

Reducing Sediment and Phosphorus in Tributary Waters with Alum and Polyacrylamide

L. B. Mason, C. Amrhein,* C. C. Goodson, M. R. Matsumoto, and M. A. Anderson

ABSTRACT

The Salton Sea is the largest inland water body in California, covering an area of 980 km². Inflow to the Salton Sea (1.6 km³ yr⁻¹) is predominately nutrient-rich agricultural wastewater, which has led to eutrophication. Because internal phosphorus release from the bottom sediments is comparatively low and external phosphorus loading to the Salton Sea is high, reduction of tributary phosphorus is expected to reduce algal blooms, increase dissolved oxygen, and reduce odors. Removing both dissolved phosphorus and phosphorus-laden sediment from agricultural drainage water (ADW) should decrease eutrophication. Both alum and polyacrylamide (PAM) are commonly used in wastewater treatment to remove phosphorus and sediment and were tested for use in tributary waters. Laboratory jar tests determined PAM effectiveness (2 mg L⁻¹) for turbidity reduction as cationic > anionic = nonionic. Although cationic PAM was the most effective at reducing turbidity at higher speeds, there was no observed difference between the neutral and anionic PAMs at velocity gradients of 18 to 45 s⁻¹. Alum (4 mg L⁻¹ Al) reduced turbidity in low energy systems (velocity gradients < 10 s⁻¹) by 95% and was necessary to reduce soluble phosphorus, which comprises 47 to 100% of the total P concentration in the tributaries. When PAM was added with alum, the anionic PAM became ineffective in aiding flocculation. The nonionic PAM (2 mg L⁻¹) + alum (4 mg L⁻¹ Al) is recommended to reduce suspended solids in higher energy systems and reduce soluble P by 93%.

THE SALTON SEA is the largest lake in California, covering an area of 980 km² (Fig. 1) (Hart et al., 1998). The Salton Sea lies below sea level (-70 m), and the only output is evaporation. The evaporation rate exceeds 1.4 m yr⁻¹ and is counterbalanced with inflow, 84% of which flows from the Whitewater River to the north, and the New River and Alamo River from the south (Fig. 1 and Table 1) (Setmire et al., 2000). Inflow to the Salton Sea (1.6 km³ yr⁻¹) is predominately agricultural drainage water (ADW); the rest is comprised of municipal effluent and less than 3% rainfall. The watershed generates \$1.3 billion in agricultural commodities per year (Anderson and Amrhein, 2002). The major inflow results from agricultural tailwater that flows off the fields and is high in nitrogen and phosphorus. This nutrient-rich water has resulted in the eutrophication of the Salton Sea and negatively impacted its beneficial uses, including recreation, fishing, and wildlife resources (Setmire et al., 2000). Some of the specific effects of

eutrophication include high algal biomass, low clarity, anoxia, massive fish kills, and noxious odors. Phosphorus (P) has been determined as the limiting nutrient for algal growth in the Salton Sea (Setmire et al., 2000). Because external phosphorus loading to the Salton Sea is high, reduction of tributary phosphorus may reduce eutrophication (Holdren and Montaño, 2002). Phosphorus is contributed to the Salton Sea in both colloidal and dissolved forms. Removing soluble phosphorus and suspended solids from ADW would reduce the overall amount of P entering the Salton Sea. In fact, total maximum daily loads (TMDLs) for suspended solids have recently been established for the New River and the Alamo River. The New and Alamo Rivers have averaged 306 and 377 mg L⁻¹ suspended solids, respectively, during 1980–2001 (California Regional Water Quality Control Board, 2002). The newly established TMDLs require the rivers carry no more than 200 mg L⁻¹ suspended solids.

Alum and/or polyacrylamide (PAM) are commonly used in municipal wastewater treatment to remove P and solids, and then the sludge is collected and disposed. The high sediment load and salinity of the ADW requires testing and possible modification to the typical procedures used in municipal treatment.

Alum (aluminum sulfate), the most widely used coagulant in water treatment (Hammer and Hammer, 1996), serves a dual role by acting as a coagulant for suspended solids removal and an adsorbant for soluble P removal. Alum has been applied in large-scale quantities in the environment to control internal P loading in lakes (Welch and Cooke, 1999).

Coagulants quickly reduce or neutralize the electrostatic forces between negatively charged particles in water, which leads to aggregation and settling (Black and Harris, 1969; Reynolds and Richards, 1995). Alum forms solid amorphous aluminum hydroxide in water, which incorporates soluble phosphorus (P_s) into its structure through either coprecipitation or adsorption onto the surface (Omoike and VanLoon, 1999). The amorphous aluminum hydroxide, or "floc," combines with the other coagulated suspended solids and settles out of the water column.

Alum has been shown to be nontoxic in the pH range of 5.5 to 9.0. At these pH values, the aluminum concentration is not expected to exceed 50 µg L⁻¹ since aluminum hydroxide is highly insoluble in this range (Kennedy and Cooke, 1982). Previous research has found that alkaline waters (>75 mg L⁻¹ CaCO₃) are not expected to have chronic or acute effects to biota with alum

L.B. Mason, C. Amrhein, C.C. Goodson, and M.A. Anderson, Department of Environmental Sciences, and M.R. Matsumoto, Department of Chemical and Environmental Engineering, University of California, Riverside, CA 92521. Received 7 Mar. 2005. *Corresponding author (christopher.amrhein@ucr.edu).

Published in J. Environ. Qual. 34:1998–2004 (2005).

