PAM in Irrigated Agriculture: Processes and Soil-PAM Interactions Influencing Canal Sealing

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Introduction

To identify or develop alternative polymers, which may successfully replace polyacrylamide (PAM) as a reservoir or canal sealant, it is important to understand the nature of the sealing processes in earthen irrigation water structures and how PAM interacts with those processes to alter water seepage. The purpose of this paper is to review mechanisms that influence water infiltration into unlined irrigation canals and ponds and consider how PAM interactions with soils may alter these processes.

Sealing Mechanisms

Sediment

It is known that sediment in ponded and flowing water can reduce infiltration and seepage losses (Trout *et al*., 1995; Bouwer *et al*., 2001). Three types of sediment-derived seals have been identified: thick-layer, thin-layer, and wash-in seals (Lentz and Freeborn, 2007).

Thick-layer Deposit. Gravitational settling of suspended and bedload sediment produces a horizontally extensive depositional layer several centimeters to tens of centimeters thick above the original soil surface. This layer is subject to compressive forces from the soil layer's own mass and that of overlying water (Behnke, 1969; Bouwer and Rice, 1989; Bouwer *et al*., 2001). The sediment particles in these deposits can vary widely in size. In ponds, incoming sediment composed of various particle sizes produced a graded depositional layer that was less permeable than that formed by uniform sediment (Bouwer *et al*., 2001).

Thin-layer Seal. Infiltration inhibition by the thick layer relies upon the force of gravity to cause the deposition, accumulation, and adherence of thick sediment layers onto the original soil surface. Sealing produced by very thin sediment deposits has also been reported. Suspended sediment carried to the wetted perimeter in flowing water, and to a limited extent by gravitational settling, can form a thin (0.1 to 2 mm), continuous, low-conductivity depositional seal on the original soil surface (Shainberg and Singer, 1985; Brown *et al*., 1988; Segeren and Trout, 1991).

In comparison to thick-layer deposition, in which substantial sediment accumulates and adheres to the stream bottom under force of its mass, the particles comprising a thin seal are held in place and consolidated, along with adjacent soil below, by negative water pressure below the soil surface (Brown *et al*., 1988; Segeren and Trout, 1991). This explains why fine soil particles that would otherwise remain suspended in the water stream adhere to the wetted perimeter upon contact. Consolidation under negative pressure causes additional conductivity reductions (Trout, 1990). Thin-layer seals can form within minutes after flow initiation (Brown *et al*., 1988; Segeren and Trout, 1991). The nature of the suspended sediment influences seal development. Dispersed fines produce high bulk density surface deposits with oriented clay layers, while flocculated fines form a more porous seal, owing to the random orientation of the particles (Shainberg and Singer, 1985; Southard *et al*., 1988).

Wash-in Seal. Unlike the previous two, the third mechanism does not require that a continuous depositional layer form over the soil surface. Instead, infiltrating water sweeps suspended particles into surface soil pores. Gravitational forces cause the particles to be deposited on the upper surfaces and ledges of soil particles within the matrix, filling in crevices and concavities on the particles (Ives, 1989). Dispersed clays suspended in infiltrating water can move as much as 5 mm into loamy soils, forming oriented clay deposits that plug finer pores (Southard *et al*., 1988). This mechanism, referred to as "wash in" or "interstitial straining" (Behnke, 1969), has been identified in sands (Hall, 1957) and soils subject to raindrop impact (McIntyre, 1958) and ponding of turbid water (Shainberg and Singer, 1985; Houston *et al*., 1999).

Several of these sealing processes may be active in some flow regimes, while certain mechanisms may dominate in others. For example, a thin-layer seal may be relatively more important in irrigation furrows or during initial filling of irrigation canals, when soils are drier and soil water potential gradients are steep. Some of the major factors that influence the complex sediment sealing process are the size distribution of solids present in the water and soil, the concentration of the sediment in the water, and the velocity of water moving vertically toward the soil surface (Behnke, 1969; Trout *et al*., 1995).

