Passive Treatment Systems for Selenium Removal

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Abstract
Passive treatment systems have been developed using biochemical reactors (BCRs) and aerobic wetlands for the treatment of selenium in effluents related to coal mining in the state of West Virginia (WV). Barrel studies were conducted to determine the best substrate mix for the BCRs for removing selenium while limiting the discharge of biological oxygen demand (BOD), low dissolved oxygen (DO), excess sulfide, and other secondary parameters typically generated from BCRs. The barrel studies demonstrated that a high-strength BCR substrate mixture can consistently remove selenium below regulatory limits of 4.7 µg/L at a 12-hr hydraulic residence time (HRT), but a 24-hr to 48-hr HRT is recommended for conservative full scale design. During the initial start-up period, BCR substrate mixtures generate elevated concentrations of secondary parameters, but concentrations quickly decrease to a level that can be treated by a downstream aerobic polishing wetland. Based on the results of the barrel studies, two full-scale passive treatment systems have been designed and constructed for a coal company in Southern WV. One passive treatment system removed selenium below detection limit during the first six months of operation spanning low and high flow conditions. The other passive treatment system received above-average flows during the first three months of operation, but still removed selenium below regulatory limits. This paper presents a compilation of results from the barrel studies and preliminary data from the full scale passive treatment systems.

Key Words: biochemical reactor, constructed treatment wetland

Introduction
Selenium is a naturally occurring element and an important micronutrient essential for all living organisms. Although selenium is essential, elevated concentrations can be toxic to aquatic wildlife. Selenium is a contaminant of potential concern found in the organic-rich shales utilized by a wide variety of industries, including mining (coal, hard rock, uranium, phosphate) and power generation (coal-fired power plants, oil refineries). In addition to these industrial activities, elevated selenium may also result from agriculture due to discharge of subsurface irrigation drainage waters and due to animal husbandry additions of this often-deficient essential element. Overall, human activities can concentrate selenium in excess of the regulatory limits and affect wetland habits. For example, at numerous industrial and mining sites, National Pollution Discharge Elimination System (NPDES) permits are now requiring discharge limits for total recoverable selenium of 4.7 micrograms per liter (µg/L) and 8.2 µg/L for monthly average and daily maximum concentrations, respectively.

Conventional, "active" treatment systems such as membrane treatment, chemical treatment by precipitation and/or coagulation, and biological treatment such as fluidized bed reactors or algal reactor tanks typically require fossil-fuel energy for pollutant removal and a high degree of maintenance and control to operate. Conventional systems also rely on steel or concrete tanks for storage and pump systems for conveyance, but may have a relatively compact site footprint.

Alternatively, passive treatment systems rely on naturally-occurring biological, chemical, and physical processes to achieve treatment and are typically plant- and soil-based systems constructed within earthen basins. These systems are typically more land-intensive than active treatment systems, but due to lower or negligible energy or chemical inputs can be significantly less expensive to operate and manage. There are

several selenium removal processes that may take place in passive treatment systems. Perhaps the fastest rate of natural removal occurs via anaerobic microbial reduction of soluble selenate and selenite to elemental selenium. For example, in a surface flow wetland receiving agricultural drainwaters with selenium predominantly as selenate, Lin and Terry (2003) found a distribution of selenium that indicated that the selenate was being transformed sequentially from selenate to selenite to elemental and organic selenium. Reducing conditions created by the depletion of oxygen by aerobic microbial respiration can also result in the chemical reduction of selenate and selenite. If sulfur is present in the water, precipitation of selenium sulfide is possible. Certain algae and microorganisms have been shown to converts selenium to organo-selenium compounds, some of which are volatilized to the atmosphere (Lundquist, 1994). The main mechanism for selenium removal in a passive treatment system will depend on the design. Surface flow wetlands tend to favor volatilization mainly because reductive processes within the wetland substrate rely on diffusion and are therefore largely isolated from most of the selenium load. As such, surface flow wetlands generally require long residence times (days to weeks) and thus larger surface areas, to achieve efficient selenium removal through either the slower pathway of volatilization or diffusive transfer within the wetland sediments. For example, Zhang and Frankenburger (2003) found reduction from selenite to elemental selenium by 89-92% in 10-16 days in constructed surface flow wetlands receiving agricultural drain water, demonstrating that although microbial selenium reduction occurs within surface flow wetlands, the rate of reaction is very slow.

