The Effects of Castor canadensis (North American Beaver) Colonization on a Mine Drainage Impacted Stream

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Abstract

Net alkaline mine drainage began discharging in 1979 and negatively impacted the aquatic and terrestrial biota near a 1.6 km reach of an unnamed tributary (UT) to Tar Creek, located in the Oklahoma, USA portion of the abandoned Tri-State Lead-Zinc Mining District. By 2015, Castor canadensis (North American Beaver) had colonized UT, transforming the stream into a series of impoundments created by beaver dams. The increased surface area and retention time provided by the impoundments reduced Fe and Cd aqueous concentrations by over 60%. However, the precipitated metals resulted in elevated Cd, Fe, Pb, and Zn concentrations in stream sediments.

Keywords: *Castor canadensis*, Beaver, Ecosystem Engineer, Tar Creek

Introduction

This paper investigated the hydrological and chemical impacts of Castor canadensis (North American Beaver) colonization on a first-order stream, contaminated with net alkaline mine drainage (MD). The stream is located within the Tar Creek Superfund Site, the Oklahoma, USA portion of the Tri-State Lead-Zinc Mining District (TSMD). The TSMD was in operation from the mid-19th century until the 1970s and produced approximately two million tons of lead and nine million tons of zinc (ODEQ, 2006). During mining, large pumps were used to dewater the mines. However, when operations ceased, groundwater recharged, filling the voids, and discharging metal-laden water under artesian pressure into receiving streams in 1979.

The study site was one of these receiving streams, an unnamed tributary (UT) to Tar Creek. The study reach of UT is approximately 1.6 km and receives two primary sources of MD. UT and the contributing sources of water are regularly monitored for water quality by The Center for Restoration of Ecosystems and Watersheds (CREW). The first source is the Southeast Commerce (SEC) discharge, located at the start of the study reach and contributing approximately 375 L/min containing 133 mg/L Fe, 9.7 mg/L Zn, 63 µg/L Pb, and 31 µg/L Cd. The second discharge, located 0.5 km downstream, is the Mayer Ranch site. In 2008, the Mayer Ranch Passive Treatment System (MRPTS) was constructed to treat 600 L/min of MD. The system has approximate effluent metals concentrations of 0.65 mg/L Fe, 0.46 mg/L Zn, with Cd and Pb below practical quantitation limits (PQL). Therefore, the raw MD in UT from the SEC discharge is diluted after the MRPTS effluent enters the stream (Figure 1)

Beaver are known as ecosystem engineers, which are organisms with the potential to significantly modify their surroundings (Naiman et al., 1986). The construction of beaver dams has been shown to improve water quality, reduce peak flows due to storm events, and increase storage capacity in streams through the creation of wetlands (Naiman et al., 1986; Snodgrass and Meffe, 1998; Hardisky, 2011; and Puttock et al., 2017). However, the impacts of beaver on MD impacted streams has not been studied. Beaver activity was noticeable on UT in 2014. By 2015, beaver had converted the study reach of UT into a series of beaver impoundments. This study investigated four aspects of Castor canadensis colonization on UT: (1) retention of metals in UT due to beaver impoundments, (2) metals contamination and leachability of sediments (3) potential for metal mobilization during dam destruction and (4) hydrologic and habitat alterations due to the presence of dams using tracer studies and rapid habitat assessments.

Methods

Large beaver dams on UT that impounded water above bankfull and maintained a change in elevation head on opposite sides of the dam were identified and sampled to address retention of metals due to beaver impoundments and consequent metals accumulation in stream sediments (Figure 1). In addition, an existing man-made low water crossing (LWC) was sampled because it also met the above criteria. Water and sediment samples were collected at the inflow and outflow of each impoundment. Inflow was defined as the location where water levels began to exceed bankfull. Outflow samples were collected in the pooled water immediately before each dam. If distinct layers of sediment were present, two samples were collected. The water and sediment samples were analyzed for total metals using hot nitric acid digestion and subsequent ICP-OES analysis (USEPA Methods 3015 and 6010). Sediment samples with the greatest metals concentrations were then analyzed for leachability using USEPA method 1311 for toxicity characteristic leaching procedure (TCLP). Three sampling events took place from August 2016 to January 2017. Due to inconsistencies with beaver activity, not every dam was present at each sampling event. If a dam was absent, that location was not sampled for that event. Sediment samples were analyzed for statistical significance using a paired, one-tailed T-Test.

