



Aluminum-Based Water Treatment Residual Use in a Constructed Wetland for Capturing Urban Runoff Phosphorus: Column Study

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Abstract Aluminum-based water treatment residuals (Al-WTRs) have a strong affinity to sorb P. In a proof-of-concept greenhouse column study, Al-WTR was surface-applied at rates equivalent to 0, 62, 124, and 248 Mg ha⁻¹ to 15 cm of soil on top of 46 cm of sand; Al-WTR rates were estimated to capture 0, 10, 20, and 40 years of P from an urban watershed entering an engineered wetland in Boise, ID, USA. Creeping red fescue (*Festuca rubra*) was established in all columns; one set of columns received no Al-WTR or plants. After plant establishment, once per week over a 12-week period, ~1.0 pore volumes of ~0.20 mg P L⁻¹ were added to each column. Infiltration rates were measured, leachate was collected and analyzed for soluble P, and fescue yield, P concentration, and uptake were determined. After plant harvest, the sand, soil, and the Al-WTR layer were collected and analyzed for Olsen P; amorphous Al, Fe, and P; P storage capacity (PSC); and soluble + Al + Fe-bound, occluded, and Ca-bound P phases. Infiltration rate increased only due to the presence of plants. Leached P decreased (50 %) with plants present; Al-WTR further reduced soluble P leaching losses (60 %). Fescue yield, P concentration, and uptake

increased with increasing Al-WTR rate, due to Al-WTR sorbing and potentially making P more plant available; Olsen-extractable P increased with increasing Al-WTR rate, supporting this contention. The PSC was reduced with the 62 Mg ha⁻¹ Al-WTR rate but maintained with greater Al-WTR rates. The 124 and 248 Mg ha⁻¹ Al-WTR rates also contained greater P associated with the soluble + Al + Fe and occluded phases which should be stable over the long term (e.g., decadal). It was recommended to apply Al-WTR near the 124 and 248 Mg ha⁻¹ rates in the future to capture urban runoff soluble P in the Boise, ID, engineered wetland.

Keywords Aluminum-based water treatment residuals · Creeping red fescue · Engineered wetland · Phosphorus sorption · Phosphorus storage capacity · Urban runoff

1 Introduction

Alum [Al₂(SO₄)₃·14H₂O], the most commonly utilized coagulant in the USA (Elliott et al. 1990), is used to remove particulate and dissolved constituents from drinking water supplies. The generated waste product, Al-based water treatment residuals (Al-WTRs), is typically stockpiled, landfilled, or discharged into municipal sewer systems. In the future, Al-WTR generation will likely increase with increasing population and more stringent drinking water standards; thus, finding beneficial, environmental reuse options will become paramount as compared to other disposal options

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(Ippolito et al. 2011). Due to their amorphous nature, Al-WTRs are proven sorbents for anionic species such as phosphorus (P) (Ippolito et al. 2003; Makris et al. 2004; Dayton and Basta 2005a; Babatunde et al. 2008; Stoner et al. 2012; Bai et al. 2014; Habibiandehkordi et al. 2014) and therefore could be utilized to capture excess soluble P in the environment.

Dayton and Basta (2005b) applied 20 Mg ha⁻¹ of Al-WTR to a 5 % sloped, grassed buffer strip in order to capture excess runoff soluble P. The authors observed up to an 86 % reduction in runoff P due to P sorption onto Al-WTR. Habibiandehkordi et al. (2015) observed a similar reduction (61–62 %) in soluble P when Al-WTR was applied at 20 Mg ha⁻¹ in a rainfall mesocosm study (5 % slope). Zhao et al. (2008) used 100 % Al-WTR in a vertical or horizontal reed bed wastewater treatment system to capture P, showing greater than 99 and 93 % P removal with both systems, respectively. In follow-up research, Zhao et al. (2010) used Al-WTR as the main substrate in an engineered wetland to remove P. Phosphorus removal efficiency was maintained above 90 % for nearly a year and then began to decrease likely due to P saturation on the Al-WTR. These results lead Zhao et al. (2010) to suggest that the use of Al-WTR in engineered wetlands could potentially solve two municipality issues: (1) cost savings of Al-WTR disposal (e.g., landfilling) and (2) designing and utilizing Al-WTR in engineered wetlands as a substrate for capturing excess soluble P.

