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A PAM Primer: A brief history of PAM and PAM-related issues

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Introduction

Polyacrylamide treatment of irrigation water may be the fastest growing conservation technology in irrigated agriculture. PAMs were registered in most Western states by late 1994, and the Natural Resources Conservation Service (NRCS) published an interim conservation practice standard for PAM-use in January 1995 *(Anonymous, 1995)*. In 1995, its first year of commercial use, about 20,000 ha were PAM-treated, saving as much as a million tons (0.9 million metric tons) of soil *(Sojka and Lentz, 1996)*. Irrigators have been attracted to the new PAM technology because they recognize irrigated agriculture's value, the threat of erosion on fragile arid-zone soils, and PAM's efficacy and ease of use.

Significance of Irrigated Agriculture

About 600 million ac (240 million ha) or 15-17% of Earth's cropland are irrigated, mostly surface irrigated *(Hoffman et al., 1990; Gleick, 1993)*. In the United States about 32 million ac. (13 million ha) of crop land (53% of the total) are surface irrigated, primarily by furrow *(Anonymous, 1996)*. The proportion of surface irrigation globally is thought to be much higher than in the US, since most of the world's irrigated acres occur in underdeveloped countries that do not have the technologic base, rural power or financial resources to develop more advanced methods of irrigation such as sprinklers or drip.

Irrigation occurs mostly in arid climates *(Bucks et al., 1990)* where photosynthetic rates are high (few clouds), and disease, insect and weed pressures are low. These factors minimize fungicide, herbicide and pesticide inputs. Arid soils seldom need potassium fertilizer or lime; furthermore, their neutral to basic pH and low organic matter minimize required rates of soil-incorporated herbicides *(Ross and Lembi, 1985)*.

Because water and nutrient availability, as well as pest control are more easily optimized under irrigation, irrigated commodities usually attain higher quality than with rain-fed production. Additionally, irrigation in arid environments allows commercial production of many high value horticultural and other cash crops that cannot be economically grown under rain-fed conditions. Irrigated yields average twice that of rain-fed agriculture, accounting for one-third of all crop yield, and half of all crop value *(Rangeley, 1987; Bucks et al., 1990)*. About 50 million ha of Earth's best irrigated land grows one-third of her entire food crop (*Tribe, 1994*).

Erosion and Irrigated Agriculture's Sustainability

Irrigated agriculture's high productivity makes possible the feeding and clothing of Earth's exploding population on a minimum extent of arable land. Yet, the arid and semi-arid soils supporting most irrigated agriculture typically have thin erodible surface horizons. Furrow outflow soil losses of 2 to 22 tons/ac/yr (5 to 50 metric tons/ha/yr) are common in the U.S. Pacific Northwest, with three to eight times the field average loss occurring near inflows *(Berg and Carter, 1980; Kemper et al, 1985; Fornstrom and Borelli, 1984; Trout, 1996)*. Thus, irrigated agriculture's productivity is seriously endangered by arid soil erodibility, and irrigation-induced erosion *(Carter, 1993)*. Some 1.2 billion ac (0.5×10^9 ha) of grasslands, rain forests or wetlands would be needed to replace irrigated agriculture's output if irrigation were eliminated *(Sojka, 1996)*.

Numerous conservation practices for furrow irrigation have been developed since 1970 *(Sojka, 1997)*. Several eliminate >80% of runoff-carried sediment. Yet, few of these practices have been widely adopted, even after two decades of promotion and demonstration. This is largely because residue placement, reduced tillage, etc. are often regarded as inconvenient or intrusive by furrow irrigators, who prefer smooth clear furrows to convey water. Conservation practices that require additional or unfamiliar field operations that occur during otherwise busy periods in the farming schedule are also avoided. Furthermore, practices that reduce sediment loss 60-70% (like sediment ponds, vegetative filter strips or buried-pipe waste water systems) still lose most of the clay-sized solids *(Brown et al., 1981)* — the soil component most critical to sustained soil fertility. These solids also are most linked to BOD, pesticide and eutrophying nutrient problems in return-flow receiving waters.

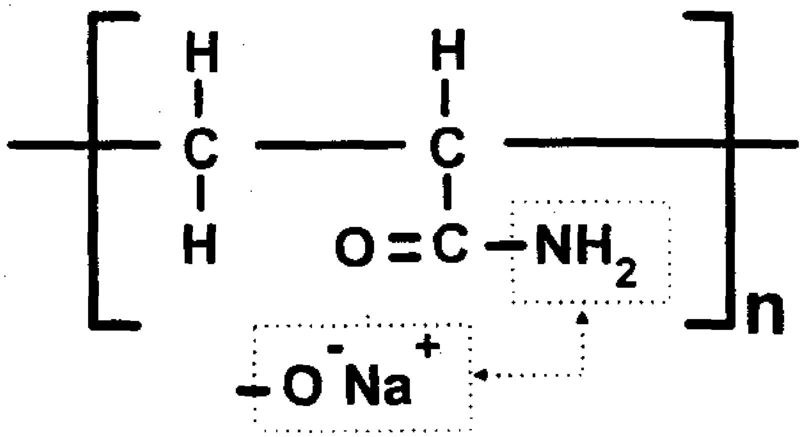
PAM-use has proven highly effective for erosion control and infiltration enhancement, and is well received by furrow irrigators. This paper summarizes the background of this new technology and the results and insights obtained over several years of experimentation with small amounts of polyacrylamide (PAM) dissolved in irrigation water. We have also attempted to itemize important practical considerations for effective and environmentally responsible use of PAM for furrow erosion control.

