POLYACRYLAMIDE TREATMENTS FOR REDUCING SEEPAGE IN SOIL-LINED RESERVOIRS: A FIELD EVALUATION

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ABSTRACT. *Irrigation water supplies are becoming limited, and there is a need to extend the usefulness of current water resources. Previous laboratory studies demonstrated that certain water-soluble polyacrylamide solution (WSPAM) and cross-linked PAM granule (XPAM) treatments effectively reduced infiltration into soils. We evaluated the efficacy of these treatments for reducing water seepage losses in an unlined irrigation reservoir. Five treatments were applied to plots on the lower side slopes of a reservoir basin before it was filled in April 2001: controls; 0.016 kg* m^{-2} *WSPAM (1000 mg* L^{-1} *solution); 0.2 kg* m^{-2} *XPAM + 0.13 kg* m^{-2} *NaCl; 0.4 kg* m^{-2} *XPAM + 0.13 kg* m^{-2} *NaCl; and 0.8 kg* m^{-2} *XPAM only. Ring-cylinder seepage meters installed in each experimental plot were used to monitored seepage rates from May through October in 2001 and 2002, without further treatment applications. The WSPAM and XPAM treatments were equally effective for reducing pond seepage in 2002 but not 2001. On average, they reduced mean seepage rates an average 50% relative to the 22.4 mm* h^{-1} *control value and prevented the loss of 19.7 m of water through the seepage rings over the two irrigation seasons. The 0.016 kg* m^{-2} *WSPAM and 0.2 kg* m^{-2} *XPAM + 0.13 kg* m^{-2} *NaCl treatments are most cost effective, but the greater XPAM rates appeared to be the most durable treatments, since they retained their efficacy through the end of the second irrigation season. Results are consistent with a previous study suggesting that adding NaCl to XPAM treatments reduced required XPAM inputs without reducing treatment efficacy. The WSPAM and XPAM treatments provide several effective options for reducing seepage losses in earthen reservoirs.*

Keywords. *Cross-linked polyacrylamide, Hydrogel, Infiltration, PAM, Superabsorbents, Water-soluble polyacrylamide.*

Increased competition for water resources and the prevalence of drought have reduced agricultural water supplies in the irrigated west. Of water diverted for irrigation in the U.S., an estimated 17%, or 89.3 M m^3 day^{-1}, is lost through evaporation and seepage before being applied to the field (USGS, 1990). Seepage losses from soil-lined reservoirs and distribution channels can range from 5% to 50% of the inflow. Such losses represent a direct monetary loss to the farmer, but they may also cause various environmental problems. Seepage may cause rising groundwater levels, resulting in soil salinity and waterlogging (Burkhalter and Gates, 2005; Cassel-S and Zoldoske, 2006), and the leaching of salts, nutrients, or pathogens, resulting in contamination of ground or surface water supplies (Parker et al., 1999). Inhibiting infiltration in soil-lined structures can be effectively accomplished by lining them with concrete or membranes of rubber, plastic, or bitumen, but the materials required for these approaches are costly and their installations sometimes laborious.

A number of natural processes associated with the presence of sediments and organic particulates in water, or growth of microorganisms in soil, are known to reduce infiltration and seepage in soil-lined reservoirs and canals. Soil particles in turbid inflows can reduce infiltration as they wash-in and plug soil pores (Behnke, 1969; Sirjacobs et al., 2000; Shainberg and Singer, 1985) or settle over the soil surface, creating a less permeable surface layer (Bouwer et al., 2001; Brown et al., 1988; Segeren and Trout. 1991). Dispersed suspended sediments commonly associated with sodic soils and waters have also been used to inhibit infiltration, and have been found to be more effective sealants than flocculated soil particles associated with saline or calcium-saturated soil or water systems (Neff, 1980; Shainberg and Singer, 1985). However, in practice, the application of silt or clay to irrigation water to inhibit infiltration in ponds or canals has not met with consistent success (Withers and Vipond, 1980).

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 linings. 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 lining) pass through or are trapped in the upper few centimeters of the soil lining (Chang et al., 1974; 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 lining. Rowsell et al. (1985) reported that coarser soil textures were

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sealed less rapidly with the organics than fine soils. Applied organics can also stimulate soil microorganism growth. Large accumulations of bacteria and algae (McCalla, 1946; Gupta and Swartzendruber, 1962; Vandevivere and Baveye, 1992; Ragusa et al., 1994) or their long-chained, high-viscosity polysaccharide exudates (Allison, 1947; Avnimelech and Nevo, 1964) have also been shown to reduce seepage through soil linings.

Laboratory studies have evaluated the effect of surfactants, water-soluble linear polymers, and cross-linked polymer gels on water conductivity through soils. Allred and Brown (1994) reported that continuously applied >0.001 mol kg^{-1} surfactant solutions to pre-saturated sand and loam soil columns produced significant conductivity reductions compared to untreated water. In another study, Lentz (2003) found that a one-time 20 mL application of a 0.1 mol kg^{-1} sodium lauryl sulfate solution (anionic surfactant) produced a 61% to >99% reduction in seepage through silt loam and clay loam soil columns, but quadrupled seepage losses through loamy sand, relative to controls. Conductivity reductions from surfactant treatments have been attributed to increased soil solution viscosity, surfactant adsorption, precipitation (Allred and Brown, 1994), and micelle formation (Miller et al., 1975), or increased soil dispersion and aggregate destabilization (Mustafa and Letey, 1969).

