CONSTRUCTED WETLAND RESEARCH FOR THE TREATMENT OF THE PLANT GORGAS COAL PILE RUNOFF[1]

by

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Abstract. Research was conducted to study the transport and fate of inorganic pollutants through a constructed wetland using a Reducing and Alkalinity Producing System (RAPS). RAPS have been used to successfully treat acid mine drainage (AMD). This wetland is designed to treat coal pile runoff, similar to AMD. A primary goal of this research was to evaluate an alternative design that might result in improved pollutant removal. The design was based on the partial re-circulation of treated water into a detention basin, located immediately upstream from the RAPS, containing untreated water. This modification created a semi-passive RAPS-based system we refer to as a Recirculating RAPS (ReRAPS).

To test the ReRAPS modification a full-scale RAPS-based wetland capable of recirculation was constructed, operated, and monitored. Factors that may promote improved pretreatment performance in the detention pond during the ReRAPS mode were evaluated using a series of batch tank studies. The wetland monitoring and tank studies have determined that the ReRAPS modification has the potential to enhance the basic RAPS wetland design by moderating the pH of contaminated water and reducing the contaminant loading prior to the RAPS component. The batch tank studies revealed that significant amounts of inorganic contaminants could be precipitated from mixtures of AMD and treated wetland water after 24 hours. Primary factors controlling the removal were pH, initial metal concentration and retention time.

Additional Key Words: reducing and alkalinity producing system, RAPS, successive alkalinity producing system, SAPS, recirculating RAPS, ReRAPS, sulfate reduction

Introduction

A wetland containing a Reducing and Alkalinity Producing System (RAPS) was constructed to treat coal pile runoff at the Plant Gorgas coal-fired steam electric power station. RAPS have been successfully used to treat acid mine drainage (AMD). This wetland was designed to treat acidic runoff from a bituminous coal pile. Research was conducted to determine the merits of recirculation and to develop design data for the removal of inorganic pollutants such as aluminum (Al), iron (Fe), and manganese (Mn) through the RAPS-based wetland.

RAPS are designed as passive, vertical-flow systems. Watzlaf et al. (2000) clarified the terminology that describes these types of systems. In this paper, a single vertical flow component that relies on reducing organic substrate and limestone dissolution will be referred to as RAPS. More than one RAPS, operated in series with each RAPS followed by aerobic settling basins, may be necessary to treat AMD to desired discharge levels. Utilizing the terminology proposed by Watzlaf et al. (2000), a treatment system where a series of RAPS components are used in conjunction with oxidation/precipitation basins may be more appropriately termed Successive Alkalinity

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Producing Systems or SAPS (Kepler and McCleary 1994).

Although similar to AMD, coal pile runoff contaminant loading is intermittent. Rain events for example, often result in "shock" loading to the system. The effects of intermittent events on contaminant removal and limestone dissolution rates in RAPS-based wetlands are not well understood. Furthermore, the long-term performance of these systems may be negatively affected by the eventual accumulation of metal precipitates within the organic and limestone substrate of the RAPS component. Pretreatment of contaminants prior to the RAPS may be one way to dampen highly variable contaminant loading, reduce plugging, reduce limestone dissolution, and ultimately increase the life expectancy of the RAPS-based wetland.

An alternative design of the RAPS system would recirculate a portion of the alkaline water produced by the system back to the detention pond, which is located immediately upstream from the RAPS component. This modification might result in the pretreatment of highly contaminated coal pile runoff, lessening the effects of "shock" loads. Recirculation would also result in increased pH in the detention pond, which would allow for the precipitation of metal hydroxides. The formation of Fe and Al hydroxides can adsorb and co-precipitate other dissolved metals (Stunm and Morgan, 1981; Langmuir, 1997). Not only would this lessen the metal loading to the RAPS component, it would also lower maintenance of the RAPS component and possibly reduce wetland size requirements. This modification to the RAPS design can be referred to as a "Recirculating RAPS" or ReRAPS.

A goal of this study has been to determine the contaminant removal rates for this newly developed ReRAPS wetland. Other goals include determining the ability of the ReRAPS to reduce metal loading and limestone dissolution in the RAPS component. In this paper, we describe the morphological, hydrological, and retention characteristics of the wetland. The performance of the wetland during the treatment of coal pile runoff resulting from a rain event is also described. This ReRAPS treatment occurred while the wetland was in its third year of operation. The results from a series of batch tank studies designed to determine the factors that may affect metal removal in the detention pond during the ReRAPS mode of operation are also presented.

Wetland Design Characteristics

The Plant Gorgas wetland employs most of the RAPS-based constructed wetland technologies to date. The 0.6ha (2.5ac) wetland has been designed and constructed to treat runoff from a 4.5ha (11ac) coal pile storage area and is capable of operating in a "once through" RAPS mode or in a "partial recirculation" ReRAPS mode. The system is designed to produce effluent meeting the regulatory limits set by the Alabama Department of Environmental Management (ADEM). The discharge limitations are as follows: pH is to be maintained between 6 and 9, total Fe and Mn are limited to levels of less than 6 and 4 mg/L, respectively, and total suspended solids to less than 50 mg/L.