Technical Reports: Surface Water Quality

doi:10.2134/jeq2005.0086

© ASA, CSSA, SSSA

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: ADW, agricultural drainage water; PAM, polyacrylamide; P_p, particulate phosphorus; P_s, soluble phosphorus; P_T, total phosphorus; TMDL, total maximum daily load.

treatments (Narf, 1990). The tributaries to the Salton Sea meet these criteria for pH and alkalinity so toxicity problems are not expected (Table 1).

Polymers are frequently applied in wastewater treatment to enhance coagulation and settling. The polymer acts as a coagulant aid by chemically bridging reactive groups and increasing floc size (Reynolds and Richards, 1995). Polymers can range in charge type (cationic, anionic, or neutral), charge density, and molecular weight. Polyacrylamide is a synthetic polymer and has been used in soil applications to reduce erosion (Sojka et al., 1998; Zhang and Miller, 1996), increase infiltration (Ben-Hur and Keren, 1997; Green et al., 2000), promote flocculation (Helalia and Letey, 1988; Aly and Letey, 1988; Laird 1997), and enhance salt removal (Aly and Letey, 1990; Malik et al., 1991).

The charge of the polymer and the type of suspended solids in the wastewater influence the degree of flocculation and settling rate. Cationic polymers directly adsorb to the negative surfaces of the clay particles, anionic polymers adsorb through cation-bridging, and nonionic polymers form floc by attaching to the clay surfaces through van der Waals forces (Seybold, 1994).

The nature of the suspended solids in the tributary water requires an assessment for the most effective polymer. The New and Alamo Rivers drain calcareous, smectitic soils that range from silty clays to sandy loams (USDA-SCS, 1981), and the suspended solids in the Whitewater River are dominated by illite and kaolinite from the coarsely textured soils at the north end of the Salton Sea (USDA-SCS, 1980).

Many reviews have been completed on PAM toxicity (Barvenik, 1994; Sojka et al., 2000). All types of PAMs are considered nontoxic to mammals. Anionic PAMs are nontoxic to aquatic life (Sojka et al., 2000), while nonionic polyelectrolytes exhibit low toxicity (LC_{50}^{96} values of 16.5 mg L^{-1} in *Daphnia magna*; Biesinger et al., 1976). Cationic polymers are of some toxicological concern, and have been documented to bind to the negatively charged gills in rainbow trout and affect ion regulation (Muir et al., 1997). Values for LC_{50} ranging from 271 to $1733 \text{ } \mu\text{g L}^{-1}$ among various cationic polymers have been reported for rainbow trout (Goodrich et al., 1991). Since federally listed species of pupfish and mud-suckers are present in the tributaries and the drains of the Imperial Valley, caution should be used when applying cationic PAM to the field. However, the acute toxicity of all types of polyelectrolytes is reduced in the presence of solids, as the PAM binds to the suspended particles.

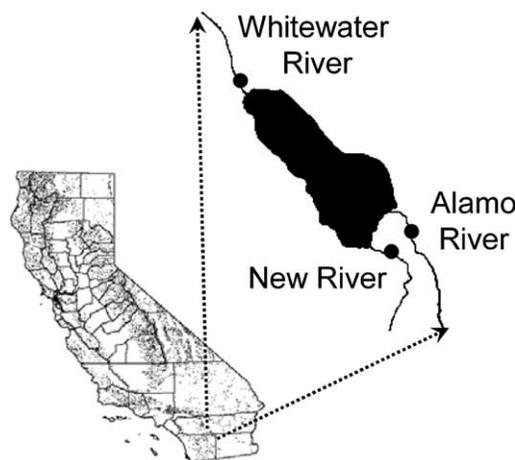


Fig. 1. Map of the Salton Sea and its tributaries: the Whitewater, New, and Alamo Rivers (● denotes sampling sites).

The monomer of PAM, acrylamide, is a neurotoxin and is regulated by the FDA, where the residual monomer cannot exceed 0.05 to 0.2% of the PAM (Seybold, 1994). Although PAM degrades at a rate of 10% per year, the degradation process does not release acrylamide (MacWilliams, 1978).

In this study, we conducted laboratory jar tests to evaluate the effectiveness of alum and different types of PAM in reducing turbidity and P in the tributaries to the Salton Sea.

MATERIALS AND METHODS

Bulk water samples were collected from the three tributaries to the Salton Sea: the Whitewater River ($33^{\circ}32.3' \text{ N}$, $116^{\circ}05.7' \text{ W}$), the New River ($33^{\circ}05.12' \text{ N}$, $115^{\circ}36.9' \text{ W}$), and the Alamo River ($33^{\circ}07.5' \text{ N}$, $115^{\circ}34.3' \text{ W}$) (Fig. 1).

Chemical and Physical Characteristics of Tributary Waters

Baseline chemical characteristics were measured on the sampled river water. Electrical conductivity (EC) was determined using a YSI 3200 conductivity instrument (Yellow Springs Instruments, Yellow Springs, OH). River water pH was measured using a combination glass electrode (Fisher Scientific, Hampton, NH) on an Expandable Ion Analyzer EA 920 (Orion Research, Boston, MA). Total suspended solids (TSS) were analyzed by filtering and drying 50 mL of river water following standard methods (American Public Health Association, 1992). Anions (chloride, nitrate, and sulfate) were analyzed using ion chromatography (Model 500; Dionex, Sunnyvale, CA), and cations (calcium, magnesium, potassium,

Table 1. Physical and chemical characterization of samples collected 3 Feb. 2004.