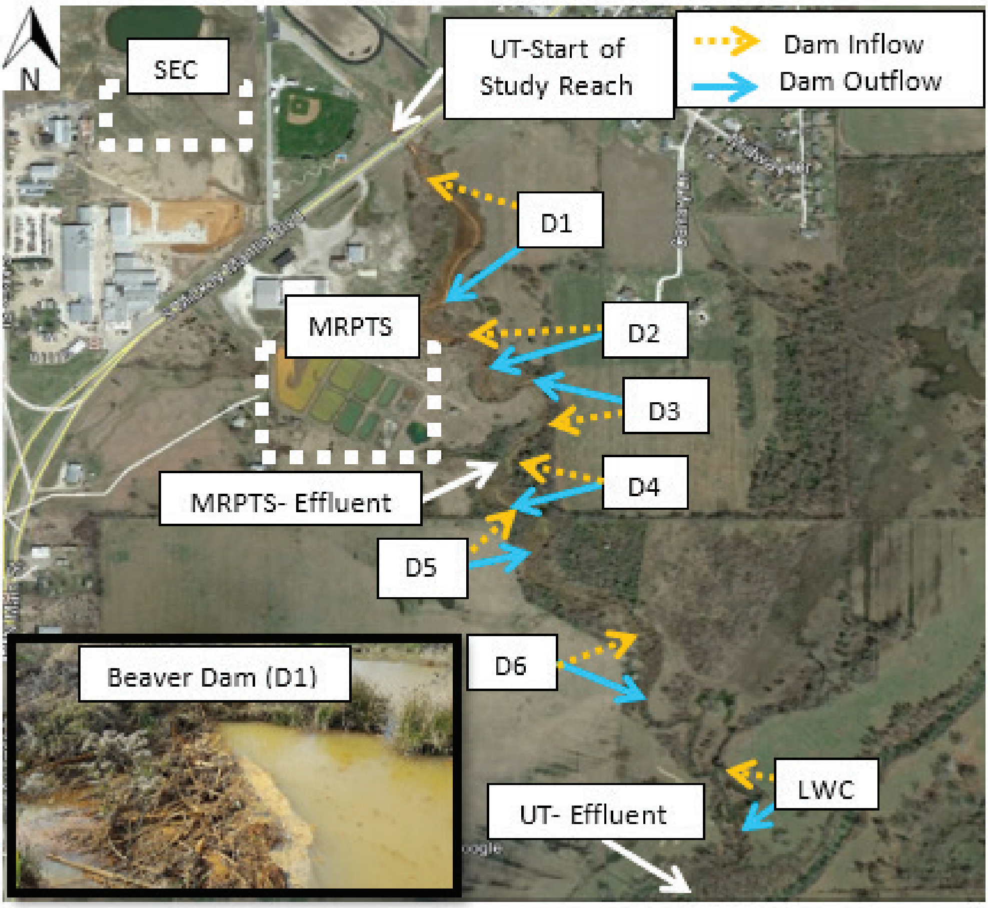

Figure 1 *Beaver dam locations along UT in Commerce, OK, USA with arrows indicating inflow and outflow of each impoundment from beaver dam construction (Google Earth, 2017). Example of a beaver dam (D1) shown in the bottom left corner. Abbreviations: Southeast Commerce site (SEC), unnamed tributary (UT), Mayer Ranch Passive Treatment System (MRPTS), low water crossing (LWC), beaver dams (D#).*

Next, metal remobilization due to beaver dam failure was evaluated. Starting at the most downstream dam (D6), every beaver dam was sequentially destroyed, using hand tools, to an elevation consistent with the streambed. Water samples for total metals analysis were collected at the location of the destroyed dam. Samples were collected 5, 35, and 65 minutes after dam removal. Five months later, the most upstream dam (D1), nearest the SEC discharge, was destroyed again and sampled every 30 minutes for six hours using an autosampler with flow determined by an acoustic Doppler current profiler.

To investigate hydrologic and habitat alterations caused by beaver colonization, two rapid habitat assessments, based on the USEPA's *Rapid Bioassessment Protocols for Use in Wadable Rivers and Streams*, were conducted over a one-month period. The first took place with all beaver dams intact and the second was conducted after dams were removed for the metal remobilization study. Multiparameter datasondes equipped with rhodamine sensors were deployed at the midpoint (near D2 Out) and the end of the UT study reach, collecting data every 30 minutes for six hours. Rhodamine was injected at the start of study reach UT with and without beaver dams.