Approximately 1.2ha (3ac) adjacent to the main Plant Gorgas coal pile were available for the construction of the wetland. Design factors such as mean flow rates, space limitations, and topography determined the size and type of routing within the components. A schematic of the wetland, along with morphometeric and hydraulic measurements, are presented in Figure 1. The wetland has been constructed to include twelve components and thirteen discharge nodes (N):

N1 Coal Pile Runoff
N2 Detention Pond
N3 Stilling Basin
N4 RAPS Component Surface Water
N5 RAPS Component Discharge Water
N6 Settling Basin
N7 Cattail Drain
N8 Aeration Drain
N9 Algae Basin
N10 Rock Drain
N11 Cattail Wetland
N12 Storage (recycled water)
N13 Storage (discharged water)

Wetland Component Descriptions

The detention pond (N1-N2) is designed to contain a 10 year-24hr rain event (Birmingham, AL–152mm (6in)). Coal pile runoff accumulates at the lower end of the coal pile and is routed into the detention pond through a culvert. Runoff storage is allowed to back up into the base of the coal pile during high volume events. Low and high volume events can be treated using a one or two pump combination to route water through N2 to the stilling basin (N2-N3). The recirculated water from N12 is stored in the detention pond to pretreat the next runoff event. An automatic switch activates the pumps at various preset stage elevations.

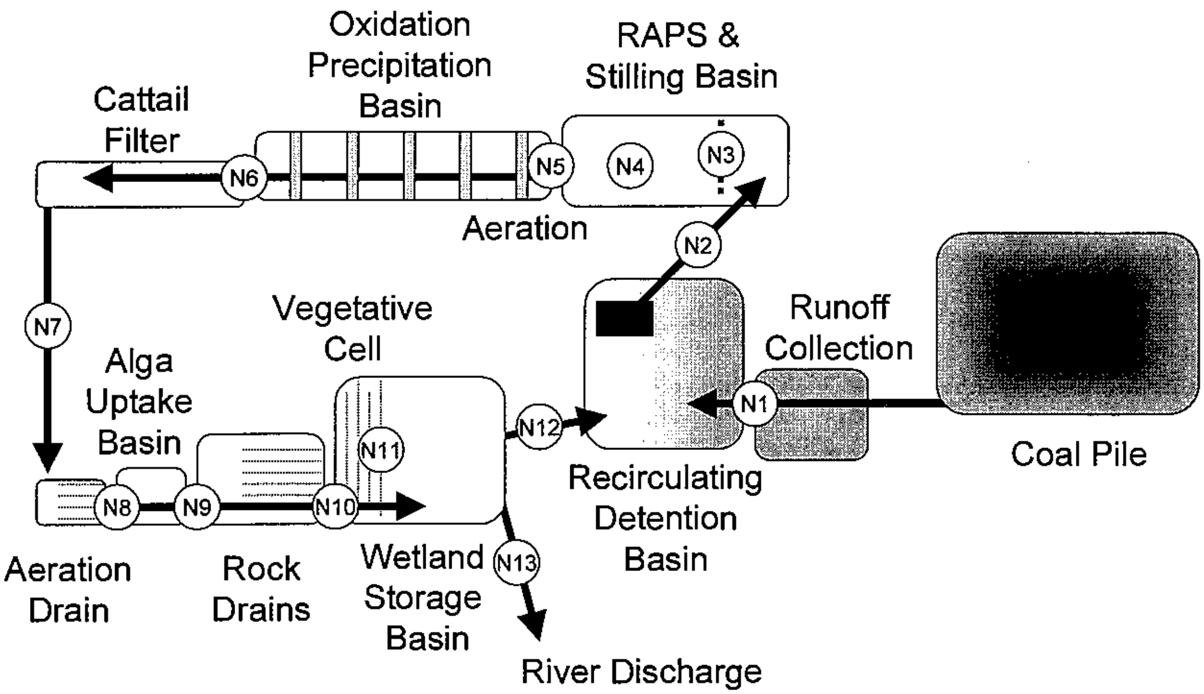


Figure 1. Schematic of the Plant Gorgas Wetland configuration.

The RAPS component (N2-N5) was constructed using high-grade 8-15cm (3-6in, >90% $CaCO_3$) limestone. A PVC pipe drain field was placed on top of a 15cm (6in) limestone layer. The drain field was covered by a 1.2m (4ft) layer of limestone. A 30cm (1ft) layer of organic material was then spread over the limestone. The organic mixture contained horse manure, chicken manure, pine bark and limestone sand. A 1m (3ft) pool of water, which includes the stilling basin, is maintained above the organic substrate (N2-N4). The 0.06 ha (6161ft^2) interface between the pooled water and the organic mixture is considered as N4. The RAPS component is constructed so that accumulated solids can be flushed directly from the drain field. This maintenance option will not be used unless plugging of the RAPS substrate occurs.

