 1994). This can be a significant water conserving effect for early irrigations.

PAM's erosion prevention properties can permit farmers to improve field infiltration uniformity. This can be done by increasing inflow rates two to three fold (compared to normal practices), thereby reducing infiltration opportunity time differences between inflow and outflow ends of furrows (Sojka and Lentz, 1997; Sojka et al, 1998b). When runoff begins, the higher initial inflow must be reduced to a flow rate that just sustains the furrow stream at the outflow end of the field. Initial observations suggest that coupling PAM with surge flow irrigation can be a beneficial practice (Bjorneberg and Sojka, unpublished data). With PAM in the water, there is still enough reconsolidation of the furrow surface for surges to accelerate advance. However, the upper-field scouring associated with doubled flows (as is common when surge valves are used) does not occur.

Sprinkler Irrigation: Farmers use PAM in sprinkler irrigation to prevent or reduce runoff/runon problems and ponding effects on stand establishment and irrigation uniformity. Water and chemical application precision are improved if infiltration occurs where water drops hit the soil. In soil box studies, PAM application rates of 2 to 4 kg ha-1 reduced runoff 70% and soil loss 75% compared to controls (Aase et al., 1998). Effectiveness of sprinkler-applied PAM is more variable than for furrow irrigation because of application strategies and system variables that affect water drop energy, the rate of water and PAM delivery, and possible application timing scenarios (Aase et al., 1998; Levin et al., 1991; Smith et al., 1990). Bjorneberg and Aase (2000) noted that greater erosion control was had by applying PAM over several sprinkler irrigations than by applying all the PAM in the initial irrigation. Ben Hur and Keren (1997), Levin et al. (1991), Aase et al., (1998) and Smith et al.(1990) all reported improved aggregate stability from sprinkler-applied PAM, leading to decreased runoff and erosion. Flanagan et al. (1997a,b) reported increased infiltration when sprinkler water contained 10 kg ML-1 PAM. They attributed this to reduced surface sealing. PAM effects under sprinkler irrigation have been more transitory, less predictable and have usually needed higher seasonal field application totals for efficacy. Sprinklers must stabilize two to three times more surface area than furrow streams, and also protect against water drop energy effects. Despite higher rates, farmers with sprinkler infiltration uniformity problems stemming from runoff or runon, e.g. damping off or nitrogen loss, have begun to use PAM. These problems are common with center pivots, especially on variable or steep slopes.

PAM Formulations: Large anionic PAM molecules are used for erosion control mainly for environmental and safety considerations, however, Lentz et al. (2000) reported that these properties also favored erosion control. Commercial anionic moderate molecular weight PAM products for erosion control are usually of two types. The most commonly used products are fine granular forms of PAM. The second most common product formulations are concentrated liquid emulsions of PAM and mineral spirits. These also include "inverse emulsions" that contain a surfactant to help disperse the PAM when mixed with water. Emulsions are more commonly used with sprinkler PAM application than in furrow irrigation. Both granular materials and emulsified concentrates require substantial turbulence or agitation and high flow rate at the point of addition to water in order to dissolve PAM to reach a desired concentration. Detailed considerations for PAM use are available in several publications on the web site <http://kimberly.ars.usda.gov/pampage.ssi>.

Environment and Safety: Environmental and safety considerations of anionic PAMs have been thoroughly reviewed (Barvenik, 1994; Bologna et al., 1999; Seybold, 1994). The most significant environmental effect of PAM use is its erosion reduction, protecting surface waters from sediment and other contaminants washed from eroding fields. PAM greatly reduces nutrients, pesticides, and biological oxygen demand (BOD) of irrigation return flows (Agassi et al., 1995; Lentz et al., 1998, 2001). In Australian tests of PAM, sediment, nutrient, and pesticide reductions exceeded levels achieved by traditional conservation farming methods (Waters et al., 1999a,b). There are some specific environmental issues related to PAM charge type and purity.