	New River	Alamo River	Whitewater River
Electrical conductivity (EC), dS m^{-1}	4.9	3.4	2.0
pH	7.3	7.4	6.9
Total suspended solids (TSS), mg L^{-1}	199	192	10
Turbidity, NTU	83	140	12
Anions (SO_4^{2-} , NO_3^- , Cl^-), mmol L^{-1}	52	36	20
Cations (Mg^{2+} , Ca^{2+} , Na^+ , K^+ , NH_4^+), mmol L^{-1}	51	35	20
Alkalinity [†] , $\text{mg CaCO}_3 \text{ L}^{-1}$	227	190	174
Flow [‡] , $\text{Mm}^3 \text{ yr}^{-1}$	601	760	65

[†] Sample date 30 Mar. 2004 from Holdren (personal communication).

[‡] From Setmire et al. (2000).

sodium, and ammonium) were analyzed using inductively coupled plasma–optical emission spectroscopy (ICP–OES) (Optima AV; PerkinElmer, Wellesley, MA).

Jar Test Method

All laboratory scale jar tests were performed in a 2-L jar apparatus (PB-700; Phipps & Bird, Richmond, VA). During preliminary studies, the jars were mixed, and the floc settled for a predetermined amount of time. Since the floc settled quickly, the effectiveness of each treatment was dependent on the length of settling time. Therefore, to properly test floc formation, settling, and strength, an alternative jar test method was developed.

This alternative method included a gradient reduction of paddle speed from 300 to 0 RPM (settling), followed by an increase in paddle speed from 0 to 300 RPM (resuspension), where each speed was held constant for 5 min. The jars were filled with river water to the 2-L mark (14.5-cm water depth), and an initial sample was collected using a pipette at a depth of approximately 3.5 cm while the water was mixed at 300 RPM. Concentrations of alum-Al (4 mg L^{-1}) and/or PAM (2 mg L^{-1}) were volumetrically added to the jars and the gradient reduction in paddle speed began. Each sample was collected by pipette (3.5-cm depth) after 5 min of a constant paddle speed while the paddle was still spinning. Samples for turbidity, P_s , and total phosphorus (P_T) were collected at 300, 200, 100, 50, 25, 15, 10, 5, and 0 RPM. The change in turbidity or phosphorus concentration was compared to the initial sample of each particular jar.

Chemical Additions

The concentration of alum [$\text{Al}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$, $n = 12\text{--}14$; technical grade; Fisher Scientific] was based on the average stoichiometric aluminum (Al) content of the alum (alum-Al). The PAM had a range of characteristics in polymer charge type and density. The anionic polymers in decreasing anionic charge density (as reported by the manufacturers) included AP1120 (GE-Betz, Trevose, PA) > Stock-O-PAM (American Soil Technologies, Pasadena, CA) = Soil fix (Ciba Specialty Chemicals, Suffolk, VA) > AP1110 (GE-Betz) > AP1100 (GE-Betz) > AP1105 (GE-Betz). One cationic polymer CP1160 (GE-Betz) and one neutral polymer AP1142 (GE-Betz) were also tested.

Turbidity

Turbidity samples were collected at a 3.5-cm depth, placed in 25-mL glass vials, and sonicated for 30 s (Model 150 Sonic Dismembrator; Fisher) to break up the floc and establish good scattering for the turbidimeter. The sonication step was found necessary to keep the floc from settling in the vial during the measurement. Turbidity measurements were made on a Micro 100 Turbidimeter (HF Scientific, Fort Myers, FL). Each jar test was completed in triplicate and the turbidity measurements were normalized to the initial turbidity reading in each jar. The values are reported as percent of the initial reading along with the error as standard deviation.

Phosphorus

Both P_s and P_T were analyzed with a modified ascorbic acid–molybdate blue method (Murphy and Riley, 1962) on an Alpkem RFA 300 Autoanalyzer (Astoria-Pacific, Clackamas, OR). The P concentrations (either soluble or total) were normalized to the initial P (soluble or total) concentration in each

jar. The values are reported as percent of initial concentration with the error as standard deviation.

Sample preparation for P_s analysis included filtration ($<0.45 \mu\text{m}$; Fisherbrand MCE membrane filters) and acidification with concentrated sulfuric acid, which decreased the pH to approximately 2.5. For P_T determination, 5 mL of acidified, unfiltered sample and 1 mL of oxidizing solution were combined in 10-mL polypropylene mailing tubes and digested using the persulfate digestion method found in American Public Health Association (1992) with the following modifications: the oxidizing solution was made of 30 g boric acid, 350 mL 1 M NaOH, and 50 g $\text{K}_2\text{S}_2\text{O}_8$ diluted to 1 L with deionized water. Samples were heated in a boiling water bath for 1.5 to 2 h then analyzed for P_T using the Alpkem RFA 300 Autoanalyzer. The particulate phosphorus (P_p) fraction was calculated as the difference between P_T and P_s . The values of P_p are reported as percent of the initial concentration along with the error as standard deviation.

RESULTS AND DISCUSSION

The river water samples were characterized for physical and chemical constituents (Table 1). There was good agreement between the sum of cations, sum of anions, and the electrical conductivity indicating excellent quantification of the chemical constituents. The alkalinity of the waters was more than sufficient to offset any acidification due to aluminum hydrolysis and prevent Al toxicity.