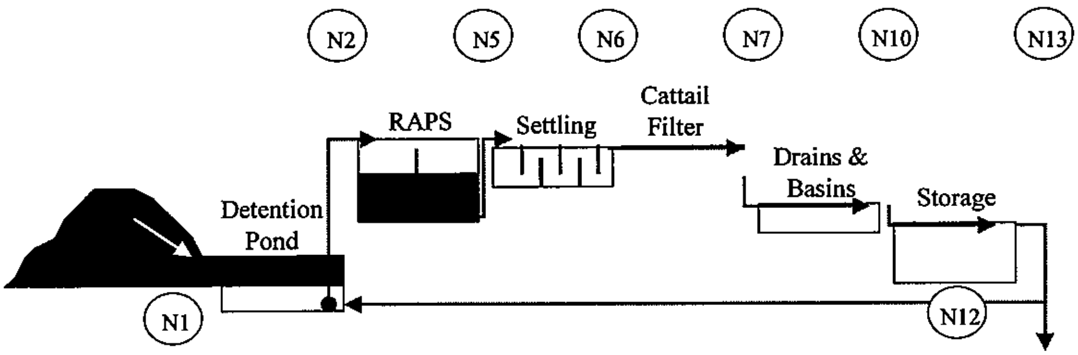
The settling basin (N5-N6) is designed to (re)aerate the anoxic RAPS effluent by routing the water under and over a series of five concrete baffles. Oxidized metals are allowed to precipitate in this basin. The cattail filter (N6-N7) contains a dense stand of vegetation to encourage filtration and further settling of oxidized metals. Additional shallow rock drains and algae basins (N7-N10) exist further downstream. These structures are designed to provide substrate with large available surface area to promote the oxidation of Mn by bacteria, cyanobacteria, diatoms, green-alga and fungi in circumneutral water (Brant and Ziemkiewicz, 1997). Robbins et al. (1999) have determined that these microbes biologically oxidize reduced Mn. The final treated water collects in the wetland storage pool (N10-N13). Treated water is discharged through N12 (recycle) and N13 (river discharge), which are in close proximity to each other. The qualities of water from these two nodes are similar and can therefore be indicated as N12/13.

Wetland Morphology

Hydrographic, land, and photagrammetric (aerial photography analyses) survey data sets were combined into a digital terrain model. The areas and volumes of the wetland were calculated using a digital CAD package. Included in Figure 2 are the typical operating surface areas, volumes, and nominal retention times for each of the main wetland components.

Wetland Hydrology

The water losses between the primary nodes (N2, N5, N6, N7, N10, N12 and N13) were measured manually on a daily basis using a bucket during steady-state flow conditions. Water losses in the detention pond were estimated by measuring stage



	Detention	RAPS	Settling	Cattails	Drains	Storage	Total
Area, ha	0.13	0.09	0.07	0.02	0.09	0.28	0.68
Vol., cu-m	841	885	583	49	414	876	3,648
114Lpm Ta (Tn), d	3.4 (5.1)	5.4 (5.4)	5.0 (3.6)	0.5 (0.3)	1.5 (2.5)	2.6 (5.4)	18.5 (19.4)
170Lpm Ta (Tn), d	2.3 (3.4)	**3.6 (3.6)**	**3.3 (2.4)**	**0.3 (0.2)**	**1.0 (1.7)**	**1.8 (3.6)**	12.3 (13.0)
284Lpm Ta (Tn), d	**1.4 (2.1)**	2.2 (2.2)	2.0 (1.4)	0.2 (0.1)	0.6 (1.0)	1.1 (2.1)	7.5 (7.7)

Figure 2. Topographic schematic of the Plant Gorgas Wetland in ReRAPS mode along with area, volume, actual (Ta), and nominal (Tn) retention values. The RAPS surface water area and total water volume including limestone voids are presented. Retention values in bold font represent components and flows that were tracer tested.

elevations using continuous recording level indicators during periods of no flow and rain. Evaporation rates were measured daily using an onsite pan evaporator. Kadlec and Knight (1996) have suggested that wetland evapotranspiration is well represented by 0.7 to 0.8 times the Class A pan evaporation. Pan evaporation at the wetland was estimated at 3.3mm/d (0.13 in/d). Using a multiplier of 0.75, the predicted evapotranspiration rate was estimated to be 2.5 mm/d (0.1in/d). Differences between the overall losses and evapotranspiration were used to estimate seepage. Overall evapotranspiration and seepage from the wetland system accounts for 9.5Lpm (2.5gpm) and 34.8Lpm (9.2gpm), respectively. An unexpected leak in the cattail filter component (N6-N7) accounted for 71% of the overall seepage. All of the wetland components were clay lined; however, the clay may have been disrupted within the cattail filter component during construction. The seepage rate ranged from 2.2-14.7 L/d/m^2 (0.8-2.5gal/wk/ft^2) in all other components

Wetland Retention

Two bromide tracer studies were performed to accurately assess retention within the major wetland components. Potassium bromide salt solutions were injected into the detention pond at N1 during the first tracer study and into the stilling basin at N2 during the second study. Automatic sequential sampling and manual sampling were performed every 1-24 hours until the tracer concentrations returned to non-detectable levels at the monitored nodes. The 50% recovery period is considered the actual (Ta) or tracer retention. Retention times for the untested flow rates are based on flow-weighted calculations (Figure 2). The nominal (Tn) retention values are based on void volume calculations.

During the first tracer study, the detention pond pumps operated at 284Lpm (75gpm) while recycling approximately 50 percent of the pumped water. Acid mine drainage from a nearby pit was used as a runoff substitute during the first study. Daily inflows (N12-recycle and N1-piped AMD) were equivalent to outflows (N2-pump). Excellent recovery of the ion was achieved to accurately determine the actual retention of the detention pond (N1-N2). Results from this study indicate that the open water design of the detention pond makes this component susceptible to short-circuiting. Short-circuiting is apparent because the 1.4-day tracer retention (Ta) time was significantly lower than the 2.1-day nominal retention (Tn) time.

The second tracer study was performed using a 170Lpm (45gpm)-flow rate at N2. Comparisons between the nominal and tracer retention times for the remaining components down stream from the detention pond reveal that they are similar. Figure 3 presents the concentration and cumulative flow fraction or residence time distribution (RTD) for the bromide ion from the second study. Again, excellent recovery of the ion was achieved to accurately determine the actual retention of the RAPS surface waters (N2-N4) and the RAPS substrate (N4-N5). A rain event reduced the recovery of the tracer for the remaining downstream nodes. However, flows were stable during the period of time required to achieve a 50% salt recovery at the later nodes (N7, N10, N12/13).