An important environmental and applicator safety consideration is the need to use PAMs that contain <0.05% acrylamide monomer (AMD). AMD is a neurotoxin, but PAMs below these AMD contents are safe, when used as directed at low concentrations. In soil, PAM degrades at rates of at least 10% per year as a result of physical, chemical, biological and photochemical processes and reactions (Tolstikh, et al. 1992; Wallace et al. 1986; Azzam et al. 1983). Because PAM is highly susceptible to UV degradation, its breakdown rate when applied at the soil surface for erosion control may be faster than the 10% per year reported rate, which was for biological degradation of PAM mixed into a large soil volume. PAM does not revert to AMD upon degradation (Mac Williams, 1978). Furthermore, AMD is easily metabolized by microorganisms in soil and biologically active waters, with a half life in tens of hours (Lande et al, 1979; Shanker et al., 1990). Bologna et al. (1999) showed that AMD is not absorbed by plant tissues, and apparently breaks down rapidly even when injected directly into living plant tissue. While anionic PAMs are safe if used as directed, prolonged overexposure can result in skin irritation and inflamation of mucus membranes. Users should read label cautions and take reasonable care not to breathe PAM dust and to avoid exposure to eyes and other mucus membranes. Another caution is that PAM spills become very slippery if wet. PAM application onto roadways should be avoided and PAM spills should be thoroughly cleaned with a dry absorbent and removed before attempting to wash down with water. Practical user considerations are numerous. Labels, website information and available extension information should be consulted before embarking upon large scale use of PAM.

Used at prescribed rates, anionic PAMs are environmentally safe. Cationic and neutral PAMs have toxicities warranting caution or preclusion from sensitive environmental uses. NRCS specifies anionic PAMs for controlling irrigation-induced erosion. Anionic PAMs are used extensively for potable water treatment, for dewatering of sewage sludge, washing and lye pealing of fruits and vegetables, clarification of sugar juice and liquor, in adhesives and paper in contact with food, as thickeners and suspending agents in animal feeds, in cosmetics, for paper manufacturing, for various mining and drilling applications and for various other sensitive uses. Negative impacts have not been documented for aquatic macrofauna, edaphic microorganisms, or crop species for the anionic PAMs used for erosion control when applied at recommended concentrations and rates Kay-Shoemake (1998a,b). Even at very high concentrations, when PAMs are introduced into waters containing sediments, humic acids or other impurities, PAM effects on biota are greatly buffered due to adsorption and deactivation associated with the suspended impurities (Buchholz, 1992; Goodrich et al., 1991).

Lentz et al. (1996) studied loss of PAM into runoff and return flows. They determined that, because of PAM's high affinity for suspended sediments and soil in waste ditch streams, only 3-5% of the PAM applied left fields in runoff. Furthermore, lost PAM only traveled 100 to 500 meters in waste ditches before being completely adsorbed on sediments in the flow or onto ditch surfaces (Lentz and Sojka, 1996). Ferguson (1997) reported on a watershed scale test of PAM, where over 1,600 ha were irrigated using PAM-treated water for a two week period. On any given day, about half of the 40 farms in the study were contributing runoff to the watershed's drainage, which collected in Conway Gulch, a tributary of the Boise River. Waste water from the fields and the drain was analyzed for P, sediment, and PAM. About half of the water in the drain was field runoff. PAM was not found detrimental to the drain's water quality, and was detected in drain water samples only twice (< 0.8 kg ML-1) during monitoring. PAM was found to be an effective sediment control practice that was well adopted by farmers and did not negatively impact the drain.

