

Drinking water treatment residuals can be beneficially used to reduce phosphorus (P) in runoff water from manured agricultural land. The objective of this study was to determine treatment residual components responsible for P sorption and reduction of P in runoff water. Using 21 aluminum- (Al-) based treatment residuals from Oklahoma utilities, chemical components related to P sorption (amorphous Al [Al_{ox} , 1.33–48.7 g/kg], iron [Fe] [Fe_{ox} , 0.23–7.44 g/kg] oxides), clay (0–100%), and water-soluble calcium (0.05–0.74 g/kg) were measured. Linearized Langmuir P sorption maxima (P_{max}) ranged from 0.30 to 5.14 g/kg, and nonlinear Freundlich P distribution coefficient (K_p) ranged from 17.5 to 1,085 L/kg. Addition of water treatment residuals (50 Mg/ha) to box plots treated with poultry litter (16.7 Mg/ha) reduced runoff P by from 14.0 to 84.9%. Reductions in runoff P were strongly correlated ($p < 0.05$) with P_{max} and Al_{ox} . Performance of treatment residuals as a P sorbent to reduce runoff P from manured land can be estimated from their P_{max} or Al_{ox} content.

Using Treatment Residuals

TO REDUCE PHOSPHORUS in agricultural runoff

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Surface runoff of nutrients nitrogen (N) and phosphorus (P) from manured agricultural land can be an important source of water quality impairments in surface waters in the United States (Parry, 1998). Application of animal manure in amounts that exceed agronomic rates based on the N requirement for crop production often results in increased loss of P from agricultural land in surface runoff and potential eutrophication of surface waters (Sharpley et al, 1994). The role of P in runoff water (Paulter & Sims, 2000; Pote et al, 1999; Correll, 1998; Daniel et al, 1998; Sharpley et al, 1994) and leaching (Sims et al, 1998; Ward & Summers, 1993; Vlahos et al, 1989) from agricultural land in the eutrophication of surface water has been well-documented. Excessive concentration of soluble P is the most common source of eutrophication in fresh surface waters (Correll, 1998). The greatest potential for surface runoff of nutrients from agricultural land and eutrophication to occur is in regions of intense animal production (Sharpley et al, 1994). Intensive poultry production in eastern Oklahoma and other regions of the United States has contributed to economic growth but has raised concerns about surface

TABLE 1 Chemical and physical properties and total content of major elements of drinking water treatment residuals

Treatment Residual	Properties—%			pH	Properties dS/m	Properties—g/kg		Major Elements—g/kg				
	Sand	Silt	Clay		EC*	WS Ca†	Organic Carbon	Aluminum	Calcium	Iron	Potassium	Phosphorus
1	76.4	21.9	11.5	7.10	0.63	0.21	80.0	107	10.4	20.1	4.17	1.44
2	77.8	16.3	6.0	7.70	0.54	0.46	75.0	135	50.0	24.7	4.91	1.22
3	82.8	17.2	0	7.00	1.09	0.050	128	93.0	4.47	33.3	2.90	1.87
4	72.1	2.69	2.69	7.80	0.60	0.36	69.0	107	30.4	38.4	5.16	3.01
5	81.9	7.52	10.6	7.80	1.08	0.63	65.0	151	51.3	21.6	4.85	4.04
6	60.9	32.3	6.74	7.46	0.84	NA‡	33.5	90.9	50.1	30.5	6.49	1.55
7	57.6	32.6	9.78	7.70	0.44	0.28	28.0	28.1	24.3	14.7	4.14	0.20
8	0	0	100	6.60	0.28	0.16	32.0	34.8	2.29	22.0	4.16	0.29
9	86.8	11.1	3.13	7.00	0.27	0.14	46.0	112.	4.92	49.9	6.69	1.27
10	49.6	50.4	0.99	6.90	0.40	0.28	62.0	96.3	28.4	44.6	4.39	1.70
11	59.6	29.5	10.9	7.70	0.59	0.25	48.0	42.3	37.9	19.7	3.30	0.37
12	72.9	24.3	4.46	5.30	0.43	0.14	78.0	177.	2.79	40.1	6.81	0.86
13	60.4	34.2	5.41	7.50	1.03	0.74	149	50.6	64.1	17.0	2.36	3.23
14	50.1	46.9	2.95	7.20	0.67	0.51	86.0	80.3	10.4	34.6	5.20	3.20
15	62.5	25.0	12.5	NA	NA	0.48	50.5	96.9	18.0	23.9	4.00	0.65
16	72.5	12.5	15.0	7.68	0.35	0.42	113	127	85.4	21.5	4.81	0.87
17	74.6	25.4	1.47	7.28	0.68	0.34	205.	42.5	106	16.2	1.70	0.76
18	92.1	3.66	4.29	7.00	0.22	0.12	60.0	131	8.51	31.6	5.43	1.76
19	NA	NA	NA	8.20	0.77	0.065	33.3	14.7	317	5.02	1.34	0.67
20	87.5	12.5	1.14	7.00	0.80	0.37	63.0	129	7.22	41.0	6.67	3.29
21	63.6	18.5	17.9	6.60	0.22	0.11	23.0	50.1	2.77	39.3	4.55	0.79
Range												
Low	0	0	0	5.30	0.22	0.050	23.0	14.7	2.29	5.02	1.34	0.20
High	92.1	50.4	100	8.20	1.09	0.74	205	177	317	49.9	6.81	4.04
Median	72.3	20.2	5.7	7.24	0.60	0.28	63.0	96.3	24.8	24.7	4.68	1.27
Soil typical range	NA	NA	NA		<4.0	NA	<30					
Low				5.0				11	1	0.7	0.8	0.22
High				8.0				79	18	56	33	1.1