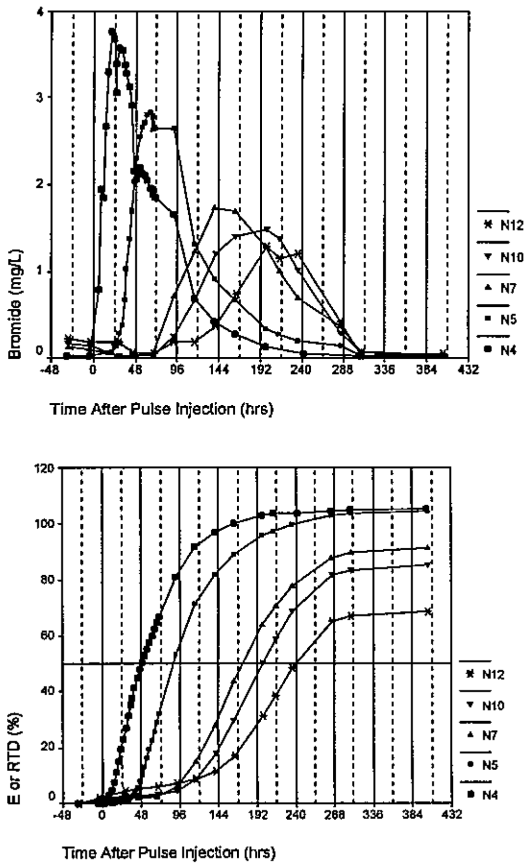


Figure 3. Bromide concentrations and cumulative RTD for all components downstream from N2. Wetland pumps operated at continuous 170Lpm (45gpm) flow rate.

The tracer tested retention at 170Lpm (45gpm) within the RAPS surface waters and the organic/limestone substrate were 2.2 and 1.4 days, respectively. Retention time within the RAPS limestone is greater than the 12-23 hour residence time considered adequate for achieving optimal limestone dissolution (Hedin and Watzlaf, 1994; Kepler and McCleary, 1994; Skovran and Clouser, 1998).

Methods

Monitoring of the wetland during the runoff treatment event occurred during January 2000. The batch tank studies were performed during June 2000. Chemical analyses and field measurements performed during both studies were conducted according to U.S. EPA (1983, 1994) methods or Standard Methods (APHA 1998). Total anions (Br, SO_4) were analyzed using ion chromatography (EPA Method 300.0 & 340.2). Total cations (Al, Fe, Mn, Ca) were analyzed using the Atomic Emission Inductively Coupled Plasma Method (ICAP, EPA Method 200.7). Alkalinity (EPA Method 310.1) and acidity (Std. Methods 2310, hot peroxide) measurements were performed within 24 hours of sampling. Field measurements included pH, water temperature, conductivity, dissolved oxygen, and oxidation-reduction potential (ORP).

Wetland Monitoring

Monitoring was performed to evaluate the treatment of coal pile runoff resulting from a 2.0cm (0.8in) 24hr rain event which occurred on January 11, 2000. The RAPS component operated for 2 years prior to this event in the ReRAPS mode. Water quality monitoring was performed daily from January 12 till flows at N2 ceased on January 25 due to low detention pond levels. Detention pond levels were continuously monitored just prior to the rain event and throughout the treatment period. Manually measured flows were also performed throughout the 14-day treatment period.

The wetland was operated in a ReRAPS mode to treat the runoff from the coal pile using the following conditions:

1. The intermittent pumping rate from the detention pond through N2 was 114 Lpm (30 gpm).
2. Treated water was allowed to recirculate back through N12 to the detention pond at a rate of approximately 57Lpm (15 gpm).
3. Excess water was discharged to the river via a storage basin standpipe (N13) or was lost due to the previously described seepage.

Batch Tank Studies

Dissolved Fe and Al in AMD react to form flocculent particles, which co-precipitate with other dissolved metals when the pH of the water increases (Stumm and Morgan, 1981; Langmuir, 1997). A series of tank or drum experiments were performed to determine the beneficial effects of recycling treated water back into acidic water for pretreatment of metals in the wetland detention pond, thus confirming the pretreatment effects which were believed to have occurred during the ReRAPS mode.

The tank studies were designed to determine the effect of factors such as pH, initial metal concentration, retention, and depth on metal removal. The 200L tanks were filled with mixtures of treated (N12) and AMD water. The AMD water was obtained from an abandoned mine pit. Mixtures of AMD and treated water that were tested contained ratios ranging from 100%-AMD:0%-N12 water to 2.5%-AMD:97.5%-N12 water. AMD water used during these series of tank studies was characterized as clear in color where 100% of the metals were dissolved into solution.

Samples were collected using a syringe and tubing at the 21, 42, 63 and 84-cm depths. Samples for total metal analyses were collected and pH measurements were performed every 8 hours for up to 48 hours.

The tank results are compared with the theoretical chemical equilibrium values using the MINTEQA2 geochemical equilibrium model developed by the U.S. EPA (Allison et al. 1991).

Results

Wetland Monitoring

Monitoring of the wetland effluent indicated that the wetland could easily produce compliance grade water in the ReRAPS mode. The total Fe and total Mn levels at the wetland discharge (N12/13) were reduced to below 6 and 4 mg/L, respectively. Field measurements for pH are presented as box plots in Figure 4. The box plots summarize data based on the median, quartile, outliers and extreme values (SPSS 1999). Measurements for pH were maintained above 6 at N12/13. Some of the pH measurements at N12/13 exceeded 9. These high pH levels were due to elevated levels of photosynthetic activity by filamentous algae, which limited dissolved CO_2 levels in the last two components. During the treatment period, the detention pond (N2) pH was significantly greater than the runoff (N1), with values of 5.3 and 3.2, respectively.