Polymer gels (superabsorbents) added to soils as conditioners to increase plant-available water capacity were also found to alter or reduce infiltration. When added to the soil at 0.4% or 0.5%, a hydrolyzed starch-polyacrylonitrile graft polymer (H-SPAN or Super Slurper) decreased infiltration rates by 25% to 76% and sorptivities by 11% to 38% in different soils (Miller, 1979; Hemyari and Nofziger, 1981). Increasing applications (0 to 16 g kg^{-1}) of an organic super gel, composed of water and humic acid, humate, and polysaccharide polymers, to sandy soils incrementally reduced soil seepage rates and penetrability, and increased soil swelling (Mustafa et al., 1988; Al-Darby, 1996), although decreasing the salinity of applied irrigation water lessened the impacts (Mustafa et al., 1989). Lentz (2001) added an anionic cross-linked polyacrylamide (XPAM) gel to loam, silt loam, clay loam, and sandy soils and measured the seepage under a constant head of sediment-bearing waters. He found that seepage rate reductions produced by the 10 g kg^{-1} XPAM treatment 21 h after inundation were 82% to 92% for silt loam and loam soils and 51% for the clay loam, but saw no reduction for the loamy sand relative to controls (Lentz, 2001, 2007). Seepage rates were reduced more when NaCl was added to the treatment than for XPAM-only applications (Lentz, 2007). Salem et al. (1991) reported that XPAM absorbed 80 to 300 mL water g^{-1} polymer. Their results showed that water absorption by XPAM increased with increasing water sodium adsorption ratio (SAR) and decreased with increasing total soluble salts. In other research, Hussain et al. (1992) concluded that the absorption reductions caused by increasing total soluble salts varied depending on dissolved salt species, $MgS0_4$ > $CaCl_2$ >> NaCl. When leached under a falling 0.45 m head of sediment-free tap water, Bhardwaj et al. (2007) reported that the reductions in hydraulic conductivity due to 2.5 and 5 g kg^{-1} XPAM treatments were only temporary in a sandy soil.

Depending on soil and application conditions WSPAM may increase or decrease water infiltration into soils (Lentz, 2003). The focus here is on WSPAM applications that reduce seepage. Infiltration of high molecular weight (10 to 15 Mg mol^{-1}) WSPAM solutions ponded on dry loamy sand or pre-saturated sand columns decreased with increasing WSPAM concentration from 0 to 400 mg L^{-1}, due primarily to increased viscosity of the WSPAM solutions (Malik and Letey, 1992; Falatah et al., 1999). Infiltration decreases were greater with increasing polymer charge density, which was attributed to increased viscosity associated with higher charge (Malik and Letey, 1992). When applied to structured soils, WSPAM will inhibit infiltration if the soil structure has been previously degraded or destroyed (Sojka et al., 1998; Lentz et al., 2000) or if soil pores are inherently stable and not susceptible to depositional seal formation (Sirjacobs et al., 2000; Trout and Ajwa, 2001; Ajwa and Trout, 2006). Lentz (2003) evaluated WSPAM and/or surfactant applications for seepage reduction in soil columns. WSPAM applied to soil surfaces at concentrations of 10 to 500 mg L^{-1} prior to ponding failed to reduce water infiltration into undisturbed silt loam soil cores, but in packed soil columns, 250 and 500 mg L^{-1} WSPAM treatments reduced seepage rate by half relative to controls. A 1000 mg L^{-1} WSPAM treatment, applied to the soil surface and allowed to dry, reduced seepage rate by 0% to >99% in packed soil columns, varying as a function of soil texture and sodium content (Lentz, 2003). When WSPAM was added to sediment-bearing channeled flows, Lentz and Freeborn (2007) found that increasing inflow PAM concentrations reduced seepage losses early in the flow period when sediment concentrations were 0.5 g L^{-1}, but had less effect at higher sediment loads (2 g L^{-1}) and later in the flow period.

While field demonstrations have examined the potential for using WSPAM and XPAM to inhibit seepage from earth-lined structures (J. Valiant, personal communication, 1998; D. Crabtree, personal communication, 1999), to our knowledge no replicated field studies of the treatments have been reported in the literature. It was hypothesized that XPAM and WSPAM treatments applied to soils, which had successfully reduced soil water seepage in previous laboratory studies (Lentz, 2003, 2007), would produce similar results when applied at the field scale. Therefore, the object of this investigation was to evaluate the efficacy of these WSPAM and XPAM treatments for reducing seepage in a soil-lined irrigation pond over a two-year period. Seepage measurements in such structures have been discussed in several reports (Bouwer, 1963; Worstell and Carpenter, 1969; Worstell, 1976).

MATERIALS AND METHODS

We applied several replicated XPAM or WSPAM treatments to plots laid out within the wetted perimeter of a drained irrigation reservoir. Seepage meters were installed in each plot. When the pond was filled, the seepage meters provided a direct measure of infiltration and an estimate of seepage loss.

SITE, SOIL, AND POLYMER

Experimental plots were laid out in an irrigation reservoir that was drained for the winter season (Nov. 2000 through late March 2001). The relatively flat-bottomed reservoir had been excavated in a Portneuf silt loam soil (coarse-silty, mixed, superactive, mesic, Durinodic Xeric Haplocalcids). The calcareous soil has a deep, loess-derived profile dominated by silt loam or very fine sandy loam textures, with silica

Table 1. Selected characteristics of surface soils (0 to 7.5 cm) in pond plots (composite of six samples).

Texture	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	pH	EC ($S\ m^{-1}$)	OC ($g\ kg^{-1}$)	$CaCO_3$ ($g\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)	SAR	ESP (%)
Silt loam	220	565	215	7.1	0.3	8.6	116	24.2	0.7	2

and calcium carbonate cemented horizons (20% to 60% cementation) occurring between depths of 33 to 130 cm. A calcareous silt loam and very fine sandy loam material with massive structure and little to no cementation extends from 130 to 260 cm depth. This overlies a very gravelly very fine sandy loam at 260 cm, which typically overlies bedrock about 50 cm below. The pond bottom was excavated to a depth of 130 to 145 cm. Thus, the soil below the experimental plots consist of 110 cm layer of very fine sandy loam or silt loam lacking in confining layers. The triangular-shaped reservoir measured approximately 67 m long, 46 m wide, and 2 m deep when full, and provided a 2500 m^3 storage capacity. The reservoir inlet is positioned near the floor of the excavation. After its construction in 1998, a 50 to 100 mm layer of bentonite clay was applied and tilled into the earthen pond lining using a spring-tooth harrow. The thickness of the modified soil layer was 80 to 130 mm. The majority of this clay was applied to the bottom section of the pond, with sloping sides receiving significantly smaller amounts. Selected characteristics of plot soils are listed in table 1. The water supplying the pond was diverted from a local river and had an average electrical conductivity (EC) of 0.05 S m^{-1} and sodium adsorption ratio (SAR) of 0.5.

