Prepared for: City of Fort Collins

Roadway Deicing Operations in the City of Fort Collins and Impacts to an Urban Stream

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EXECUTIVE SUMMARY

As part of its ongoing efforts to evaluate and reduce the impacts of various operations on local waterways, and under the direction of City Council, the City of Fort Collins Stormwater Utility and Streets Department commissioned this study to evaluate the impacts of roadway deicing operations (RDO) on the water quality of Spring Creek. The study was conducted in collaboration with the Colorado State University Colorado Stormwater Center from November 2017-April 2018. The primary objectives of the study were to:

1) Evaluate the amount of chloride applied and delivered within the Spring Creek watershed for the 2017-2018 winter and compare to previous studies
2) Investigate the fate of chlorides which are applied but not ultimately delivered to Spring Creek during the winter season
3) Summarize the effects of deicing materials on urban stream quality in terms of Cl- concentrations and its impacts on aquatic life
4) Analyze changes of baseflow chloride concentrations between the 2011-2012, 2016-2017, and current study
5) Analyze roadway recovery attributed to RDO during winter storm events to determine if chloride application can be improved or optimized

The study was conducted for the Spring Creek watershed in Fort Collins, CO. The watershed was partitioned into four subwatersheds with a water quality sensor and pressure transducer located at each subwatershed outfall. Grab samples were also collected at the outfalls which, when combined with data from the in-stream sensors, yielded two primary datasets that were used to quantify the amount of chloride delivered to Spring Creek. The water quality sensors provided timeseries of specific conductivity that were correlated to timeseries of chloride concentrations through the use of grab samples and regression analysis. The pressure transducer allowed for the calculation of a flow timeseries which was used to quantify the load of chloride delivered during various storms at each subwatershed outfall.

In the winter of 2017-2018, the study was improved with two modifications. The first was the in-stream sampling time was moved closer to the beginning of the storm. This was done in hopes of better capturing the peak chloride content. Looking at past timeseries of chloride concentrations in streams, it was evident that waiting 24 hours after the beginning of snowfall, as was previously recommended, was not appropriate to capture the peak chloride concentration. Instead the time should be between 6-18 hours depending on the temperature at the beginning of the storm. The second modification included the addition of a pressure transducer that more accurately predicted water depth. This provided a much better approximation of flow, which better defined the total chloride load at the four different monitoring stations.

The in-stream chloride loads were compared to the amount of chloride that was applied as part of RDO. Automated vehicle location (AVL) data was provided to the Stormwater Center by the City of Fort Collins Street Department. AVL data provided information regarding the time, location, amount, and type of deicer applied by RDO. Using this dataset allowed for the quantification of total chloride applied within each subwatershed for each snow event, which then led to the comparison with the quantity that was delivered to the stream. Additionally, the Streets Department provided the Stormwater Center with pavement performance data so that an analysis could be conducted to determine the effectiveness of current RDO.

Figure ES.1 shows the amount of chloride that was applied during snow events from November 2017 until April 2018. Also displayed in the figure is the amount of chloride that was actually delivered to each of the monitoring stations located at each subwatershed outfall. It is evident from the figure that only a fraction of the deicer applied within each subwatershed was delivered to Spring Creek, begging the question, what is happening to the chloride?

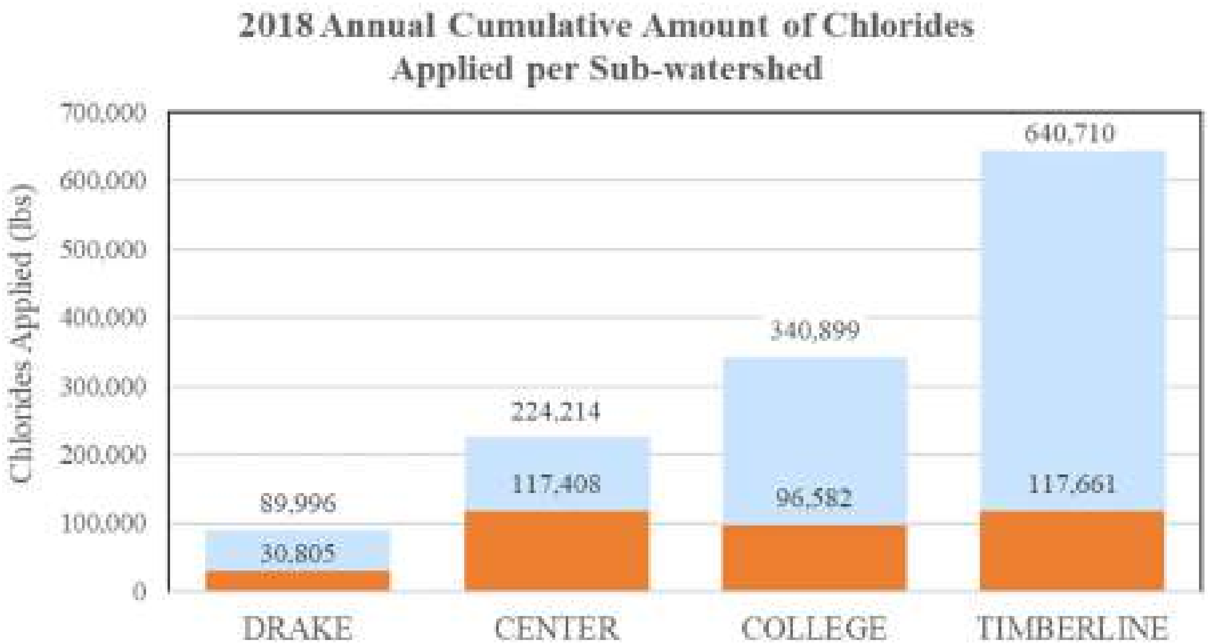

Figure ES.1: Chlorides applied for RDO compared to the amount of chlorides measured at each monitoring location

Several potential fates of chloride were considered including storm sewer solids collected in inlets, storm sewer solids swept up after storms, roadside solids, groundwater interactions along stream, or remaining on pavement. In this study three of these potential fates were investigated: storm sewer solids collected in inlets, roadside solids, and groundwater interactions along stream. Based on sampling of all the investigated fates for chloride content, it was determined that storm sewer solids were not a significant fate of chlorides, however roadside solids and groundwater could be potential reservoirs of chloride. Considering the amount of chloride that was not received in the stream, it is evident that the natural system has the capacity to capture large amounts of chloride.

In order to gain a better understanding of how chloride levels are impacting water quality, the timeseries of in-stream chloride concentrations were compared to the United States Environmental Protection Agency (USEPA) recommendations as well as lethality levels of chloride from a Colorado study completed in 1999. Based on the results, there are a few instances where the EPA recommendations were exceeded, but there were no instances in the 2017-2018 winter that the lethal concentrations were exceeded for three Colorado aquatic species. This illustrates that even though rising chloride levels may be a concern, they are not to the extent that water habitat or supply is severely threatened as of yet. However, one concerning trend that has been witnessed across multiple studies, is the gradual rise in baseline chloride concentrations after the winter runoff event is over. It has been theorized that this trend is being fueled by local chloride reservoirs gradually leaching chlorides back into waterways.

Figure ES.2 shows the measured baseline chloride concentrations. Baseline concentrations were determined by considering the most commonly occurring concentration at each stream monitoring station once all winter runoff had been received and flows returned to normal levels. Assuming baseline chloride concentrations continue to rise at the observed rate, it would take the Drake, Center, College, and Timberline subwatersheds 13.3 years, 5.3 years, 6.7 years, and 22.2 years to reach the chronic toxicity level of 230 mg/L, a level set by the Colorado Department of Public Health and Environment for water to be used as a drinking water source.