Turbidity

Turbidity reductions were measured in the jar tests to determine the removal efficiency of phosphorus-laden sediment in the tributaries. Turbidity in the treated water varied as a function of both mechanical energy inputs and chemical amendments (Fig. 2). Subsequent increase in paddle speeds (resuspension) for all the jar tests resulted in increased turbidity, although levels were generally lower than found during settling. This suggests that the floc collected at the bottom of the jar during settling required more energy to break apart and resuspend. It is important that this floc remain settled so as to not resuspend and reconstitute to the suspended sediment load in the tributaries.

Relative to the control, the alum addition actually increased the turbidity during the settling period from 300 to 50 RPM. This slightly higher turbidity (above the initial turbidity sample) is explained as the formation of the colloidal $\text{Al}(\text{OH})_3$. Although this floc increased turbidity at high speeds, alum reduced the turbidity to that seen in the PAM-treated water at speeds less than 5 RPM (Fig. 2).

The PAM treatments resulted in turbidity measurements lower than the control throughout the experiment, showing the PAM was capable of settling suspended solids at higher speeds. The cationic PAM-treated water had the lowest turbidities of all the treatments, even at a paddle speed of 300 RPM. The turbidity in the jars was low and remained low after the paddle speeds had been reduced to 25 RPM for both the anionic and nonionic PAMs. Optimal floc formation occurred between paddle speeds of 25 and 50 RPM to reduce turbidity to $<10\%$ (Fig. 2).

The mixing speed, or power input, can be described by the G value (velocity gradient):

$$G = \sqrt{W/\mu}$$

where W is the power imparted to the water per unit volume of the basin, and μ is the absolute viscosity of the water (Reynolds and Richards, 1995). In the jar tests, the value of W depends on the container, paddle geometry, and paddle speed (Lai et al., 1975). The G value is the common variable for comparing mixing between the jar tests and larger scale flows, like furrows or drains.

The corresponding G values associated with the paddle speeds of 25 and 50 RPM are 18 and 45 s^{-1} (at 22°C), respectively (Hudson, 1981). These paddle speeds resulted in efficient collisions and effective bridging interactions for floc formation between the suspended solids and the anionic or nonionic polymer. Any G value above these limits destabilized the floc (Young et al., 2000). Power input to river water will need to satisfy a velocity gradient of 18 to 45 s^{-1} to promote optimal flocculation and settling with anionic or nonionic PAM. The alum treatment, however, required slower mixing speeds (<5 RPM) for proper floc settling ($G < 10 s^{-1}$).

Previous jar tests have also measured different optimum G values between polymer (70–100 s^{-1}) and alum flocculation (40 s^{-1}) (Young et al., 2000). The G value of the rivers is dependent on channel depth, channel width, flow rate, and head loss throughout the length of the river. Based on these variables, the power imparted in the three tributaries is estimated to range from 50 to 100 s^{-1} . Therefore, the velocity gradient for optimum flocculation with PAM and alum may require either a settling basin or lower flow system than typically found in the rivers.

Since all of the polymers reduced the turbidity to less than 10% of the initial turbidity in the jars at 25 RPM ($G = 18 s^{-1}$), a comparison of the flocculation capacity for the polymers was determined at a higher paddle speed (50 RPM, or G value of 45 s^{-1}). This higher paddle speed demonstrated the ability of the polymer to form a floc and settle out of the rivers in slow reaches.

Since the Whitewater River had such low turbidity readings (Table 1), the effect of the PAM addition on the suspended solids was difficult to measure. Therefore, the more turbid New and Alamo Rivers to the south, which are the main contributors of suspended solids to the Salton Sea, were used to measure the effectiveness of the PAM treatment. As previously stated, the majority of settling occurs between 25 and 50 RPM; therefore, the ability to flocculate at the 50 RPM paddle speed could potentially differentiate between the different charge densities of the polymers tested. Cationic PAM was the exception and outperformed the anionic and nonionic PAMs. The cationic polymer CP1160 sufficiently reduced turbidity even at speeds of 300 RPM (G value 300 s^{-1}) (Fig. 2) and is not included in the following analysis at 50 RPM.

Applications of anionic and nonionic polymer showed no observed difference for turbidity reduction at a higher

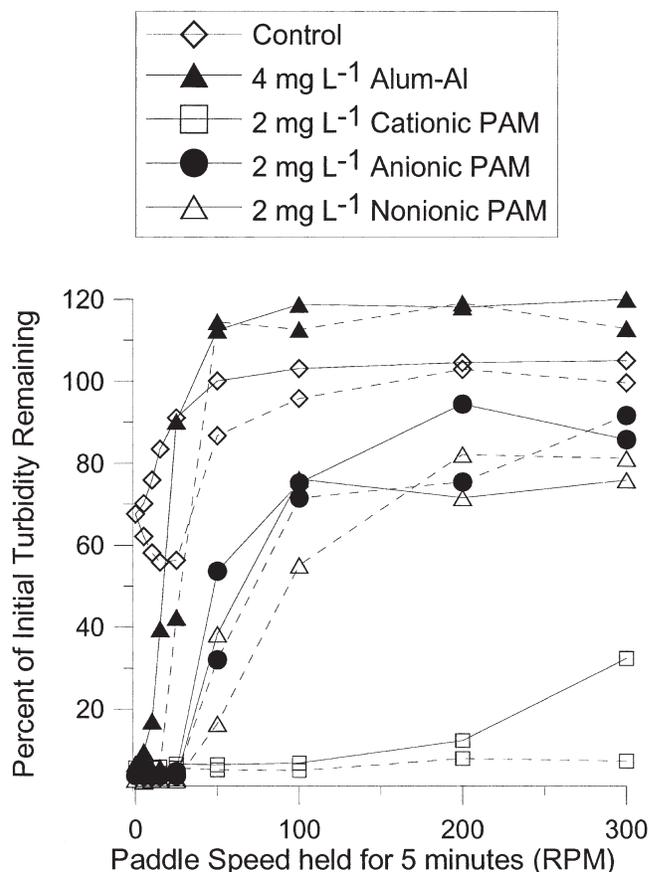


Fig. 2. Results of 2-L jar tests performed with New River water and various amendment additions as the paddle speed is reduced (settling, solid line) then increased (resuspension, dashed line).