The XPAM treatments employed an anionic cross-linked potassium-acrylate/polyacrylamide copolymer (Stockosorb Agro-F, Stockhausen, Inc., Greensboro, N.C.). The product is comprised of talc-sized granules (<300 μm diameter). The XPAM was manufactured by cross-linking the linear polyacrylamide copolymer molecules having an anionic charge density of 27% to 35% and molecular weight of 12 to 15 Mg mol^{-1}. The resulting cross-linked XPAM products attain a cross-link density of 0.5% to 1%, a charge density of 27% to 35%, and contained 90% to 95% active ingredient and 5% to 10% water. A WSPAM treatment employed a linear anionic polyacrylamide co-polymer with 20% charge density and 12 to 15 Mg mol^{-1} molecular weight (AN-923-PWG, Chemtall, Inc., Riceboro, Ga.). The NaCl included in the XPAM + NaCl treatments was of reagent-grade quality (>99% pure).

EXPERIMENTAL DESIGN

Experimental plots were arranged in a randomized complete block design with six treatments and three replications (blocks). The 2 × 2 m square plots were laid out in a single strip along a topographic contour in the drained pond, being positioned on the reservoir's lower side slope at an elevation approximately 0.32 m above the pond bottom. Because subsurface soils beneath the plots were deep and lacked confining layers, we concluded that seepage interference between adjacent plots would be minimal. The pond bottom may experience relatively lower seepage losses than side slopes due to the previous bentonite application and possibly due to greater sediment deposition occurring there (Worstell and Carpenter, 1969). To avoid this potential low seepage zone, we positioned the experimental plots above the pond bottom, low enough to reduce exposure of the plots during pond drawdown events. Three additional control plots were located on the side slope above each treatment block, at an elevation 0.85 m above the reservoir bottom. The additional control plots were added to examine the effect of slope position on seepage losses. In addition to the controls, the experiment included four other treatments: a WSPAM application, two different XPAM plus NaCl treatments, and an XPAM-only treatment. Details of each treatment are presented in table 2.

Experimental treatments were applied on 16 and 17 April 2001. Surface soils in the plot area were modified prior to treatment to reduce plot-to-plot variability. A patchy organic layer of dried algae and moss was removed from the soil surface by raking, and then the soil was rototilled to a depth of 5 cm. A 1000 mg L^{-1} A.I. WSPAM stock solution (16 L) was prepared for each WSPAM plot with tap water that had an EC of 0.075 S m^{-1} and SAR of 1.7. The volume was divided into three roughly equal portions. To minimized runoff, these were applied to the WSPAM plot in three separate distributions over a 2.5 h period. This WSPAM treatment duplicated that of the previous laboratory study (Lentz, 2003).

The XPAM treatments were modeled after a previous laboratory study (Lentz, 2007) with respect to the XPAM concentrations and thickness of the treated soil layer. The field application differed from the laboratory in that we covered the XPAM-treated soil with a layer of untreated soil. This was done to minimize the movement of applied salt between adjacent plots. The treated soil in WSPAM plots was not covered because the polymer is strongly adsorbed to soil particles. For XPAM plots, a 3 to 4 cm layer of surface soil was skimmed from the plot and placed onto a polyethylene tarp. The soil was too moist to mix uniformly with the amendment, so it was sieved through a 3 mm screen and allowed to dry in the sun for 2 to 5 h. For each plot, three 19 L pails of the dried soil were mixed with the XPAM and NaCl (if specified) using a concrete mixer. Next, a 25 to 40 mm layer of soil was scraped

Table 2. Descriptions of experimental treatments.

Treatment	WSPAM ($kg\ m^{-2}$)	XPAM		NaCl		Form Applied	Plot Elev. above Pond Bottom (m)
		($kg\ m^{-2}$)[a]	($g\ kg^{-1}$ soil)[b]	($kg\ m^{-2}$)[a]	($g\ kg^{-1}$ soil)[b]		
Control	--	--	--	--	--	--	0.32
Control-HE	--	--	--	--	--	--	0.85
WSPAM	0.016	--	--	--	--	1000 mg L^{-1} A.I. solution (16 L m^{-2})	0.32
0.2 XPAM+	--	0.2	5	0.13	3.4	Granular mixture	0.32
0.4 XPAM+	--	0.4	10	0.13	3.4	Granular mixture	0.32
0.8 XPAM	--	0.8	20	--	--	Granular mixture	0.32

[a] Areal basis.

[b] Concentration of additive in treated layer with installed layer thickness of 35 mm.

off one-third of the plot area. One 19 L pail of the soil-amendment mixture was spread evenly over the exposed soil surface and then covered over with untreated soil. The procedure was repeated two more times to complete the plot treatment. The process of covering the treated layer with untreated soil caused some mixing, such that the final treated layer was 30 to 35 mm thick.

SEEPAGE METERS

A seepage meter was installed in each plot (fig. 1). Each meter consisted of a covered 300 mm diameter, 360 mm long aluminum ring infiltrometer, a floating tank, and a main water storage tank (fig. 2). We constructed each floating tank from a 140 × 280 × 178 mm deep open metal box. Six tanks from each block were bolted together and supported in the water by a buoyant ring made from 76 mm diameter PVC pipe. Each main water storage tank was constructed of 152 mm diameter vertically oriented PVC pipe capped on the bottom. Six cylinders for each block were grouped together. The six included a range of heights, 610 to 1460 mm, to accommodate a range of storage volumes and seepage rates. The ring infiltrometer was inserted at least 230 mm into the soil lining the reservoir. We wanted the bottom edge of the seepage ring to penetrate below the soil layer disturbed by treatments and form a seal in the undisturbed soil beneath. The infiltrometer was connected by flexible tube to the tank floating on the reservoir surface, and a second tube was vented to the atmosphere 0.5 m above the high water level. The vent tube removed any air that may have accumulated in the infiltrometer. Water seeping from the infiltrometer ring into the soil was supplied by that stored in the floating tank. The water level in the floating tank was maintained at the same elevation as the reservoir water surface using a float valve, which supplied water via a flexible tube from a main storage tank located on the pond bank at least 0.8 m above water level. When attendants were not on site, an electric pump automatically refilled all the main storage tanks at 2 h intervals. The replacement water was drawn from the irrigation reservoir at an elevation 300 mm above that of the seepage meters. A clear-view tube on the side of each main storage tank and scale allowed us to measure infiltration over time. In addition, a data logger coupled to pressure transducers mounted at the base of each main storage tank recorded water levels over seepage measurement periods. The volume of water stored in the main storage tanks permitted infiltration to be measured over periods of 4 to 12 h. The site was visited briefly at least four times a week during the irrigation season to ensure that the seepage meters were functioning properly. Seepage measurements were conducted using the schedule described below.