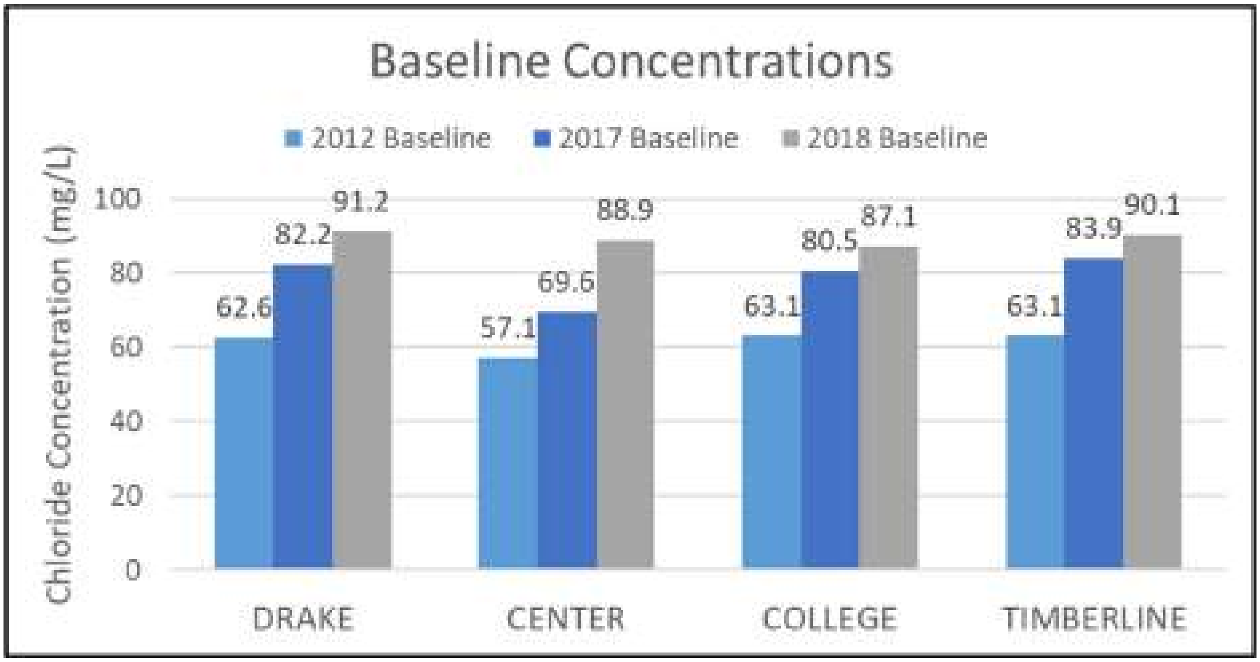

Figure ES.2: Baseline Concentrations at each monitoring location based on the 2012, 2017 and 2018 winters

Rising baseline concentrations may be evidence toward rising concentrations of chlorides in groundwater. Many communities, particularly those farming in eastern Colorado, are becoming increasingly concerned over rising groundwater salinity levels. One potential source for these rising levels could be RDO from cities along the Front Range. When several thousand pounds of salts are added to the groundwater system in each city each year, the baseline salinity would naturally increase. This could result in higher salinity in farming soils if that groundwater is pumped and used for irrigation. For this reason, potential partners are becoming available in the agriculture industry to further investigate methods for improving RDO. Another important point to consider when looking at rising baseline concentrations, is the timeframe over which results from mitigation efforts would be observed. What is meant by this is there is a lack of understanding if rising baseline concentrations are a result of high application rates of deicers from the current year, or from application of deicers over the last 20 years, or if it is a continual leaching process. Because the natural system appears to have the capacity to retain large amounts of chloride, as evident by the lack of chlorides being delivered, it is unknown whether or not changes to the RDO program would result in any short-term accomplishments.

Even though not all of the chloride applied was ultimately delivered, there was still a positive regression relationship between what was applied and what was delivered, inferring that if the amount of chloride applied was reduced, the amount of chloride delivered would also be reduced, though not by the same degree in the short-term. Reducing the amount of chloride applied however, may be what is necessary to prevent the continued increase of chloride baseline concentrations in the stream. Even though a comparable reduction of in-stream chloride would not be expected with a reduction in chloride applied, the long-term benefits may be worth it, even if the timing of the benefit is uncertain.

In order to identify how to safely reduce the amount of deicer agents used by the Streets Department, an analysis of pavement performance sensor data, including snow/ice/water accumulation, level of grip, pavement temperature, wind speed, humidity, etc., was conducted. From the pavement performance analysis, it appears that a smaller but more frequent application of chloride deicers results in better performance of roadway conditions. The pavement performance analysis also demonstrated that under the right conditions (no expected rainfall before a snow storm), a pre-application of deicer as part of an anti-icing effort substantially improved the recovery of the road, specifically for short storms, and can reduce the amount of time and deicer agent required to achieve desired roadway performance levels.

The results of this study indicate that there are still additional questions that need to be answered through further research. One of the primary questions that remains is how to account for chlorides that are not being delivered to the stream. Future analysis should include a more in-depth groundwater monitoring effort in order to more accurately determine the timing of the pulse, which would potentially help quantify the magnitude of the transfer taking place. This could be accomplished by installing a water quality sonde in a groundwater well to collect timeseries of chloride concentration, in addition to pulling groundwater samples for laboratory analysis. Additionally, more samples of roadside solids as well as solids that are swept off the roadway after a winter runoff event should be investigated for elevated chloride concentrations. Also, a year-round monitoring effort could provide insight into the timing of when chlorides are eventually being received by Spring Creek. Extended monitoring would capture data on chlorides potentially being flushed through the system during summer rainfall events.

Another recommendation for further study would be to continue to analyze and evaluate roadway performance data in order to optimize the application of deicer. Utilization of this data should allow for reductions in deicer application, while continuing to maintain safe and drivable road conditions during winter events. Reducing chloride application is not only beneficial for the environment, it also helps lower costs for the Streets Department. The roadway performance study could be enhanced by ensuring the accuracy and calibration of AVL systems for both amount of deicer applied, and timing of the application.

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BACKGROUND AND PROJECT MOTIVATION

In 2008, the City of Fort Collins (City) conducted a review of chemicals used for City operations. In 2009, the Fort Collins City Council (Council) directed staff to report on the impacts of its various operations on the water quality in local lakes and streams. One operation Council expressed interest in was roadway deicing operations (RDO). The City of Fort Collins Streets Department (Streets) is responsible for keeping roadways safe and passable during and after winter storms. In order to achieve those goals, the Streets Department generally uses a combination of snowplowing and RDO. RDO involves the application of one or more types of materials either before the storm begins (anti-icing) or during the storm (deicing). Chemicals applied during RDO lower the freezing point of water, thus preventing or reducing ice buildup on roadways. Melting snow or ice dissolves these materials and carries them into local waterways through surface runoff. These materials may contain a variety of constituents that have the potential to negatively impact water quality including biochemical oxygen demand (BOD), metals, nutrients, chloride, etc.

Maintaining safe road conditions during winter months in urban and sub-urban areas are a major concern for regions that experience significant snowfall. Chemical deicing agents have been widely used to maintain and restore roadway conditions for safe passage during winter storms (Ramakrishna et al. 2005). The use of chemical deicing agents like NaCl (Sodium Chloride), MgCl2 (Magnesium Chloride), and CaCl2 (Calcium Chloride) have become a concern for their environmental impact on urban waterways and roadside vegetation (Ramakrishna et al. 2005, Rubin et al. 2010, Cunningham et al. 2008, Cooper et al. 2014).