Organic Particulates

Organic particulates present in secondary effluent, industrial wastewaters, or wastewaters produced by confined animal feed operations can act via similar physical mechanisms to reduce seepage through soil at the wetted perimeter. Larger organic particles tend to be deposited as a mat over the soil surface, particularly over finer-textured soils (DeTar, 1979; Houston *et al*., 1999), while smaller organic particles (relative to the sizes of soil pores in the seepage face) pass through or are trapped in the upper few centimeters of the soil (Barrington and Madramootoo, 1989). DeTar (1979) and Cihan *et al*. (2006) found that seal efficacy was more sensitive to the amount of organic solids present than to the saturated hydraulic conductivity of the untreated soil. Organic solids tend to seal finer-textured soils more rapidly than coarser soils (Rowsell *et al*., 1985).

Microorganisms

Applied organics can also stimulate soil microorganism growth. Large accumulations of bacteria and algae (McCalla, 1945; Gupta and Swartzendruber, 1962; Vandevivere and Baveye, 1992, Ragusa *et al*., 1994) or their long-chained, high-viscosity polysaccharide exudates (Avnimelech and Nevo, 1964) have also been shown to reduce seepage through soil linings.

Processes Opposing Sealing

Any process that scours sediment previously deposited on the canal or reservoir wetted perimeter attacks the thin depositional layer that has formed over an infiltrating surface, perforates the infiltration-inhibiting layer created near the soil surface, or alters macropore structure may increase infiltration and enhance seepage losses. In some cases, these processes allow stored or transported water to contact newly exposed, deeper soil strata whose original pore structure is intact (Lehrsch and Kincaid, 2006). Erosive processes are more likely to occur in channeled flows than in static ponds.

Channel downcutting may occur in response to a change in the channel hydraulics, such as velocity or shear stress, or to a change in sediment load (Leopold *et al*., 1964; Lentz and Freeborn, 2007). Thus, channel scour and fill processes may arise at the same channel location at different times (Leopold *et al*., 1964). Erosion and abrading of stream beds alter channel surface morphology, disrupt previously formed seals, expose new soil surfaces, and increase seepage. Channel wall erosion and sloughing are important processes in channelized flow (Lentz and Freeborn, 2007; Smith and Dragovich, 2008) and are responsible for exposing new soil surfaces to inundation and infiltration.

Animal disturbance caused by burrowing animals such as rodents and worms penetrate any surface seals that may have formed and is an important avenue for seepage flow (Kemper and Trout, 1987; Kahlown and Kemper, 2004). The hooves of livestock tracking through irrigation canals and ponds can perforate existing surface seals and increase seepage potential.

Macropore flow can develop in continuous pores formed from old root channels or insect burrows, which are open to the soil surface. Poiseuille's law describes laminar water flow through a cylindrical soil pore (Hillel, 1998) as

$$Q = (\pi r^4 \, \Delta P) / (8\eta L) \qquad (1)$$

where Q = water flux through a cylindrical pore, r = pore radius, ΔP = change in hydraulic head, η = viscosity of the fluid, and L = pore length. Because the water flux in the pore is directly proportional to the fourth power of the pore radius, infiltration through a few large pores substantially increases seepage losses. In silty soils under relatively large hydraulic heads, the velocity of flow through macropores can be sufficient to cause erosion and enlargement of the pore's cross section. The resulting piping greatly increases seepage losses. In some cases, macropores develop in depositional seals along the channel perimeter and enhance seepage losses. Such pores may result from entrapped air escaping from the soil and be only a few millimeters deep, but are sufficient to penetrate the thin depositional seal and provide a pathway for surface water to rapidly infiltrate (Lentz and Freeborn, 2007).

Aqueous Pam Interactions with Soil

In furrow irrigation applications, PAM is commonly dissolved in flowing water at concentrations of 1 to 10 mg L^{-1} using brief, or continuous, applications (Lentz and Sojka, 2000). Polyacrylamide-soil interactions even at these dilute concentrations are substantial.