The City of Boise, ID (Ada County, Idaho), owns the Hyatt Hidden Lakes Reserve, an 18-ha site consisting of 9 ha of wetlands. The site is located in the midst of established residential neighborhoods; the Ada County Highway District expressed interest in potentially engineering 0.30 ha of the Hyatt wetlands to detain and treat urban stormwater runoff for capturing soluble P prior to water release into the Boise River. The City also generates Al-WTR as a waste product from drinking water treatment. Thus, an opportunity exists in Boise, ID, to meet the two-pronged approach suggested by Zhao et al. (2010). Our research objective was, in a proof-of-concept column experiment, to identify relatively long-term Al-WTR application rates for sorbing soluble P based on P concentrations similar to those found in Boise's urban runoff.

2 Materials and Methods

2.1 Material Characterization

The Al-WTR was collected from the City of Boise, Idaho's Public Works Department, along with soil and sand stockpiled on site for use at the Hyatt wetlands. The Al-WTR was generated via the use of polyaluminum chloride at the city's water treatment facility. All materials were returned to the laboratory and air-dried; the Al-WTR and soil were ground to pass a 2-mm sieve. All materials were then analyzed for pH using a 1:1 material/deionized H₂O extraction (Thomas 1996); total elements (EPA method 3051A; US EPA 2007); and amorphous Al, Fe, and associated P (ammonium oxalate extraction; Loeppert and Inskeep 1996) using inductively coupled plasma-optical emission spectroscopy (ICP-OES) and for Olsen-extractable P (Olsen et al. 1954) colorimetrically using the ascorbic acid molybdate blue method at 882 nm (Murphy and Riley 1962). All materials were also analyzed for H₂O-soluble P, whereby 1.00-g soil was shaken at 180 rpm for 2 h with 20 mL of deionized water. The mixture was centrifuged at 1500 rpm (~500×g) for 10 min; the solution decanted, filtered through a 0.45-μm membrane, and analyzed colorimetrically as previously described. In addition, all materials were analyzed for inorganic P fractionation using a modified Hedley sequential extraction for (a) soluble + Al + Fe-bound P, (b) occluded (i.e., Fe-coated) P, and (c) Ca-bound P (Kuo 1996), with solutions from each step analyzed colorimetrically as previously described. Chemical analyses of the Al-WTR, soil, and sand are presented in Table 1. Particle size analysis, using the hydrometer method (Gee and Or 2002), showed that the soil was a sandy loam (54 % sand, 33 % silt, 13 % clay).

2.2 Column Experiment

A column greenhouse experiment was performed to mimic the future engineered wetland site. A 2-mm stainless steel screen was attached to the base of a PVC column (17-cm diameter×76 cm tall) with a stainless steel hose clamp. Approximately 5 cm of pea gravel (~2-cm diameter) was placed in the bottom of the

Table 1 Aluminum-based water treatment residual (Al-WTR), soil, and sand chemical analyses

Property	Al-WTR (mg kg ⁻¹)	Soil (mg kg ⁻¹)	Sand (mg kg ⁻¹)
pH	6.1	7.6	7.5
Total Al	55,920	15,110	2231
Total Fe	28,330	17,190	6085
Total P	1684	418.0	144.4
Total Ca	7564	8218	686.8
Total K	4088	2477	510.2
Total Mg	4720	3879	1010
Total Mn	1903	385.1	109.4
Total Na	340.4	281.8	49.29
Total Zn	136.7	53.21	12.68
Amorphous Al	14,980	472.2	88.45
Amorphous Fe	4171	929.0	900.7
Amorphous P	541.8	119.7	ND
Olsen P	37.2	14.6	0.63
H ₂ O-soluble P	2.78	9.81	3.78
Inorganic P fractionation ^a			
Soluble + Al + Fe-bound P	140	22.1	5.88
Occluded P (i.e., Fe-coated)	107	47.1	6.66
Ca-bound P	267	206	120
Phosphorus storage capacity	2343	42	90

ND not detected

^a As determined by a modified Hedley sequential extraction (Kuo 1996)

column for material support. Next, 46 cm of sand was added to the column followed by 15 cm of soil.

The Al-WTR application rates consisted of a one-time surface application (no incorporation) of rates equivalent to 0, 62, 124, or 248 Mg ha⁻¹. Within individual columns, the Al-WTR was applied at 0, 6.17 e⁶, 1.23 e⁷, and 2.47 e⁷ mg m⁻² for each rate, respectively. Application rates were based on the following steps:

1. The City of Boise, ID, provided yearly (2000–2009) stormwater data for all city stormwater monitoring locations; the average dissolved P concentration = 0.19 mg L⁻¹.
2. The 0.30 ha of proposed engineered wetlands will be designed to receive 25.4 cm of urban runoff per year. This amount of water was estimated based on a 0.86-cm rain event over the adjacent urban watershed. Following a rainfall event, the urban runoff water will be collected in a retention basin adjacent to the wetland and then released over the entire engineered system. Assuming that the stormwater

contained 0.19 mg dissolved P L⁻¹, this would equal 144,780 mg of dissolved P.