Urban ecosystems for aquatic organisms can be negatively impacted by pulses of high chloride concentrations that are delivered from snowmelt containing deicing agents as well as from rising baseline chloride concentrations (Ramakrishna et al. 2005). The USEPA has recommended that Cl- concentrations not exceed 230 mg/L for chronic exposure and 860 mg/L for acute exposure for the protection of aquatic wildlife. (USEPA 1988). Chloride concentrations have been measured above 860 mg/L on multiple occasions during the winter monitoring of an urban stream in Fort Collins, CO.

Near roadways salt application can increase the Na+ concertation in the soil to levels that are toxic to native plants and protozoa living in the soil (Cunningham et al. 2008). High salt concentrations in soils can also lead to the release of heavy metals in the soil (Novotny et al. 2008). In Sweden it was found that 40-70% of all dissolved cadmium in winter was in a Cl-complex and free copper and zinc increased by 30% and 40%, respectively (Backstrom et al. 2003). The increase of salt concentrations in soil can lead to a reduction in terrestrial biodiversity with native salt intolerant species being replaced with invasive salt tolerant species (Cunningham et al 2008). Urban lakes affected by runoff that contain chemical deicing agents can become stratified by the runoff that has a greater density than the water in the lake. Stratification of urban lakes can lead to an oxygen decrease in the hypolimnion which can cause excess phosphorus to be released from the sediment at the bottom the lake and can even prevent seasonal lake turnover (Ramakrishna 2005, Novotny 2008).

Road salts like NaCl will become suspended in solution and can be hard to remove for streams and lakes they impact (Corsi 2010). Given this implication, the most practical solution for reducing chloride concentrations in urban waterways is to the reduce use of chloride and other salt based deicing agents.

Due to project constraints (schedule and budget) the scope was limited to only evaluating the fate, transport, and effects of chloride (Cl-) on water quality. Chloride was selected over the other potential constituents for several reasons: 1) it is generally found at very high concentrations in most deicing materials, 2) it has documented water quality criteria for protection of aquatic life, and 3) it is a stable and conservative constituent in natural waters that would allow for analyzing the fate and transport of deicing materials through a watershed.

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PROJECT APPROACH

The study area for the project was the Spring Creek watershed in Fort Collins, CO. Spring Creek serves a drainage area of 31 sq. km. The approach for this project was to extensively monitor chloride deicers in both application and in-stream concentrations for a single watershed within the City of Fort Collins from November 2017 – April 2018. The Spring Creek watershed was selected for study based on several factors. First, it contains a good mix of land uses and street types (e.g. residential, commercial, etc.) which generally receive different deicing application rates. Second, more deicing material is applied overall within the Spring Creek watershed than any other watershed within the City (based on analysis from the previous study), and third, the Spring Creek trail provided easy access to almost any location within the watershed.

Focusing efforts within a single watershed allowed for data to be collected at several different points within the watershed, thus supporting a better understanding of the fate and transport of deicing materials throughout the entire watershed. It also provided data for several smaller subwatersheds, within which new strategies for controlling the application of deicing materials could be tested. The watershed was split into four subwatersheds Drake, Center, College, and Timberline to evaluate changes of chloride concentrations and loads as Spring Creek flowed through the City of Fort Collins.

The Drake subwatershed serves primarily low-density development and open space. The Center subwaterhsed serves primarily residential units. The College subwatershed contains the highest density land use and receives runoff from U.S. Highway 287/College Avenue. Finally, the Timberline subwatershed also serves low density development and open space similar to the Drake subwatershed. For each watershed the amount of chloride deicers applied as a part of roadway deicing operations (RDO) was tracked as well as the amount of chloride found at each monitoring location along Spring Creek. Figure 1 provides locational information for each subwatershed and stream monitoring location.

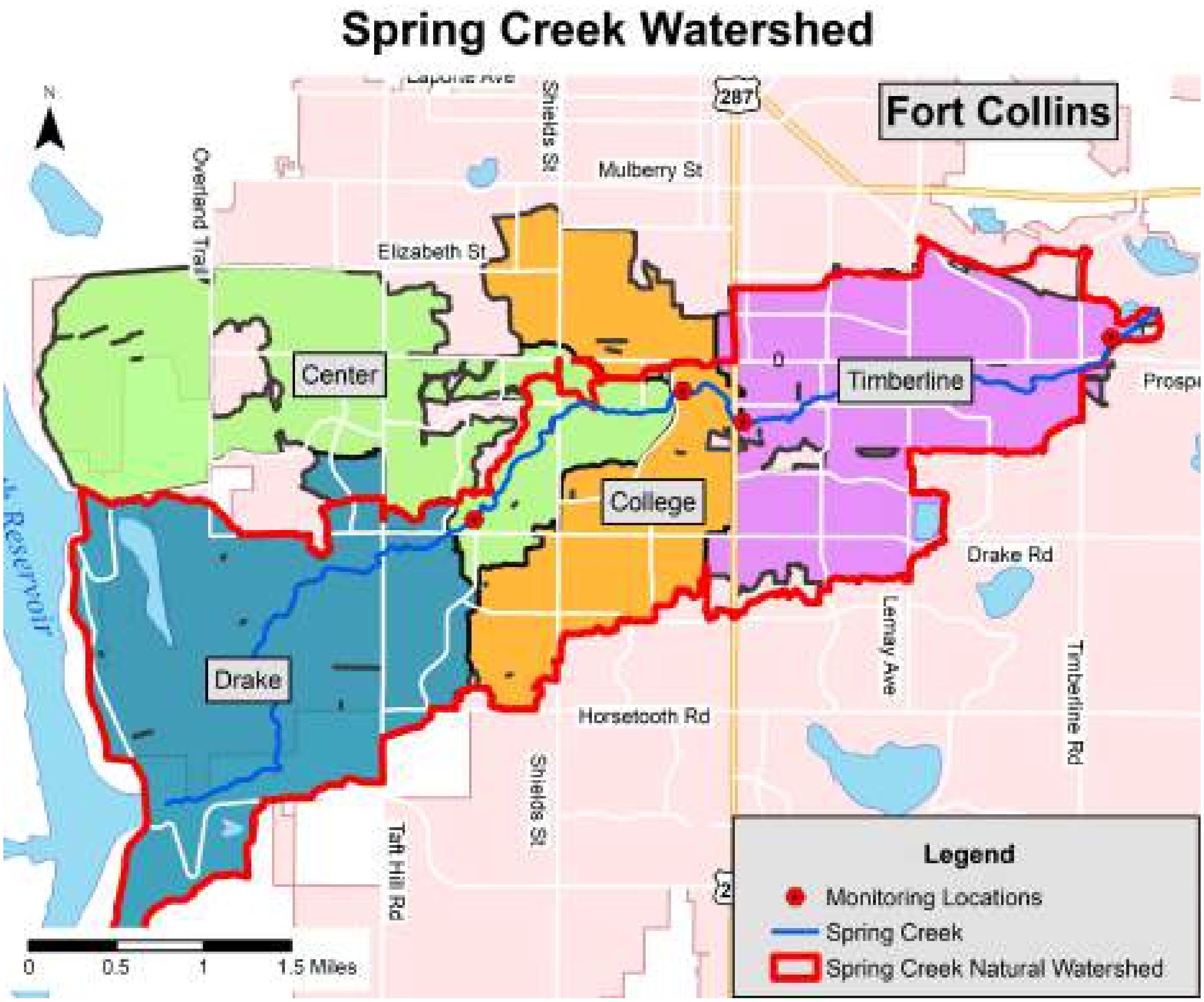

Figure 1: Spring Creek subwatersheds and monitoring site locations at Drake Road, Center Avenue, College Avenue and Timberline Road.