SEEPAGE MEASUREMENT AND ANALYSIS

Pond seepage monitoring started shortly after the reservoir was filled in late April 2001 and ended at the close of the irrigation season in October 2001. At that time, the reservoir was allowed to dry down and most of the equipment, including the infiltration ring tops, was removed from the field. Only the open infiltration rings remained. Thus, the plots, including soil enclosed within the infiltration rings, was subject to the same environmental conditions as the other reservoir surfaces between the 2001 and 2002 irrigation seasons. Treatments were not reapplied to plots in 2002. The seepage moni–

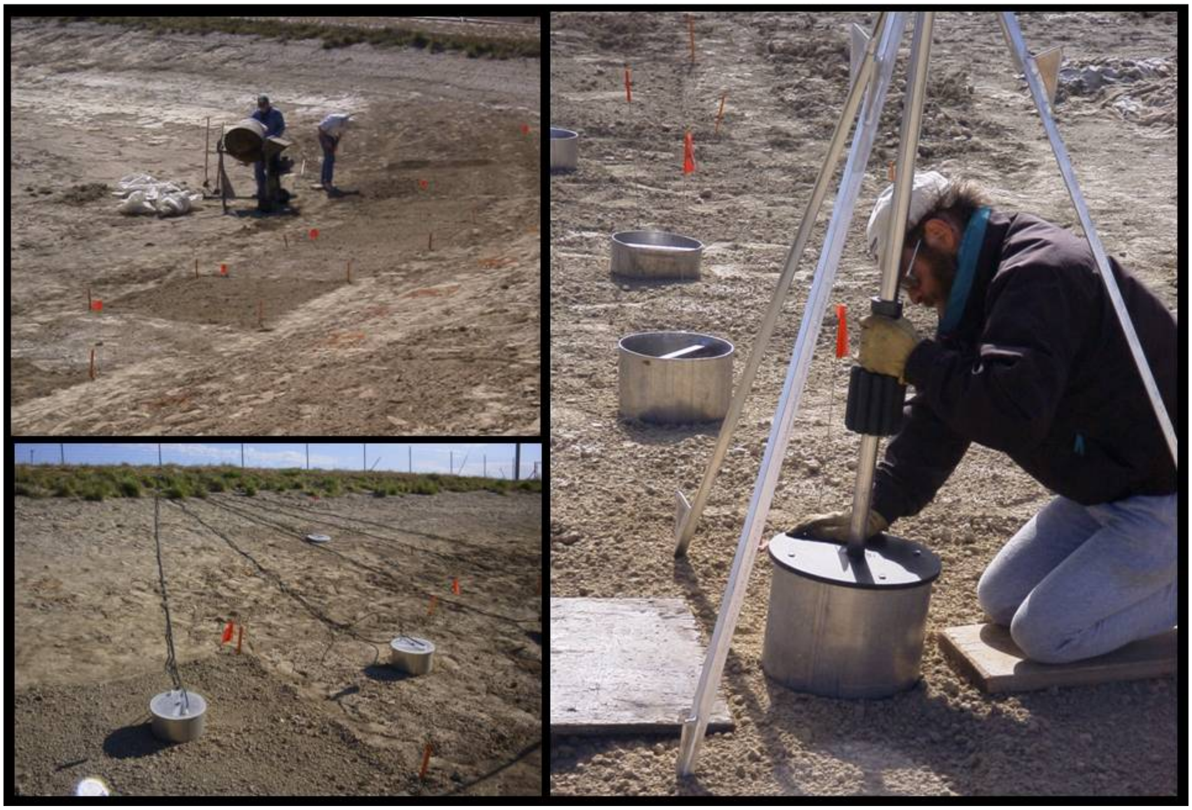

Figure 1. Views of plot preparation and treatment application, seepage ring installation, and completed plot treatment application and ring installation (clockwise from upper left photo).

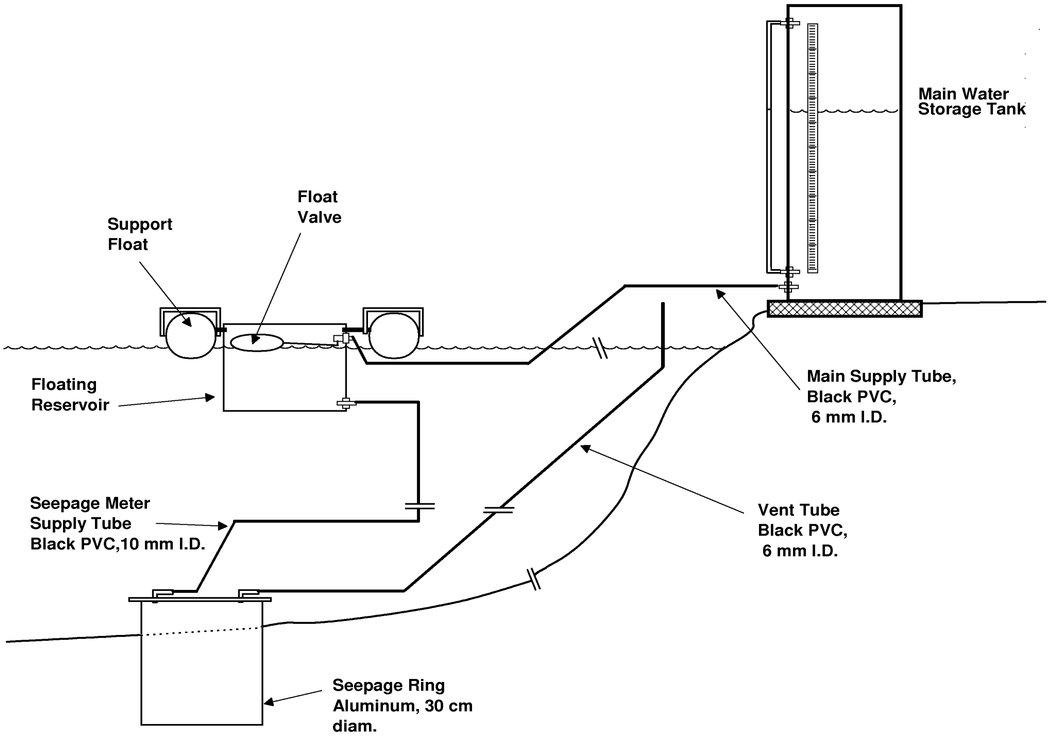

Figure 2. Diagram of the seepage meter monitoring system installed in each experimental unit in the water storage reservoir.