paddle speed of 50 RPM (Fig. 3). There were differences between the turbidity readings during settling and resuspension for all polymers, with lower resuspension turbidities (Fig. 2). The lower turbidities during resuspension are a measure of the strength of the floc formed during the settling process. The larger the difference between the settling and resuspension turbidities at 50 RPM, the more energy that was needed to break apart the floc, and the more tightly the floc was held together. A stronger floc will allow the flocculated sediment to resist resuspension as the drain or river flow increases. The floc strength (unitless) of the various polymers was nearly the same (21 ± 5) (Fig. 3), and was extremely low for alum (3.3) at 50 RPM (Fig. 2). However, when PAM was used in combination with alum the floc strength varied substantially among the polymers (discussed below).

Although alum and PAM are able to reduce turbidity at different G values, combining the two treatments could improve the turbidity removal compared to the application of each treatment alone. However, the addition of alum with the polymers reduced the effectiveness for turbidity removal in Alamo River water (Fig. 4) relative to the polymers alone (Fig. 3b). The addition of alum had a lesser effect on the flocculation and settling efficiency when used with the nonionic AP1142 poly-

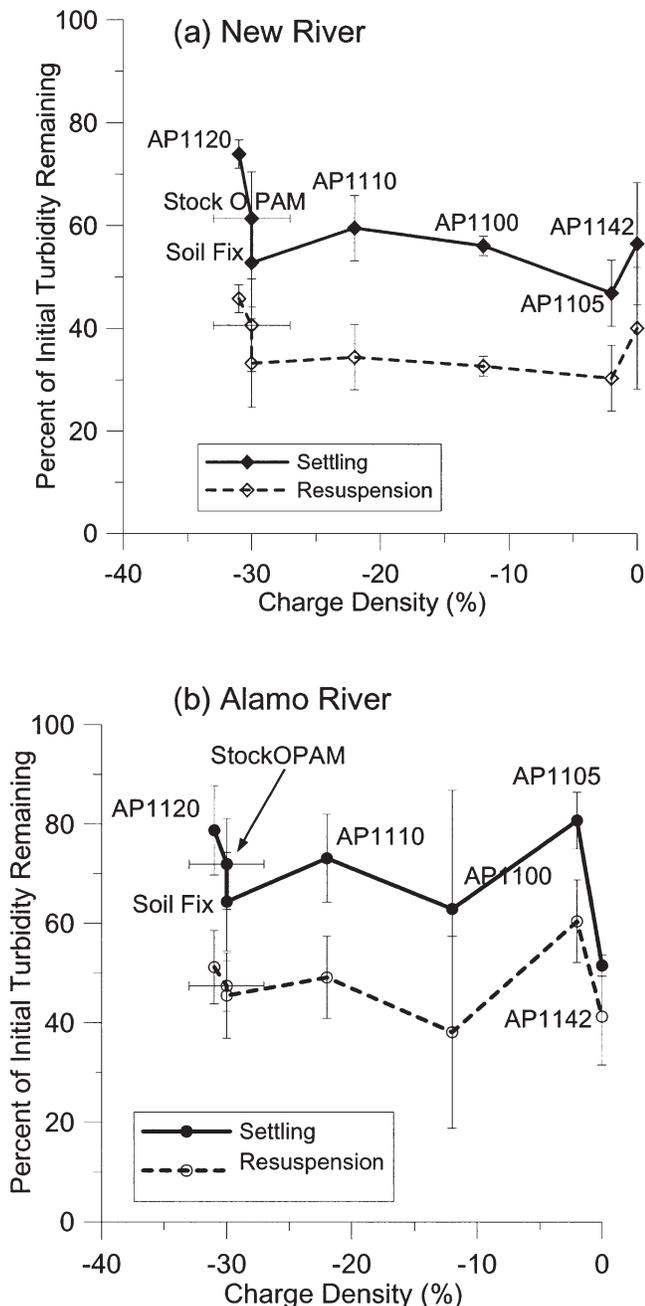


Fig. 3. Turbidity removal at 50 RPM in jar tests performed with various polyacrylamide (PAM) (2 mg L^{-1}) in both (a) New River and (b) Alamo River water, where charge density (%) is reported by the manufacturers.

mer. In fact, the difference between the settling and resuspension turbidities of the different GE-Betz polymers (of similar molecular weight) increased with decreasing polymer charge (Fig. 5). Other research has shown that higher molecular weight polymers enhance flocculation by better bridging between particles (Laird, 1997). However, the GE-Betz polymers were similar in molecular weight to each other (approximately $5 \times 10^6 \text{ g mol}^{-1}$), and can serve as a good indication of how polymer charge alone affects flocculation.