PAM's Origins and Properties

Chemical soil conditioners were used as early as World War II to allow rapid construction of roads and runways under adverse conditions *(Wilson and Crisp, 1975)*. The technology found its way into the US agricultural arena in the 1950s, with a variety of synthetic compounds, including various types of PAMs that were used to enhance aggregate stability of soil in the tilled surface layer of agricultural fields. Various uses for soil structure stabilization in horticultural, agronomic and construction applications were extensively researched through the 1970s *(Azzam, 1980; De Boodt et al., 1993; Gabriels, 1990)*.

Fig. 1 — The depiction of an individual acrylamide monomer component as found in a polyacrylamide molecule

Polyacrylamide (PAM)



Substitution of the sodium formate functional group for the amide group, as occurs in about one in five polymer units as shown. This is the subsitution that, when sodium dissociates from the copolymer chain, provides net negative charge on the "PAM" molecule.

"Polyacrylamide" and "PAM" are generic terms. PAMs are polymers made up of many repeating subunits (monomers). As with all polymers, the properties of PAMs are very dependant on the size of the polymer. A familiar analogy in nature is the way simple glucose monomers are progressively polymerized into polysacharides, pectins, starches and cellulose (wood). PAMs also vary in molecular size, depending on the number of acrylamide monomers (AMD) that are combined to form the polyacrylamide chain. In addition, PAMs can be altered through modification of some of the subunits.

The most common raw material for polyacrylamide synthesis is natural gas, a resource often burned off at petroleum well heads. The PAMs used in irrigation water to fight erosion are copolymers. They consist of high molecular weight polyacrylamide, typically 12-15 Mg/mole (>150,000 AMD monomer units per molecule), with substitution of functional groups in about one in five AMD monomer units (Fig. 1). This imparts a net negative charge. The PAMs used in the Idaho work typically had a negative charge density of about 18% (ie. substitutions in about one of every five monomers). In these PAMs, one in five amide groups is replaced with sodium formate. The sodium cation dissociates in water, leaving a negative charge on the polymer for each cation dissociated.

In its original mode of use 40 years ago, PAM or other soil stabilizers were applied at rates of 500 to 1000 lbs/ac (560-1120 kg/ha). They were usually sprayed onto soil, then rototilled or otherwise incorporated. Sometimes multiple applications were necessary to achieve the application level required to stabilize the soil aggregates created in the tillage process. The concept was to improve the tillage layer's soil structure and stability. The application rates needed to achieve stabilization for this soil volume proved uneconomical for all but high value uses.

Numerous laboratory column and lysimeter studies were conducted in the 1970s and '80s to study PAM effects on soil dispersion, PAM adsorption-desorption phenomena and infiltration effects. During this period the chemistry of polyacrylamide synthesis and copolymerization continued to improve, broadening the choices of polyacrylamide copolymers available for use. Since the early 1980s, several papers have reported infiltration and erosion effects from rain-simulator studies on soil pre-treated with PAM.

Effects of a soil conditioner placed in furrow irrigation water was first reported by Paganyas (1975). The report referred only vaguely to the conditioners as "K" compounds, although their description suggests they were PAM-like chemicals. Small amounts placed in the advancing furrow stream were used to pretreat the furrow. After pre-treatment the furrows were irrigated, with great reductions in erosion. Mitchell (1986) reported use of anionic PAMs applied during the stream advance phase of furrow irrigation at rates of 25, 50 and 150 ppm. His focus was on infiltration effects, but in a side observation he noted that soil dispersion was reduced and runoff was nearly clear in PAM-treated irrigation furrows.

Lentz et al. (1992) gave the first detailed report of PAM-use in furrow irrigation for erosion control and net infiltration improvement. Their approach, like Mitchell's in 1986, involved PAM treatment of the furrow advance stream (only). Efficacious treatment was possible with net PAM application rates of only about 1 lb/ac (1 kg/ha) applied in the advance stream (only) at 10 ppm. McCutchan et al. (1993) reported similar findings, although their approach involved application of PAM at 2.5 ppm continuously throughout the irrigation.

The very small total amounts of PAM needed to achieve desired results, when applying PAM in the eroding irrigation stream has proven to be a significant breakthrough. Applying PAM in the furrow water is effective at low rates because only the thin layer of soil immediately affected by the dispersion and sheer of the furrow stream is treated by water infiltrating into the soil (Fig. 2, see next page).

A simple calculation demonstrates how such low rates can be effective. Based on the old PAM application rates of 500 lbs/ac incorporated in the tillage layer (surface 6 in., or 15 cm), the fact that water in furrows only wets about 25% of the field surface area, and that PAM only penetrates about 1/16 in. (1-2 mm) into the soil, we see that:

(500 lbs/ac.) (25%) (1%) = 1.25 lbs/ac

The potential of creating significant changes in soil response to irrigation water application with such small amounts of PAM is what has driven the development of this new technology.