Early passive treatment system designs focused on surface flow wetlands and were mainly constructed to treat elevated selenium associated with petroleum production or agricultural runoff. The Chevron oil company implemented a 36-hectare surface flow constructed wetland at the Richmond Refinery located adjacent to the San Francisco Bay, California (CA) (Duda, 1992; Hansen et al, 1998). The system consisted of three planted cells and treated flows of about 6500 m^3/d resulting in a nominal detention of approximately 7 – 10 days. Analysis of the wetland inlet and outlet waters showed that the constructed wetland was successful in removing 89 percent of the selenium from the wastewater passing through it. Inflow selenium concentrations of 20-30 µg/L decreased to <5 µg/L in the outflow (Hansen et al., 1998). Measurements showed that natural biological volatilization might have accounted for 10-30 percent of the total selenium removed. Rates of volatilization were much higher in vegetated areas than in non-vegetated areas. Azaizeh et al (1997) determined that the process was bacterially mediated, and that selenomethionine was the principal volatilized species, followed by selenite. Two additional surface flow wetlands that have treated selenium related to agriculture runoff were constructed in the Imperial Valley, CA. The first system, constructed in Imperial, CA, has a sedimentation basin, followed by a four-cell series surface flow wetland. The overall concentration reduction was 32% over a three-year period of record, although load reductions were greater (47-59%) because of infiltration (Tetra Tech, 2006). The first order rate constant for removal of selenium was calculated to be 12 m/yr for the Imperial wetland. A companion system was located at Brawley, CA, also in the Imperial Valley. This system contained a sedimentation basin and two surface flow wetland cells in series. Data on the inflow and outflow dissolved selenium concentrations for the Brawley wetland showed essentially no concentration reduction, but load reductions were (29-60%) because of infiltration. First order rate constants for removal of selenium were nominally 0.5 m/yr.

While surface flow wetland design has demonstrated early success in selenium removal, the residence time and therefore area requirements are too great for most outfalls requiring selenium removal. Alternatively, biochemical reactors (BCRs), which are designed for vertical flow of influent water through a reducing organic substrate, target microbial and chemical reduction of selenium and as such have shorter residence times and smaller footprints for construction. While BCRs have been employed for treatment of a variety of mine impacted waters, their incorporation into passive treatment systems for selenium reduction is fairly new. For example, selenium was successfully removed on a consistent year-round basis from September 2008 until October 2009 during a 13-month pilot BCR study test at a gravel pit in Grand Junction, Colorado (CO) (Walker and Golder Associates, 2010). In the pilot study, a single

4,380 cubic-foot (ft^3) pilot BCR was constructed to treat flows ranging from 2 – 24 gallons per minute (gpm). The reactor contained media composed of cow manure, hay, sawdust, wood chips and limestone. Influent was drawn from a gravel pit dewatering trench next to the Colorado River. The pilot achieved maximum selenium removal rates of 98 percent with a hydraulic retention time of 2.4 days and a minimum effluent concentration of 0.5 µg/L. The highest mass removal rate achieved by the BCR was 73 $mg/day/m^3$ of substrate and the cumulative mass of total selenium removal was 600 grams during the 13-month period. The BCR treatment process was effective throughout the cold winter months, during which time total selenium removal rates remained greater than 90 percent.

While incorporating BCR cells into a passive treatment system design can significantly reduce the required residence time and therefore overall system footprint, the BCR does generate secondary parameters (e.g., biological oxygen demand, color, sulfide) that require treatment before final effluent is discharged from the passive treatment system. Thus, passive treatment systems that incorporate BCRs are always designed with at least one aerobic polish wetland downstream from the BCR to reduce secondary parameters to appropriate concentrations. The aerobic polishing wetland functions by trapping particulate organic particles, increasing the dissolved oxygen content of the BCR effluent, as well as oxidizing any chemical or biologic oxygen demand present. The aerobic polishing wetland may also act to polish any residual selenium remaining in the BCR effluent.

Purpose of presentation

A growing number of surface coal mines in West Virginia (WV) are investigating or applying passive treatment for selenium control. Given the steep topography in the WV coal mining region, there is limited space available for construction of large scale passive treatment systems and therefore, BCRs offer the best method of minimizing space requirements, while maximizing treatment. However, the BCR organic substrate must be well balanced to also minimize the size requirements needed for aerobic polishing of secondary parameters. This paper summarizes the results of barrel studies used to develop design parameters (e.g., BCR substrate recipe, loading rate) for two full scale passive treatment systems and the first six months of performance of the full scale passive treatment systems.