One item of note regarding the subwatersheds is the discrepancy between what was once the natural boundary of Spring Creek and the actual watershed boundaries of Spring Creek and the relationship to the urban storm drainage system (stormwater system). When considering the stormwater system, an extensive part of northern Fort Collins is actually routed to Spring Creek. Any application that occurred in the entirety of the subwatershed was included when determining the amount of deicers applied upstream of each monitoring location.

QUANTIFICATION OF CHLORIDES APPLIED AND DELIVERED

A primary objective of the study was to calculate the total amount of chloride applied as a part of RDO and comparing that to the amount of chloride that was received in Spring Creek during winter runoff events. This required the collection of two main types of data. First, the amount of deicers that were applied as a part of RDO was collected via the Automated Vehicle Location (AVL) system used by the Streets Department on each snowplow. The second dataset was in-stream chloride and flow measurements to quantify the delivered chloride load at each monitoring location in the stream. In-stream data was collected using water quality sondes placed at each monitoring location. Both datasets were combined to establish a comprehensive analysis of RDO application of chlorides and their delivery to Spring Creek.

Application of Deicers Summary

The amount of chlorides applied in the use of roadway deicers was determined using the AVL data as well as results of lab analysis to determine the chloride composition of each deicer product. Fort Collins currently uses three types of liquid deicers and one granular deicer. The liquid deicers include two magnesium chloride products - NexGen Torch and APEX Meltdown and one sodium chloride product, a brine that is mixed by City staff. The granular deicer is a rock salt that is sprayed with APEX to improve performance. For each storm the total amount of solid and liquid deicer used in each subwatershed was determined as well as the projected chloride content. The summary of chloride applied was then compared to the amount measured at each of the monitoring locations.

Automated Vehicle Location (AVL) Data

The amount of deicing materials applied through RDO was monitored by the Automated Vehicle Location (AVL) system used by Streets on its snowplows. Data was provided to CSU by Scott Bowman in the Streets Department. During the period of November 2017 to April 2018, RDO applied deicing materials for 9 different events; November 7, 2017; December 21, 2017; December 31, 2017; January 15, 2018; January 21, 2018; February 1, 2018; February 9, 2018; February 19, 2018; and February 23, 2018. There were two additional storms, one in March, 2018 and one in April, 2018 that did not receive any deicer application but were still monitored for in-stream chloride concentrations. For each of the events with deicer, the total amount of granular salt products and amount of liquid deicer, as well as deicer type, was collected and summarized.

AVL data is provided as geospatial points where each point contains information about the amount of deicer that has been applied since the previous point. Information included in the AVL dataset is snowplow id, date, time, heading, total deicer applied as solid (pounds), and total deicer applied as liquid (gallons). The 2017-2018 AVL data points are shown in Figure 2. Of note, deicer is only applied to roads and routes prioritized by the Streets Department

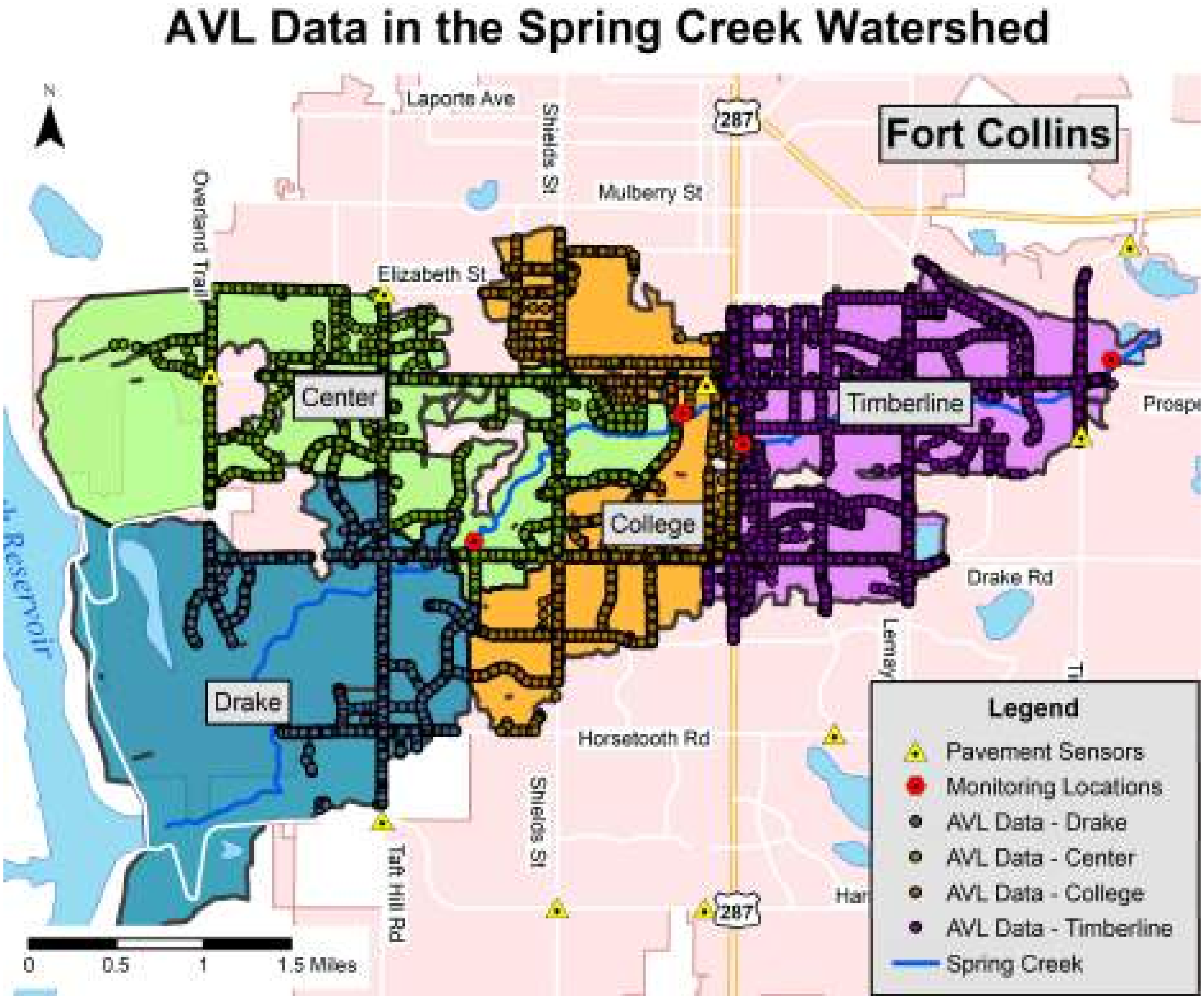

Figure 2: Total amount of deicing agents that were applied to roadways within the Spring Creek watershed. Also displayed in this image are the locations of the pavement sensors which monitor pavement performance.

Deicer Chloride Content

The amount of deicer applied within each subwatershed does not directly correspond to the amount of chlorides applied. To understand the total chloride applied in each subwatershed for each storm, the chloride content of each deicing agent was determined through lab analysis of the deicing materials. Table 1 shows the chloride content for each deicing agent used in Fort Collins. Once the total amount of deicer applied for each storm within each sewershed was computed , the total amount of chloride applied was then calculated using the determined chloride contents.