Flocculation of Suspended Sediments

Polyacrylamide flocculates sediment suspended in the water stream, increasing the mean diameter of soil particles entrained and deposited in downstream reaches (Ben-Hur and Keren, 1997; Lentz *et al*., 2002). However, as the polymer concentration increases relative to sediment load, PAM reverses its activity, and instead functions as a particle dispersant (Figure 1).

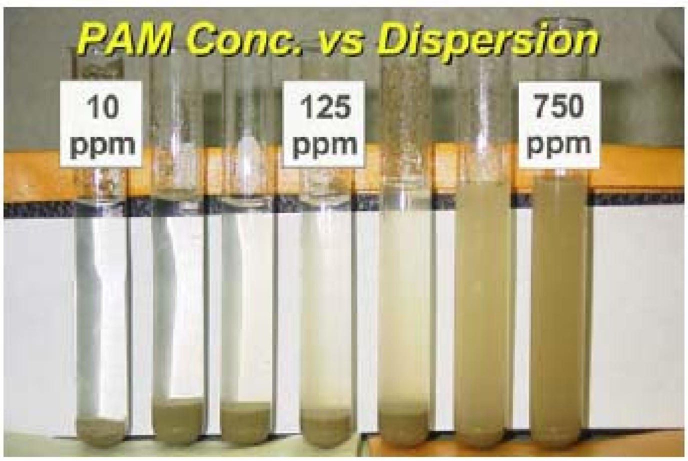

Figure 1. Test series showing how PAM concentration affects the polymer's ability to flocculate or stabilize sediment suspensions.

Stabilizing Soil Structure and Porosity

Polyacrylamide stabilizes soil structure and pores (Mitchell, 1986; Sojka *et al*., 1998b); wet aggregate stability percentages of amended soil increase with increasing treatment PAM concentration from 0 to 50 mg L^{-1} (Helalia and Letey, 1989; Nadler *et al*., 1996). This stream channel stabilization helps maintain soil structure and pore integrity, inhibits soil dispersion and entrainment, and delays or prevents depositional seal formation over the wetted-perimeter, resulting in higher infiltration rates than that in untreated channels (Lentz *et al*., 1992; Lentz and Sojka, 1994; Trout *et al*., 1995). Conversely, if sediment-ladened waters are treated with PAM, the flocculated sediment may be deposited over the stabilized surface layer, negating the latter’s infiltration enhancements.

Viscosity Effects on Soil Water Flow

Increasing PAM concentration from 0 to 25 mg L^{-1} in water slightly increases the solution’s viscosity when measured by a Cannon-Fenske-type viscometer, but relative viscosity increases are greater as PAM concentrations rise above 25 mg L^{-1} (Lentz, 2003). These determinations were derived from flow measurements made in 0.25- to 1-mm-diameter tubes. Polymer solution viscosity is more sensitive to PAM concentration changes when measurements are made through smaller-diameter pores like those common in soil (Malik and Letey, 1992). This increased sensitivity has been attributed to extensional viscosity effects (Song *et al*., 1996) and dynamic adsorption-entanglement processes (Grattoni *et al*., 2004). Since flow in soil pores is inversely proportional to water viscosity (Equation [1]), PAM amendment tends to reduce infiltration and conductivity of treated water through soil (Mitchell, 1986; Malik and Letey, 1992; Falatah *et al*., 1999; Lentz, 2003; Ajwa and Trout, 2006).

Other PAM-Soil Interactions

Polyacrylamide-treated soils may show a slightly enhanced soil wettability compared with untreated soils, although this may vary with soil texture (Hartmann *et al*., 1976). It is also known that dilute concentrations of high molecular weight polymers reduce fluid drag in turbulent pipe flow (McCormick *et al*., 1990). In soils, drag reduction effects would likely be restricted to flow in larger soil pores or macropores. Larger pores may experience turbulent flow regimes, whereas laminar water flow tends to prevail in smaller soil pores (Hillel, 1998).