Barrel Studies

The BCR organic substrate is specifically designed to provide both short-term and long-term carbon to the microbial community over the life of the substrate, which is generally estimated to be greater than 10 years (Denholm et al., 2010). The organic substrate is generally composed of wood products (woodchips or sawdust) to supply long-term carbon; and hay or compost to supply short-term carbon. Limestone sand is added to the media to create a near-neutral pH, as fermentation and cellulose degradation can generate acidity. This is especially true in the early stages of substrate evolution. Manure is added as a seed to help quickly establish a robust anaerobic microbial community. While adding more manure can help jump start a system and provide high removal rates of selenium, too much manure can overwhelm the downstream cells with elevated oxygen demand.

A preferred mix of the ingredients listed above would produce negligible odor, low color, and both chemical and biological oxygen demand that can be treated within the downstream space available for oxygenation and polishing while at the same time support high selenium removal rates over a wide range of climatic (i.e., temperature, precipitation) conditions and loading rates (i.e., selenium, hydraulic). While the general ingredients and basic requirements of the media are largely understood, the availability of suitable components depends on the local industry and available suitable “waste products”.

Four different organic substrates were tested in barrels using water sourced from the toe of a valley fill in Southern WV (Figure 1). The purpose of this testing was to determine an appropriate mix of materials for BCR substrate that will satisfy the following goals:

- provide both short-term and long-term carbon sources that create a robust microbial community suited for chemical reduction of selenium;
- provide a media with sufficient structure and hydraulic conductivity to sustain appropriate hydraulics in a vertically-flowing passive BCR treatment system; and
- minimize the production of nuisance conditions including odors, color, and oxygen demand.

Figure 1. Barrel Study Setup Showing Weir Inlet Line and Four Tank Array in Upflow Mode

Barrel testing setup and design

The barrel testing was conducted from July – October 2010. Water was collected and flowed via gravity to a pilot system consisting of four 55-gallon barrels each containing different substrate mixes. Table 1 lists the substrate mix used in each barrel. Flow rate was determined at the effluent of each barrel by the timed volume method ("bucket and stopwatch") using a small graduated cylinder and a stopwatch. The graduated cylinder was allowed to fill for 20 – 40 second intervals and the volume and time recorded. Each flow was measured in triplicate with the average value being used to calculate the flow rate in gpm or gallons per day. Initially, the flow rate was set at 120 milliliters per minute (mL/min) (≈0.03 gpm) for each tank. This flow rate corresponded to an approximate hydraulic residence time (HRT) of 24 hours for each of the barrels. After six weeks of operation, flows to the barrels were doubled (resulting in a 12 hour HRT) in an attempt to increase the observed selenium removal by increasing the selenium load applied. Significant increases in the effluent selenium concentrations prompted a decrease in flow rate after 12 weeks of operation with an average HRT of approximately 18 hours (Figure 2).

Table 1. Barrel study substrate recipes

Tank	Peat Moss	Organic Peat	Composted Manure	Sawdust	Wood Chips	Hay	Limestone Chips
A	100%	--	--	--	--	--	--
B	20%	20%	--	20%	20%	15%	5%
C	--	--	15%	47%	16%	16%	6%

D	--	--	23%	30%	20%	20%	7%

Results and Discussion

Field parameters

Field parameters measured during the study included pH, temperature (in °C), conductivity, oxidation-reduction potential (ORP), and dissolved oxygen (DO) (Table 2). The influent (measured at the weir) and effluent pH was consistently near-neutral and showed little variation over the course of the study. The one exception is the effluent pH from barrel A (peat only) which had a low initial effluent pH. This low pH can be attributed to multiple factors including high initial flow rates, little to no buffering capacity in peat (no limestone was added to the peat substrate), and likely low microbial activity during the initial startup.