3. Next, the Al-WTR P storage capacity (PSC; Oladeji et al. 2007) was calculated as follows:

$$\text{Al-WTR}_{\text{PSC}} (\text{mg kg}^{-1}) = [(0.15 - \text{Al-WTR}_{\text{PSI}}) * (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})] * 31 \quad (1)$$

where the Al-WTR phosphorus sorption index ($\text{Al-WTR}_{\text{PSI}} = (\text{P}_{\text{ox}}) / (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})$), and P_{ox} , Al_{ox} , and Fe_{ox} are the amorphous P, Al, and Fe concentrations in millimole per kilogram. The $\text{Al-WTR}_{\text{PSC}} = 2343 \text{ mg P kg}^{-1}$ (Table 1).

- (a) The soil and sand PSCs were determined similarly, having 25 to 55 times less PSC than the Al-WTR (Table 1).

4. If the site received 144,780 mg of dissolved P per rain event and the $\text{Al-WTR}_{\text{PSC}}=2343 \text{ mg P kg}^{-1}$, it would require 62 kg of Al-WTR to sorb the dissolved P from one rain event.
5. The City of Boise receives approximately 25 cm of rainfall per year. This would equate to 25 cm/0.86 cm or 30 rainfall events per year.

$30 \text{ rainfall events} * 62 \text{ kg of Al-WTR per rain event} = 1.86 \text{ Mg of Al-WTR}$

Thus, it would require 1.86 Mg of Al-WTR to sorb all urban runoff soluble P per year.

6. Al-WTR surface application rates (no incorporation) were utilized that targeted an estimated sorption of 0, 10, 20, and 40 years of urban runoff soluble P. This equated to $1.86 \text{ Mg} * 0, 10, 20,$ and $40 = 0, 18.6, 37.2,$ and $74.4 \text{ Mg of Al-WTR}$

These Al-WTR rates were based on the application to 0.3 ha; therefore, the target surface application rates equaled 0, 62, 124, and 248 Mg ha^{-1} .

All columns received 200 mL of reverse osmosis water to moisten the top several centimeters. Then, the top 0.6 cm was lightly hand raked, creeping red fescue (*Festuca rubra*) seed was applied at a rate suggested for new lawns (0.024 kg m^{-2}), and the seed was covered by again lightly hand raking the top 0.6 cm. Columns received between 100 and 150 mL of reverse osmosis water every 1 to 2 days for a month and then approximately 200 mL of reverse osmosis water every 2 to 3 days for an additional month. After 2 months, the plants were well established. Near the end of 2 months, another set of columns (no Al-WTR or plants) were established to determine column pore volume quantity.

Columns were supported 40 cm off the ground using rustproof-painted metal support gratings and concrete blocks (Fig. 1). The study consisted of five treatments (0 Al-WTR + no plants, 0 Al-WTR + plants, $62 \text{ Mg Al-WTR ha}^{-1}$ + plants, $124 \text{ Mg Al-WTR ha}^{-1}$ + plants, and $248 \text{ Mg Al-WTR ha}^{-1}$ + plants) in a randomized complete block design with four replicates.

Once per week, over a 12-week period, a bulk soluble P solution containing approximately 0.20 mg P L^{-1} was added to each column. Columns were filled to the top with the bulk P solution, the 2.54-cm infiltration rate was measured at the time the solution was added via a demarcation inside each column, and then, extra solution was added after adequate infiltration in order to leach 1.0 to 1.1 pore volumes ($\sim 5500 \text{ mL}$). Columns were allowed to freely drain overnight into plastic



Fig. 1 Columns supported 40 cm off the ground using rustproof-painted metal support gratings and concrete blocks

buckets placed directly underneath each column, and then, drainage volume was determined. The bulk P solution and the column leachates were filtered through a $0.45\text{-}\mu\text{m}$ membrane and analyzed colorimetrically for P using the ascorbic acid molybdate blue method at 882 nm (Murphy and Riley 1962). Once or twice between leaching events, approximately 250 mL of reverse osmosis H_2O was added to maintain plants.