toring equipment was reinstalled in the reservoir in late April 2002, and monitoring was continued in May 2002 after the reservoir was refilled. During the 2001 monitoring season, we visited the site at approximately two-week intervals, verified that the seepage network was functioning properly, and started a seepage measurement. Seepage losses were measured over a 90 to 300 min period during late morning to early afternoon. Monitoring was suspended between 7 and 24 September 2001 when the reservoir was drained for pump intake repairs. During the 2002 irrigation season, plot seepage losses were measured in May, June, August, and October. Three to four seepage measurements were completed during a 2 to 3 week period in each of the four months using the same procedure used in 2001. The experimental-unit value reported for each month is the mean of the 3 to 4 measurements.

Seepage loss (S_R, mm h^{-1}) was calculated using:

$$S_R = (\Delta D \cdot A_R)(P \cdot A_S)^{-1} \quad (1)$$

where D is the change in main storage tank water depth (mm), A_R is the area of the main storage tank (mm^2), P is the measurement period (h), and A_S is the area of the infiltration ring (mm^2).

The tops of main water storage tanks were covered to inhibit evaporation, but floating tanks were uncovered. Thus, the obtained seepage values slightly overestimate the actual flux, since they include some loss due to evaporation from the floating tanks. Since the greatest evaporation from the pond surface occurred on days having the greatest evapotranspiration rate (10.4 mm h^{-1}), we used this value to estimate the maximum error caused by evaporation rate from the floating tanks. This error was less than 0.4 mm h^{-1}; hence, no correction was made to the seepage values. Mean treatment seepage loss rates for 2001 were calculated from interval seepage rate values weighted by interval period, which was given as a fraction of the total season length. The interval period for each measured seepage value was the sum of half the time between the current and previous measurement times and half the time between the current and the next measurement times. Cumulative seepage losses were computed by summing the products of seepage rate and interval length over the irrigation season. No seepage was contributed for the period in September 2001 when the reservoir was drained.

We also installed a platinum resistance temperature sensor in the reservoir at the soil-water interface near one of the seepage meters. Reservoir water temperatures were recorded during times of seepage measurement. Air temperatures were recorded simultaneously from a weather station located 5.6 km northeast of the experimental plots.

Seepage from the entire reservoir was measured in October 2002 after irrigation withdrawals had ceased for the season. The pond was filled, pumping was curtailed, and water depth on a staff gauge was measured periodically for two weeks. Reservoir water temperature and air temperature were monitored as well. The decline in reservoir level was attributed entirely to seepage loss, since evaporation losses were minimal. Potential evapotranspiration (ET$_P$) during the test period averaged 1.5 mm d^{-1}. Hence, the evaporation from the reservoir surface during this time was estimated to be 0.06 mm h^{-1}. As the water level declined, the proportion of reservoir side slope contributing to seepage losses changed. The side slope fraction was computed as the side slope area divided by the total wetted area in the reservoir.

We initially performed an analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (SAS, 1999) to test for seepage rate differences between the two control treatments. A second ANOVA analysis using the PROC MIXED procedure with orthogonal contrasts (1) examined treatment class effects (control vs. others, WSPAM vs. all XPAM, and XPAM only vs. XPAM + NaCl) on mean seepage loss rates and cumulative seepage, and (2) evaluated individual treatment separations using the Tukey-Kramer method ($P = 0.05$). Finally, a third ANOVA using PROC MIXED tested for the effect of observation year on seepage loss rates and cumulative seepage losses.

Table 3. Summary of ANOVAs and orthogonal comparisons testing the null hypothesis that treatments, blocks, or treatment classes are samples from the same population relative to seepage rate and cumulative seepage in 2001 and 2002. The probability values associated with the F-tests are presented.

	2001		2002	
Sources	Seepage Rate	Cumul. Seepage	Seepage Rate	Cumul. Seepage
Treatment	0.02	0.02	0.05	0.05
Block	ns[a]	ns	ns	ns
Orthogonal comparisons:				
(a) Control vs. others	0.002	0.005	0.006	0.007
(b) WSPAM vs. all XPAM	0.002	ns	ns	ns
(c) XPAM-only vs. XPAM + NaCl	ns	ns	ns	ns

[a] ns = non-significant.

RESULTS AND DISCUSSION

EFFECTIVENESS OF TREATMENTS

In 2001, the mean seepage rate for the lower side slope control plots (22.7 mm h^{-1}) was quite similar to that for the upper side slope control-HE plots (25.6 mm h^{-1}). Since the seepage values for the two sites were not significantly different ($P = 0.34$), the two control responses from each block were averaged together prior to subsequent analyses.

As a whole, the WSPAM and XPAM treatments significantly reduced season-long mean seepage rate and cumulative seepage losses (table 3a, table 4). The WSPAM and XPAM treatments were equivalent except in 2001, when WSPAM produced significantly higher seepage-loss rates than the XPAM treatments (table 3b, table 4). Furthermore, in both 2001 and 2002, the XPAM-only and the two XPAM + NaCl treatments were equally effective at reducing seepage rate and cumulative seepage losses relative to controls (table 3c). These results are consistent with those of Lentz (2007), which indicated that adding NaCl effectively reduced the amount of XPAM required to obtain an equivalent seepage reduction goal.

Statistical separations for individual treatment means (table 4), which have less power than the single degree-of-freedom orthogonal contrasts (table 3), generally conform to the orthogonal results. The one exception was the comparison between control and 0.4 XPAM+ treatments. In this case, the mean separation test showed no significant difference between the two treatments. This is a consequence of the relatively high within-treatment variability as indicated by their associated standard errors, 3.85 m for controls and 2.46 m for 0.4 XPAM+ (table 4). Indeed, cumulative seepage responses among treatments produced substantial ranges in variability, although Levene's test for homogeneity of variance indicated that treatment variances were equal ($P = 0.06$). The standard error (SE) for cumulative seepage responses ranged from 0.34 to 4.52 m over both years.