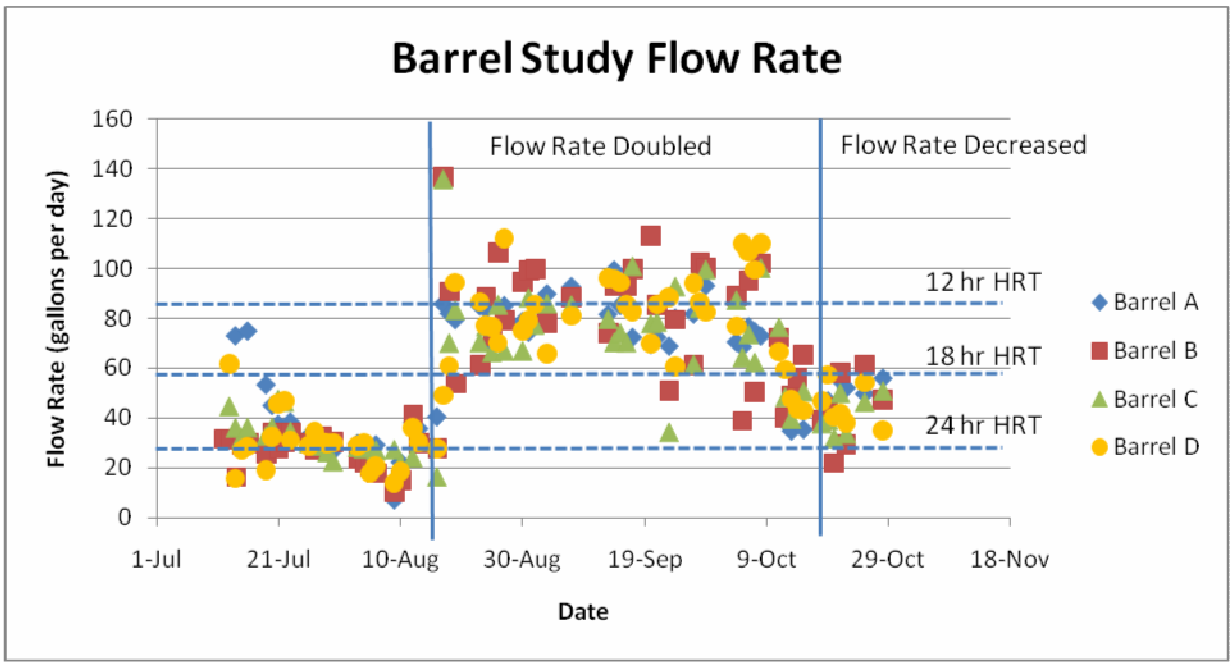

Figure 2. Daily flow rate from the barrel study

The influent temperature measured at the weir was approximately 15°C consistently, which is consistent with the valley fill drain flow. The effluent temperature of all tanks was consistently >20°C and as high as 39°C during the target flow regime (i.e., 24 hr HRT). After the flow rate increase to a 12 hr HRT, the average effluent barrel temperature dropped to approximately 20°C with ephemeral lows and highs noted, but in general effluent temperature remained higher than influent. With the onset of cooler nights beginning in October, the effluent temperature dropped consistently below the influent temperature. Speculation over daily thermal expansion and contraction of the tanks creating preferential flow paths along the tank walls at high flow rates prompted a decrease in flow rate to an 18 hr HRT in mid-October. Temperatures continued to remain at or below the influent temperature despite the adjustment in flow. The lower temperatures were attributed to multiple causes, including thermal loss in the influent pipe between the weir and the barrels; effluent temperature measurement in the early morning, which reflects the effect of overnight low temperatures on the un-insulated barrels; effluent water ponding on the substrate surface before leaving the system and therefore losing heat through exchange with the cooler air temperature; and the potential for preferential flow along the barrel walls.

Table 2. Minimum, average, and maximum range of concentrations for barrel study select parameters

Barrel	Statistics	pH	Temp ℃	Conductivity (umhos)	TSS (mg/L)	Selenium (ug/L)	Dissolved Selenium (ug/L)	Sulfates (mg/L)	TDS (mg/L)	Dissolved Oxygen (mg/L)	Turbidity (NTU)	BOD (mg/L)	COD (mg/L)
Influent	Min	6.7	13.0	937	2.0	17.41	16.95	30	676	3.35	0.2	N/D	5.4
	Average	7.0	14.7	1341	3.0	23.83	23.26	439	1000	7.04	1.2	N/D	19.5
	Max	7.5	22.0	1665	5.0	30.95	30.66	760	1270	13.10	7.2	N/D	40.2
Barrel A	Min	5.1	12.0	910	3.0	1.13	0.38	25	140	0.58	0.1	2.0	10.7
	Average	6.7	22.9	1328	6.6	12.80	12.38	406	932	1.92	2.6	3.0	32.7
	Max	7.2	39.0	1547	15.0	24.01	22.38	660	1200	5.28	19.2	4.0	72.3
Barrel B	Min	6.4	12.0	973	2.0	0.83	0.37	7	188	0.45	0.3	2.0	18.8
	Average	6.8	21.9	1476	10.7	3.88	3.65	284	900	1.12	103.6	33.8	192.1
	Max	7.0	35.0	2679	30.0	9.19	8.98	700	1360	2.70	344.1	179.0	1152.0
Barrel C	Min	6.5	12.0	970	2.0	1.01	0.33	15	198	0.29	2.5	3.0	5.4
	Average	6.9	22.3	1388	10.0	4.47	3.43	328	960	0.88	131.7	80.3	125.9
	Max	7.2	37.0	1574	30.0	11.89	11.26	640	1325	2.82	613.7	274.0	584.0
Barrel D	Min	6.6	12.0	964	2.0	0.95	0.60	7	197	0.43	2.1	2.0	13.4
	Average	6.9	21.6	1453	9.3	2.89	2.76	298	946	1.06	92.8	28.5	71.7
	Max	7.2	37.0	2538	30.0	6.56	6.24	620	1425	2.80	334.3	148.0	348.3