Effects of Polymer Characteristics on PAM Activity

The magnitude of the PAM effect on soil stabilization, flocculation, or water viscosity generally increases with increasing size of the hydrated PAM molecule in solution, which increases with its molecular weight and charge density (Kulicke *et al*., 1982; Nadler *et al*., 1996; Falatah *et al*., 1999), and decreases with increasing salt concentration in the water (Tam and Tiu, 1993). However, the hydrated PAM radius at which maximum flocculation occurs can differ depending on sediment characteristics and sediment and polymer concentration (LaMer and Healy, 1963; Hocking et al., 1999).

PAM Effects on Sealing Processes

Thick-layer Deposit. If suspended sediment is present in irrigation canals and reservoirs, the addition of PAM will promote settling of suspended sediment present in the water column. If the sediment supply is continuous, a prolonged PAM application could result in extensive thick-layer sediment deposits. The PAM amendment may make these accumulations more cohesive, stabilizing them against flow velocity changes that may otherwise tend to scour such deposits (Lentz and Freeborn, 2007).

Thin-layer or Depositional Seals. Polyacrylamide research at the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) laboratory in Kimberly, ID, addresses sealing mechanisms directly because surface sealing of their silt loams is the main process that reduces infiltration during furrow irrigation. Polyacrylamide's ultimate effect on furrow infiltration results from its combined influence on pore integrity, seal formation, and water viscosity (Sojka *et al*., 1998a; Ajwa and Trout, 2006). For example, when Lentz and Sojka (2000) applied PAM continuously to furrow stream inflows, a 2 mg L^{-1} PAM application effectively stabilized soil and reduced seal formation (99 percent reduction in sediment loss relative to controls), whereas the 0.5 mg L^{-1} PAM treatment less successfully stabilized furrow soils (75 percent sediment loss reduction), yet produced an infiltration gain equal to that of the 2 mg L^{-1} treatment (Figure 2). The difference in soil stabilizing power of the two treatments apparently was offset by viscosity effects.

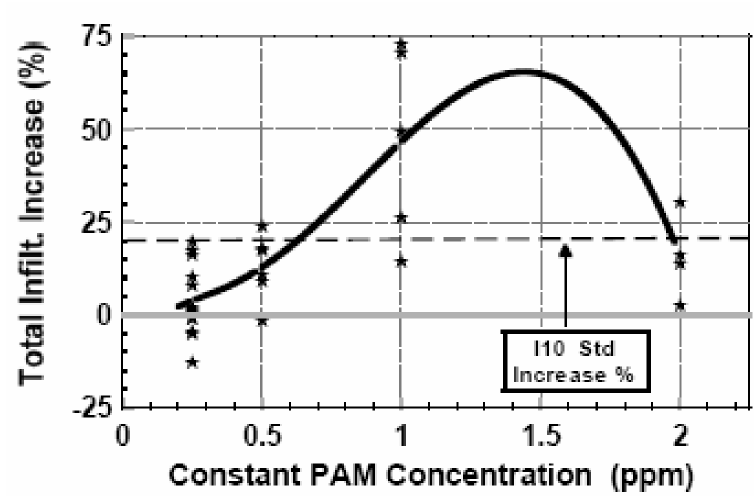

Figure 2. Influence of concentration on net infiltration increase obtained using continuous PAM applications (Lentz and Sojka 2000).

However, the infiltration benefit was not realized 1) if soil structure was degraded prior to PAM application by wheel traffic or repeated irrigations (Sojka *et al*., 1998b; Lentz *et al*., 2000), or 2) for inherently stable soils with large pores and not susceptible to depositional seal formation (Trout and Ajwa, 2001; Ajwa and Trout, 2006).

Thin-layer depositional seals formed by flocculated sediments are more permeable than those formed by nonflocculated particles (Southard *et al*., 1988; Sojka *et al*., 1998a), which suggests that PAM treatment of sediment-bearing flows in unlined channels should result in greater infiltration and seepage losses than for untreated flows. Compared to controls, deposition seals in furrows treated with medium and high molecular weight PAM contained greater numbers of flow-conducting pores with diameters of less than 0.30 mm and less than 0.75 mm (Figure 3).