*EC—electrical conductivity
†WS Ca—water-soluble calcium
‡NA—not available

water pollution. Poultry litter is an inexpensive N fertilizer and is often applied to permanent pastures without incorporation. Surface application of poultry litter increases P concentrations in surface agricultural runoff water (Liu et al, 1997; Sharpley, 1997).

As a result of increased concern, many states are developing manure application limits to protect surface water quality (Sims et al, 1999). Too often, application of manure and biosolids is based on crop N requirements resulting in a twofold to threefold excess application of P (Parry, 1998).

Current strategies used to reduce P transport to surface water include conservation tillage, crop residue management, cover crops, buffer strips, contour tillage, runoff water impoundment, and terracing. These strategies are

effective in controlling particulate P but not dissolved P in runoff (Daniel et al, 1998; Sharpley et al, 1994). In order to control dissolved P transport to surface water, new best management practices (BMPs) must be developed and implemented (Sims et al, 1999).

One possible BMP is to remove dissolved P from runoff by applying P-sorbing materials such as aluminum (Al) or iron (Fe) oxide or hydroxide to land. P sorption, by land application of Fe oxide-rich bauxite-mining residual, has been successfully used to reduce P runoff (Peters, 1996) or leaching (Ward & Summers, 1993; Vlahos et al, 1989) to protect surface water or groundwater quality.

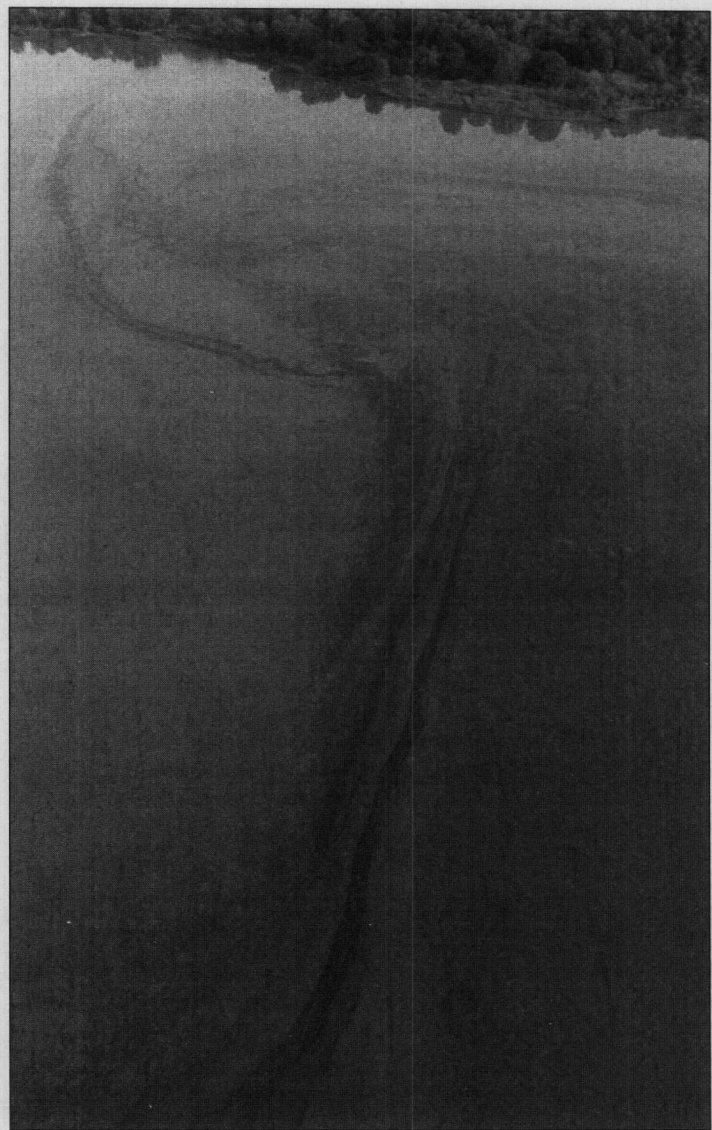
Drinking water treatment residuals that contain Al or Fe oxide may be beneficially used as a BMP to protect surface water quality by removing dissolved P from agri-