Following the last leaching event, plants were harvested at 5 cm above the soil surface, dried at $60 \text{ }^\circ\text{C}$ for 72 h, weighed, and then ground to pass a 20-mesh sieve. A 0.50-g subsample was placed in a 100-mL beaker and ashed at $500 \text{ }^\circ\text{C}$ for 5 h. The samples were allowed to cool and weighed, and 10 mL of 1 M HNO_3 was added. The samples were then heated on a hot plate until condensation no longer occurred on the inside of the beaker. Finally, all samples were brought to a 50-mL final volume by weight with de-ionized H_2O , stirred, filtered through Whatman #50 filter paper, and analyzed for total P using ICP-OES. Plant P uptake was determined by multiplying plant weight times plant total P concentration.

Approximately a week after plant harvest, column materials were collected for further analyses. The depth encompassing the Al-WTR layer was carefully removed by hand ($\sim 0.6, 0.9,$ and 1.9 cm deep for the $62, 124,$ or 248 Mg ha^{-1} Al-WTR treatments, respectively), and then, the soil (0–15-cm depth) and sand (15–61-cm depth) were sampled using a 2.54-cm-diameter bucket auger; three cores were collected from each column. All materials were allowed to air-dry. The Al-WTR was passed by hand through a 2-mm sieve while the soil

was ground to pass a 2-mm sieve. All materials were then analyzed for Olsen-extractable P; amorphous Al, Fe, and P (to determine PSC); and inorganic P fractionation using a modified Hedley sequential extraction as previously described.

2.3 Statistical Analysis

Infiltration rates were averaged, and soluble P concentrations applied and leached were summed over all leaching events. These data, along with plant biomass, plant P concentration, and uptake, and comparisons within column layers for Olsen P; amorphous Al, Fe, and P; and the sequential P extraction data were analyzed using analysis of variance with the Proc GLM model in SAS (SAS Institute 2008) with a significance level (α) of 0.05. Means were separated using the Fisher's protected LSD procedure. The results and discussion focus primarily on P dynamics in the AI-WTR layer. Data for the soil and sand layers are presented in the supplemental material.

3 Results and Discussion

3.1 Infiltration Rates

Infiltration rate significantly increased only due to the presence of fescue (Table 2). Infiltration rates were three to five times faster in the presence of fescue as compared to no fescue, likely due to roots and root channels. Indeed, infiltration has been shown to improve in the presence of root channels (Meek et al. 1992). Improved

infiltration rates, over that of the control (i.e., no plants), were important to the City of Boise, ID, because plants will be grown on-site and to reduce on-site standing water in the engineered system, as the system will be designed to process up to 25.4 cm of urban runoff.

3.2 Soluble P Added and Leached and Fescue Yield, P Concentration, and Uptake

The amount of soluble P added increased from 5.78 to 6.87 mg column⁻¹ from the 0 AI-WTR + no fescue control to the 248 Mg AI-WTR ha⁻¹ + fescue treatment (Table 2). The increase in P added was due to extra solution required to leach 1.0 to 1.1 pore volumes in the AI-WTR treatments, as the AI-WTR must have retained some liquid. Regardless, the amount of P leached significantly decreased when plants (~50 % reduction) and AI-WTR (~60 % reduction) were added (Table 2). Removal efficiency was not as great as observed by others (e.g., Babatunde et al. 2009; >90 %), likely due to short contact time between the P solution and AI-WTR as suggested by Wagner et al. (2008).

Fescue yield, P concentration, and P uptake all significantly increased with increasing AI-WTR rate (Table 2). Increasing the AI-WTR rate likely led to more soluble P sorbed and made P more available for plant growth and uptake. Similarly, Mahdy et al. (2007) showed that AI-WTR rates of up to 67 Mg ha⁻¹ increased corn (*Zea mays* L.) yield and P concentrations; greater AI-WTR rates caused a decrease and an increase in corn P content when applied to clay and sandy soils (as in our system), respectively. However, more typical are observations of decreased plant yields and P

Table 2 Average 2.54 cm s⁻¹ infiltration rates; total amount of soluble P added and leached from the columns; and creeping red fescue (*Festuca rubra*) biomass, P concentration, and P uptake