PAM and Calcium: Wallace and Wallace (1996) noted the need for calcium electrolytes in irrigation water when using anionic PAM for infiltration and erosion control. This need was demonstrated quantitatively by Orts et al. (2001). Calcium ions act as a bridge between anionic soil surfaces and the anionic PAM macromolecule. Calcium has a double charge and small hydrated radius which favors flocculation. Sodium, on the other hand, has a large hydrated radius which generally prevents ion bridging, generally leading to dispersion rather than flocculation of solids. Lentz and Sojka (1996) noted that when irrigation water SAR was increased from 0.7 to 9.0 [m molc L-1]0.5 that PAM's infiltration enhancement over control water was greatly diminished. Water low in electrolytes or with high SAR can be amended relatively easily through addition of gypsum (calcium sulfate) or calcium nitrate fertilizer. PAM has been used in conjunction with gypsum to accelerate leaching of sodic soils, by reducing surface sealing (Malik et al., 1991a)

Recent Findings: Broad categories of microorganisms carried across and among furrow-irrigated fields by furrow streams, runoff and return flows are reduced by PAM in irrigation water (Sojka and Entry, 1999, 2000; Entry and Sojka, 1999). Similar reductions occur for weed seed in runoff (Sojka and Morishita, unpublished data). These findings point to potential improved management that may ultimately reduce pesticide use. New research has begun investigating new polymers synthesized from organic byproducts of crop agriculture and shell fish food processing which may supplement PAM for certain uses where enhanced biodegradability is needed or where bio-based chemistry is perceived to be an environmental benefit (Orts et al., 1999, 2000).

References:

Aase, J.K., D.L. Bjorneberg, and R.E. Sojka. 1998. Sprinkler irrigation runoff and erosion control with polyacrylamide--Laboratory tests. Soil Sci. Soc. Am. J. 62:1681-1687. 1998.

Agassi, M., J. Letey, W.J. Farmer, and P. Clark. 1995. Soil erosion contribution to pesticide transport by furrow irrigation. J. Environ. Qual. 24:892-895.

Anonymous. 1995. Natural Resources Conservation Service West National Technical Center Interim Conservation Practice Standard – Irrigation Erosion Control (Polyacrylamide)–WNTC 201 – 1.5 pages.

Azzam, R., O.A. El-Hady, A.A. Lofty, and M. Hegela. 1983. San-RAPG combination simulating fertile clayey soils, parts I-IV. Int. Atomic Energy Agency. SM-267/15:321-349.

Barvenik, F.W. 1994. Polyacrylamide characteristics related to soil applications. Soil Sci. 158:235-243.

Ben Hur, M., and R. Keren. 1997. Polymer effects on water infiltration and soil aggregation. Soil Sci. Soc. Am. J. 61:565-570.

Bjorneberg, D.L. 1998. Temperature, concentration, and pumping effects on PAM viscosity. Trans. ASAE. 41:1651-1655.

Bjorneberg, D.L., and J.K. Aase. 2000. Multiple polyacrylamide applications for controlling sprinkler irrigation runoff and erosion. Applied Eng. Ag. 16:501-504.

Bologna, L.S., F.F. Andrawes, F.W. Barvenik, R.D. Lentz, and R.E. Sojka. 1999. Analysis of residual acrylamide in field crops. Journal of Chromatographic Science. 37:240-244.

Buchholz, F.L. 1992. Polyacrylamides and polyacrylic acids. In Ullmann's Encyclopedia of Industrial Chemistry. Vol. A21. B. Elvers, S. Hawkins & G. Schulz (ed.) VCH Weinheim, Germany. pp.143-146.

Entry, J.A., and R.E. Sojka. 1999. Influence of polyacrylamide application to soil on movement of microorganisms in irrigation water. Pages 93-99. Proceedings Irrigation Association's International Irrigation Show & Technical Conference. Orlando, FL, 7-9 Nov., 1999.

Ferguson, D.F. 1997. Conway Gulch PAM Demonstration. Report to the Idaho Soil Conservation Commission. October 29, 1997.

Flanagan, D.C., L.D. Norton, and I. Shainberg. 1997a. Effect of water chemistry and soil amendments on a silt loam soil – Part 1: Infiltration and runoff. Trans. ASAE. 40:1549-1554.

Flanagan, D.C., L.D. Norton, and I. Shainberg. 1997b. Effect of water chemistry and soil amendments on a silt loam soil – Part 2: Soil erosion. Trans. ASAE. 40:1555-1561.