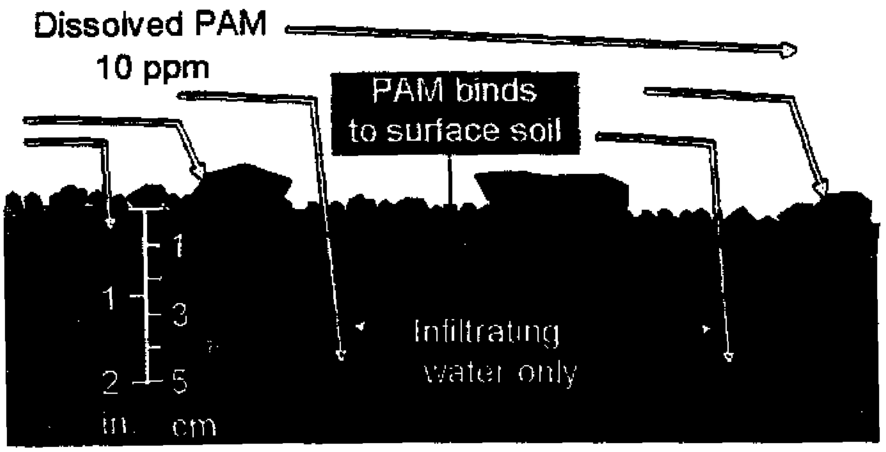
General Methodology

The findings discussed herein were obtained largely from a series of studies conducted from 1991 through 1995 at or near the USDA Agricultural Research Service's Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. Soils included Xerollic Haplargids and Haploxerollic Durargids, but most studies were on Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthids). Surface horizons and general physical and chemical characteristics of all soils were similar. Textures were silt loams (10-21% clay, 60-75% silt). Organic matter ranged from 10-13 g/kg. Saturated paste extract EC was 0.7 to 1.3 dS/m, ESP was 1.4 to 1.7, pH was 7.6-8.0 with $CaCO_3$ equivalent of 2-8%. Slopes varied from 0.5 to 3.5%, but unless noted otherwise, data generally reflect slopes of 1 to 1.5%.

Water was applied as furrow irrigation (usually either via spigoted plastic pipe or siphon tubes) to conventionally tilled fields, usually disked in autumn and spring, then roller harrowed following incorporation of fertilizer and herbicides prior to planting. Furrows ranged from 570 to 860 ft (175 to 264 m) in length; they varied from 4 to 8 ins. (10 to 20 cm) in depth, depending on crop grown, and were prepared with weighted 75° shaping tools. Furrow spacing varied with crops, which included edible dry beans *(Phaseolus vulgaris)* at 22 ins. (56 cm), corn *(Zea mays)* at 30 ins. (76 cm) and potato *(Solanum tuberosum)* at 36 ins. (91.5 cm). Irrigation was normally on every other furrow only, usually in wheel-track furrows. Per hectare sediment-loss and infiltration were calculated based on the spacing between irrigated furrows. Irrigation water was withdrawn from the Twin Falls Canal Company system and had an electrical conductivity (EC) of 0.5 dS/m and a sodium adsorption ratio (SAR) of 0.4 to 0.7. Net infiltration, runoff, and sediment-loss measurements were accomplished by use of periodic flow monitoring and sampling and automated data analysis similar to methods described in detail elsewhere *(Sojka et al. 1992 and 1994, Lentz and Sojka, 1994a and 1995)*.

Fig. 2

PAM-Treated Furrow Irrigation



Schematic depiction of PAM deposition from treated water onto soil aggregates in the surface few millimeters of soil in an irrigated furrow

Polyacrylamide (PAM) copolymer used, unless noted otherwise, was a dry granular material having an approximate molecular weight of 12-15 Mg/mole, with an 18% negative charge density, manufactured by CYTEC Industries of Wayne, NJ. It is marketed in the US by American Cyanamid Company under the trade name Superfloc 836A. Numerous similar materials, granular, compressed cakes, high concentrate aqueous solutions and oil-emulsified PAM concentrates are widely available world wide. Unless noted otherwise, our most frequent means of application involved preparation of liquid stock solutions of 1200-2400 ppm (g/m^3) concentration which were metered into furrow stream flows to achieve a concentration of 10 ppm (g/m^3) in the advancing water flow before runoff began. Typical flow rates ranged 3.5 to 10 gpm (13 to 38 L/min) during advance, reduced to 3.5 to 6 gpm (13-23 L/min) at runoff initiation.