Note that the block factor (in the experimental design) did not have a significant effect on seepage parameters in either 2001 or 2002 (table 3). This implies that soil properties across the field plots were relatively uniform. Hence, the large variability observed for some treatments likely was not related to a soil property gradient in the field, but to a random dynamic present in the infiltration process or to an inherent instability of the treatment itself.

The effect of observation year also did not have a significant effect on mean seepage rates ($P = 0.36$) or cumulative seepage values ($P = 0.56$) (table 3). When averaged over both years, seepage rates were 22.4 mm h^{-1} for controls, compared to 12.9 mm h^{-1} for WSPAM, 11.5 and 11.4 mm h^{-1} for the two XPAM + NaCl treatments, and 9.49 mm h^{-1} for the 0.8 XPAM-only treatment. Thus, the WSPAM and three XPAM treatments reduced seepage loss rate by an average 50% relative to controls (11.3 vs. 22.4 mm h^{-1} for controls). Season-long cumulative seepage loss over both years averaged 20.1 m for controls, compared to 11.5 m for WSPAM, 10.3 and 10.8 m for XPAM + NaCl treatments, and 8.4 m for the

Table 4. Treatment seepage rates and cumulative seepage for 2001 and 2002, and reductions thereof, given in comparison to controls. Included are treatment means, standard errors (in parentheses), and mean separations (Tukey-Kramer method).[a]

		Treatment Value[b]					Reduction Due to Treatment (Relative to Controls, %)			
		Control	WSPAM	0.2 XPAM+	0.4 XPAM+	0.8 XPAM	WSPAM	0.2 XPAM+	0.4 XPAM+	0.8 XPAM
2001	Seepage rate (mm h^{-1})	24.1 a (1.55)	15.6 b (1.82)	11.5 c (1.0)	10.1 c (1.26)	10 c (1.02)	35.3	52.3	58.1	58.5
	Cumulative seepage (m)	21.3 a (0.61)	13.7 b (4.52)	10.1 b (0.34)	10.0 b (0.90)	8.7 b (2.74)	35.7	52.6	53.1	59.2
2002	Seepage rate (mm h^{-1})	20.6 a (2.74)	10.1 b (2.60)	11.4 b (2.17)	12.6 b 1.57)	8.8 b (1.21)	51.0	44.7	38.8	57.3
	Cumulative seepage (m)	18.8 a (3.85)	9.2 b (2.87)	10.4 b (0.74)	11.5 ab (2.46)	8.0 b (0.18)	51.1	44.7	38.8	57.4
Mean (2001 and 2002)										
	Seepage rate (mm h^{-1})	22.4	12.9	11.5	11.4	9.4	43.1	48.5	48.5	57.9
	Cumulative seepage (m)	20.1	11.5	10.3	10.8	8.4	43.4	48.6	45.9	58.3

[a] WSPAM = 0.016 kg m-2 WSPAM; 0.2 XPAM+ = 0.2 kg m-2 XPAM + 0.13 kg m-2 NaCl; 0.4 XPAM+ = 0.4 kg m-2 XPAM + 0.13 kg m-2 NaCl; and 0.8 XPAM = 0.8 kg m-2 XPAM only.

[b] Values in the same row followed by the same letter are not significantly different.

0.8 XPAM-only treatment. On average, the WSPAM and other XPAM treatments reduced cumulative seepage by an average 49% relative to controls (10.25 m vs. 20.1 m for controls).

Over the two irrigation seasons, the average total depth of water lost as seepage through the infiltration ring cross-section was 40.1 m for controls, compared to an average loss for the WSPAM and XPAM treatments of 20.5 m. Thus, the treatments prevented the loss of 19.6 m water through the seepage ring cross-sections. This does not mean that the treatments could have prevented the loss of 19.6 m of water across the entire area of the reservoir, because seepage losses at the lower slope reservoir positions where the seepage meter rings were located may differ from that occurring at the reservoir bottom.

In both years, seepage rates generally started low, increased toward the middle of the season, and then declined near season's end (figs. 3 and 4). Two exceptions to this rule were evident in 2002 for WSPAM and 0.2 XPAM+ treatments, where seepage rates increased at the end of the irrigation season. This suggests that these treatments may have begun to fail near the end of the second season after application. The overall ascending and descending pattern may have been a response to the general rise and fall of reservoir water temperatures during the irrigation season. Infiltration is directly related to inflowing water temperature (Jaynes, 1990; Lentz and Bjorneberg, 2002); however, seepage is also influenced by other factors. For example, initial low seepage rates may have been due to air trapped in the soil pores during the reservoir filling process. With time, the air dissolved and was removed in leaching water or escaped to the atmosphere, which caused seepage to increase. Avnimelech and Nevo (1964) noted gas bubbles and bacterial exudates present in sand column during the first few days after wet-up. When these disappeared several days later, the hydraulic conductivity of the sand increased (see also Wang et al., 1998).

Clearly, the seepage data do not uniformly coincide with the temperature curves, indicating that other factors are influencing seepage processes. Another indication of this is seen in the 2001 plot of seepage rate vs. time. Seepage measurements were made more frequently in 2001 than in 2002, and they show substantial fluctuations in seepage rate from one period to the next (fig. 3). A similar pattern was observed by DeTar (1979) and Hills (1976). De Tar (1979) attributed the changes to the opening and internal erosion of preferential pathways, which permitted temporary increases in seepage rates. Seepage rates then decreased when solids suspended in infiltrating waters were deposited in the open channel, clogging and inhibiting water flow. These dynamics and those described in the previous paragraph may also explain why seepage rates measured by the infiltration rings exhibited large variability among experimental blocks. The coefficients of variation for individual treatments, averaged over all measurement times in 2001, ranged from 33% to 70%.