Table 1: Chloride contents of deicing materials applied to the Spring Creek watershed reported in fraction by weight for granular salt and concentration for salt brine, Apex, and Torch liquids

Deicing Material	Cl^- Content[1]	Cl^- Content[2]	Average
Rock Salt	612,000 mg/kg	550,000 mg/kg	581,000 mg/kg
APEX Meltdown	224,500 mg/L	195,000 mg/L	209,750 mg/L
NexGen Torch	215,500 mg/L	-	215,500 mg/L
Salt Brine	135,000 mg/L	128,000 mg/L	131,500 mg/L
[1] Materials analyzed by Stewart Environmental Consultants, LLC in 2017 [2] Materials analyzed by MMS Labs, LLC in 2018 (Formally Stewart)			

Deicer Application Summary

During the duration of the study, there were nine storms for which deicer agents were applied by the City of Fort Collins. For each subwatershed and each storm event, the amount of deicer that was applied and the corresponding chloride content was determined. Table 2 shows the results from this analysis.

Table 2: Summary of the applied deicer agents for each storm event in each subwatershed and the corresponding chloride content.

Event Start Date	Deicing Material				Chloride Content		
	Granular (lbs)	APEX (gallons)	Brine (gallons)	Torch (gallons)	Granular (lbs)	Liquid (lbs)	Total (lbs)
Drake							
11/7/2017	4,413	804	0	0	2,701	1,405	**3,969**
12/21/2017	15,231	1,626	454	110	9,321	3,538	**12,387**
12/31/2017	8,480	34	0	510	5,190	975	**5,902**
1/15/2018	7,921	0	0	1,237	4,848	2,221	**6,823**
1/21/2018	15,121	109	0	2,038	9,254	3,850	**12,635**
2/1/2018	10,782	0	0	1,050	6,599	1,886	**8,150**
2/9/2018	25,990	288	0	652	15,906	1,674	**16,775**
2/19/2018	12,164	1,814	0	745	7,444	4,509	**11,576**
2/23/2018	12,485	1,918	297	472	7,641	4,526	**11,779**
Center							
11/7/2017	5,846	1,405	0	0	3,397	2,456	**5,852**
12/21/2017	22,534	3,968	1,052	154	13,092	8,365	**21,458**
12/31/2017	13,496	105	0	1,195	7,841	2,330	**10,171**
1/15/2018	10,252	13	0	1,373	5,956	2,488	**8,444**
1/21/2018	18,363	143	0	3,520	10,669	6,571	**17,240**
2/1/2018	16,508	3	0	1,869	9,591	3,361	**12,952**
2/9/2018	35,584	1,465	0	1,126	20,674	4,582	**25,256**
2/19/2018	13,329	3,534	0	496	7,744	7,068	**14,812**
2/23/2018	19,739	3,529	351	6	11,468	6,563	**18,032**

College							
11/7/2017	7,868	1,126	0	0	4,571	1,969	**6,540**
12/21/2017	21,449	3,092	593	187	12,462	6,390	**18,852**
12/31/2017	12,880	80	0	1,179	7,483	2,256	**9,739**
1/15/2018	9,691	45	0	1,285	5,630	2,386	**8,016**
1/21/2018	17,450	233	0	2,842	10,138	5,512	**15,650**
2/1/2018	15,352	47	0	1,256	8,919	2,338	**11,257**
2/9/2018	26,183	1,505	0	984	15,213	4,397	**19,610**
2/19/2018	12,233	2,754	0	600	7,108	5,893	**13,000**
2/23/2018	14,853	2,632	661	37	8,629	5,391	**14,020**
Timberline							
11/7/2017	25,948	1,026	0	0	15,076	1,794	**16,869**
12/21/2017	58,837	12,293	770	803	34,184	23,773	**57,957**
12/31/2017	29,986	2,254	0	1,170	17,422	6,040	**23,461**
1/15/2018	18,876	140	0	3,850	10,967	7,158	**18,125**
1/21/2018	63,429	2,685	0	7,221	36,852	17,660	**54,512**
2/1/2018	22,788	29	0	5,034	13,240	9,090	**22,330**
2/9/2018	83,005	5,301	0	1,780	48,226	12,462	**60,688**
2/19/2018	16,638	3,552	0	6,086	9,667	17,138	**26,805**
2/23/2018	15,210	2,125	4,873	654	8,837	10,228	**19,065**

The total amount of chloride that was applied within each subwatershed was then compared to the amount of chlorides received in Spring Creek. One thing to keep in mind, the chloride that is applied in the Drake subwatershed should be measured at the Drake monitoring location. However, because the subwatersheds occur in series (i.e. downstream), the chloride present at the Center monitoring location contains chloride from both the Drake and Center subwatersheds. Likewise, the College monitoring location includes chloride from Drake, Center, and College subwatersheds. Finally, the Timberline monitoring location includes chloride from all four monitoring subwatersheds.

In-Stream Chloride Concentration & Loads

After determining the amount of the chlorides applied from RDO for each storm, the amount of chloride that was received by Spring Creek was measured at four locations along Spring Creek. Each of the four locations, Drake, Center, College, and Timberline correspond to a subwatershed (Figure 1). In order to determine the amount of chlorides received in Spring Creek, three different datasets were collected at each monitoring location. First a timeseries of specific conductivity (SpC) was used as a surrogate for chloride concentrations. The second dataset was a collection of grab samples, analyzed for chloride then used to correlate specific conductivity to chloride concentration. Finally, a timerseries of flow was used to calculate the chloride load delivered to each monitoring location.

Continuous monitoring of in-stream water quality and water depth was measured in order to provide timeseries of both chloride concentrations and flow. Timeseries were collected due to the sporadic nature of snow accumulation, deicing operations, and subsequent melting. Continuous monitoring of in-stream water quality, specifically SpC, was collected using four In-Situ WaterTroll 9500 sondes and water depth was collected using four Hobo U-20 Data Loggers. These instruments measured pressure and temperature every ten minutes during the monitoring period. The In-Situ WaterTroll 9500 sondes were installed in December 2017. The first Hobo U-20 Data Loggers was also installed at the Drake site in December, with the remaining loggers installed at the remaining sites in February 2018. All monitoring devices were installed until April 2018.

Specific Conductivity

Although instruments that measure in-stream Cl- concentration directly are available, such instruments have produced inaccurate readings under variable field conditions. SpC was measured due to the reliability of the results under long periods of time and with variable field conditions. SpC is a measurement of the waters total ionic strength, in which Cl- is a major contribution during winter runoff event. The timeseries of SpC supplied by the water quality sondes coupled with grab samples collected throughout the sample period allowed for a relationship to be determined linking SpC to chloride concentrations.

Chloride Grab Samples

In-stream grab samples were collected at all four sites (Table 3). Baseline samples were collected on March 21 and April 2, 2018. The remaining samples represent winter storm runoff events. Samples were submitted to the Soil and Water Laboratory at Colorado State University (CSU) and MMS Environmental Consultants (MMS) for Cl- analysis. The reported Cl- concentrations were then used to develop a relationship between sampled Cl- measurements and SpC values recoded from the In-Situ WaterTroll 9500 sondes.

Table 3: Grab samples collected to correlate specific conductivity to chloride concentrations

Site	Date & Time	SpC (µS/cm)	Chloride Conc. (mg/L)	Lab
Drake	1/22/18 13:40	2030	365	MMS
Centre	1/22/18 14:10	6398	1480	MMS
College	1/22/18 14:30	2513	528	MMS
Timberline	1/22/18 15:00	1612	224	MMS
Drake	2/11/18 13:10	1654	284	CSU
Centre	2/11/18 13:30	1872	356	CSU
College	2/11/18 13:50	1611	325	CSU
Timberline	2/11/18 14:10	1413	222	CSU
Centre	2/20/18 17:00	2179	434	MMS
College	2/20/18 16:50	1038	87	MMS
Drake	2/24/18 14:00	5353	1240	MMS
Centre	2/24/18 14:00	4792	953	MMS
College	2/24/18 14:30	6607	1700	MMS
Timberline	2/24/18 15:00	1885	339	MMS
Drake	3/12/18 9:10	977	55.3	MMS
Centre	3/12/18 10:20	939	75.6	MMS
College	3/12/18 11:10	947	78.7	MMS
Timberline	3/12/18 12:30	927	86.2	MMS
Drake	4/6/18 13:30	750	61.8	MMS
Centre	4/6/18 13:50	876	72.1	MMS
College	4/6/18 14:10	797	79.1	MMS
Timberline	4/6/18 14:10	934	52.6	MMS

The SpC and chloride concentrations were then plotted and a linear regression was used to represent the relationship between SpC and chloride concentrations. The regression contained an R^2 value of 0.99, demonstrating a very strong relationship. Figure 3 shows the relationship between specific conductivity and chloride concentration as well as the equation used to correlate specific conductivity to chloride concentrations. From this relationship a timeseries of chloride concentrations was used to determine both the chloride load delivered to the stream and potential environmental consequences of RDO.