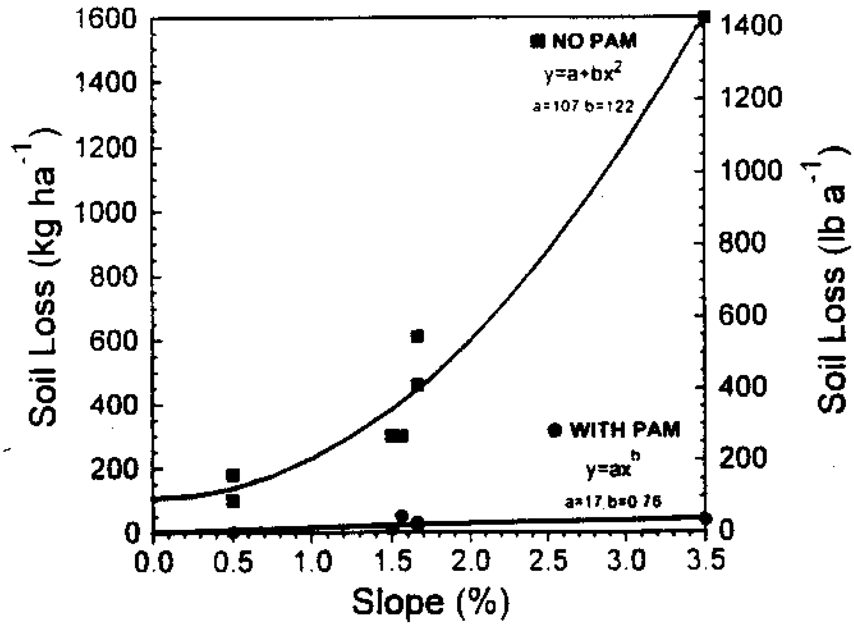
Conservation Benefits, Mode of Action and Cost

Polyacrylamide (PAM) has been an effective, economical erosion preventative under a variety of field conditions (Fig. 3) when dissolved at 10 ppm (g/m^3) in the advance phase (only) of furrow irrigation inflow streams *(Lentz et al., 1992; Lentz and Sojka, 1994b; Lentz, 1995)*. PAM copolymers with molecular weights of 12-15 Mg/mol and charge densities of 8-35% are most effective.

Advancing furrow streams containing 10 ppm (g/m^3) PAM provided a 94% reduction in runoff-sediment in three years of tests in Idaho *(Lentz et al., 1992; Sojka and Lentz, 1993; Trout and Lentz, 1993; Lentz and Sojka, 1994b, Sojka and Lentz, 1993, 1994a)*. With PAM-use, sediments were retained on fields, even with conventional clean-tillage, using no other conservation practices *(Lentz and Sojka, 1994b)*. PAM is a potent flocculent that effectively retains nearly all clay-sized material.

PAM, used according to the NRCS practice standard *(Anonymous, 1995)*, increased infiltration 15% on Portneuf silt loam *(Lentz et al, 1992, Trout and Lentz, 1993; Lentz and Sojka, 1994b; Trout et al., 1995; Sojka et al., 1996)* and up to 50% on finer textured soils *(McCutchan et al., 1994)*. PAM can increase initial infiltration on swelling soils, but may not always affect net infiltration of prolonged irrigations since subsoil swelling blocks water entry as an irrigation proceeds *(Mitchell, 1986)*. Because PAM-treated furrows did not

Fig. 3



Estimate of soil saved as a function of slope for 12-hr irrigations on Portneuf silt loam using inflows of 23-38 L/min for an approximately 200 m long field.

"down-cut" (ie. erode a deeper channel), water infiltrated in Idaho tests moved 25% further laterally from 4-in. (10 cm) deep furrows between level soil beds *(Lentz et al., 1992)*. Thus PAM-use can save water in early irrigations when only enough needs to be applied to reach planted seeds or young seedlings.

The most effective and environmentally safe PAMs are large negatively charged molecules *(Lentz et al., 1993, Barvenik, 1994)*. It has been suggested that divalent cations in water bridge the PAM and soil, increasing soil cohesion and strengthening aggregates contacted in the furrow *(De Boodt et al., 1990; Barvenik, 1994, Sojka and Lentz, 1994b)*. Soil particles at the furrow's soil-water interface are bound together, preventing detachment and transport of sediments in runoff. Soil erodibility is reduced by improved inter-aggregate bonding and by protecting surface roughness. PAM only penetrates soil 1/16 to 2/16 in. (a few millimeters) in the furrow *(Malik et al., 1991)*. These, however, are the few millimeters critical to the erosion process. Since the wetted perimeter only exposes about 25-30% of the soil surface to flowing water, PAM's properties are effective at very low application rates, typically 1 lb/ac (0.9 kg/ha).

PAM is a settling agent. It flocculates (clusters together) dispersed clay and silt particles carried in turbid flow, enabling them to settle to the furrow bottom in a loose pervious layer. Flocculation reduces the amount of suspended fines that enter and plug pores, decreasing infiltration in untreated sediment-laden water. Pore aperture maintenance was confirmed in treated furrows by higher infiltration rates under tension compared to controls *(Ross et al., 1996)*. Higher net infiltration decreases runoff rate and amount, further reducing stream force, carrying capacity and transport volume.

PAM's large molecular size slightly increases the viscosity and surface tension of water *(Malik and Letey, 1992)*. It may also induce laminar flow near the soil-water interface. Further research needs to determine the extent to which these changes affect propagation and transfer of shear forces causing detachment of soil particles.