Phosphorus in agricultural runoff water feeds algae and causes algal blooms—such as this one in an eastern Oklahoma lake—which are detrimental to water quality.

cultural runoff water. Often treatment residuals are disposed of in landfills (at significant expense to municipalities), stored in onsite lagoons, or discharged into sanitary sewer systems. Using water treatment residuals as P sorbents could provide an economic benefit to municipalities and economic and environmental benefits to communities by preserving surface water quality.

Treatment residuals are the by-product of treatment processes that use coagulation to remove turbidity, color, odor, and taste from raw water and to speed sedimentation. Residuals generated using alum as a coagulant can contain 50–150 g/kg amorphous Al hydroxide (ASCE, 1996), which strongly binds P.

Incorporating treatment residuals into soil has reduced excessive soluble P resulting from manure application (Cox et al, 1997; Peters & Basta, 1996). Phosphorus solubility in biosolids was reduced by coapplication with water treatment residuals (Ippolito et al, 1999). Surface application of treatment residuals has reduced soluble P in runoff water from pastureland manured with poultry litter (Gallimore et al, 1999; Daniel et al, 1999; Basta & Storm, 1997; Peters, 1996). The most effective surface application of water treatment residuals was as a buffer strip (44.8 Mg/ha treatment residual) applied to a pasture treated with poultry litter (Gallimore et al, 1999). Soluble P was reduced by treatment residual from 15 to 8.1 mg/L, but large differences (16 and 47%) in soluble P reduction were found between the water treatment residuals from two treatment plants that were used in the study (Gallimore et al, 1999). Treatment plants use different source water and different treatment chemicals, producing treatment residuals with different chemical compositions and P sorption capacities. Treatment chemical type and dosage vary among treatment plants and over time at the same plant. Therefore, treatment residual performance as a P sorbent will vary. Estimating treatment residual performance as a P sorbent is important to effectively reduce runoff P and for accurate calibration of field applications. Because of the wide range of types and amounts of treatment chemicals used to treat different source water, each treatment plant produces a unique treatment residual, making it difficult to predict P sorption based on water treatment method (e.g., alum, polymer, Fe). A better approach is to identify treatment residual components that are responsible for P sorption. The objective of this work was to measure treatment residual



components related to P sorption and to determine which are responsible for the P sorption capacity of various Al-based treatment residuals.

MATERIALS AND METHODS

Twenty-one Al-based treatment residuals were collected from municipal drinking water treatment plants in Oklahoma, air dried, and crushed to pass through a 2.0-mm sieve.

Chemical characterization. To characterize the materials, treatment residual chemical and physical properties were measured. In 1:2 treatment residual:0.01 M calcium chloride solutions, pH was measured using a glass electrode (McLean, 1982). Electrical conductivity (EC) was measured in 1:2 treatment residual:deionized water solutions (Rhoades, 1996). Organic carbon was determined by dichromate oxidation followed by colorimetric analysis (Nelson & Sommers, 1996). Water soluble calcium (Ca) was determined by batch extraction using 5:25 treatment residual:deionized water and analysis by using induc-