With few exceptions, the barrel effluent conductivity matched the influent conductivity. Higher conductivity values were observed during the initial barrel start up and may reflect the flushing of residual salts associated with the fresh substrates. The substrate mixtures in barrels B and D were replaced with fresh substrate of a different recipe 8 weeks into the study resulting in a transient spike in conductivity similar to start-up. In both the initial start-up and the replacement substrate phase, the duration of elevated conductivity in effluent from the barrels was short.

Sulfate concentrations were reduced from an average inflow of 439 mg/L to outflow concentrations ranging from 284 mg/L in barrel D (35% reduction) to 408 mg/L in barrel A (7% reduction). Barrels B through D showed evidence of bacterial sulfate reduction with the presence of sulfide in the effluent and the presence of colloidal sulfur in the water pooled atop the substrate. In contrast, there was no sulfide measured in the effluent of barrel A and no indications of active sulfate reduction in the substrate. However, because sulfide from the substrate pore water was able to oxidize on the substrate surface before leaving the barrels tanks, estimated sulfate concentration reductions are approximate.

ORP in the substrate is one of the strongest indicators of selenium reduction potential, since it describes the overall chemical reduction capacity of the substrate. The ORP was not measured until after the increase in flow rate to a 12 hr HRT. However, the ORP was reducing (i.e., -200 to -250 mV) for barrels B through D for every measurement taken. In contrast, the peat only substrate (barrel A) had little impact on redox with the influent and effluent ORP values being approximately the same (i.e., +125 mV) for most of the study.

Similar to ORP, the DO values measured in the effluent were typically < 1 mg/L. In contrast, the peat only substrate yielded DO values between 1 to 3 mg/L following the increase in flow rate to a 12 hr HRT; this is consistent with the higher ORP values measured for the effluent of barrel A.
Effluent sulfide was measured periodically from water ponded on top of the substrate in each tank. Sulfide was not detected in the peat substrate (barrel A) during any measurements, while sulfide was detected in almost every sample measured from barrels B through D. Moreover, the presence of white precipitates on the top of barrels B through D is interpreted as colloidal elemental sulfur, which forms from the oxidation of sulfide under microaerophilic conditions (i.e., <2 mg/L DO).

Water quality data – selenium removal

Total selenium from the inlet weir ranged from 17 to 31 µg/L during the study (Figure 3). Dissolved selenium values were always within 10% of total selenium values. The following trends were observed for each of the four barrels (Figure 3):

- Barrel A: during the initial 24-hr HRT period, selenium concentrations in outflow from Barrel A decreased steadily from approximately 17 µg/L to 4 µg/L. After doubling the flows, selenium concentrations immediately rose to approximately 22 µg/L but dropped to 7.4 µg/L at the second sampling event after changing the flow regime. With the onset of cooler overnight temperatures, selenium removal ranged from 13% to 33% of the total influent selenium and tended to track the influent selenium concentrations. Following the decrease in flow to an 18-hr HRT, total selenium concentrations dropped to approximately 8 µg/L correlated with approximately 40% of the total influent selenium; the selenium removal rate stabilized at approximately 60% in barrel A under low flow, cooler conditions.
- Barrel B: during the initial 24-hr HRT operational period, effluent selenium concentrations were consistently <1.0 µg/L. The effluent selenium concentration rose gradually towards the end of the 12-hr HRT period reaching a maximum concentration of 2.6 µg/L. The substrate was changed approximately 2 months into the study and resulted in a temporary increase in effluent selenium concentration starting at 5.3 µg/L and gradually decreasing to approximately 2 µg/L after 10 weeks of operation. The effluent selenium concentration increased to 9.2 µg/L in early October with the onset of much cooler weather and prior to the decrease in flow rate from a 12-hr HRT to an 18-hour HRT. Following the decrease in flow rate to the 18-hr HRT, the selenium removal rate stabilized at approximately 80% removal.
- Barrel C: during the initial 24-hr HRT period, effluent selenium concentrations varied from below detection limits to as high as 1.5 µg/L. After doubling of flows to the 12-hr HRT, selenium concentrations reached approximately 3 µg/L before gradually declining to approximately 1 µg/L towards the end of September. Similar to barrel B, elevated effluent selenium concentrations approaching 10 µg/L coincided with the onset of cooler overnight temperature in early October. In contrast to barrel B, the selenium concentration remained elevated until the flow was decreased to the 18-hr HRT after which time the selenium concentration dropped to approximately 3 µg/L, corresponding to an approximate removal rate of 90% removal.
- Barrel D: during the initial 24-hr HRT period, effluent selenium concentrations were consistently below 1.0 µg/L with several samples below detection limits. After doubling the flows to the 12-hr HRT, selenium concentrations remained at or below 2 µg/L until the substrate was changed in early September. Following the substrate change, the effluent selenium concentration increased to between 6 – 7 µg/L before dropping below detection limits during the last two weeks of September. As with the other barrels, the effluent selenium concentrations spiked with the onset of cooler overnight temperatures to approximately 5 µg/L and fluctuated between 1 – 5 µg/L even after the decrease in flow rate. In general the barrel continued to remove between 80% to 95% of the influent selenium.