PAM is used most often as follows *(Anonymous, 1995)*: One of several registered polyacrylamide copolymer products is used. These PAM copolymers are large molecules, containing >150,000 monomer units per molecule. They typically have 18% negative charge density. U.S. products contain <0.05% free (unreacted) acrylamide monomer by weight (<0.025% in Europe).

These water soluble PAMs are metered into irrigation supply ditches, either as concentrated stock solutions, or as dry granules. If dry granules are metered into the flow, one must also provide turbulence in the head ditch just below the point of PAM addition to promote uniform PAM dissolution and distribution. Supply-ditch PAM concentration is brought to 10 ppm (10 g/m^3) *(Lentz et al., 1995)*. The 10 ppm (10 g/m^3) water is delivered to dry furrows at inflow rates that rapidly advance water across the field.

It is essential that no untreated water wet the furrow ahead of the PAM-treated flow. Untreated water destroys soil structure of erodible soils before PAM-treatment, greatly reducing PAM's effect. Wet furrows also reduce infiltration of PAM-treated water through the soil-water interface, delivering less PAM to the thin layer of soil along the wetted perimeter. This reduced application efficiency may also increase PAM-loss, increasing cost and the risk of delivering PAM to non-targeted waters.

When water reaches the end of the furrow, introduction of PAM into the head ditch is stopped. Untreated water is used for the balance of the irrigation. In most production fields the advance period consists of about the first quarter of a total irrigation period, which typically lasts either 12 or 24 hrs. When runoff begins, it is recommended that inflows be reduced to the least needed to sustain a minimal runoff rate.

In five years of testing in Idaho, this application method has required about 1 kg/ha of PAM per treatment *(Lentz and Sojka, 1994b, Lentz and Sojka, 1996ab)*. If furrows are undisturbed between irrigations, erosion protection declines about 50% per untreated irrigation *(Lentz et al. 1992)*. Furrows disturbed by traffic or cultivation must be retreated at the 10 ppm (10 g/m3) rate during inflow advance. Undisturbed furrows typically erode less late in the season *(Brown et al., 1995)*. Vegetation often intrudes into furrow bottoms late in the season. Shading of furrows slows UV deterioration of PAM and physical destruction of polymer bonds caused by soil shrinking and swelling.

Season-long application requirement varies with crop, cultural practices and growing season (number of irrigations). Typically three to seven treated (at 1 lb/ac or 0.9 kg/ha) irrigations will provide excellent seasonal erosion reduction. Granular PAM is available to farmers for $4/lb to $5.50/lb ($9/kg to $12/kg). PAM head ditch applicators can be purchased for a few hundred dollars each. Seasonal costs are low enough to be attractive to most farmers. In addition, costs are offset by eliminated need to construct sediment retention basins, or at least, reduced basin maintenance, and enabling all or some of the area used for settling basins to be returned to production. Furrow reshaping (cultivation), at $3.50-$7/ac ($9-$18/ha), is often eliminated.

Environmental Considerations

Environmental regulation, safety and toxicity issues were reviewed by Seybold (1994) and Barvenik (1994) and are addressed in this proceedings in papers by Deskin (1996) and Barvenik et al. (1996). In the US, anionic PAMs are used extensively in potable water treatment, for dewatering of sewerage sludges, 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 applications. No significant negative impacts have been documented for aquatic, edaphic or crop species for PAM applied at recommended concentrations and rates.

It is important to emphasize the need to use anionic PAMs in these applications. Neutral PAMs and especially cationic PAMs have been shown to have LC50s low enough for concern to certain aquatic organisms, whereas anionic PAMs have not. Cationics are attracted to the hemoglobin in fish gills. Suffocation occurs when fish are placed in otherwise clean waters that contain low levels of cationic PAM. It should be noted, however, that when PAMs are introduced into waters containing sediments, humic acids or other impurities, the effects of the PAMs on biota are greatly buffered *(Buchholz, 1992; Goodrich et al., 1991)*.

PAMs require registration as an irrigation applied soil amendment in most states. The PAMs registered for these uses are usually required to contain no more that 0.05% free acrylamide monomer as a contaminant. The acrylamide (AMD) monomer is a neurotoxin, but at these levels anionic PAMs are approved for a variety of sensitive uses where the high purity PAM is held below various concentration thresholds in the regulated processes.

Since early in the PAM erosion program, significant effort has been exerted to assure that loss of PAM from target fields is minimized, and to determine that any loss that did occur would not result in unacceptable levels to receiving riparian waters. Lentz et al. (1996) developed a sensitive flocculation assay to determine PAM concentrations in surface waters at concentration as low as 0.25 ppm. Subsequently the assay was employed to follow the amounts of PAM lost from treated fields.

Lentz and Sojka (1996b) determined that when applied according to the NRCS standard, PAM losses did not exceed 5% of applied amounts. Furthermore, the small amount lost from fields was adsorbed onto suspended sediments encountered in return flows (continued flocculation) and onto exposed surfaces of return-flow ditches. PAM concentrations fell below detectable limits in 300-1500 ft (100 to 500 m) of travel in tail water ditches, depending on seasonal factors.