The concentrations, loadings, percent removals, and removal rates for the components prior to N7 are

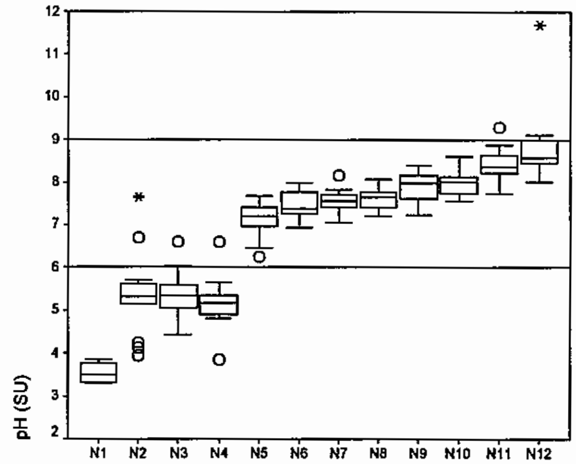


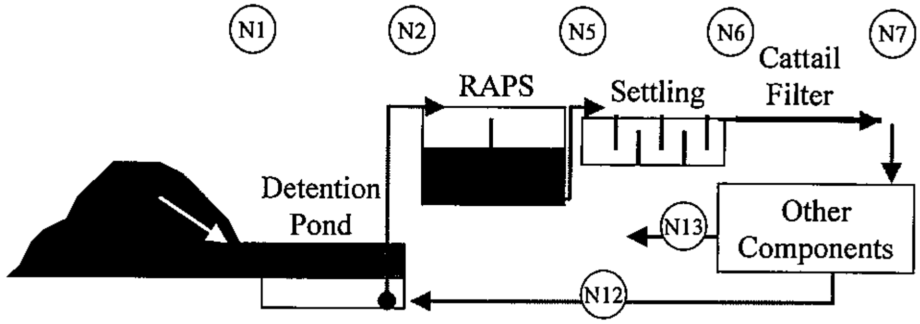
Figure 4. Box plot of pH values from the wetland. nodes N1-N12 (n=14).

presented in Figure 5. Over 92% of the primary contaminants (Al, Fe, Mn and acidity) were removed prior to the discharge of the cattail filter (N7).

Results from this treatment reveal that the majority of contaminant removal occurred in the detention pond or within the RAPS component. The resulting pH from the mixture of CPR (N1) and recirculated water (N12) in the detention pond promoted the development of metal precipitates. Nearly all of the Fe (98%) was removed in the detention pond. Excellent removal of Al (81%) and acidity (75%) were achieved. Significant amounts of Mn (40%) were also removed in the detention pond.

Figure 6 presents the cumulative percent removal for contaminants within the RAPS component. The majority of contaminant removal in the RAPS component occurred within the organic/limestone substrate. Aluminum removal in the RAPS surface water (N2-N4) and substrate (N4-N5) accounted for 4 and 14 percent of the overall wetland removal, respectively. There was no significant removal of Mn in the surface waters (N2-N4). However another 28% of the Mn was removed in the RAPS substrate (N4-N5).

A small amount of acidity removal (3%) occurred in the RAPS surface water, but the remaining 20% was removed inside the substrate layer. Within the RAPS component, the net alkalinity measured by titration balanced favorably with values indirectly obtained by accounting for any calcium ion increases and sulfate ion decreases. Even though hydrogen sulfide gas production was observed and



	Concentrations, mg/L				
	CPR	Detention	RAPS	Settling	Filter
Al	43.5	2.6	0.1	0.1	0.1
Fe	51.9	0.3	0.0	0.0	0.0
Mn	6.9	1.3	0.6	0.3	0.2
Acidity	509.0	38.8	1.9	0.0	0.0

	CPR	Removals, Percent of CPR Loading			
	Loading (kg)	Detention	RAPS	Settling	Filter
Al	30.4	80.8	99.5	99.5	99.4
Fe	36.6	97.5	99.8	99.9	99.9
Mn	4.8	40.2	68.1	86.7	92.0
Acidity	356.5	75.1	98.7	100.0	100.0

		Removal Rates, g/day/sq-m (g/day/cu-m)			
		Detention	RAPS	Settling	Filter
Al		1.3 (4.8)	0.7 (1.1)	0.0 (0.0)	0.0 (0.0)
Fe		1.9 (7.0)	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)
Mn		0.1 (0.4)	0.2 (0.3)	0.1 (0.1)	0.1 (0.4)
Acidity		14.4 (52.4)	9.9 (16.3)	0.5 (0.5)	0.0 (0.0)

Figure 5. Concentrations, loadings, removal percentages, and removal rates for total Al, total Fe, total Mn, and Acidity (as $CaCO_3$).