Secondary parameters

Barrel study results indicate that barrel B through D substrates are more reducing and have higher selenium removal capacity than the other substrate mixes tested. However, these richer substrates have a higher potential for generating secondary "nuisance" parameters which should be addressed during design to protect downstream water quality. These parameters include oxygen demand, suspended solids, nutrients, and metals such as iron and manganese.

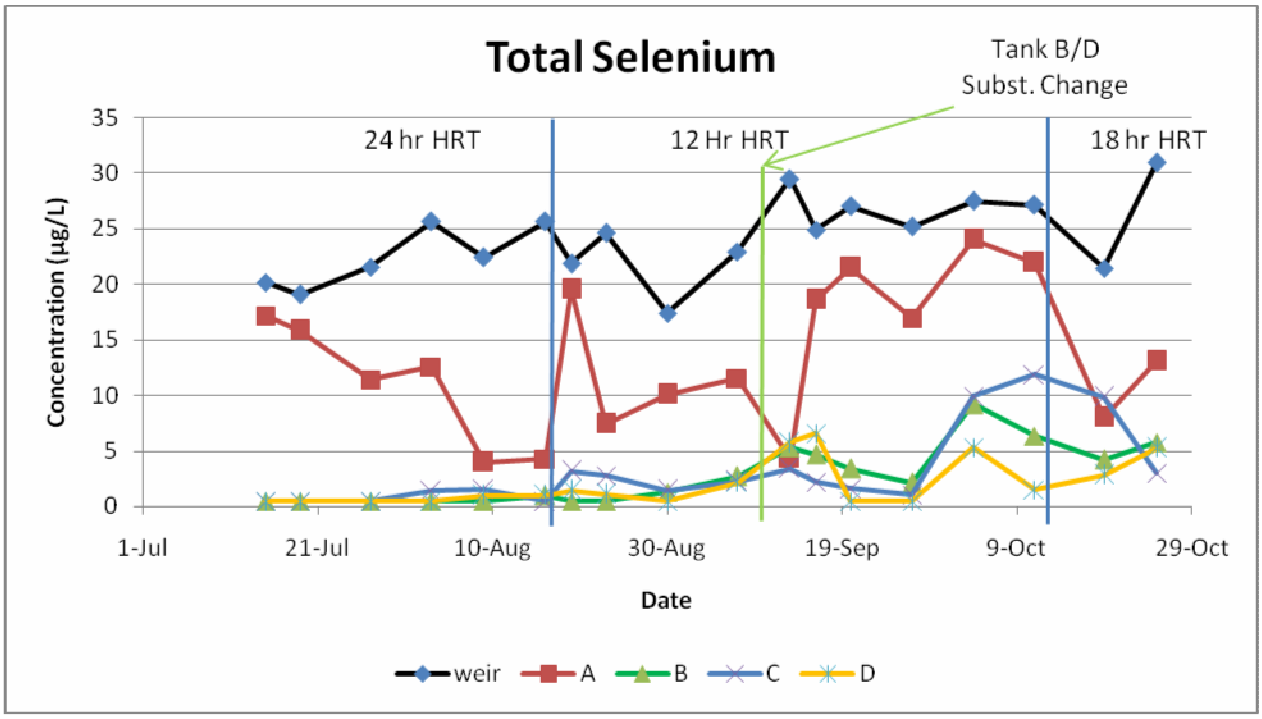

Figure 3. Barrel study total selenium concentration

While having a higher capacity for selenium removal, the biochemical oxygen demand (BOD) and the chemical oxygen demand (COD) from the BCR substrates (barrel B-D) was consistently higher than the peat only substrate (Barrel A). All four barrels had effluent DO generally averaging between 1 to 3 mg/L. While low in DO, the effluent from barrel A consistently had BOD < 5 mg/L. In contrast, the effluent from barrels B through D yielded samples with total BOD greater than 250 mg/L. In an effort to evaluate how much of the BOD was attributable to particulate matter, samples were filtered to evaluate the actual "dissolved" BOD. Results following filtration demonstrate that the very high BOD values are associated with particulate matter and that the dissolved fraction is very low (generally < 10 mg/L and no higher than 40 mg/L). Following the substrate change in barrels B an D and prior to the filtration of BOD samples, the effluent BOD values rose to >150 mg/L for barrels B and D, showing the short term flushing of particulate and labile organics that is expected during start-up. Filtered samples showed significantly lower concentrations. This suggests that much of the BOD released from the BCR substrate can be retained in the downstream units as particulate BOD, which can be utilized and even beneficial over the long term operation of the system. Moreover, the dissolved BOD is within the treatment capabilities of the downstream aerobic polishing wetlands.

The total suspended solids (TSS) and turbidity released from the substrates can result in transport of excessive BOD in the form of particulate organic matter, and may be a concern to receiving water quality. For barrel A, there was essentially no turbidity in the effluent over the entire course of the study with no fluctuations noted as changes in flow rate were made. During the initial the 24-hr HRT flow rate, barrel A effluent generated the lowest effluent TSS, but the concentrations remained higher than the influent TSS. Following the increase in flow rate to the 12-hr HRT, the barrel A effluent TSS increased, while the effluent from the BCR barrels decreased such that barrel A had the highest TSS during the first month of the 12-hr HRT flow. The high TSS and low turbidity in the effluent from barrel A during high flow is attributed to very fine particulate matter mobilized from the peat as discrete particles so that turbid conditions were not generated. The effluent generated from the BCR barrels (B-D) demonstrated variable turbidity (from 30 to 250 NTUs) during the initial target flow regime, but generally tended to decrease