FIGURE 1 Water treatment residual P sorption isotherms

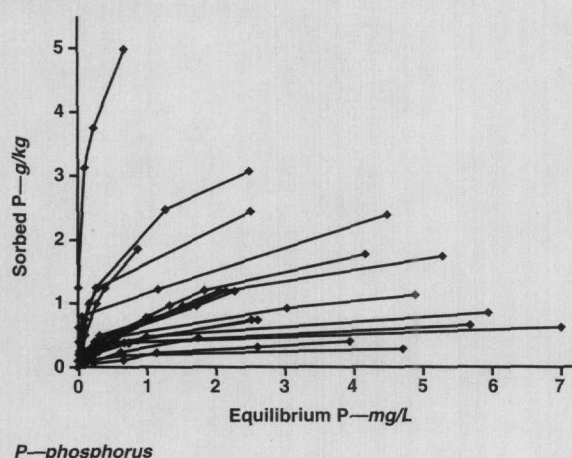
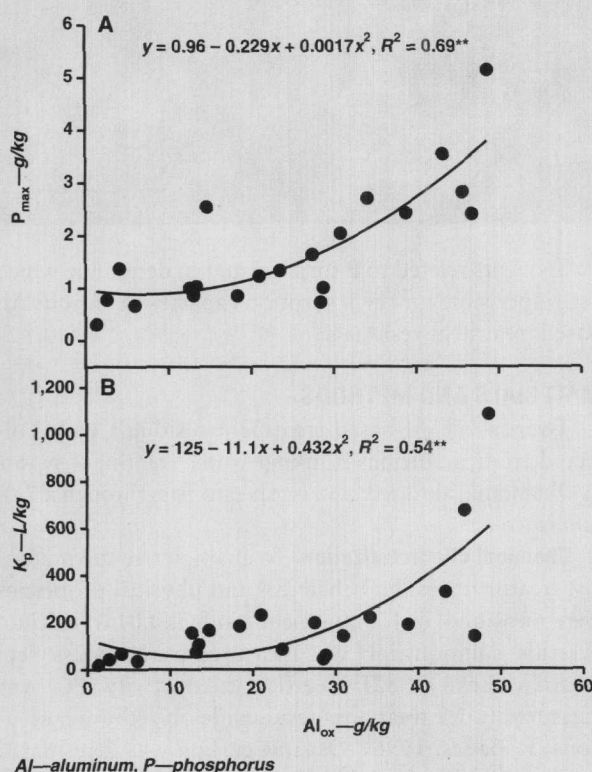


FIGURE 2 Water treatment residual Langmuir P sorption maxima (P_{\max}) (A) and Freundlich P distribution coefficient (K_p) (B) versus acid ammonium oxalate extractable Al (Al_{ox}) (** $p < 0.001$)



tively coupled plasma atomic emission spectroscopy (ICP). Particle size analysis was determined using the pipet method (Gee & Bauder, 1986). Total treatment residual content of Al, Ca, Fe, potassium (K), and P was determined using nitric/perchloric acid digestion and subsequent analysis of elements using ICP (Amacher, 1996). Amorphous Al and Fe oxide (Al_{ox} and Fe_{ox}) and hydroxide were determined by acid ammonium oxalate extraction (McKeague & Day, 1993), followed by ICP analysis.

P sorption. P sorption isotherms were generated by batch equilibration by shaking 1:25 treatment residual:P solutions (0–100 mg/L P) prepared from monobasic sodium phosphate. After a 15-h equilibration, solutions were centrifuged at 10,000 rpm for 12 min, and the liquid was decanted for analysis of P. Five P equilibration solutions were used to generate adsorption isotherms. Equilibrium solution P was determined by the modified Murphy-Riley colorimetric method (Kuo, 1996), and sorbed P was calculated by difference. The linearized Langmuir P sorption maxima (P_{\max}) and the nonlinear Freundlich P distribution coefficient (K_p) were determined as two measures of P sorption by treatment residual. The linearized Langmuir equation (Eq 1) (Sparks, 1995) used was:

$$c/x/m = 1/kb + c/b \quad (1)$$

in which c is the equilibrium solution P (mg/L), x/m is the sorbed P (mg/kg), k is the bonding energy coefficient, and b is the P_{\max} (mg/kg). The nonlinear Freundlich equation (Eq 2) (Sparks, 1995) used was:

$$q = K_p C^{1/n} \quad (2)$$

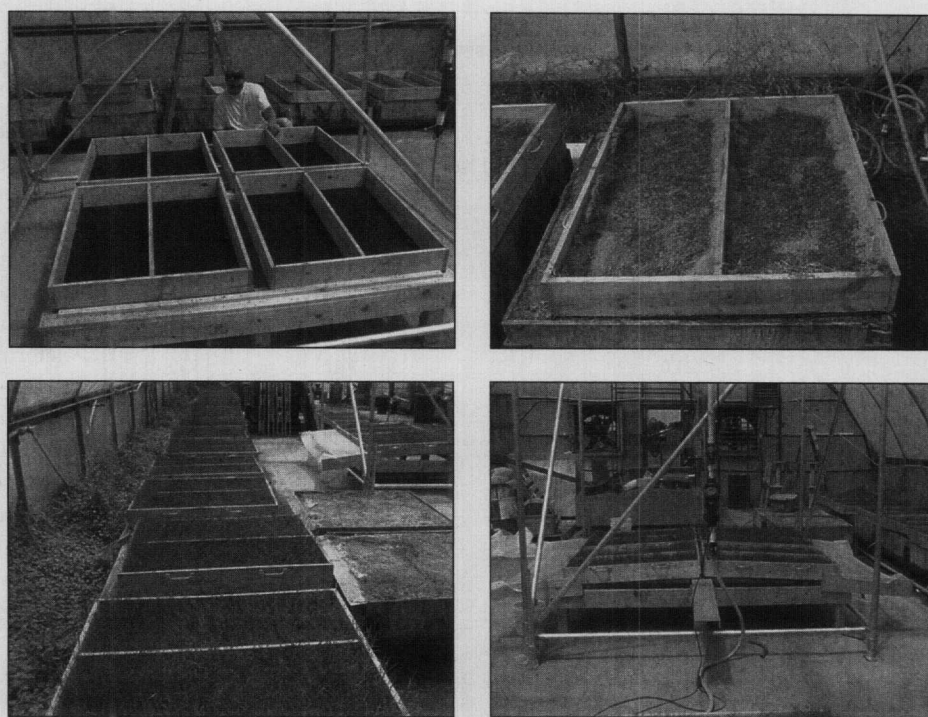
in which q is the sorbed P (mmol/kg), K_p is the P distribution coefficient (L/kg), C is the equilibrium solution P (mmol/L), and n is a constant.

Runoff water study. To determine whether differences in measured treatment residual P sorption capacity would result in different reductions of dissolved P in runoff water (runoff P) in a field situation, a rainfall simulation study was conducted to simulate field conditions. A subset of 11 treatment residuals was chosen, based on a means comparison (Steele et al, 1997) to include those residuals with high, medium, and low P_{\max} . Box plots (1 × 0.4 m [3.29 × 1.32 ft]) with mesh bottoms to allow for free drainage were constructed, filled with 50 mm (2 in.) of a silt loam, and planted with Bermuda grass (*Cynodon dactylon*) sod. The sod was allowed to grow until it rooted through the soil to avoid preferential flow pathways between the sod and the soil. Plots were set to provide a 5% slope and were saturated immediately prior to applying treatments; rain simulation began immediately following treatment application. Treatments consisted of applying poultry litter to the upslope 750 mm (29.5 in.) of each plot (16.7 Mg/ha) and applying treatment

residuals in a buffer strip to the downslope 250 mm (9.8 in.) of each plot (50 Mg/ha). Rainfall simulations were performed on each plot prior to applying treatments to obtain background P runoff levels that were subtracted from final runoff P. Each residual treatment was replicated four times. Six replications of poultry litter without treatment residual were averaged for the control. The simulated rain was supplied (at a rate of 7.0 cm/h [2.7 in./acre]) by a solenoid-operated variable-intensity rainfall simulator (uniformity coefficient = 0.89) (Miller, 1987). Water was supplied by the city of Stillwater, Okla., and contained negligible amounts of ammonium and P. Simulated runoff water was collected for 30 min after it began, and dissolved P in filtered (0.45- μ m) runoff was measured using the modified Murphy-Riley method (Kuo, 1996).

RESULTS AND DISCUSSION

Chemical characterization. Chemical properties and components used to characterize treatment residuals are summarized in Table 1. The treatment residual pH ranged from 5.30 to 8.20 with a median of 7.24. The generally neutral pH was within the normal range for soils (Bohn et al, 1985) and is the result of pH adjustment with alkaline materials (i.e., calcium hydroxide) during drinking water treatment. The EC ranged from 0.22 to 1.09 dS/m with a median of 0.60 dS/m, well below the 4.0 dS/m associated with saline soil (Brady & Weil, 1996). Thus, phytotoxicity due to salt problems is not expected. Organic carbon content ranged from 23.0 to 205 g/kg with a median of 63.0 g/kg, whereas soil typically contains <30 g/kg (Brady & Weil, 1996). High treatment residual organic carbon may be attributed to sediment organic matter, coagulated algal cells, and small amounts of activated charcoal or organic polymer added during treatment. Of the major elements measured (Table 1), treatment residual Al, Ca, and P concentrations were higher than those typically found in soils. Total treatment residual Al ranged from 14.7 to 177 g/kg, whereas the typical soil range is from 11 to 79 g/kg. Total treatment residual Ca ranged from 2.29 to 317 g/kg, whereas the typical soil range is from 1 to 18 g/kg (Isaac & Kerber, 1971). The