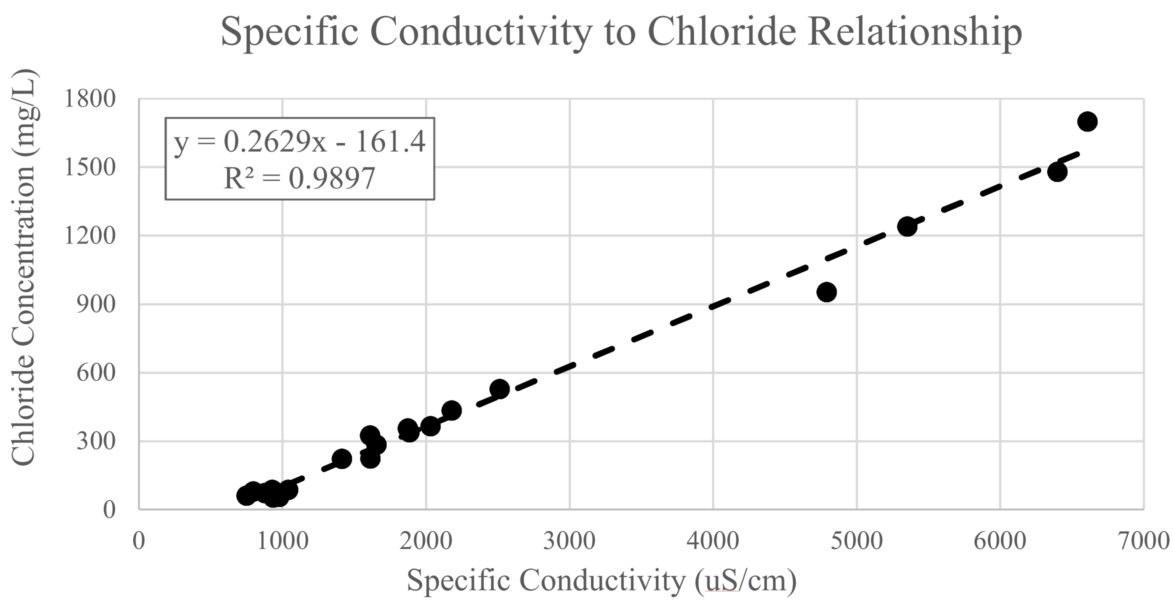

Figure 3: Plot demonstrating the relationship between specific conductivity and chloride concentrations

Plots were generated for each monitoring location for which deicer was applied and instrumentation was installed (December 2017 – February 2018). Timeseries of chloride concentrations at each site are presented in Appendix A. The plots also include recorded precipitation collected from the Colorado State University Christman Field weather station. This station was selected because it reports snow precipitation in rainfall equivalent depth in 10-minute intervals and is located near the center of the Spring Creek watershed.

Water Levels & Flow

The flowrate in Spring Creek was estimated using the eRAMS cross-section tool. The Environmental Resource Assessment and Management System (eRAMS) is a web-based GIS platform developed by the One Water Solutions Institute at Colorado State University. The cross-section analysis tool is based on Manning's equation and allows a user to upload a surveyed cross-section to calculate the necessary parameters of Manning's equation. Manning's equation (Equation 1) was used to determine the flow based on the cross-section properties of the channel, Manning's roughness and the channel slope.

Equation 1

$$Q = \frac{1.49}{n} * A * R_H^{\frac{2}{3}} * S^{\frac{1}{2}}$$

Where:

- Q = flow rate (cfs)
- n = Manning's roughness
- R_H = Hydraulic radius (ft)
- S = Channel slope (ft/ft)

Figure 4 and Figure 5 provide examples of the cross-section analysis tool. It was necessary to survey the cross-section at each of the four monitoring locations in order to use the tool. Appendix B contains figures for each of the surveyed cross-sections at the four monitored locations. The area and hydraulic radius values were calculated based on the stream cross-section characteristics at the measured depths using the pressure transducer in the WaterTroll 9500 Sondes and Hobo U-20 Data Loggers. These characteristics where calculated by the cross-section analysis tool seen in Figure 5. A Manning's n value of 0.035 was assumed for the natural stream channel with some weeds and stones (Chaudhry 2008). The average slope was estimated for each site from surveying the thalweg points in the stream channel 25' above and 25' below the monitored location. The parameter values were assumed to be constant throughout sampling and are reported for each site in Appendix A.