over time. Following the increase in flow rate, there was a sharp drop followed by a rapid rise in turbidity. Turbidity dropped off sharply following the change in substrate in barrels B and D, but continues to increase in the effluent from barrel C which did not have a substrate change. Within two weeks of changing the substrates in barrels B and D, all the effluent turbidity values had decreased to generally < 40 NTUs where they remained until the tanks were shaken lightly concomitant with the decrease in flow rate. The TSS in the effluent from the BCR barrels decreased following initial start up and continued to decrease following the increase in flow rate. However, following the change in substrate in barrel's B and D, the TSS was very sporadic with one large notable spike on September 27 occurring in each tank. The elevated and sporadic TSS following the decrease in flow rate can be attributed to the light shaking that was done to minimize the potential for preferential flow.

In general, the total dissolved solids (TDS) values are correlated to conductivity as the two are measures of ionic content. Similar to conductivity, the barrels have little impact on the effluent TDS relative to the TDS measured at the weir. For the first half of the study, the influent TDS was generally higher than any of the barrel effluent TDS. This trend continued until late September when the barrel effluent TDS started trending higher than the influent TDS. This may be attributable to colloidal particles of native sulfur or iron sulfide being entrained in the effluent and impacting the TDS measurements as they are fine enough to pass through the filters used for TDS analysis.

Full Scale Passive Treatment Systems – First Six Months of Performance

Using the design parameters developed during the barrel studies, two full scale passive treatment systems were constructed in southern WV to treat selenium-rich effluent from two separate coal mining outfalls. The first passive treatment system ("PTS-A") consists of four cells in sequence: a downflow BCR using "barrel B" substrate mix, an upflow BCR using "barrel A" peat substrate, a fill-and-drain subsurface flow wetland and a surface flow wetland. The average influent selenium concentration at the PTS-A site is 12 µg/L with an average flow rate of 60 gpm, however the system was designed to process up to 100 gpm during storm events. The initial BCR cell has a surface area of 0.13 acres and the total footprint of the passive treatment system is 0.54 acres. Start-up of PTS-A was initiated in July 2011 during a period of below average flow rates. The average flow rate between July 2011 and January 2012 was 10 gpm not including three storm events, where the flows were measured at 50, 70, and 70 gpm, respectively. Influent selenium concentrations averaged 11 µg/L, while the selenium concentrations in the discharge have been consistently below the detection limit (1.08 µg/L).