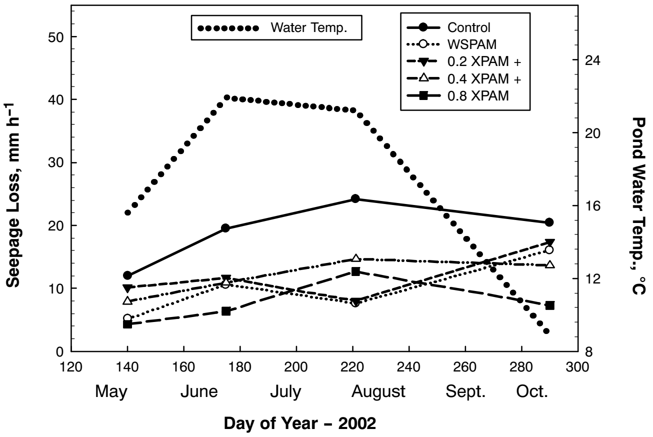

Figure 4. Effect of WSPAM and XPAM treatments on seepage rate and seepage-face water temperature during the 2002 irrigation season.

The mean overall seepage rate from the filled reservoir was approximately 6 mm h^{-1} in mid-October 2002 (DOY 290 to 292 in fig. 5), while the mean seepage rate for control plots in mid-October 2002 was 20.4 mm h^{-1} (DOY 290 in fig. 4). This suggests that seepage occurring at the reservoir side slope positions where the control plots were located was substantially greater than that occurring across the bottom of the reservoir. This discrepancy is likely the result of the non-uniform bentonite application made after reservoir construction, or to the proportionally greater thickness of settled sediments and their compression over the bottom location where water depths were greater (Bouwer and Rice, 1989; Houston et al., 1999; Bouwer et al., 2001).

The reservoir water mass significantly buffered the impact of diurnal energy cycles on the temperature of water present at the seepage boundary. The diurnal temperature range at the

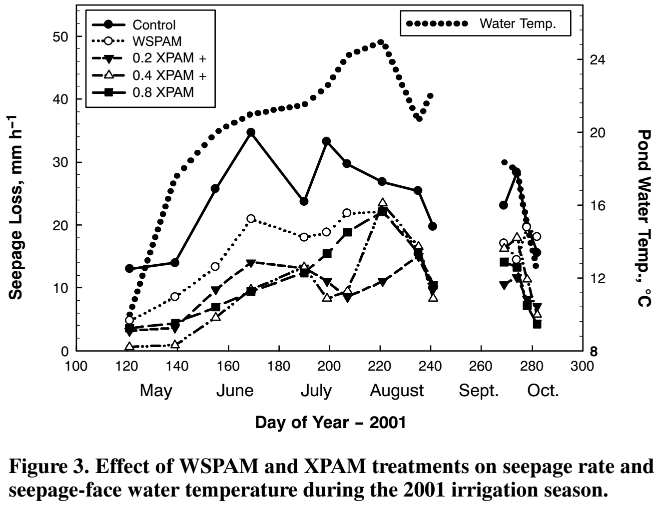

Figure 3. Effect of WSPAM and XPAM treatments on seepage rate and seepage-face water temperature during the 2001 irrigation season.

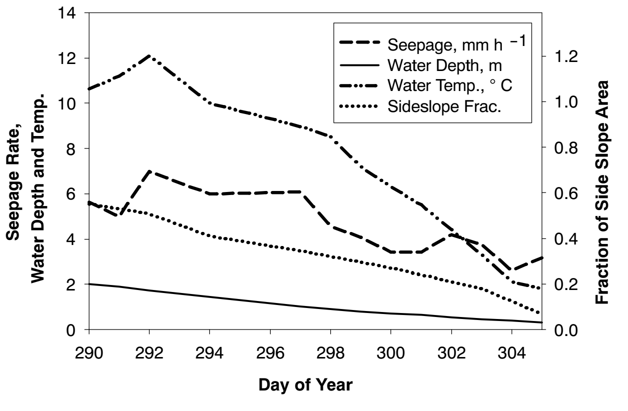

Figure 5. Change in whole-reservoir seepage rate, water depth, and temperature, and side slope fraction determined by a seepage test conducted in October 2002.

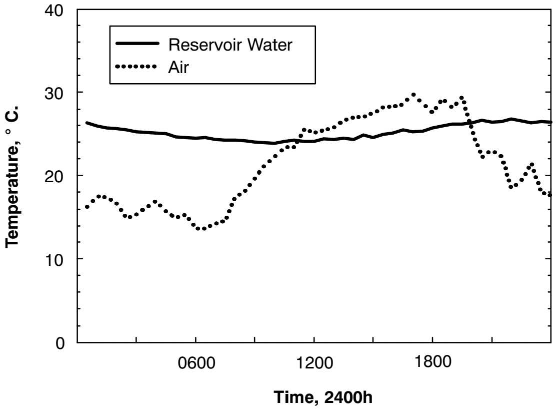

Figure 6. Plot of the diurnal temperature change in air (2 m above ground) and in reservoir water at the seepage interface for 13 July 2001.

seepage interface was one-tenth that of the air temperature (fig. 6). While temperature of infiltrating water directly influences hydraulic conductivity through soil (by as much as 2% per °C, Lentz and Bjorneberg, 2002), buffering imposed by the water mass substantially decreased effects of the diurnal energy cycle on reservoir seepage loss rates.

COMPARISON TO LABORATORY RESULTS

By comparing our field results to the previous laboratory study (Lentz, 2007), it may be possible to approximate how the field treatments may work on other types of soils. The field treatments do not exactly duplicate those employed in the laboratory study. For example, the 0.8 XPAM treatment in the current study applied the same amount of XPAM as the 10 g kg^{-2} XPAM laboratory treatment on an areal basis (0.8 kg m^{-2}), but the XPAM concentration in the field-treated soil layer was twice that of the laboratory experiment because the field-treated soil layer was thinner. The field study also differed from the laboratory study with respect to the length of the test period and the coarseness of soil aggregates into which XPAM was mixed, possibly influencing XPAM distribution and uniformity in the treated layer. These dissimilarities may explain why seepage reduction obtained in the field for the 0.8 XPAM treatment was less than that observed in the laboratory.