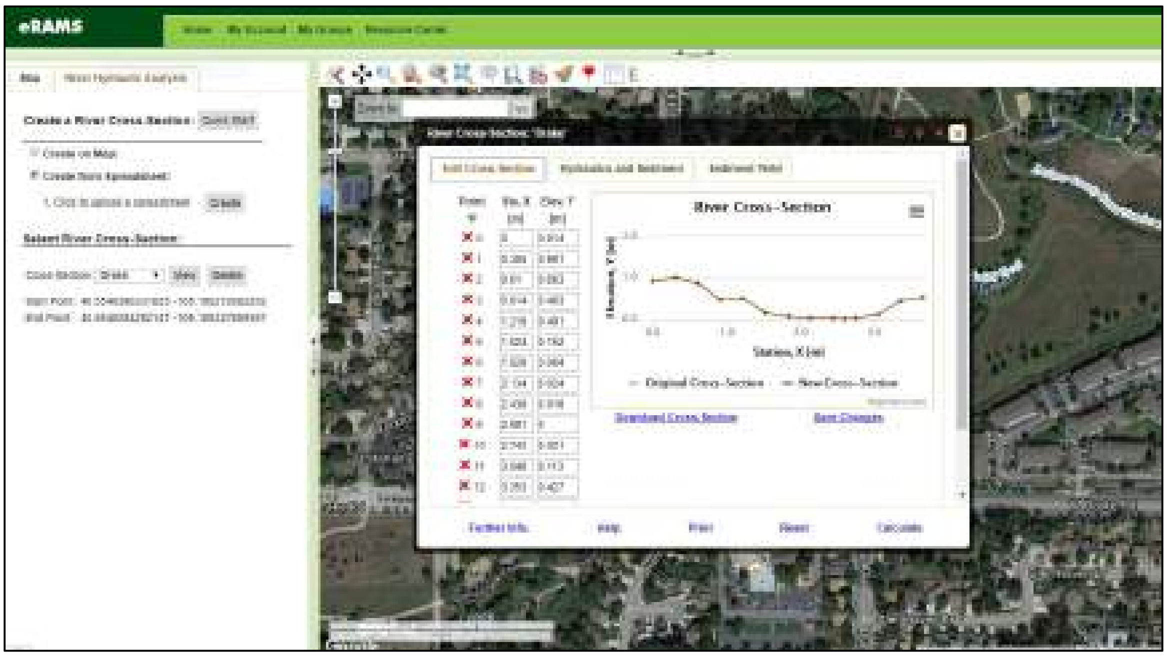

Figure 4: Example of the eRAMS Cross-Section Analysis tool

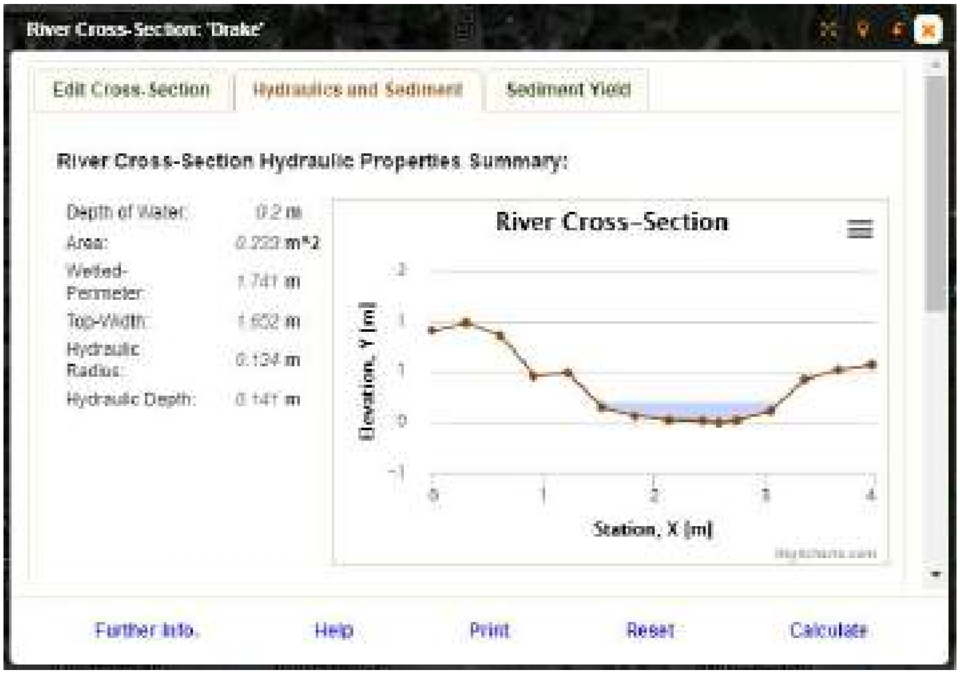

Figure 5: Example of the Cross-Section Analysis tool calculating the hydraulic radius based on depth

In order to calculate flows, csv files of the measured depths from the WaterTroll 9500 were used in the cross-section tool. Outputs from the cross-section analysis tool yielded a timeseries of flows that corresponded to measured depths which was corroborated with gage data provided by the City from the flood warning alert system.

Chloride Loads Delivered

The in-stream instruments provided continuous (15-minute interval) measurements of stream depth and SpC, which were subsequently used to estimate the instantaneous flowrate and Cl^- concentration, respectively. The total mass of Cl^- in Spring Creek over some time period Δt was then calculated using Equation 2.

Equation 2

$$M = a * Q * C * \Delta t$$

Where:

- M = mass (lbs)
- a = unit conversion
- Q = stream flowrate (cfs)
- Δt = time interval (seconds)
- C = chloride concentration (mg/L)

The total load that was received by Spring Creek at each monitoring station was then calculated for each winter event. The duration of events was determined by measuring the start of the winter event when chloride concentrations began to rise above baseline concentrations and the end of the winter event based on when chloride levels returned to baseline concentrations. Table 4 displays the chloride loads that were measured as delivered from the various winter events in

2017-2018 for each of the monitoring locations. Individual plots showing the load of chloride that was applied and delivered within each subwatershed for each winter event are presented in Appendix C.

Table 4: Chloride loads that were recorded as delivered at each monitoring location

Event Date	Chloride Delivered (lbs)			
	Drake	Center	College	Timberline
12/21/2017	4,261	16,203	13,548	8,846
12/31/2017	3,397	5,446	1,709	7,135
1/15/2018	2,349	5,257	5,368	4,260
1/21/2018	4,810	25,408	18,372	33,615
2/1/2018	7,221	14,355	13,925	10,944
2/9/2018	4,688	16,340	11,755	20,298
2/19/2018	N/A	12,331	11,525	N/A
2/23/2018	4,079	22,068	20,380	32,564

Mass Balance Comparison

The amount of chlorides recorded as delivered was then compared to the amount of chlorides applied for RDO. Figure 6 displays the amount chlorides that were applied in both the 2016-2017 winter and the 2017-2018 winter. This plot demonstrates the amount of chloride applied in both seasons was roughly the same which creates some interesting implications. First, it could be that Fort Collins receives roughly the same types of storms each year requiring similar amounts of deicer. Alternatively, it could mean that the City expects to use a certain amount of deicer and ends up using that approximate amount regardless of the storms.

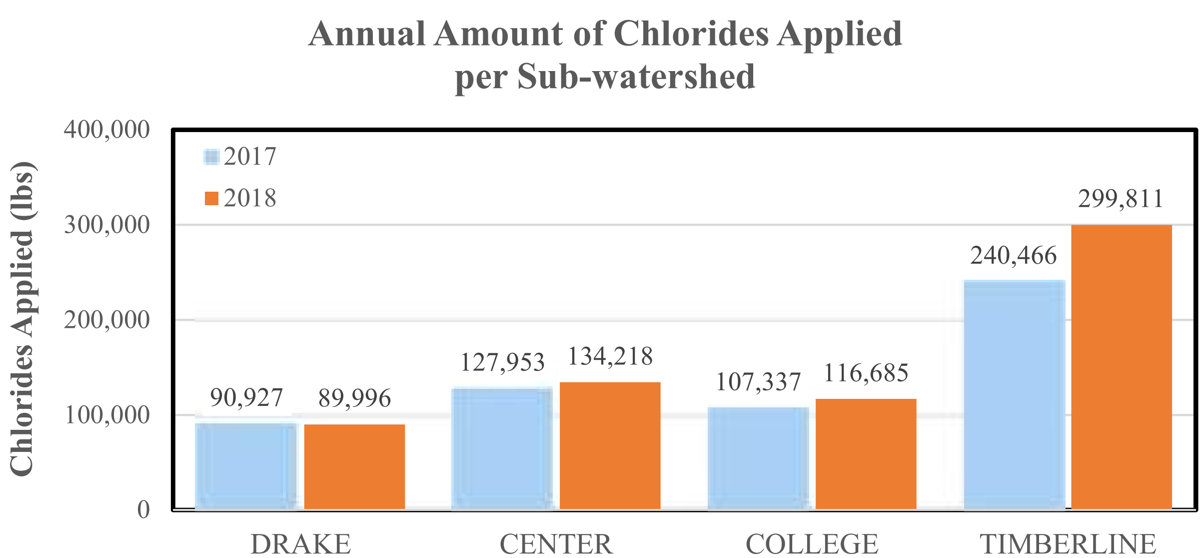

Figure 6: The amount of chlorides applied in the 2016-2017 winter and the amount applied in the 2017-2018 winter within each sewershed

Given the nature of the watershed with each subwatershed located downstream from one another, the amount of deicers applied in upstream watersheds should be present at each of the downstream monitoring locations (i.e. the chlorides delivered to the College monitoring station should include all deicer applied in the Drake, Center, and College subwatersheds). Figure 7 shows the amount of chlorides that were cumulatively applied in each subwatershed and expected to reach the corresponding monitoring location. Also shown in Figure 7 is the actual amount of chlorides that were recorded reaching each monitoring station.