Barvenik (1994) stated "...dry anionic PAMs of the type that are effective in soil systems show no toxicity to fish (LC50 >100 mg/L)." It should be emphasized that the LC50 did not equal 100 mg/L, but rather, was undetermined, because 50% lethality never occurred in that concentration range. Hence, the "greater than" symbol is used to indicate that a relatively high threshold of tolerance exists, and that further tests at higher concentrations were not conducted to find the lower limit.

In assessing the risk of PAM-loss to return-flow riparian receiving waters, several facts are apparent. The 10 ppm PAM concentration recommended in the NRCS standard for treatment of the advancing stream is itself one-tenth the reported >100 mg/L value. The average PAM concentration of waters leaving a field from a 24 hr irrigation is 1/1000 the >100 mg/L value, or about 0.1 ppm, which is actually below the current detectability of PAM in natural waters. These calculations assume following the NRCS PAM application standard of 1 lb/ac applied in the stream advance only, with irrigation water applied at a rate of 200 gpm over the course of the irrigation and assuming a 5% loss of applied PAM. Furthermore, if 10% of irrigation inflows in a watershed were PAM-treated, that implies that the average concentration of PAM would be 0.01 ppm in return flows (or 1/10,000 the >100 mg/L value).

As stated earlier, data has shown that PAM continues to adsorb to surfaces and to flocculate suspended particulates in tailwater streams. In reality, other non-agricultural (ie. non-treated) inflows will further dilute these values.

Regarding concern for AMD content, the same simple dilution scenario would limit AMD concentration to 0.000005 ppm in return flows, where 10% of all inflows were being treated on a given day. It should be noted that AMD has been shown to decompose rapidly in biologically active systems. Numerous citations to this effect were reviewed by Barvenik (1994). This suggests AMD concentration would be further reduced beyond the effects described above.

Decomposition of both polyacrylamide and acrylamide monomer in soil and water systems has been previously reported and were also reviewed by Barvenik (1994). Both compounds are susceptible to varying degrees of biological and photochemical degradation. In addition the large polyacrylamide molecule is slowly degraded by physical breakage due to mechanical forces such as abrasion, freeze-thaw action, and particle shrinking and swelling. Acrylamide monomer, which is strictly limited by U.S. regulation in these PAMs to no more that 0.05% by weight, decomposes in hours in soils and water. Polyacrylamide in bulk soil systems has been reported to decompose at a rate of about 10% per year *(Azzam et al., 1983)*. These are probably conservative estimates for PAM applied only at the furrow surface.

Since furrow irrigation-applied polyacrylamide remains unincorporated into the soil volume for a prolonged period after application, UV radiation is high and mechanical effects are intensified. These are actually the primary degrading factors once soil micro-organisms have removed the easily metabolized amide functional groups as a nitrogen source. Finally, because the amide functional group is rapidly metabolized as a nitrogen source by soil microbiota, further breakdown of the polyacrylamide molecule does not produce a renewed source of acrylamide monomer. Others have also stated that breakdown of polyacrylamide to release acrylamide is thermodynamically impossible *(MacWilliams, 1978)*. Finally, recent work has shown that polyacrylamide application following the NRCS standard does not adversely affect soil microbial processes or population dynamics *(Watwood and Kay-Shoemake, 1996; Kay-Shoemake and Watwood, 1996)*. Furthermore, acrylamide monomer is not absorbed at detectable levels into harvested plant tissue, even when applying polyacrylamide at rates of 1000 lb/ac. *(Barvenik et al., 1996)*.

Halting erosion prevents exposure in furrow bottoms of soil not treated with herbicides, thus reducing potential late-season weed problems. Applied pesticide and fertilizer inputs are better retained on the field, with less loss by erosion to receiving waters or riparian areas *(Agassi et al., 1995; Singh et al., 1996; Bahr et al., 1996; Bahr and Steiber, 1996)*. Because virtually no soil is suspended in flowing water, the runoff contains far lower nutrient and pesticide levels, furthermore the reduced organic substrate greatly lowers BOD *(Lentz and Sojka, 1994b; Bahr et al., 1996)*.

PAM was used to increase furrow inflows while still controlling erosion *(Sojka et al. 1995; Sojka and Lentz, 1996)*. This reduced water advance time, allowing more uniform infiltration from upper to lower field ends, improving potato yield and grade, and reducing the risk of nitrate leaching from over-irrigating upper reaches.

Important User Considerations

For the farmer-user, it is useful to synthesize these numerous observations into a concise list of considerations. These considerations are itemized below. For better understanding of some of the statements listed, it may be necessary to read additional papers presented or cited in these proceedings. Several user-oriented publications are available to help farmers implement PAM application *(Sojka and Lentz, 1994b; Lentz et al. 1995; Lentz and Sojka, 1996cdef)*. Farmers should also be familiar with the current NRCS application standard *(Anonymous, 1995)*.

1. **Purchase only polyacrylamide (PAM) labeled for this use by your state** (if registration and labeling are required). Purchasing from known reputable agricultural chemical suppliers may avoid acquiring ineffective or dangerous formulations inappropriate for this use.