average ORP values were –256mv at N5, there was no significant sulfate removal within the RAPS substrate (N4-N5). Alkalinity is produced due to sulfate reduction based on the following assumed stoichiometric relationship:

$$2CH_2O+SO_4^{2-} \rightarrow H_2S+2HCO_3^- \quad (1)$$

Where: 1mg/L decrease in sulfate yields 1.04mg/L alkalinity as $CaCO_3$

There were no significant reductions in total sulfate concentrations prior to (N4) or after the RAPS substrate (N5). Average sulfate levels were 1632 mg/L. Therefore nearly all of the alkalinity generated was due to limestone dissolution based on the following stoichiometric relationship:

$$2H^++CaCO_3 \rightarrow Ca^{2+}+CO_2+H_2O \quad (2)$$

$$CO_2+H_2O+CaCO_3 \rightarrow 2HCO_3^-+ Ca^{2+} \quad (3)$$

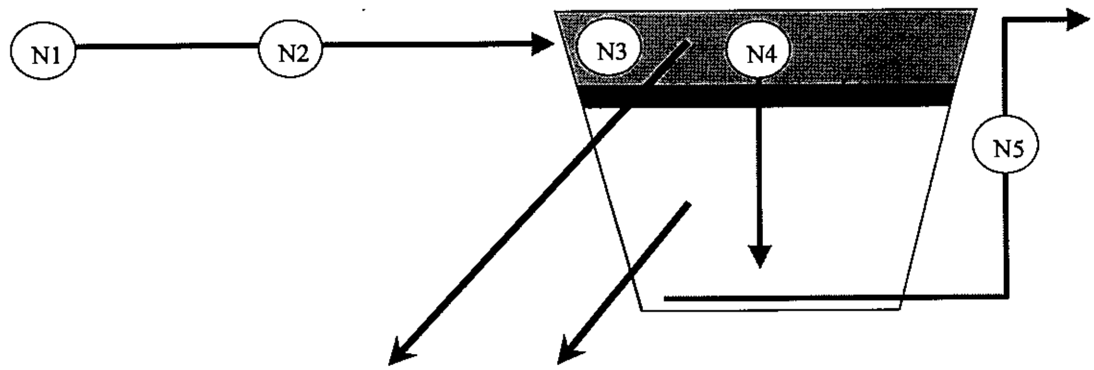
Where: 1mg/L increase in calcium yields 2.50mg/L alkalinity as $CaCO_3$

Based on the dissolved calcium values, approximately $23gd^{-1}m^{-2}$ as $CaCO_3$ were generated within the RAPS component ($572m^2$ RAPS surface, 114 Lpm, 7-day flow).

This indirectly measured alkalinity estimate balances with the net alkalinity, based on the following equation:

$$\text{Acidity Consumed + Available Alkalinity} = \text{Net Alkalinity (as } CaCO_3) \quad (4)$$

Acidity was consumed at a rate of $10gd^{-1}m^{-2}$ and the available alkalinity was measured at $13gd^{-1}m^{-2}$.



	Cumulative Percent Removal		
	Detention	Surface	Substrate
Al	80.8	85.2	99.5
Fe	97.9	99.1	99.8
Mn	40.2	39.6	68.1
Acidity	75.1	78.8	98.7

Figure 6. Cumulative percent removal of total aluminum, total iron, total manganese and acidity prior to (N1-N2) and within the RAPS component (N2-N5).

Therefore, the overall net alkalinity generated is $23 gd^{-1}m^{-2}$ $CaCO_3$. This alkalinity generation rate is less than those reported by Watzlaf et al. (2000), which range from 43-62 $gd^{-1}m^{-2}$ as $CaCO_3$ for RAPS which receive direct inflows from AMD. However, Watzlaf et al. (2000) report that for a second RAPS, receiving pretreatment from a previous RAPS/settling basin in series, the alkalinity generation rates reduce to 16-21$gd^{-1}m^{-2}$. As previously described, a series of RAPS may otherwise be known as a SAPS.

Batch Tank Study

As previously discussed, the purpose of the batch tank study was to reveal factors that may influence the removal of total Al, Fe, and Mn in the detention pond where runoff water and recirculated treated waters are mixed. Batch tank study results using AMD show that significant reductions of total Fe and Al could occur within 48 hours and that these removals were highly pH dependent. Neither total Al nor total Fe concentrations measured during the tank study approached the minimum detectable levels (MDL) possible with the Inductively Coupled Plasma Method (ICAP, EPA Method 200.7). Figure 7 presents the concentrations of Al and Fe at various pHs after 24 hours in the batch tanks. Significant reductions in Fe and Al occurred at pH values greater than 4 and 5.5, respectively. The results from the tank study support the observed rapid removal of Fe and Al inside the detention pond, which had an average pH of 5.3. The 40% removal of Mn inside the detention pond was not supported by the tank study. Significant removal of Mn did not occur in the batch tanks within a 48-hour period.

SPSS (1999) statistical modeling software was used to evaluate factors that may influence metal removal in large open mixtures of treated and untreated water. A parametric stepwise regression analysis evaluated factors that improved the prediction of tank metal concentrations after 24 hours of retention. The log transformed Al concentrations were best explained by the pH main effect alone ($r^2=0.95$, $p<0.05$). The log-transformed Fe concentration may be best explained by pH, the initial Fe concentration in the tank, and the retention time ($r^2=0.95$, $p<0.05$).