The nonionic AP1142 polymer formed a stronger floc

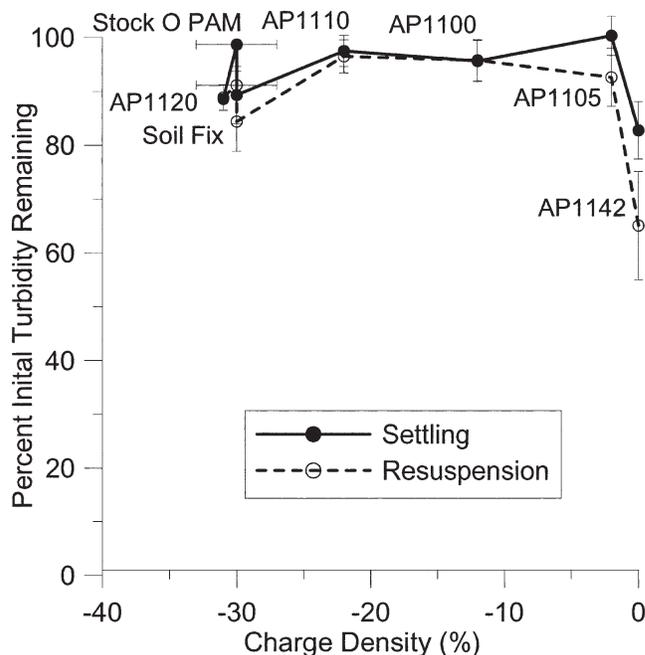


Fig. 4. Turbidity at 50 RPM in jar tests (2 mg L^{-1} polyacrylamide [PAM] + 4 mg L^{-1} alum-Al) with Alamo River water, where charge density (%) is reported by the manufacturers.

and had a greater reduction in turbidity in the presence of alum compared to the anionic PAMs. These results can be attributed to the adsorption of the trivalent aluminum ion onto the negatively charged polymers, thereby reducing the effectiveness of both the anionic polymers and the alum. This appears to contradict the belief that polyvalent cations (like calcium and aluminum) encourage “cation-bridging” between polymer and clay (Theng, 1982; Laird, 1997). Peng and Di (1994) observed results similar to ours when studying kaolin flocculation at pH 6.0. They attributed their results to the precipitation of $\text{Al}(\text{OH})_{3(s)}$ on the clay surfaces and to the adsorption of Al^{3+} , $\text{Al}(\text{OH})^{2+}$, and $\text{Al}(\text{OH})_2^+$ on the anionic charged sites of the PAM. In our studies using Alamo River water, the alum decreased flocculation capacity of all the anionic polymers, whereas the alum did not affect the ability of the nonionic PAM to reduce turbidity. There were no interferences in turbidity removal when cationic PAM was used in combination with alum (data not shown), further supporting the findings of Peng and Di (1994).

Phosphorus

Phosphorus loading to the Salton Sea must be minimized to reduce eutrophic conditions. Although a reduction in sediment loading from ADW reduces P_p , P_s is the predominant fraction of P_T (Table 2). Thus, removal of the readily bioavailable P_s is essential to reduce external P loading.

To compare the difference between PAM and alum for P removal in river water, we tested anionic (AP1110)

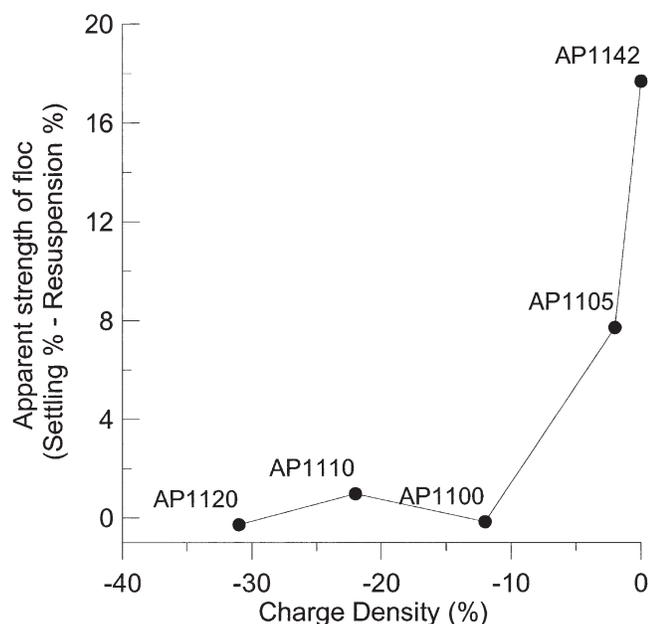


Fig. 5. Effect of polymer charge density on the strength of the floc formed in the presence of 2 mg L^{-1} polyacrylamide [PAM] + 4 mg L^{-1} alum-Al additions in Alamo River water, where charge density (%) is reported by the manufacturers.

PAM, nonionic (AP1142) PAM, and alum using a 5-min settling period at 0 RPM. During this settling period all of the floc that had formed was able to settle out of the water column. The floc formed by the PAM removed suspended solids but not P_s , and the floc formed by alum removed both suspended solids and up to 75% of P_s (Fig. 6).

As previously mentioned, unlike PAM, the alum floc was weak and not capable of settling out of the water column at higher paddle speeds. Although the alum floc absorbs the P_s in the water, the PAM is necessary to enhance flocculation by settling the alum floc and keep the floc settled (floc strength).

A combination of the nonionic PAM, AP1142 (which was capable of reducing turbidity in the presence of alum), and alum are recommended for both P_s and P_p removal in the tributary waters. When these two treatments were added and allowed to settle for 5 min (0 RPM), only 7.2 and 3.4% of P_s and P_p remained suspended in the jar, respectively. These two amendments working together allow the alum to adsorb the P_s fraction, and the PAM to flocculate both the suspended solids and the alum floc.