Results and Discussion

Table 1 shows mean metals concentrations of the three sampling events in and out of each beaver dam. The most upstream dams, nearest the SEC discharge, had greater initial metals concentrations and showed greater Fe removal rates than downstream dams that were influenced by the dilution of treated MD downstream of the MRPTS effluent. Only three dams (D1, D4, and LWC) had samples collected for all three events, therefore only these dams were used for statistical analyses using a paired, one-tailed T-test. D1 showed significant decreases in Cd, Fe, Pb, and Zn ($p<0.05$), while dams downstream of MRPTS (D4 and LWC) did not show statistically significant decreases in metals concentrations ($p>0.05$). The beaver impoundments resembled a series of oxidation wetlands due to increased surface area and retention time, allowing Fe to precipitate and settle as iron oxyhydroxides. The decrease in Cd was likely the result of sorption to the precipitated Fe, which has been documented in the MRPTS oxidation pond, resulting in nearly identical Fe and Cd removal trends (Nairn et al., 2009). Oxidation ponds are often designed to remove 20 g Fe m^{-2} day^{-1}, by comparison, the Fe removal rate at D1 had a calculated average of 4.12 g Fe m^{-2} day^{-1}. Utilizing the flowrate of 375 L/min, D1 removed approximately 12 kg Fe per day.

Pb showed minimal changes in concentration after D1. In passive treatment, Pb is removed via vertical flow bioreactors that promote bacterial sulfate reduction in an anoxic environment (Nairn et al., 2009). The reducing environment necessary to remove Pb was likely not present in the beaver impoundments, which is supported by the small changes in the Pb concentrations (Table 1).

Table 1. *Total aqueous metals concentrations (mg/L) in and out of beaver impounded water in a MD impacted tributary to Tar Creek located in Oklahoma, USA*

Site	Cd		Fe		Pb		Zn	
	In	Out	In	Out	In	Out	In	Out
D1	0.012	0.004	45.03	22.40	0.048	0.036	6.37	4.77
D2	0.003	0.002	4.99	11.55	0.033	0.033	4.81	3.87
D3	0.002	0.002	10.24	8.45	0.034	0.031	3.97	3.93
D4			3.78	3.36	0.032	0.029	2.72	2.32
D5			4.90	3.58	0.036	0.034	2.06	1.98
D6			0.49	0.49	0.034	0.026		
LWC			0.65	0.39	0.028	0.025	1.78	1.80

All sediment samples had at least one metal that exceeded the probable effects concentrations (PEC) specific to the Tar Creek Superfund Site (Ingersoll et al. 2009; Table 2). Cd, Pb, and Zn concentrations were 7, 3, and 4.5 times the PEC, respectively, and five sediment samples contained greater than 20% Fe. Most of the sediment samples collected at the outflow of dams had clear stratification (D4, D5, and D6), attributed to sedimentation occurring near the dam. Cd and Fe concentrations were significantly greater in the surface layer of sediment compared to the bottom layer ($p=0.018$ and $p=0.020$, respectively). The inflow sediment samples had significantly lower Fe and Zn concentrations when compared to the surface layers of the outflow sediments ($p=0.023$ and $p=0.049$, respectively). The greater concentrations of metals at the surface layer of the dam outflow compared to both the inflow and bottom layer of the outflow sediment samples were attributed to the precipitated metals settling near the base of the beaver dam.

Seven sediment samples were selected for TCLP analysis. None of the samples had Pb concentrations that exceeded the Resource Conservation and Recovery Act (RCRA) standard of 5.0 mg/L, while only a single site, D4 In, exceeded the Cd RCRA standard of 1.0 mg/L, containing 1.08 mg/L. The remaining six samples showed an average of 0.2 mg/L Cd, therefore further sampling should be conducted to confirm the Cd concentration at D4.

The removal of each beaver dam using hand tools created a flushing event, releasing a pulse of water that suspended precipitated metals. Table 3 shows the metals concentrations collected at 5-, 35-, and 65-minute intervals after each dam was destroyed. These data showed increasing concentrations of Fe over the one-hour time interval at all dams, with Cd following the same trend at D1. Zn and Pb did not produce consistent trends over time at each dam, suggesting Pb and Zn are not as readily mobilized compared to Fe and Cd.

Utilizing data from the rapid habitat assessments, the estimated volume of water stored by each beaver dam was calculated and used to determine the mass of metals mobilized at each dam (Table 3). Since D1 is the most upstream dam, nearest the SEC discharge, it had the highest initial concentrations of metals, resulting in the greatest mass of mobilized metals. At D1, Fe contributed 98% of the mobilized mass of metals of the four metals presented in Table 3. Using the Fe removal rate for D1 of 12 kg Fe per day, D1 mobilized 4.5 days of retained Fe after dam removal.