Treatment	Infiltration rate (2.54 cm s ⁻¹)	Soluble P added (mg column ⁻¹)	Soluble P leached (mg column ⁻¹)	Fescue yield (g column ⁻¹)	Fescue P conc. (mg kg ⁻¹)	Fescue P uptake (mg column ⁻¹)
0 AI-WTR + no fescue	340 (108) a	5.78 (0.01)d	17.7 (1.77) a	— ^a	—	—
0 AI-WTR + fescue	112 (22) b	6.22 (0.04) c	8.58 (0.14) b	13.1 (2.22) c	1830 (198) b	23.8 (3.26) c
62 Mg AI-WTR ha ⁻¹ + fescue	90 (23) b	6.26 (0.04) c	6.71 (0.70) c	18.1 (1.99) b	1590 (82.4) c	28.8 (3.72) c
124 Mg AI-WTR ha ⁻¹ + fescue	71 (15) b	6.45 (0.12) b	7.15 (0.59) bc	21.3 (1.94) ab	1770 (120) bc	37.9 (5.28) b
248 Mg AI-WTR ha ⁻¹ + fescue	68 (10) b	6.87 (0.08) a	7.15 (1.01) bc	24.0 (2.37) a	2180 (108) a	52.3 (5.22) a

Means within each column are significantly different if followed by a different letter, as determined by the Fisher's protected LSD procedure ($p < 0.05$). Values inside parentheses represent the standard deviation of the mean ($n=4$)

^a Plants were not grown in this treatment

concentrations (e.g., Rengasamy et al. 1980; Heil and Barbarick 1989; Ippolito et al. 1999; Codling et al. 2002; Oladeji et al. 2007).

3.3 Olsen P

The Olsen-extractable P concentrations significantly increased in the AI-WTR layer with increasing AI-WTR rate (Table 3), supporting the contention that AI-WTR rate likely led to greater amounts of P available for plant growth and uptake. Phosphorus was sorbed quickly onto the AI-WTR, as shown by others (Wagner et al. 2008; Makris et al. 2005). Yet, the form of P in this case was still present as an available form and, given any of the AI-WTR rates, could sustain P availability without additional P fertilizer inputs for southern Idaho irrigated pastures (Shewmaker et al. 2009). Perhaps, given a longer period of time, however, P availability would decrease. Agyin-Birikorang and O'Connor (2007) aged AI-WTR in soil for 4.5 years, finding after the time period that labile P was not readily released. Ippolito et al. (2003) found a similar result over a 211-day shaking period. The current study only lasted 3 months. Plants were likely able to mine P from the soil and sand layers, as the presence of plants caused a decrease in the Olsen-extractable P in these zones (Supplemental Table S1).

3.4 Phosphorus Storage Capacity

Following 12 leaching events of 1.0 to 1.1 pore volumes containing $\sim 0.20 \text{ mg P L}^{-1}$, the PSC appeared to be maintained in the AI-WTR layer of the 124 and 248 Mg AI-WTR ha^{-1} treatments (Table 3). It is recommended to apply AI-WTR at or near these rates in the future.

However, the PSC in the 62 Mg AI-WTR ha^{-1} treatment was reduced by two thirds; this result was unexplainable. The 62 Mg AI-WTR ha^{-1} treatment received, on average, 6580 mL of solution per leaching event (similar solution quantities were added for the other treatments). Given the cylinder radius of 8.5 cm, the height of liquid added equaled 29 cm per leaching event. Twelve leaching events occurred, equaling a total liquid height of 348 cm added. This would be equivalent to 14 rain events, as the engineered site will be designed to handle up to $\sim 25 \text{ cm}$ per rain event ($25 \text{ cm} \times 12$ leaching events = 300 cm total, as compared $29 \text{ cm} \times 12$ leaching events = 348 cm total; approximately, 50 cm or two rainfall events greater in the current study as compared to future site conditions). Based on the initial calculations, the 62 Mg AI-WTR ha^{-1} treatment should have been able to receive 10 years of 30 rainfall events per year or 300 total rainfall events before reaching the PSC. Yet, 14 simulated rainfall events reduced the PSC by two thirds, suggesting that only 7 more rainfall events

Table 3 Olsen P; amorphous Al, Fe, and P; soluble + Al + Fe-bound P, occluded P, and Ca-bound P; and initial and final P storage capacity in the AI-WTR layer in columns treated with increasing AI-WTR rates and planted with creeping red fescue (*Festuca rubra*)