2. **By law, irrigation PAMs should contain no more than 0.05% free acrylamide monomer (AMD) by weight** (in Europe, no more than 0.025%). The specific PAM copolymer formulation should be anionic (NOT cationic). The charge density may vary from 8-30 %; a value of 18% is typical. Molecular weight can vary, but higher molecular weights are usually more effective than lower for equal amounts of material applied and result in less AMD application for equal erosion control. Recent literature suggests that molecular weights of 12-15 Mg/mole are optimal.

3. **The PAMs designated for this use are regarded as "water soluble" or "linear" or "non-crosslinked" PAMs.** Do not purchase "crosslinked" or "super water-absorbent" PAMs for use in irrigation water. The latter do not act the same as linear PAMs in water or in the soil, and they have a different function and purpose.

4. **The PAM you purchase should have a reasonably high analysis.** PAMs purchased as dry "granular," "bead" or "powder" from reputable chemical companies will usually contain 80% or higher active ingredient (ai). Remember that what you pay for as PAM depends on the amount of active ingredient purchased. You may be purchasing convenience of application or some other consideration if the active ingredient content is lower, but be aware of how much you are spending on PAM per se.

5. **As of this writing, PAMs come formulated for use in four major forms,** dry bead or "powder" (>80 % ai), predissolved aqueous concentrate (usually around 3% ai), compressed blocks or cubes (> 80 % ai) for suspension in flowing ditches or furrow streams, oil-emulsified concentrates (usually 30 or 50% ai). Each form has various advantages and drawbacks.

- **Powders** are easy to store, transport and meter into head ditches, but require vigorous agitation to make them dissolve. Numerous inexpensive metered powder applicators are available. Powder applicators should be placed on the head ditch immediately above a source of substantial turbulence. Location of the applicator on the head ditch at 100 to 300 ft above the first irrigated furrow provides mixing opportunity. Powder applied in turbulent fountains with weed screens must apply the PAM below the screen on the outflow side to avoid clogging the screens. Placement of powder patches directly in furrows has been successful for erosion control, but infiltration effectiveness and on-field PAM retention are not yet thoroughly understood. Patches can be buried or broken up and washed downstream, or missed by the stream flow depending on siphon, spigot or gate stream size, pattern and impact point.

- **Aqueous Concentrates** are limited as to the strength of concentrate that can be prepared before viscosity impairs practical use. The main advantage of ACs is better dissolving in stock solutions or in the head ditch than powders. The disadvantage is unknown storage effects and low ai for weight and volume of material handled.

• **Blocks and Cubes** are easy to handle and place, but do not dissolve uniformly. Cubes placed in furrows can wash downstream. Erosion and infiltration performance has been more variable than with other application methods.

• **Emulsified Concentrates** provide the same advantages as ACs, but achieve ten times the ai, greatly reducing volume and weight transport considerations. ECs also have much lower viscosity than ACs, despite their higher ai. ECs may be suitable for individual furrow application via a drip line at the upper field end; current tests are underway but are not yet conclusive. Shelf life and storage conditions may be factors for adverse climates. Metering is somewhat simplified, but temperature related viscosity changes may affect calibration in some areas and at some times in the season.

6. **Be aware that, although all PAMs are polymers, NOT ALL POLYMERS ARE PAM.** The media's recent high interest in PAM and the many stories reporting the effectiveness of PAM have often referred to the PAM only as "polymer" or as "the polymer." This has encouraged some entrepreneurial exploitation of the word "polymer" in the agricultural community. The results achieved with the specific class of PAMs described above are not known to be achievable with other affordable chemical polymers.

7. **When applying PAM to furrows, the first drop of water to reach the furrow should already be at the recommended 10 ppm concentration.** If dry soil first becomes wet by contact with untreated water, the soil structure and pore geometry will be severely degraded almost immediately. PAM flowing down the furrow only a few seconds later will have a greatly diminished ability to reduce erosion or improve infiltration. PAM can stabilize existing structure, but it cannot create structure. Similarly, PAM cannot remediate existing soil structure damage from other effects such as compaction etc. It has also been observed that when soils are damp (e.g. following a rain shower), or if the soil water content is higher than normal for an irrigation, PAM effectiveness is reduced. This is probably because of reduced infiltration of the PAM-treated water that normally carries PAM to surface aggregates. It is also possible that damp soil (water films on aggregates) prevents intimate adsorption of PAM under these conditions.

8. **If water in the head ditch is high in sediments, application of PAM to the head ditch may settle enough sediment in the ditch to cause problems.** Farmers with consistently high sediment concentrations in their water supply have had good success with creation of small sedimentation ponds at the upper end of the field to catch sediment immediately below the point of PAM application to the supply stream. This prevents overflow of head ditches and clogging of siphon tubes. If sediment load is particularly high, the PAM application rate may need to be slightly increased to compensate for deactivation of PAM by the flocculated sediment. Some farmers claim that cutting the PAM concentration in the head ditch to 5 ppm in the presence of high sediments gives the desired performance in the furrow, but reduces sedimentation in the head ditch. The rationale is that the optimal concentration for flocculation is higher than for erosion control. None of these approaches has been studied in controlled experiments. The use of in-furrow application methods (cubes, powder-patches, drip lines) help spread inflow sediment on the field where it causes fewer problems.