Goodrich, M.S., L.H. Dulak, M.A. Freidman, and J.J. Lech. 1991. Acute and longterm toxicity of water-soluble cationic polymers to rainbow trout (Oncorhynchus mykus) and the modification of toxicity by humic acid. Environ. Toxicol. Chem. 10:509-551.

Kay-Shoemake, J.L., M.E. Watwood, R.D. Lentz, and R.E. Sojka 1998a. Polyacrylamide as an organic nitrogen source for soil microorganisms with potential impact on inorganic soil nitrogen in agricultural soil. Soil Biol. and Biochem. 30:1045-1052.

Kay-Shoemake, J.L., M.E. Watwood, R.E. Sojka., and R.D. Lentz. 1998b. Polyacrylamide as a substrate for microbial amidase. Soil Biol. and Biochem. 30:1647-1654.

Lande, S.S., S.J. Bosch, and P.H. Howard. 1979. Degradation and leaching of acrylamide in soil. J. Environ. Qual. 8:133-137.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow 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 and infiltration. Soil Science 158:274-282.

Lentz, R.D., and R.E. Sojka. 1996. Five-year research summary using PAM in furrow irrigation. p.20-27. In R.E. Sojka and R.D. Lentz (ed.) Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. Proc., College of Southern Idaho, Twin Falls, ID, 6-8 May, 1996. Univ. of Idaho Misc. Publ. 101-96.

Lentz, R.D., and R.E. Sojka. 1999. Applying polymers to irrigation water: Evaluating strategies for furrow erosion control. ASAE Paper No. 992014. ASAE St. Joseph, MI.

Lentz, R.D., R.E. Sojka, and J.A. Foerster. 1996. Estimating polyacrylamide concentration in irrigation water. J. Environ. Qual. 25:1015-1024.

Lentz, R.D., R.E. Sojka, and C.W. Robbins. 1998. Reducing phosphorus losses from irrigated fields. J. Env. Qual. 27:305-312.

Lentz, R.D., R.E. Sojka, and C.W. Ross. 2000a. Polymer charge and molecular weight effects on treated irrigation furrow processes. International Journal of Sediment Research. 15:17-30..

Lentz, R.D., R.E. Sojka, C.W. Robbins, D.C. Kincaid, and D.T. Westermann. 2001. Polyacrylamide for surface irrigation to increase nutrient-use efficiency and protect water quality. Commun. Soil Sci. Plant Anal. (In Press).

Levin, J., M. Ben-Hur, M.Gal, and G.J. Levy. 1991. Rain energy and soil amendments effects on infiltration and erosion of three different soil types. Aust. J. Soil Res. 29:455-465.

MacWilliams, D.C. 1978. Acrylamides. In Encyclopedia of Chemical Technology, 3rd. Ed., Vol. 1. I. Kirk and D.F. Othmer (eds.). Wiley, New York, pp. 298-311.

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

Malik, M, C. Amrhein, and J. Letey. 1991a. Polyacrylamide to improve water flow and salt removal in a high shrink-swell soil. Soil Sci. Soc. Am. J. 55:1664-1667.

Malik, M., A. Nadler, and J. Letey. 1991b. Mobility of polyacrylamide and polysaccharide polymer through soil materials. Soil Technol. 4:255-263.

McCutchan, H., P. Osterli, and J. Letey. 1994. Polymers check furrow erosion, help river life. Calif. Ag. 47:10-11

Mitchell, A.R. 1986. Polyacrylamide application in irrigation water to increase infiltration. Soil Sci. 141:353-358.

Orts, W.J., R.E. Sojka, and G.M. Glenn. 2000. Biopolymer additives to reduce soil erosion-induced soil losses during irrigation. Industrial Crops & Products. 11:19-29.

Orts, W.J., R.E. Sojka, G.M. Glenn, and R.A. Gross. 1999. Preventing Soil Erosion with Polymer Additives. Polymer News. December, 1999, Vol. 24, pp. 406-413

Orts, W.J., R.E. Sojka, G.M. Glenn, and R.A. Gross. 2001. Biopolymer additives for the reduction of soil erosion losses during irrigation. Pages 102-116. In: R.A. Gross and Carmen Scholz (eds.) Biopolymers from Polysaccharides and Agroproteins. ACS Series 786. Am. Chem. Soc., Washington, DC.