Wash-in Seal. Polyacrylamide can influence the wash-in process through its effect on stabilizing surface structure and porosity and by altering the number and size of suspended particles in the water. Polyacrylamide preserves large surface pores. While water flux through a simple cylindrical pore is directly proportional to the fourth power of its radius (Equation [1]), the pore's wall area is directly proportional to the pore radius. Thus, in larger pores, the influx of water and sediment in proportion to the pore wall area is far greater than that in small pores. As a consequence, larger-diameter pores may be more susceptible to wash-in than small pores.

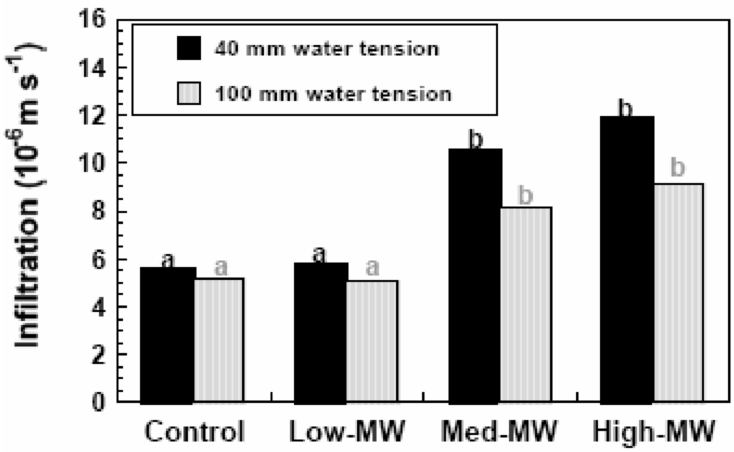

Figure 3. PAM molecular weight effects on water infiltration through semi-consolidated furrows and depositional seals at water tensions of 40 and 100 mm. (From Lentz *et al*., 2000).

Polyacrylamide also flocculates sediment suspended in the water stream, increasing the mean diameter of soil particles present in the water (Ben-Hur and Keren, 1997; Lentz *et al*., 2002). Lentz and Freeborn (2007) reported that clay floccules created by PAM ranged in size from 50 to 400 µm depending on the concentration ratio of PAM to sediment in the water. In contrast, silt flocs were only 20 to 30 µm in diameter. For particles suspended in streamflow to enter surface pores, their horizontal momentum must be overcome by forces originating in the flow of downward-moving water draining through the pore. Since a particle's horizontal momentum is proportional to its mass, the larger particles are less likely to be redirected into the surface pores with infiltrating water. In addition, the larger soil floccules created by PAM will be too large to enter some soil pores. If the larger floccules dominate the system, then wash-in processes may be active only in a relatively small number of the greatest-sized pores. Thus, PAM's effect on wash-in seal processes may vary depending on several factors related to PAM and sediment concentration and suspended soil particle size.

Influence of Sediment Type

The type of sediment suspended in the flowing stream also influences how PAM affects seepage rates. Lentz and Freeborn (2007) measured seepage loss from mini-flume channels for PAM-treated inflows containing either silt or clay-sized sediment (Figure 4). Note that sealing was immediate with clay, but more gradual for silt, especially at higher silt concentrations. Also, the effect of increasing sediment content on seepage loss differed for clay and silt particles.