The sequential dam removal event confirmed that metal remobilization may occur, but it did not indicate how long the concentrations may remain elevated. A six-hour sampling event conducted at D1 was designed to investigate the duration of the elevated metals concentrations. The experiment

Table 2. *Sediment metals concentrations (mg/kg) at varying depths (cm) in and out of beaver impounded water in a MD impacted tributary to Tar Creek located in Oklahoma, USA*

Site	Depth	As	Cd	Fe	Pb	Zn
PEC			11.1		150	2,083
D1 In	0-60	8.17	75.4	204,000	500	9,240
D1 Out	0-50	39.9	88.6	167,000	377	10,300
D4 In	0-20	11.9	146	122,000	522	10,600
D4 Out	25-35	7.21	11.6	19,900	1,360	1,460
D4 Out	0-25	57.2	70.2	228,000	477	9,400
D5 In	0-45	5.3	8.38	14,000	28.8	863
D5 Out	20-50	10.1	21.7	51,000	419	2,500
D5 Out	0-20	53.8	137	266,000	384	21,400
D6 In	0-15	5.44	20.3	26,100	628	22,400
D6 Out	7-30	18.6	120	149,000	626	14,700
D6 Out	0-7	18.5	234	252,000	538	13,000
LWC In	0-30	4.08	21.2	9,560	192	2,930
LWC Out	0-45	23.8	93.2	221,000	360	13,500

Table 3. *Total aqueous metals concentrations collected at 5-, 35-, and 65-minute intervals after each dam was removed and calculated mean mass of metals mobilized based on volume of water released at each dam in a MD impacted tributary to Tar Creek located in Oklahoma, USA*

Dam #	Volume	Time	Cd	Fe	Pb	Zn	Cd	Fe	Pb	Zn
	(m³)	(min)	Aqueous Concentration (mg/L)				Mass of Metals Mobilized (g)			
D1	1315	5	0.004	22.7	0.037	4.55	9.16	55,300	54.7	4,580
		35	0.007	43	0.039	3.83				
		65	0.010	60.4	0.049	3.23				
D4	296	5	<PQL*	1.04	0.029	0.211		513	9.38	94
		35	<PQL*	1.75	0.032	0.356				
		65	<PQL*	2.41	0.035	0.519				
D5	503	5	<PQL*	0.763	0.031	0.102		580	14.1	44.8
		35	0.001	0.785	0.025	0.074				
		65	<PQL*	1.91	0.028	0.092				
D6	96	5	<PQL*	0.75	0.032	0.106		75.5	2.89	8.85
		35	<PQL*	0.599	0.03	0.09				
		65	<PQL*	1	0.028	0.079				

was originally designed for twelve hours of sampling, but water levels were too low to collect water samples after six hours. The first sample after the dam was removed had elevated metals concentrations attributed to the initial disturbance of precipitated metals. After one hour, Pb and Zn showed no change in concentrations over time (Figure 2). From the sixty-minute sample to the 270-minute sample, an increasing trend in Fe and Cd concentrations was shown (Figure 2). In contrast, velocity demonstrated a decreasing trend for the first two hours, starting at three meters per second and falling below the detection limit of the instrument after two hours. The decreasing velocity over time while Fe and Cd concentrations increased suggest the initial pulse is the driving force that suspends the metals, and the six-hour sampling period is an insufficient amount of time for the metals to resettle. Iron sludge settling rates can vary between 0.2 cm/min and 1.9 cm/min, noting that any disturbance has the potential to decrease the rate (Dempsey and Jeon, 2001; Dietz and Dempsey, 2002). The dam removal in this study was performed using hand tools, it is hypothesized that in the event the dams fail due to storm events, the mass of metals mobilized will increase due to the greater velocities and disturbance associated with a storm event capable of destroying the beaver dams.

The rapid habitat assessment conducted with and without beaver dams that the presence of beaver dams resulted in overall greater habitat scores, 140 points with dams and 128 points without dams, but there was no significant difference between the categories of the classification system. The notable difference between the two habitat assessments was the greater mean width of water with dams, 7.7 m, compared to 3.3 meters without dams. From the habitat assessment parameters, the total volume of water stored by the beaver dams was approximately 2,500 m^3. The volume was verified using stream gauge stations on Tar Creek upstream and downstream of the UT confluence. The spike in the downstream hydrograph following dam removal was subtracted from the base flow to find the volume of water released. The second method resulted in a stored volume of approximately 3,200 m^3.