The MINTEQA2 model (Allison et al. 1991) was used to compare the resulting batch tank metal concentrations to the theoretical equilibrium concentrations at various pHs. Aluminum concentrations in the tank study did not approach the minimum equilibrium values for the pH adjusted AMD water predicted by MINTEQA2. Further Al

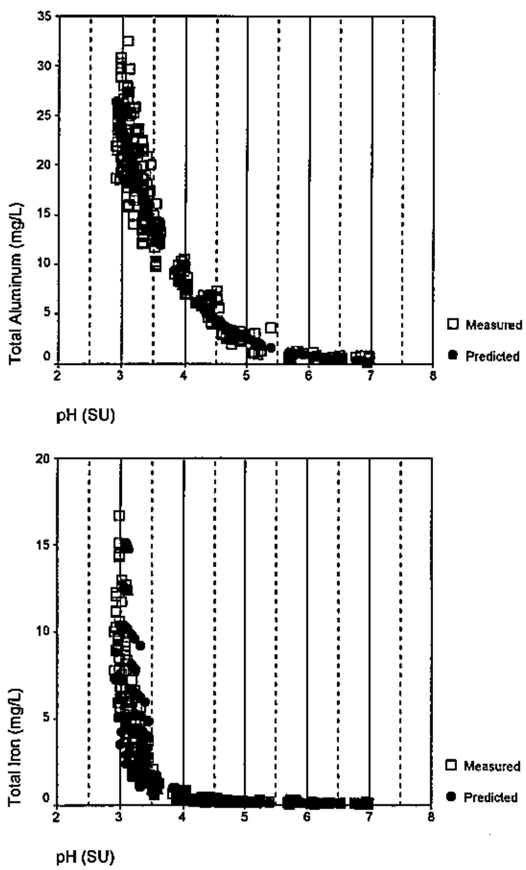


Figure 7. Concentrations of total Al and total Fe in tank mixtures of AMD and wetland storage water.

removal may be limited by the relatively low specific gravity of the Al hydroxide floc particles.

Currents induced by thermal gradients within the tanks may also resuspend the floc. This was not the case with Fe. Iron concentrations in the tank study did approach the minimum equilibrium values for the pH adjusted AMD water predicted by MINTEQA2 for pH values ranging from 4.5 to 6.5. MINTEQA2 also predicts that, at equilibrium, any Fe in solution exists in the ferrous form Fe(II) form. The total Fe in the AMD used in this study contained 18mg/L of the ferric form (Fe(III)) and 2mg/L of Fe(II). Therefore, the complete removal of Fe would be limited by the presence of Fe(II). Again, the regression analyses revealed that the initial total Fe concentration, which is positively correlated with Fe(II), was a factor which significantly affected Fe removal in the tanks.

Conclusion

The monitoring of a coal pile runoff treatment and a series of tank studies have determined that the ReRAPS modification has the potential to enhance the basic RAPS wetland design. The Plant Gorgas Wetland easily produced compliance grade effluent water when treating the coal pile runoff in a ReRAPS mode. Locating the wetland discharge near an open water area should be discouraged due to photosynthetic consumption of CO_2 by algae. Water should be routed through a rock drain or dense stand of emergent vegetation prior to being discharged.

The detention pond pretreated the acidity, Fe, Al, and Mn in the ReRAPS mode of operation. The retention and the pH of the detention pond were sufficiently high to promote the precipitation of Fe and Al based on the results of the batch tank study and MINTEQA2 equilibrium modeling. The MINTEQA2 equilibrium results do predict that the pretreatment of Fe in the detention pond may be hindered by the presence of Fe(II). Ferrous iron levels were not measured at N2. However, subsequent sampling of CPR treatments has shown that Fe(II) is routed to the RAPS. MINTEQA2 was not used to predict any effects in the detention pond due to co-precipitation. However, the pretreatment of Mn is possibly due to adsorption, co-precipitation, or bio-oxidative processes, which could not be duplicated in the tank study.

Pretreatment of these contaminants prior to the RAPS component reduces limestone dissolution and the buildup of solids within the substrate of the RAPS component. A 75% pretreatment of acidity could conceivably increase the operational life of the RAPS limestone by 4 fold. Approximately 50% of the (12,323cu-ft total) limestone can be consumed to maintain the recommended 12-15hr retention within the substrate at 170Lpm (45gpm). Therefore, it is estimated that the normal once-through RAPS mode of treatment would consume the available limestone in approximately 14 years (assuming: 96.6lbs/cu-ft loose bulk density, 90% $CaCO_3$, 60in rain/yr, 50% initial abstraction of rain, 11 ac runoff basin, 509mg/L runoff acidity as $CaCO_3$). The use of the ReRAPS mode could increase the operational life of the Plant Gorgas wetland to more than 50 years.

Assuming that the plugging of the limestone voids is a controlling factor, the life expectancy of the system could be increased by 10-fold when operating in a ReRAPS mode. This estimate also assumes that the buildups of Al and Fe oxides are similar in their effects and that there is a near complete pretreatment of Fe and 80% pretreatment of Al. A detention pond designed for better mixing could eliminate any Al and Fe fouling of the RAPS component and any build up of precipitates could be easily removed from an open detention basin.

Prior to January 2000, the Plant Gorgas wetland had been operating in the ReRAPS mode for over 2 years. Evidence of the past pretreatment capabilities of the ReRAPS wetland was demonstrated when the treatment mode was changed to a "once-through" RAPS mode after the January 2000 treatment. After another series of rains, the pH in the detention pond dropped, Fe was solubilized and portions of the previously pretreated contaminants were pumped directly into the RAPS component. This event clearly demonstrated that the detention pond had been accumulating metal precipitates while operating in the ReRAPS mode. However, it also demonstrates that excessive runoff would overwhelm the detention pond and threaten to re-suspend the previously pretreated metals. Further research and careful design of the detention pond storage is required. Design criteria such as detention pond storage, retention, runoff flow, recirculation flow, and pumping schemes should be carefully developed if a stable pretreatment of the detention pond is required. Other design options could consider multiple detention pools and the use of flow control weirs to reduce the shock loading effects of the detention pond.