CONCLUSIONS

Both alum and PAM were able to reduce turbidity, but the alum floc required a lower velocity gradient (G value) to settle out of the water column and formed a weaker floc than the PAM. Although cationic PAM was the most effective to reduce turbidity, it is not recommended as a treatment option since endangered and threatened fish are present in tributary waters in the Imperial Valley. The alum reduced P_s , which is the ma-

Table 2. Average soluble phosphorus (P_s) and total phosphorus (P_T) concentrations of initial river water samples.

	New River	Alamo River	Whitewater River
Collection date	20 Apr. 2004	7 June 2004	20 May 2004
Average P_s , mg L^{-1}	0.69 ± 0.23	0.43 ± 0.15	1.32 ± 0.06
Average P_T , mg L^{-1}	1.46 ± 0.11	0.66 ± 0.05	1.32 ± 0.13
Percent P_s , %	47	65	100

jority of the external P load to the Salton Sea. In lower energy systems, the alum can reduce both turbidity and P_s , but may not stay settled at higher G values (measured by floc strength). The nonionic PAM settled both suspended solids and the alum floc at higher G values, and formed the strongest floc once settled. Therefore, a combination of nonionic PAM (AP1142) in addition to alum is the best application to reduce turbidity and P_s . This stronger floc can remain settled so it can then be periodically dredged from either the riverbed or settling basins, removed from the system, and returned to the agricultural fields or disposed. To meet newly established sedimentation TMDLs, suspended solids would need to be reduced by approximately one-third. If the suggested treatments are applied, nonionic PAM ($\$7.83 \text{ kg}^{-1}$) and alum ($\0.57 kg^{-1}), an estimate of $\$19$ million per year would be required to reduce P_s and P_p loading to the Salton Sea by approximately one-third.

ACKNOWLEDGMENTS

We thank the California State Water Resources Control Board (Contract #02-051-257-1) and the Salton Sea Authority for their financial support. We also appreciate the field and lab assistance of Greg Schwartz, Ed Betty, Jason Adelaars, Woody Smith, and Peggy Resketo. Kevin Crockford at G.E.-Betz provided complimentary polymers for this study.

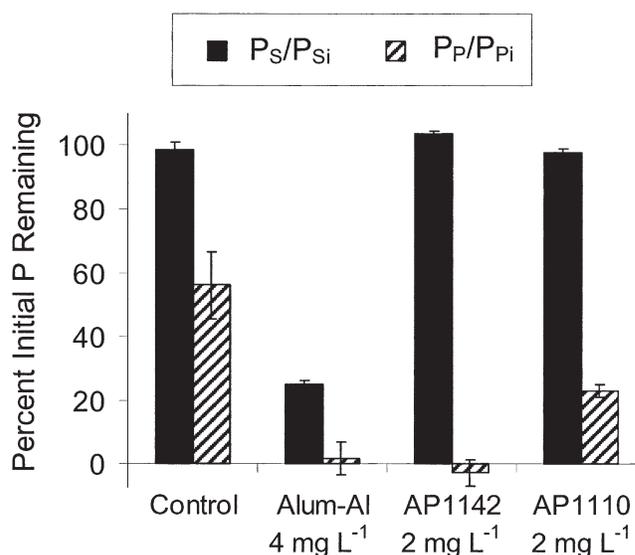


Fig. 6. Phosphorus removal after 5 min of settling at 0 RPM in the jar tests with Alamo River water, expressed as a fraction of the initial soluble phosphorus (P_{s_i}) and initial particulate phosphorus (P_{p_i}).