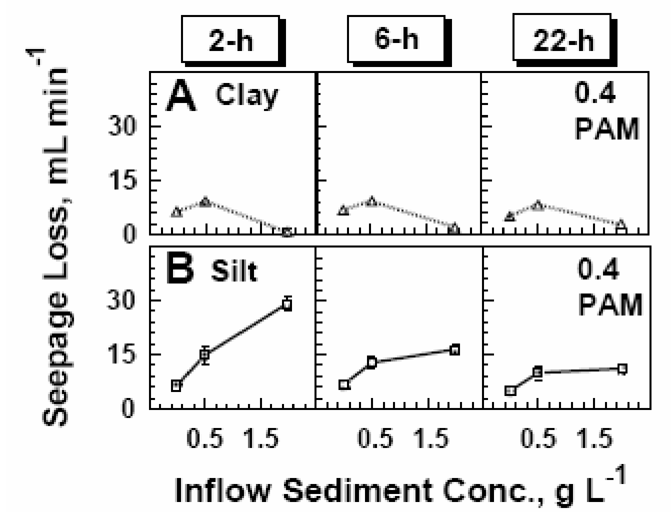

Figure 4. Effect of inflow clay (A) or silt (B) concentration on channel seepage loss rates for inflow PAM concentration of 0.4 mg L^{-1} at 2-, 6-, and 22-h sampling times.

Effect of PAM Application

The effect of PAM on seepage rates can differ depending on how the polymer is applied. In a silt loam soil column study, a 0.1 percent (wt/wt) PAM solution was applied immediately before water was ponded on the surface (wet treatment) or applied and allowed to dry for 24 h before inundation (dry treatment). This was done with or without sediment additions to the ponded water. Sediment was mixed into the ponded water during the first 6 h of the test and measurements were continued for several days thereafter. The effect of treatment method on seepage rate was similar for sediment and no-sediment treatments. Early in the seepage test, the wet treatment had a lower seepage rate than the dry (Figure 5). Later, however, the wet treatment produced greater seepage losses than the dry. The addition of sediment tended to reduce seepage rates. When the experiment was repeated with a sand soil column for the sediment treatment, there was no difference between the wet and dry treatments (Figure 6). Thus, soil structure and/or texture appear to interact with application method in controlling seepage rates.

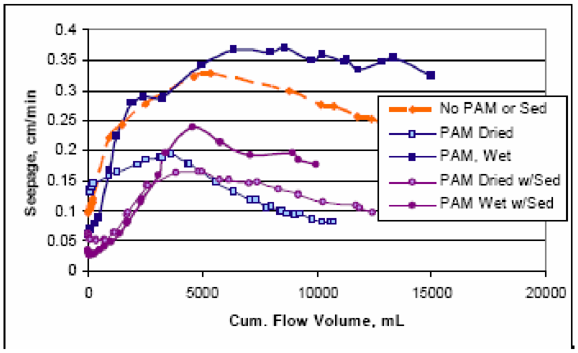

Figure 5. Seepage rate from medium-textured soil treated with 0.1% (wt/wt) PAM solutions and allowed to dry or not (wet), both with and without sediment.

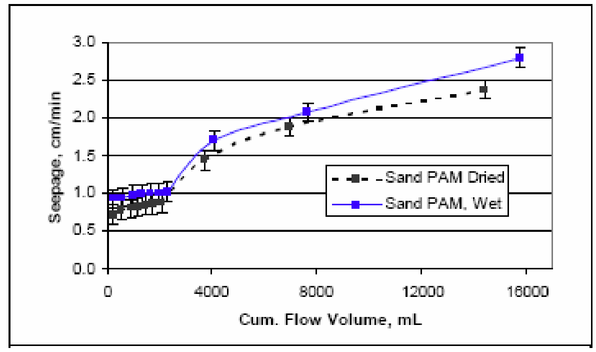

Figure 6. Seepage rate from sandy soil treated with 0.1% (wt/wt) PAM solutions allowed to dry or not (wet), with sediment added.