Paganyas, K.P. 1975. Results of the use of "K" compounds for the control of irrigation soil erosion. Sov. Soil Sci. 5:591-598.

Seybold, C.A., 1994. Polyacrylamide review: Soil conditioning and environmental fate. Comm. Soil Sci. Plant Anal. 25:2171-2185.

Shanker, R., C. Ramakrishna, and P.K. Seth. 1990. Microbial degradation of acrylamide monomer. Arch. Microbiol. 154:192-198.

Smith, H.J.C., G.J. Levy, and I. Shainberg. 1990. Water-droplet engergy and soil amendments: Effect on infiltration and erosion. Soil Sci. Soc. Am. J. 54:1084-1087.

Sojka, R.E. and Entry, J.A. 1999. The influence of polyacrylamide application to soil on movement of microorganisms in water. Proceedings of the ASCE 1999 International Water Resources Engineering Conference, Seattle, WA, Aug. 8-11, 1999.

Sojka, R.E., and J.A. Entry. 2000. Influence of polyacrylamide application to soil on movement of microorganisms in runoff water. Environmental Pollution. 108:405-412.

Sojka, R.E., and R.D. Lentz. 1997. Reducing furrow irrigation erosion with polyacrylamide (PAM). J. Prod. Agric. 10:1-2 and 47-52.

Sojka, R.E., R.D. Lentz. T.J. Trout, C.W. Ross, D.L. Bjorneberg, and J.K. Aase. 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. J. Soil Water Conserv. 53:325-331.

Sojka, R.E., D.T. Westermann, and R.D. Lentz. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. 1998b. Soil Sci. Soc. Am. J. 62:1672-1680.

Sojka, R.E., Lentz, R.D., Bjorneberg, D.L., and Aase, J.K. 1998c. The PAMphlet: A concise guide for safe and practical use of polyacrylamide (PAM) for irrigation-induced erosion control and infiltration enhancement. USDA-ARS

Northwest Irrigation & Soils Research Lab, Kimberly, ID, Station Note #02-98.

Tolstikh, L.I., N.I. Akimov, I.A. Golubeva, and I.A. Shvetsov. 1992. Degradation and stabilization of polyacrylamide in polymer flooding conditions. Int. J. Polymeric Material. 17:177-193.

Trout, T.J., R.E. Sojka and R.D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. Trans ASAE. 38(3):761-765.

Wallace, A., and G.A. Wallace. 1996. Need for solution or exchangeable calcium and/or critical EC level for flocculation of clay by polyacrylamides. p. 59-63. IN: R.E. Sojka and R.D. Lentz (eds.) Managing Irrigation-Induced Erosion and Infiltration with Polyacrylamide. Proc., College of Southern Idaho, Twin Falls, ID 6-8 May, 1996. Univ. of Idaho Misc. Publ. No. 101-96.

Wallace, A., G.A. Wallace, and A.M. Abouzamzam. 1986. Effects of excess levels of a polymer as a soil conditioner on yields and mineral nutrition of plants. Soil Sci. 141:377-379.

Waters, D., Drysdale, R., Kimber, S. 1999a. Benefits of planting into wheat stubble. - The Australian Cotton Grower Magazine, Volume 20 No. 4 pp8-13.

Waters, D., Drysdale, R., Kimber, S. 1999b. Reducing off-site movement of sediment and nutrients in a cotton production system. Proc. NPIRD Nutrient Conference. Brisbane- Qld, June.

Weeks, L.E., and W.G. Colter. 1952. Effect of synthetic soil conditioners on erosion control. Soil Sci. 73:473-484.

Wilson, A.D. and S. Crisp. 1975. Rigid highly carboxylated ionic polymers. IN: Ionic Polymers. L. Holiday (ed.). Chapman and Hall, New York, pp208-257.