The setup for the runoff water phosphorus study included 1 x 0.4 m boxes with mesh bottoms (top left) and Bermudagrass sod planted on 50 mm of soil (top right). The sod is shown after two weeks of growth (bottom left) and when it is ready to collect runoff (bottom right).

higher-than-typical treatment residual level of these two elements results from Al (coagulant) and Ca (i.e., calcium carbonate, calcium oxide) added during treatment. The total treatment residual P level ranged from 0.20 to 4.04 g/kg with a median of 1.27 g/kg, higher than the typical soil range of 0.22–1.1 g/kg (Isaac & Kerber, 1971). High treatment residual P is probably due to its being concentrated in the residual after removal from raw water during treatment. Total treatment residual Fe ranged from 5.02 to 49.9 g/kg, and K ranged from 1.34 to 6.81 g/kg. Both were within the normal range typical for soil (Table 1) (Isaac & Kerber, 1971).

P sorption. There was a wide range in P sorption among the 21 treatment residuals (Figure 1). The large variability in treatment residual P sorption probably is due to differences in water treatment processes (i.e., how much coagulant is used) and differences in particle size distribution and surface area between treatment residuals. Adsorption of P in soil is related to amorphous hydrous metal oxide (Al_{ox} and Fe_{ox}) content (Sparks, 1995; McBride, 1994; Sposito, 1989). Acid ammonium oxalate extraction (McKeague & Day, 1993) was used to measure Al_{ox} and Fe_{ox} in water treatment residuals. Residual Al_{ox} content, ranging from 1.33 to 48.7 g/kg with a median of 23.5 g/kg, was substantially higher than treatment residual Fe_{ox} , which ranged from 0.23 to 7.44 g/kg with a median of 2.94 g/kg (Table 2). The disproportionate treatment residual Al_{ox} results from the amorphous Al_{ox} gen-

TABLE 2 Amorphous Al and Fe content, P_{\max} , and K_p of drinking water treatment residuals*

Treatment Residual	Al_{ox}^{\dagger} —g/kg	Fe_{ox}^{\ddagger} —g/kg	P_{\max} —g/kg	K_p —L/kg
1	43.3	2.10	3.54	328
2	46.8	2.48	2.40	138
3	30.9	6.98	2.04	140
4	27.5	4.49	1.63	195
5	45.7	2.06	2.82	675
6	21.0	1.78	1.22	229
7	4.14	3.23	1.37	66.0
8	1.33	6.84	0.30	17.5
9	18.4	5.50	0.85	184
10	23.5	7.44	1.33	84.9
11	13.1	1.00	0.86	74.5
12	48.7	3.95	5.14	1,085
13	14.7	2.94	2.54	165
14	13.4	3.04	1.03	105
15	38.8	4.31	2.43	189
16	34.2	1.49	2.70	218
17	12.6	2.52	1.00	156
18	28.8	2.67	1.00	57.1
19	2.64	0.23	0.77	420
20	28.5	3.13	0.72	41.9
21	6.03	2.14	0.66	35.5
Range	1.33–48.7	0.23–7.44	0.30–5.14	17.5–1,085
Median	23.5	2.94	1.33	140

*Al—aluminum, Fe—iron, P—phosphorus, P_{\max} —linearized Langmuir P sorption maxima, K_p —nonlinear Freundlich P distribution coefficient
 $\dagger Al_{ox}$ —acid ammonium oxalate extractable Al
 $\ddagger Fe_{ox}$ —acid ammonium oxalate extractable Fe

TABLE 3 Reduction in runoff P* from manured plots by drinking water treatment residual application

Treatment Residual	Runoff P—mg/L	Runoff P Reduction—%
4	25.4	53.8
7	29.6	46.2
8	24.7	55.1
10	21.1	61.6
11	36.0	34.6
12	10.7	80.6
14	47.3	14.0
16	8.29	84.9
18	23.7	56.9
19	30.3	44.9
21	29.2	46.9
Control	55.0	NA†
Range	8.29–47.3	14.0–84.9
Median	25.4	53.8