REFERENCES

- Aly, S.M., and J. Letey. 1988. Polymer and water quality effects on flocculation of montmorillonite. *Soil Sci. Soc. Am. J.* 52:1453–1458.
- Aly, S.M., and J. Letey. 1990. Physical properties of sodium-treated soil as affected by two polymers. *Soil Sci. Soc. Am. J.* 54:501–504.
- American Public Health Association. 1992. Standard methods for the examination of water and wastewater. 18th ed. APHA, Washington, DC.
- Anderson, M.A., and C. Amrhein. 2002. Nutrient cycling in the Salton Sea. Final report to Salton Sea Authority, La Quinta, CA.
- Barvenik, F.W. 1994. Polyacrylamide characteristics related to soil applications. *Soil Sci.* 158:235–243.
- Ben-Hur, M., and R. Keren. 1997. Polymer effects on water infiltration and soil aggregation. *Soil Sci. Soc. Am. J.* 61:565–570.
- Biesinger, K.E., A.E. Lemke, W.E. Smith, and R.M. Tyo. 1976. Comparative toxicity of polyelectrolytes to selected aquatic animals. *J. Water Pollut. Control Fed.* 48:183–187.
- Black, A., and R. Harris. 1969. New dimensions for the old jar test. *Water Wastes Eng.* 49:49–51.
- California Regional Water Quality Control Board. 2002. Water quality control plan. Colorado River Basin-Region 7. Available at www.waterboards.ca.gov/coloradoriver/documents/RB7Plan.pdf (verified 12 July 2005). CRWQCB, Sacramento.
- Goodrich, M.S., L.H. Dulak, M.A. Friedman, and J.J. Lech. 1991. Acute and long-term toxicity of water-soluble cationic polymers to rainbow trout (*Oncorhynchus mykiss*) and the modification of toxicity by humic acid. *Environ. Toxicol. Chem.* 10:509–515.
- Green, V.S., D.E. Scott, L.D. Norton, and J.G. Graveel. 2000. Polyacrylamide molecular weight and charge effects on infiltration under simulated rainfall. *Soil Sci. Soc. Am. J.* 64:1786–1791.
- Hammer, M.J., and M.J. Hammer. 1996. Water and wastewater technology. 3rd ed. Prentice Hall, Columbus, OH.
- Hart, C.M., M.R. Gonzales, E.P. Simpson, and S.H. Hurlbert. 1998. Salinity and fish effects in Salton Sea microecosystems: Zooplankton and nekton. *Hydrobiologia* 381:129–152.
- Helalia, A.M., and J. Letey. 1988. Polymer type and water quality effects on soil dispersion. *Soil Sci. Soc. Am. J.* 52:243–246.
- Holdren, G.C., and A. Montaño. 2002. Chemical and physical characteristics of the Salton Sea, California. *Hydrobiologia* 473:1–21.
- Hudson, H.E., Jr. 1981. Water clarification processes practical design and evaluation. Van Nostrand Reinhold, New York.
- Kennedy, R., and G. Cooke. 1982. Control of lake phosphorus with aluminum sulfate: Dose determination and application techniques. *Water Resour. Bull.* 18:389–395.
- Lai, R.L., H.E. Hudson, and J.E. Singley. 1975. Velocity gradient calibrations of jar test equipment. *J. Am. Water Works Assoc.* 67:553–557.
- Laird, D.A. 1997. Bonding between polyacrylamide and clay mineral surfaces. *Soil Sci.* 162:826–832.
- MacWilliams, D.C. 1978. Acrylamides, p. 298–311. In I. Kirk and D.F. Othmer (ed.) *Encyclopedia of chemical technology*. 3rd ed. John Wiley & Sons, New York.
- Malik, M., C. Amrhein, and J. Letey. 1991. Polyacrylamide to improve water flow and salt removal in high shrink-swell soil. *Soil Sci. Soc. Am. J.* 55:1664–1667.
- Muir, M.M., K.G. Kosteretz, and J.J. Lech. 1997. Localization, depuration, bioaccumulation and impairment of ion regulation associated with cationic polymer exposure in rainbow trout. *Xenobiotica* 27:1005–1014.
- Murphy, J., and J.P. Riley. 1962. A modified simple solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27:31–36.
- Narf, R.P. 1990. Interaction of Chironomidae and Chaoboridae (Diptera) with aluminum sulfate treated lake sediments. *Lake Reservoir Manage.* 6:33–42.
- Omoike, A.I., and G.W. VanLoon. 1999. Removal of phosphorus and organic matter removal by alum during wastewater treatment. *Water Res.* 33:3617–3627.
- Peng, F.F., and P. Di. 1994. Effect of multivalent salts, calcium and aluminum on the flocculation of kaolin suspension with anionic polyacrylamide. *J. Colloid Interface Sci.* 164:229–237.
- Reynolds, T.D., and P.A. Richards. 1995. Unit operations and processes in environmental engineering. 2nd ed. PWS Publ., Boston.
- Setmire, J., C. Holdren, D. Robertson, C. Amrhein, J. Elder, R. Schroeder, G. Schladow, H. McKellar, and R. Gersberg. 2000. Eutrophic conditions at the Salton Sea. A white paper resulting from a Salton Sea Science Committee Panel Meeting, 7–8 Sept. 2000. Salton Sea Authority, La Quinta, CA.
- Seybold, C.A. 1994. Polyacrylamide review: Soil conditioning and environmental fate. *Commun. Soil Sci. Plant Anal.* 25:2171–2185.
- Sojka, R.E., R.D. Lentz, I. Shainberg, T.J. Trout, C.W. Ross, C.W. Robbins, J.A. Entry, J.K. Aase, D.L. Bjorneberg, W.J. Orts, D.T. Westermann, D.W. Morishita, M.E. Watwood, T.L. Spofford, and F.W. Barvenik. 2000. Irrigating with polyacrylamide (PAM): Nine years and a million acres of experience. p. 161–169. In R.G. Evans, B.L. Benham, and T.P. Trooien (ed.) *Proc. of the National Irrigation Symp., 4th Decennial Symp., Phoenix, AZ. 14–16 Nov. 2000.* Publ. 701P0004. Am. Soc. of Agric. Eng., St. Joseph, MI.
- Sojka, R.E., R.D. Lentz, and D.T. Westermann. 1998. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. *Soil Sci. Soc. Am. J.* 62:1672–1680.
- Theng, B.K.G. 1982. Clay-polymer interactions: Summary and perspectives. *Clays Clay Miner.* 30:1–10.
- USDA-SCS. 1980. Soil survey of Riverside County, California, Coachella Valley area. U.S. Gov. Print. Office, Washington, DC.
- USDA-SCS. 1981. Soil survey of Imperial County, California, Imperial Valley area. U.S. Gov. Print. Office, Washington, DC.
- Welch, E.B., and G.D. Cooke. 1999. Effectiveness and longevity of phosphorus inactivation with alum. *Lake Reservoir Manage.* 15:5–27.
- Young, S., S. Stanley, and D.W. Smith. 2000. Effect of mixing on the kinetics of polymer-aided flocculation. *J. Water Supply Res. Technol.* 49:1–8.
- Zhang, X.C., and W.P. Miller. 1996. Polyacrylamide effect on infiltration and erosion in furrows. *Soil Sci. Soc. Am. J.* 60:866–872.