The second passive treatment system ("PTS-B") consists of three cells: an initial "head tank" cell designed to equalize stormwater inflow by detaining water during storm events and then slowly releasing the water over time; a large, 0.51 acre layered upflow BCR cell with "barrel B" substrate mixture overlain by "barrel A" peat substrate; followed by a single 0.27 acre surface flow wetland for polishing. Water flows into an existing 0.38 acre sedimentation pond before discharging. The influent selenium concentration at the PTS-B site averaged 24 µg/L with an average flow rate of 190 gpm. Start-up of PTS-B was in November 2011 during the onset of cooler temperatures and wetter conditions at the site. With the exception of the first week of start-up, the system has consistently been receiving flow at rates above the design average of 263 gpm where between November 2011 and February 2012 there was an average flow rate of 309 gpm. The influent selenium concentration was initially 23 µg/L, but steadily decreased to 9 µg/L through early 2012. Selenium concentration in the system outflow has been consistently below discharge limits, averaging 3.33 µg/L (4.79 µg/L maximum) since start-up.

Conclusions

Based on the results from the barrel study and the preliminary findings from the start-up monitoring of the two full-scale passive treatment systems, the following conclusions can be drawn:

- For selenium concentrations of 10-20 ug/L, high strength organic substrate can remove selenium to the water quality standard within a 12-hour HRT. A 24- to 48-hour HRT may be more conservative for typical design
- High strength substrate initially generates elevated concentrations of secondary parameters (BOD, COD, low DO, etc.). Concentrations typically decrease within 8-12 weeks and can be treated with aerobic polishing wetlands of reasonable size.
- Low strength (i.e., "barrel A" peat) substrate results in lower selenium removal rates *but also* lower concentrations of secondary parameters.
- Both full scale passive treatment systems are achieving selenium compliance requirements, even though the PTS-B start-up occurred at the onset of winter with seasonal hydraulic loading rates sustained above average design criteria.
- Winter temperatures did not affect have a significant effect on selenium removal rate.

References

Azaizeh, HA, S. Gowthaman, and N. Terry. 1997. Microbial selenium volatilization in rhizosphere and bulk soils from constructed wetlands. Journal of Environmental Quality 26: 666-672.

Chapman, P.M., Adams, W.J., Brooks, M.L., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., Shaw, D.P. 2009. Ecological assessment of selenium in the aquatic environment: Summary of a SETAC Pellston Workshop. Pensacola FL (USA): Society of Environmental Toxicology and Chemistry (SETAC).

Denholm, C., Johnson, D., Taylor, W., Shearer, R., Danehy, T., Busler, S., Dunn, M. 2010. Case Study: "The Jennings System" – Over a Decade of Successful Passive Treatment *in* R.I. Barnhisel (Ed.) Bridging Reclamation, Science and the Community, Proceedings of the 2010 National Meeting of the American Society of Mining and Reclamation, Pittsburgh, PA June 5 - 11, 2010. p. 154 – 169.

Duda, P. J. 1992. *Chevron's Richmond Refinery Water Enhancement Wetland*; Report to the Regional Water Quality Control Board; Oakland, CA.

Hansen, D., P. J. Duda, Adelzayed, and N. Terry. 1998. Selenium Removal by Constructed Wetlands: Role of Biological Volatilization. Environ. Sci. Technol. 32: 591-597.

Lin, Z.Q. and Terry, N. 2003. Selenium removal by constructed wetlands: quantitative importance of biological volatilization in the treatment of selenium-laden agricultural drainage water. Environ. Sci. Technol. 37: 606-615.

Lundquist, T.J., Green, F.B., Tresan, R.B., Newman, R.D., and W.J. Oswald. 1994. The algal bacterial selenium removal system: mechanisms and field study. p. 251-278. *In* W.T. Frankenberger and S. Benson. Selenium in the Environment. Marcel Dekker, New York.

Walker, R. and Golder Associates. 2010. Final report: Passive selenium-bioreactor pilot scale testing. Bureau of Reclamation Science and Technology Program (PN 4414).

Zhang, Y. and W.T. Frankenberger, Jr. 2003. Removal of selenate in simulated agricultural drainage water by a rice straw bioreactor channel system. *Journal of Environmental Quality*, 32: 1650-1657.

Acronyms

BCR – Biochemical Reactor
BOD – Biologic Oxygen Demand
COD – Chemical Oxygen Demand
DO – Dissolved Oxygen
HRT – Hydraulic Residence Time
NPDES – National Pollution Discharge Elimination System
ORP – Oxidation–Reduction Potential
PTS – Passive Treatment System
TDS – Total Dissolved Solids
TSS – Total Suspended Solids