*P—phosphorus
 \dagger NA—not applicable

erated as a result of water treatment processes that use Al-based coagulants. Water-soluble Ca in treatment residuals was measured to determine whether precipitation of calcium phosphate minerals was occurring during the batch equilibration. Water-soluble Ca content ranged from 0.05 to 0.63 g/kg with a median of 0.28 g/kg. Residual clay content was measured to determine whether P was adsorbing to clay surfaces during batch equilibration. Residual clay content ranged from 0 to 100% with a median of 5.7% (Table 1).

The P sorption isotherm data conformed well to the linearized Langmuir ($p < 0.05$) and the nonlinear Freundlich ($p < 0.05$) equations. The treatment residual linearized Langmuir P_{\max} ranged from 0.30 to 5.14 g/kg, and the nonlinear Freundlich P distribution coefficients (K_p) ranged from 17.5 to 1,085 L/kg (Table 2). Although it does not resolve mechanistic questions, the Langmuir sorption model has the distinct advantage of providing a calculated P_{\max} , allowing the sorption capacity of a material to be determined. The Freundlich K_p relates to the affinity of a material for P. For similar values of n (Eq 2), the K_p can be used to compare the amount of P sorbed by different materials relative to each other but does not provide a sorption maxima. The wide range in K_p values (Table 2) indicates considerable variability in treatment residual affinity for P.

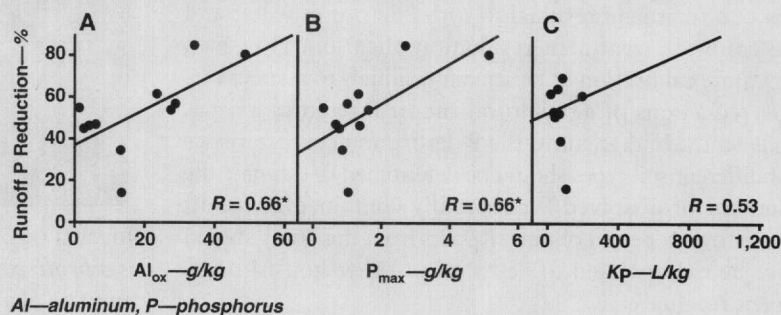
In order to estimate treatment residual performance as a P sorbent, the authors looked for a relationship between measures of P sorption, P_{\max} , and K_p , and chemical components related to P sorption Al_{ox} and Fe_{ox} , water-soluble Ca, and clay content. Significant ($p < 0.001$) quadratic relationships were found between P_{\max} and Al_{ox} (Figure 2, part A) and K_p and Al_{ox} (Figure 2, part B) but not between P_{\max} or K_p and Fe_{ox} , clay content, or water-soluble Ca. Inclusion of clay content, Fe_{ox} , and water-soluble Ca with Al_{ox} as dependent variables in multiple regression models did not improve the relationship between P_{\max}

or K_p and Al_{ox} . Elliott et al (1990) reported significant linear regressions ($R^2 > 0.85$) between P sorption parameters (equilibrium P concentration and phosphorus buffering capacity) and amorphous Al and Fe (measured using citrate dithionate bicarbonate extraction) in soils amended with alum residuals. Because soils in that study were amended with alum treatment residual at ≤ 100 g/kg, P sorption was probably influenced by both soil and treatment residual properties.

Runoff water study. Differences in treatment residual P sorption capacity, found in the P sorption study, did relate to differences in runoff P reduction. Runoff P was reduced by 14.0–84.9% with a median reduction of 53.8% from an average 55 mg/L P in the control plots (Table 3). A significant linear relationship ($p < 0.05$) was found between runoff P reduction and Al_{ox} (Figure 3, part A) and P_{max} (Figure 3, part B), but not with K_p (Figure 3, part C) or Fe_{ox} .

Results show that treatment residual P_{max} may be used to predict its relative performance as a P sorbent to reduce dissolved P in runoff water from manured land. The strong relationship between runoff P and Al_{ox} suggests that the Al_{ox} content of treatment residuals can also be used

FIGURE 3 Percent runoff P reduction versus water treatment residual amorphous Al (Al_{ox}) (A), Langmuir P sorption maxima (P_{max}) ($*p < 0.05$) (B), and Freundlich P distribution coefficients (C)



to predict the performance of treatment residuals to serve as a P sorbent under field conditions. Management decisions, such as the amount of treatment residual to be land-applied to reduce P runoff, should be based on treatment residual P_{max} or Al_{ox} .