Property	62 Mg AI-WTR ha^{-1} + fescue	124 Mg AI-WTR ha^{-1} + fescue	248 Mg AI-WTR ha^{-1} + fescue
	mg kg^{-1}		
Olsen P	20.5 (2.1) b	38.8 (10.4) a	35.0 (2.7) a
Amorphous Al	5260 (508) b	15,700 (1310) a	17,100 (850) a
Amorphous Fe	2590 (187) b	4910 (421) a	5220 (188) a
Amorphous P	275 (27.8) b	700 (47.5) a	732 (30.0) a
Soluble + Al + Fe-bound P	47.5 (13.0) b	127 (12.4) a	148 (18.5) a
Occluded P	64.8 (7.11) b	141 (21.0) a	117 (15.9) a
Ca-bound P	225 (6.84) a	234 (37.6) a	234 (33.4) a
	kg		
Initial P storage capacity ^a	145	290	580
Final P storage capacity	52 (5)	300 (26)	656 (34)

Means within each row are significantly different if followed by a different letter, as determined by the Fisher's protected LSD procedure ($p < 0.05$). Values inside parentheses represent the standard deviation of the mean ($n=4$)

^a As determined by the following: P storage capacity (kg) = $[(0.15 - \text{AI-WTR}_{\text{PSI}}) * (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})] * 31 * \text{AI-WTR application rate (Mg ha}^{-1}) / 1000$. The AI-WTR phosphorus sorption index ($\text{AI-WTR}_{\text{PSI}} = (\text{P}_{\text{ox}}) / (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})$), and P_{ox} , Al_{ox} , and Fe_{ox} are the amorphous P, Al, and Fe concentrations in millimole per kilogram

(or 21 rainfall events total) would maximize the PSC in this treatment. Thus, this treatment would not be acceptable for use in this engineered wetland.

3.5 Inorganic P Fractionation

In the Al-WTR layer, the 124 and 248 Mg Al-WTR ha⁻¹ treatments contained greater P concentrations in the soluble + Al + Fe-bound and occluded phases as compared to the 62 Mg Al-WTR ha⁻¹ treatment (Table 3), likely because of more Al-WTR present. Greater P concentrations in the soluble + Al + Fe-bound fraction were also a result of P being bound to amorphous Al phases, as shown by others (e.g., Ippolito et al. 2003; Makris et al. 2005). Greater P content in the occluded phase represents greater P within retaining components or minerals (Evans and Syers 1971). Bayley et al. (2008) studied short- and long-term Al-WTR applications to a shortgrass steppe rangeland soil, showing that Al-WTR contributed to increased P content in the occluded phase as well as the soluble + Al + Fe-bound phase. The authors suggested that these fractions were relatively stable over the long term (e.g., decadal) and thus possibly would be stable in the current system studied.

3.6 Metal Leaching Risk

In terms of Al-WTR land application and Al concentrations contained within, creation of plant Al toxicity and enhanced Al leaching have been expressed as concerns by researchers; yet, these effects are minimal at circumneutral soil pH conditions (Ippolito et al. 2011) as in the current study. In fact, it is at low soil pH values (e.g., <5.0–5.2) where Al solubility is enhanced and thus may create plant toxicity conditions (Sparks 2003). Thus, although not measured in this study, Al leaching should be of minimal concern.

4 Conclusions

The research objective was to determine surface-applied Al-WTR application rates that could potentially supply long-term P sorbing capacities and make a recommendation to the City of Boise, ID, for applying Al-WTR in an engineered wetland for removing soluble P from urban runoff prior to water discharge to the Boise River. Four Al-WTR application rates (0, 62, 124, and 248 Mg ha⁻¹) were studied that, theoretically,

encompassed PSCs of 0, 10, 20, and 40 years. The lower Al-WTR application rates (0 and 62 Mg ha⁻¹) were unacceptable based on soluble P moving through the system as well as the reduction in P storage capacity. However, the 124 and 248 Mg ha⁻¹ Al-WTR application rates significantly reduced soluble P leaching, increased Olsen-extractable P content (i.e., plant available P), and subsequently improved creeping red fescue yield, P concentration, and uptake as compared to the lower rates. The greater Al-WTR rates stored more P in the soluble + Al + Fe-bound and occluded phases which can be considered stable over longer periods of time. Equally as important, the 124 and 248 Mg ha⁻¹ Al-WTR application rates maintained the initial P storage capacity even after applying the equivalent of 14 rain events. This suggests that targeting these greater Al-WTR rates would be ideal for capturing soluble P from urban runoff while maintaining plant growth on-site. These results support those of Zhao et al. (2010) where the use of Al-WTR in engineered wetlands could solve the two municipality issues of cost savings (due to landfill avoidance) and beneficial reuse of Al-WTR in engineered wetlands for capturing excess soluble P prior to water body release.

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