Results from the tracer studies have shown that the Plant Gorgas wetland behaves like a series of mixed reactors. However, the detention pond component does exhibit short-circuiting. A reconfiguration of the open water scheme into an initial mixing basin followed by a series of settling chambers would improve pretreatment in the detention pond. This configuration would need to account for changes in water level. The initial mixing chamber which would receive inflows from treated recycled wetland water and untreated runoff or AMD would need a dead storage of sufficient volume to moderate the initial flush of runoff resulting from a rain event.

The overall size of the RAPS-based wetland is dependent on the final removal of Mn. It has been shown that Mn removal is dependent on the initial removal of Fe. The pretreatment of Fe would likely move the primary Mn removal front into the settling basin and may reduce the size or eliminate the need for other downstream components (i.e. rock drains or cattail filters).

Most RAPS-based wetlands are configured to operate passively (without pumps). A disadvantage of the ReRAPS mode of operation (recirculation) is that a pump is required. However, pumps have been required to lift contaminated water to an available wetland site, as is the case with the Plant Gorgas wetland. A ReRAPS design should be considered in these cases.

This wetland uses a 2.2KW (3hp) and a 2.6KW (3.5hp) pump. If continuously used and assuming an electrical cost of $0.07/KWH, the operational costs for the two-pump operation would range from $1,200 to $3,600/year. Alabama typically receives 152cm (60in) of rain per year. The treatment of coal pile runoff in Alabama during a ReRAPS mode could approach a third of the continuous duty electrical cost assuming a 50% initial abstraction of rain and a 50% recirculation of pumped water. However, the cost of pumping in the normal RAPS mode could be reduced to one-fifth of the continuous duty cost.

A passive variant of the ReRAPS mode is possible if an alternate dependable source of alkaline water were available to moderate the pH of contaminated water in a detention pond prior to the RAPS component.

In a ReRAPS wetland the detention pond removes most of the contaminants by recycling a portion of the generated alkalinity. In a RAPS wetland the RAPS component collects nearly all of the Al precipitant, a significant portion of the Fe, and wastes all of the alkalinity to the wetland discharge. The ReRAPS design may eliminate potential plugging and short-circuiting due to precipitant buildup in the substrate of the RAPS component. The reuse of alkalinity greatly increases the operational life of the system. The ReRAPS wetland may accomplish these things at the cost of pumping and the use of a well-designed detention pond.

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Literature Cited

Allison, J.D., D.S. Brown, and K.J. Novo-Gradac. 1991. MINTEQA2, a geochemical assessment data base and test cases for environmental systems: Vers. 3.0 User's Manual. Report EPA/600/3-91/-21. Athens, GA: U.S. EPA.

APHA. 1998. Standard methods for the examination of water and wastewater. 20th ed. American Public Health Association Washington, DC.

Brant, D. and P. Ziemkiewicz. 1997. Passive removal of manganese from acid mine drainage. p. 634-638. In: Proceedings of the 1997 National Meeting of the American Society for Surface Mining and Reclamation. (Austin, TX, May 10-15, 1997).
https://doi.org/10.21000/jasmr97010741

EPA. 1983. Methods for chemical analysis of water and wastes: Report EPA/600/4-79-020 Revised March 1983. Cincinnati, OH. U.S. EPA.

EPA. 1994. Methods for the determination of metals in environmental samples. Report EPA 600/R-94-111. Supplement 1, May 1994. Cincinnati, OH. U.S. EPA.

Hedin, R.S. and G.R. Watzlaf. 1994. The effects of anoxic limestone drains on mine water chemistry. p. 185-194. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage. Volume 1 of 4. (Pittsburgh, PA, April 1994).
https://doi.org/10.21000/JASMR94010185

Kadlec, R.H. and R.L Knight. 1996. Treatment Wetlands. CRC Press, Boca Raton. FL.

Kepler, D.A. and E.C. McCleary. 1994. Successive alkalinity producing systems (SAPS) for the treatment of acidic mine drainage. p.195-204. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage. Volume I of 4. (Pittsburgh, PA, April 1994).
https://doi.org/10.21000/JASMR94010195

Langmuir, D. 1997. Aqueous Environmental Geochemistry. Prentice-Hall, Inc. Upper Saddle River, N.J.

Robbins, E., D. Brant, P. Ziemkiewicz. 1999. Microbial, algal, and fungal strategies for manganese oxidation at a Shade Township coal mine, Somerset County, Penna. p. 634-640. In: Proceedings of the 1999 National Meeting of the American Society for Surface Mining and Reclamation. (Scottsdale, AZ, August 13-19, 1999).
https://doi.org/10.21000/JASMR99010634

Skovran, G.A. and C.R. Clouser. 1998. Design considerations and construction techniques for successive alkalinity producing systems. p. 235-242 In: Proceeding of the 1998 National Meeting of the American Society for Surface Mining and Reclamation. (St. Louis, MO, May 16-21, 1998).
https://doi.org/10.21000/JASMR98010235

SPSS. 1999. Base 10.0 User's Guide. SPSS Inc. Chicago, IL.

Stumm, W. and J. Morgan. 1981. Aquatic Chemistry, 2nd ed.. John Wiley, N.Y.

Watzlaf, G.R., K.T. Shroeder and C. Kairies. 2000. Long-term performance of alkalinity-producing passive systems for the treatment of mine drainage. p.262-274. In: Proceedings of the 2000 National Meeting of the American Society for Surface Mining and Reclamation. (Tampa, FL, June 11-15, 2000).

https://doi.org/10.21000/JASMR00010262