The field 0.8 XPAM treatment produced a mean seepage rate reduction over two years that was equivalent to that of an approximately a 3 g kg^{-1} XPAM treatment over 21 h in the laboratory (based on interpolation between XPAM treatment rates shown in fig. 4 of Lentz, 2007). Hence, from figure 4 in Lentz's (2007) study, one may anticipate that the 0.8 XPAM field treatment, like the 3 g kg^{-1} XPAM laboratory treatment, would produce a 60% to 75% seepage reduction in other clay loam and loam soils. Similarly, the 1000 mg L^{-1} WSPAM field treatment did not produce as great a seepage reduction as observed in the laboratory for a similar soil (Lentz, 2003). Again, this was the result of differences between testing conditions. Lentz's (2003) data suggest that the field WSPAM treatment may produce slightly better seepage reductions on clay loam soils and poorer reductions on high-sodium silt loam soils, relative to results from this current study. The laboratory studies suggest that the XPAM and WSPAM field treatments would not provide effective seepage reduction in sandy soils, although further study is needed to confirm this and previously stated extrapolations.

GENERAL COST ANALYSIS

While a detailed cost analysis is beyond the scope of this article, an effort was made to project material costs for the WSPAM and 0.2 XPAM+ treatments per unit water saved and compare them to that of a membrane-based reservoir sealing application. Estimates are based on treating the entire reservoir. The main difficulty involved in this exercise is estimating the total depth of water that would be saved over the entire reservoir area. This arises because side slope seepage losses apparently are greater than losses that occurred at reservoir bottom positions.

Given that *(i)* overall seepage losses measured in the full reservoir mid-October 2002 were between 5 and 8 mm h^{-1}, *(ii)* untreated-plot seepage losses measured at this time were lower than observed during the summer, and *(iii)* 2001 seepage losses were higher than those in 2002, we estimated that the seepage losses over the entire reservoir would average about 13 mm h^{-1} for the two-year period. Using this number and the two-year mean for seepage loss over the reservoir side slope (50% of total reservoir area), 22.4 mm h^{-1}, we can derive the mean seepage loss rate for the reservoir bottom area, 3.6 mm h^{-1}. Assuming that the PAM treatments would reduce seepage losses along the reservoir bottom by the same amount as they did on the side slopes, i.e., 50%, the fractional seepage loss rate for the two reservoir positions was used to estimate the total water saved over two years in the reservoir bottom, or 3.2 m. Thus, the estimated total water savings had the entire reservoir been treated would be 2.3 ha m.

The cost of treatment materials per unit water saved was calculated assuming that the PAM treatments have a useful life of two years (table 5). The WSPAM treatment ($0.12 ha^{-1} mm^{-1}) is substantially more economical than the 0.2 XPAM+ treatment ($1.23 ha^{-1} mm^{-1}) and even more economical than membrane application ($0.22 ha^{-1} mm^{-1}), which has a longer life span. However, it is possible that the XPAM durability may exceed two years (Lentz, 2007), which would improve its cost effectiveness. The XPAM treatment may also demonstrate a self-healing capacity when disturbed by livestock tracking through the pond, due to its promotion of soil swelling (Lentz, 2007). Thus, other factors besides cost need to be considered when selecting one treatment over another.

To be successful, a seepage prevention treatment must provide benefits that justify the cost of implementation. If the producer's crop is experiencing water stress, then the additional water provided by seepage treatments will increase crop yields (Payero et al., 2006; Ali et al., 2007) and income (table 5). The additional income received per unit of supplemental water supplied is a function of crop type and other factors. For instance, corn yields respond more favorably to supplemental water than wheat (table 5). Especially for corn crops, then, it appears that both WSPAM and 0.2 XPAM+ treatments potentially can provide substantial benefits to the producer's bottom line. For example, a WSPAM treatment that supplies 100 mm supplemental irrigation to a water-stressed corn crop could result in a (100 mm)(5.23 $ ha^{-1} mm^{-1}) = $523 ha^{-1} increase in yield value at a material cost of (100 mm)($0.12 ha^{-1} mm^{-1}) = $12 ha^{-1} (table 5).

Table 5. Estimated 2008 costs and benefits of cross-linked PAM (XPAM) and water-soluble PAM (WSPAM) treatments in comparison to a membrane pond lining application.

Treatment	Treatment Duration[a] (years)	Water Saved per Duration[b] (ha m)	Cost of Combined Product[c]	Cost of Water Saved over Treatment Duration[d]		Estimated Yield Increase Due to Additional Water[e] ($T\ ha^{-1}\ mm^{-1}$)		Value of Increased Crop Yield Due to Additional Water[f] ($\$\ ha^{-1}\ mm^{-1}$)	
				$\$\ ha^{-1}\ mm^{-1}$	$\$\ ac^{-1}\ ft^{-1}$	Corn	Wheat	Corn	Wheat
0.2 XPAM + NaCl	2	2.3	\$7 to \$12 kg^{-1}	1.23 to 2.10	152 to 259	0.025	0.0033 to 0.0125	5.23	0.85 to 3.20
WSPAM	2	2.3	\$8.80 kg^{-1}	0.12	15				
36 mil polyethelene membrane + geotextile cover	17	70.2	\$8.18 m^2	0.22	27				

[a] Duration of PAM treatments was limited to length of monitoring; actual duration may be longer. Duration of membrane treatment is mean of estimated range.

[b] 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 two-year period), and reservoir bottom position (50% of total area, with seepage water saved equal to 3.2 m per two-year period).

[c] Membrane treatment was assumed to have a 90% seepage reduction efficiency.

[d] 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.

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

[f] Based on current local corn price of \$209 Mg^{-1} (\$5.32 bu^{-1}) and wheat price of \$257 Mg^{-1} (\$7 bu^{-1})

CONCLUSIONS

This research employed ring-cylinder seepage meters to evaluate the efficacy of WSPAM and XPAM + NaCl treatments for reducing water seepage losses in an unlined irrigation reservoir. The 0.016 kg m^{-2} WSPAM and 0.8 kg m^{-2} XPAM treatments tested here demonstrated strong potential for seepage reduction in irrigation reservoirs like that employed in this study. They reduced cumulative seepage losses by 49% relative to controls. The data are consistent with results of a previous laboratory study (Lentz, 2007), which indicated that NaCl additions can reduce the XPAM application amounts needed to attain seepage reduction targets. Comparisons with previous laboratory data suggest that the field treatments may be appropriate for other soils as well.

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