Cost Effectiveness

One way to evaluate the economic value of seepage control treatments is to examine the cost of irrigation water saved by the treatment, relative to its value to the producer (Lentz and Kincaid, 2008). One assumes that the seepage treatments are applied to irrigation canals and reservoirs during droughty periods when water is in shortest supply. The value of the saved water can be determined from the increase in production expected from each millimeter of additional water supplied to a deficit irrigated crop. Lentz and Kincaid (2008) made these calculations for water-soluble PAM applied at a rate of 0.016 kg m^{-2}, cross-linked PAM applied at a rate of 0.2 kg m^{-2}, and a 36-mil membrane-geotextile treatment. In spite of its presumed shorter treatment lifetime, the extra water made available by the water-soluble PAM (WSPAM) application cost less per unit water saved than that provided by the longer-lasting membrane-geotextile treatment (Table 1). Furthermore, the value of water saved in terms of increased crop yield was 7 to 44 times greater than the cost of WSPAM needed for application. This analysis underscores the potential value of the PAM seepage control solutions to producers.

Conclusions

PAM can substantially influence seepage processes in earthen canals and ponds; however, to maximize seepage reduction, it is important to understand how the polymer interacts with soil to affect infiltration. The relative complexity of these PAM-soil interactions likely explains why seepage reduction obtained from treatments tested in the field are often lower than those obtained from equivalent laboratory tests. More study is needed to better understand the character and dynamic nature of processes affecting seepage in canals and reservoirs. Polyacrylamide can be a cost-effective seepage-reduction tool, especially when untreated water supplies cannot provide the entire crop needs and where short-term seepage control is desired.

Table 1. Estimated costs and benefits of water-soluble PAM (WSPAM) and cross-linked PAM (XPAM) treatments in comparison to a membrane-lined pond (Lentz and Kincaid, 2008).

<table>
<tr><th rowspan="2"></th><th rowspan="2">Expected treatment lifespan†</th><th rowspan="2">Water saved over lifespan of treatment ‡</th><th rowspan="2">Cost of combined product §</th><th colspan="2" rowspan="2">Cost of water saved over treatment lifespan ¶</th><th colspan="2">Estimated yield increase due to additional water #</th><th colspan="2">Value of increased crop yield due to additional water ††</th></tr>
<tr><th>Corn</th><th>Wheat</th><th>Corn</th><th>Wheat</th></tr>
<tr><td>Treatment</td><td>years</td><td>ha m</td><td>--</td><td>$ (ha mm)$^{-1}$</td><td>$ (ac ft)$^{-1}$</td><td colspan="2">T (ha mm)$^{-1}$</td><td colspan="2">$ (ha mm)$^{-1}$</td></tr>
<tr><td>0.2 XPAM + NaCl</td><td>2</td><td>2.3</td><td>$7 to $12 kg^{-1}</td><td>1.23 to 2.10</td><td>152 to 259</td><td></td><td></td><td></td><td></td></tr>
<tr><td>WSPAM</td><td>2</td><td>2.3</td><td>$8.80 kg^{-1}</td><td>0.12</td><td>15</td><td rowspan="2">0.025</td><td rowspan="2">0.0033 to 0.0125</td><td rowspan="2">5.23</td><td rowspan="2">0.85 to 3.20</td></tr>
<tr><td>36-mil polyethelene membrane + geotextile cover</td><td>17</td><td>70.2</td><td>$8.18 m^2</td><td>0.22</td><td>27</td></tr>
</table>

†Lifespan of PAM treatments was limited to length of monitoring, actual duration may be longer. Lifespan of membrane treatment is mean of estimated range.

‡ Based on two seepage zones in the reservoir: side slope positions (50 % of total area, total seepage water saved equal to that in control plots, 19.6 m per 2-y period), and reservoir bottom position (50 % of total area, with seepage water saved equal to 3.2 m per 2-y period).

§ Membrane treatment was assumed to have a 90 percent seepage reduction efficiency.

¶ Price of XPAM ranges more widely than WSPAM due to variable supply and demand conditions. Cost of membrane treatment includes $0.11 m^2 yearly maintenance fee. Estimate does not include installation costs.

Reported from the literature for corn (Payero *et al*., 2006) and wheat (Ali *et al*., 2007).

†† Based on current local corn price of $209 Mg^{-1} ($5.32 bu^{-1}) and wheat price of $257 Mg^{-1} ($7 bu^{-1}).

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