9. **To date, published data confirm that use of 10 ppm in the advancing furrow stream (only) provides the greatest erosion control with the least PAM used and the least PAM lost from the treated field.** Low rates of PAM continuously applied may be more costly, and lead to environmental risks in some situations. Farmers should also note that too high a PAM concentration, or too much PAM applied can eventually seal furrows, limiting infiltration. At very high concentrations PAM can stabilize suspension of particulates, rather than flocculating them. Therefore, farmers are strongly encouraged to adhere to the NRCS standard, and to be very cautious in their approach when local conditions prompt attempts to deviate from the standard.

10. **Because PAM alters surface sealing, resulting in more pervious seals, the net infiltration rate of PAM-treated fields will be higher than in untreated fields.** Farmers will need to increase their inflow rates to prevent furrow stream advance times from becoming excessively long. Farmers are strongly encouraged to take advantage of PAM's erosion preventing properties to GREATLY increase inflow rates (two to three times). Doubling or tripling inflows will greatly reduce stream advance times and significantly improve infiltration uniformity while still greatly reducing erosion. NOTE HOWEVER, that to take best advantage of this new management option provided by PAM, the farmer should also cut back inflow rates to the minimum sustainable inflows once water has advanced and runoff begins. This is a higher order of management, but data confirm that crops sensitive to irrigation uniformity, such as Russet Burbank potatoes, can see significantly increased yield and quality, providing a substantial economic incentive for the change in management.

Conclusions

PAM-use for erosion control can be a formidable tool for achieving agricultural sustainability. It provides a potent environmental benefit. It halts furrow irrigation erosion by about a half ton of soil per oz. (16 kg/g) of PAM used. It removes most sediment, phosphorus and pesticides from return flows, and greatly reduces return flow BOD. It increases infiltration, enabling water conservation. Reduced sediment and nutrient loading of riparian areas can ultimately be expected to reduce the frequency and intensity of algal blooms, reduce turbidity and sedimentation of stream bottoms, decelerate reservoir sedimentation and wear on hydropower machinery.

PAM-use allows changes in furrow management that should provide more uniform water application. Coupling PAM-use with improved water management (e.g. accelerated inflow advance to improve field infiltration uniformity) is expected to reduce leaching of applied nitrates and to increase crop quality and net returns.

Detailed cost analyses of PAM-use are not yet available, but we do know that expenses related to furrow reshaping and sediment pond or ditch cleaning are reduced. PAM-use also conserves fuel, lessens air pollution and reduces equipment wear and labor.

Perhaps most importantly, farmers have been enthusiastic in their adoption of this new practice. Because there is enthusiasm for the practice, its potential for implementation and, hence, erosion and pollution reduction is particularly promising.

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Five-Year Research Summary Using PAM in Furrow Irrigation

R. D. Lentz and R. E. Sojka

A previous conference paper (Sojka and Lentz, 1996) presented an historic perspective and some general results of PAM investigations conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, Idaho. This paper presents the experimental methods and summarizes results from those studies, conducted over a five-year period.

Studies initiated since 1991 determined best mode of PAM application, established PAM's effectiveness under different furrow irrigation scenarios and sought to define its potential environmental impacts *(Lentz, et al., 1992; Sojka and Lentz, 1993, Sojka et al., 1994; Lentz, 1996; Trout et al., 1995)*. Kimberly ARS field experiments initially sought to determine the PAM application method that most efficiently and effectively controlled furrow-irrigation induced soil loss and infiltration. We investigated the following PAM application parameters:

PAM form — dry granular, stock solution, oil emulsion

PAM type — polymer charge type, charge density, molecular weight

Application method — standard: PAM added to irrigation water; non-standard: PAM applied to furrow soil

Application strategy — timing, rate, and period of PAM application

Irrigation water quality —effect of a water's total salt or sodium adsorption ratio on PAM effectiveness

Experiments that examined effects of PAM type on furrow processes are presented in a separate paper *(Lentz and Sojka, 1996)*. A series of studies documented PAM's usefulness over a range of furrow-irrigated field conditions. PAM was tested on different soils, furrow slopes, and using different furrow inflow rates and irrigation waters. Several studies examined PAM's environmental impacts. We first developed an analytical procedure for measuring PAM concentration in irrigation water to document the fate of PAM applied to furrow irrigation inflows. A permanent PAM field site was established to study effects of long-term PAM applications on soil properties, microbiology *(Watwood and Kay-Shoemake, 1996)*, productivity and solute leaching. Another experiment documented PAM s influence on field runoff water-quality. Finally, a plot treated with excessive PAM additions was used to determine the potential for acrylamide-monomer accumulation in crop-tissue *(Barvenik et al., 1996)*.

Materials and methods

Field studies were conducted at the USDA-ARS Northwest Irrigation and Soils Research Laboratory at Kimberly, ID, and on fields of cooperating farmers near Filer, Hansen and Emmett, ID. Soils included Durixerollic Calciorthids, Xerollic Haplargids, and Haploxerollic Durargids. Surface soils in these studies were similar, though subsoils