CONCLUSIONS

The drinking water treatment residuals examined in this study exhibited a wide range of P-sorption capacities. Therefore, the ability of surface-applied treatment residuals to reduce P in runoff water from manured land will

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vary. Before a treatment residual is used as a P sorbent, the sorption capacity should be determined to predict its performance. The empirical relationship between treatment residual Al_{ox} and P_{max} may be used to estimate the ability of a treatment residual to sorb P in runoff water and to calibrate treatment residual application. However, accurate calibration of treatment residuals to achieve target reductions of agricultural runoff P requires a separate study. In that study, the P desorption characteristics of different soil types should be determined to estimate the amount of dissolved P potentially contained in runoff water over a period of time. Results from this study should not be extrapolated to Fe-based or other non-Al treatment residuals.

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FOOTNOTES

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Page 130 **Performance-based approach for groundwater systems**

Bill Davis

This article suggests a more objective approach to evaluating the condition of a water system—including source, treatment, and distribution—based on performance data. Most groundwater systems are currently evaluated by managers and regulators through a combination of compliance monitoring and sanitary survey inspections. However, field experience has demonstrated types of monitoring that can be performed at groundwater systems to comprehensively evaluate their ability to resist microbiological contamination.

Utility managers will benefit from this information because it shows how process-control-type monitoring, compared with nonregulatory goals, can help improve utilities' ability to prevent contamination.

It is hoped that the information provided will encourage groundwater utilities to begin collecting and analyzing performance data and lead to a better understanding of how each barrier can be improved.—LH

Page 141 **ClO₂ and by-product persistence in a drinking water system**

Robert C. Hoehn, Christine S. Ellenberger, Daniel L. Gallagher, Eurman ("Toby") V. Wiseman Jr., Robert W. Benninger, and Aaron Rosenblatt

Chlorine dioxide (ClO₂) has become increasingly popular for drinking water treatment, partly because it oxidizes rather than chlorinates organic matter and therefore does not form trihalomethanes or other chlorination by-products. Its reactions with organic matter, however, produce chlorite ion (ClO₂⁻) and chlorate ion (ClO₃⁻).

This study, conducted at the Spring Hollow Water Treatment Facility (SHWTF) in Virginia, was the first full-scale evaluation of a chlorine gas–solid sodium chlorite ClO₂ generation system. In addition to evaluating the system, the utility wanted to determine the efficacy of its deep-bed granular activated carbon (GAC) filters following conventional filtration for removing ClO₂⁻. Finally, SHWTF wanted to determine the relationship between ClO₂⁻

concentrations leaving the treatment plant and the levels of ClO₂ that reformed following final chlorination and led to complaints from customers of odors resembling kerosene and cat urine.

Utilities facing similar customer complaints may try reducing the ClO₂ dosage, but complaints will not be completely eliminated until ClO₂⁻ concentrations in water leaving the treatment plant are <0.4 mg/L. GAC contactors afford limited protection against high ClO₂⁻ concentrations entering the distribution system if the ClO₂ dosage remains low, but the effectiveness of GAC declines rapidly. To keep ClO₂ dosages at an effective treatment level without triggering odor complaints, water providers can either remove ClO₂⁻ at the treatment plant or substitute chloramines for free chlorine in the distribution system.—MPM

Page 151 **Using treatment residuals to reduce phosphorus in agricultural runoff**

Elizabeth A. Dayton, Nicholas T. Basta, Christopher A. Jakober, and Jeffory A. Hattey

Land application of drinking water treatment residuals to reduce phosphorus (P) from agricultural land could provide economic and environmental benefits to municipalities and communities by preserving surface water quality. Only treatment residuals that have significant P sorption capacity will reduce runoff P, and the ability of different treatment residuals from different plants to reduce P runoff varies greatly.

The authors describe a simple test that can determine whether a treatment residual will serve as a P sorbent and the

relative amount that should be land-applied. Currently, most utilities are landfilling their treatment residuals. Utility managers will be interested in land application of their residuals because it will decrease their waste-disposal expenses, and it may help protect their source water from agricultural runoff. The major stumbling block for utilities is obtaining permits for land application. However, predicting the performance of a given treatment residual to reduce runoff P is necessary to obtain permits from regulatory agencies. —LH