The rhodamine study found the presence of beaver dams increased the retention time of UT by 23%, Most of the excess retention time occurred on the downstream half of the study reach (Table 4). Since this study was conducted in a MD impacted stream, sorption of rhodamine to Fe was problematic and caused low recoveries, 9% with dams and 24% without dams. Similar studies conducted on non-MD impacted streams reported up to 89% rhodamine recovery (Jin et al., 2009).

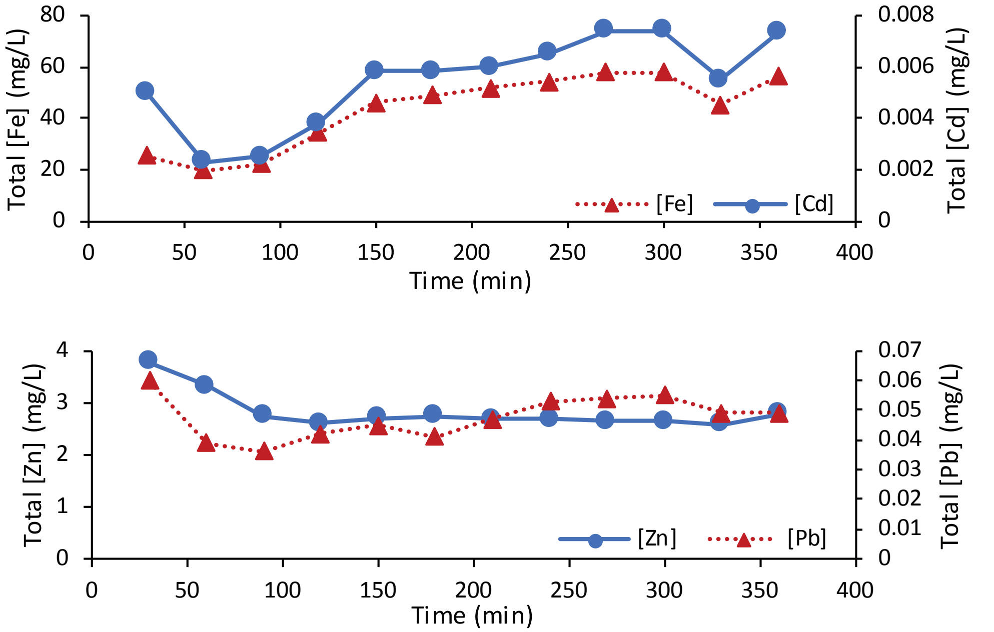

Figure 2 *Total aqueous metals concentration collected every 30 minutes for six hours after D1 beaver dam removal in a MD impacted tributary to Tar Creek located in Oklahoma, USA*

Table 4. *Conservative tracer studies using rhodamine using two sensors located at the midpoint and end of a MD impacted tributary to Tar Creek located in Oklahoma, USA conducted with and without beaver dams*

Parameter	With Dams		Without Dams	
	Midpoint	End	Midpoint	End
Recovery (%)	8.61	9.15	28.47	23.50
Total time until pulse passes (hrs.)	79.0	242.5	113.5	177.0
Mean retention time (hrs. after injection)	48.0	155.0	52.2	126.0
Dispersion coefficient (m2/s)	0.14	20.87	1.61	5.13
Dead volume per bulk volume	53.2	36.6	-162.3	-84.8
Index of short circuiting	-0.21	0.85	0.46	0.27

There were also environmental factors that influenced the results. An inescapable issue when working with beaver was their ability to rapidly reconstruct dams. A pressure sensor in UT recorded continuously increasing water depths associated with beaver reconstructing a dam starting four hours after being destroyed. The immediate reconstruction of dams likely caused an increased retention time because the stream did not remain free of beaver dams.

Conclusions

Beaver colonization on a net alkaline mine drainage impacted stream was shown to decrease metals concentrations via the construction of beaver dams, causing large impoundments with greater surface area and increased retention time. The precipitated metals caused elevated stream sediment concentrations, with the greatest concentrations occurring in the surface layer of sediment nearest the dams. In the event of beaver dam failure, whether caused by man or storm events, a portion of the retained oxidized metals will be mobilized downstream. Overall, beaver are ecosystem engineers providing valuable services by not only improving water quality of a MD impacted stream, but also by establishing wetlands which promote biodiversity and flood attenuation by increasing storage capacity of the stream (Snodgrass and Meffe, 1998; Hardisky, 2011; and Puttock et al., 2017).

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