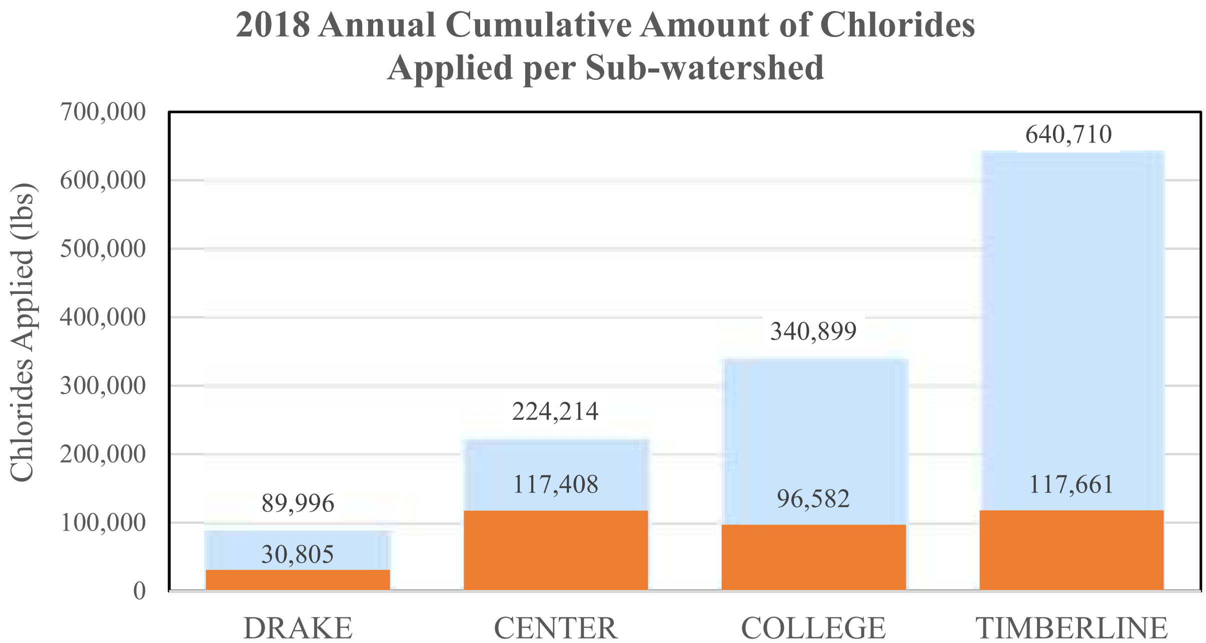

Figure 7: Chlorides applied for RDO compared to the amount of chlorides measured at each monitoring location

In each monitoring location the amount of applied chlorides did not match the amount of chlorides delivered to the watershed. This was especially true of the Timberline location which only recorded 18.3% of the total chlorides applied from deicer of RDO. One of the major questions that the study sought to answer included the fate of the chloride which was not delivered during the winter runoff event. Despite this lack of chloride delivery, a slight positive relationship between the amount of chlorides applied and the amount delivered was typically observed. This demonstrates that it should be possible to reduce the amount of chlorides that enter the Spring Creek by simply reducing the amount of chlorides applied. However, the weak correlation shown by low R^2 values suggest that this may not be the most effective way to reduce chlorides in urban streams, but will still remove chlorides from other sources such as groundwater, which could be causing other long-term water quality problems as discussed below.

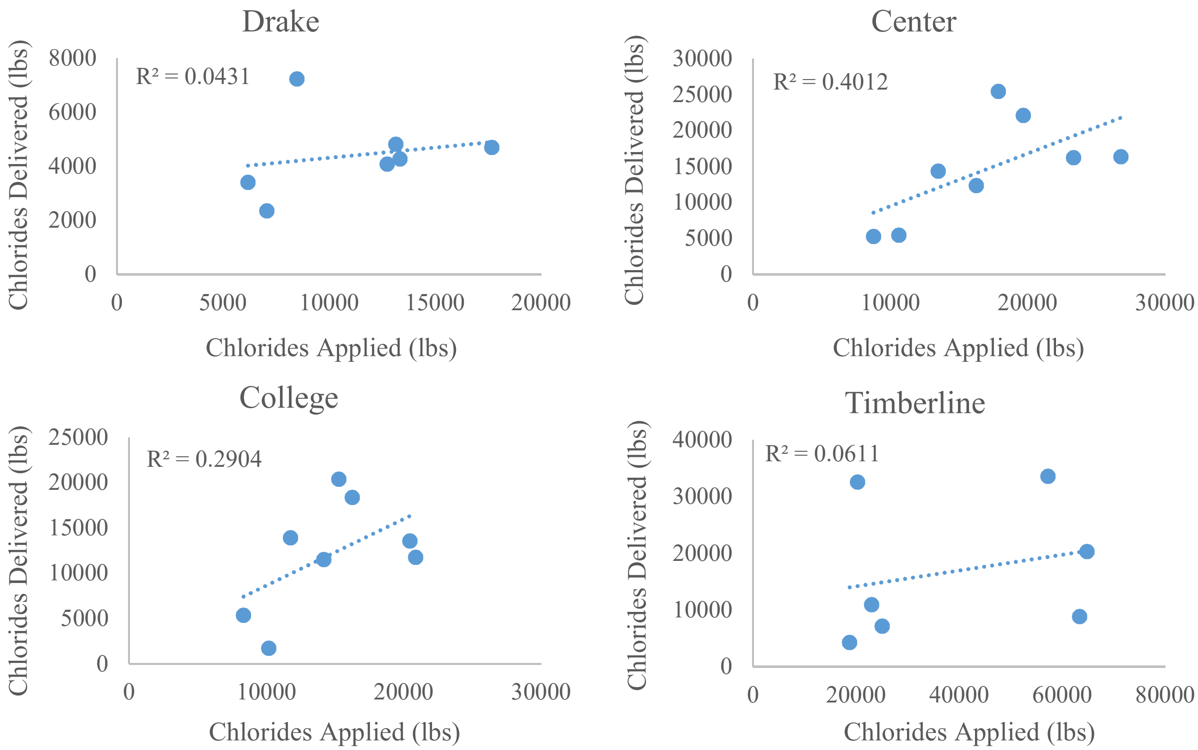

Figure 8: Comparison of the amount of chlorides applied and the amount of chlorides delivered. A positive relationship shows that more chlorides applied result in more chlorides delivered. The low R^2 value demonstrates that the correlation between the chlorides applied and delivered is not very strong.

Discrepancy Between Applied and Delivered Chlorides

As there was a large discrepancy between the amount of chlorides applied from deicer and the amount of chloride delivered to Spring Creek, an investigation was conducted to determine reasons for the discrepancy. In short, it was desired to determine where the chloride that did not make it to the stream ended up.

Several potential locations were considered including storm sewer solids collected in inlets, storm sewer solids swept up after storms, roadside solids, groundwater interactions along stream, or remaining on pavement. In this study three of these potential sources were investigated: storm sewer solids collected in inlets, roadside solids, and groundwater interactions along stream.

Storm Sewer Solids

Storm sewer solids collect at inlets to the storm sewer systems. The study explored the relationship between storm sewer solids contained and high concentrations of chlorides to determine if this could be one of the ultimate fates of chlorides. Storm inlets would be an ideal place for the chlorides to end up as each spring inlets are cleaned as a pollution prevention strategy in the City. Therefore, if any chlorides were contained in the storm sewer solids at the inlets, they would be removed as part of the current City operations.

For this analysis, samples were collected from five different inlets as well as at two different stormwater control measures including a wetland basin and an inlet containing a stormwater snout. Figure 9 shows the chloride concentrations of the solids that were sampled. Based on the concentrations found from the lab analysis and the amount of storm sewer solids that are typically removed from all inlets, it was determined that this was not a significant fate of chlorides.

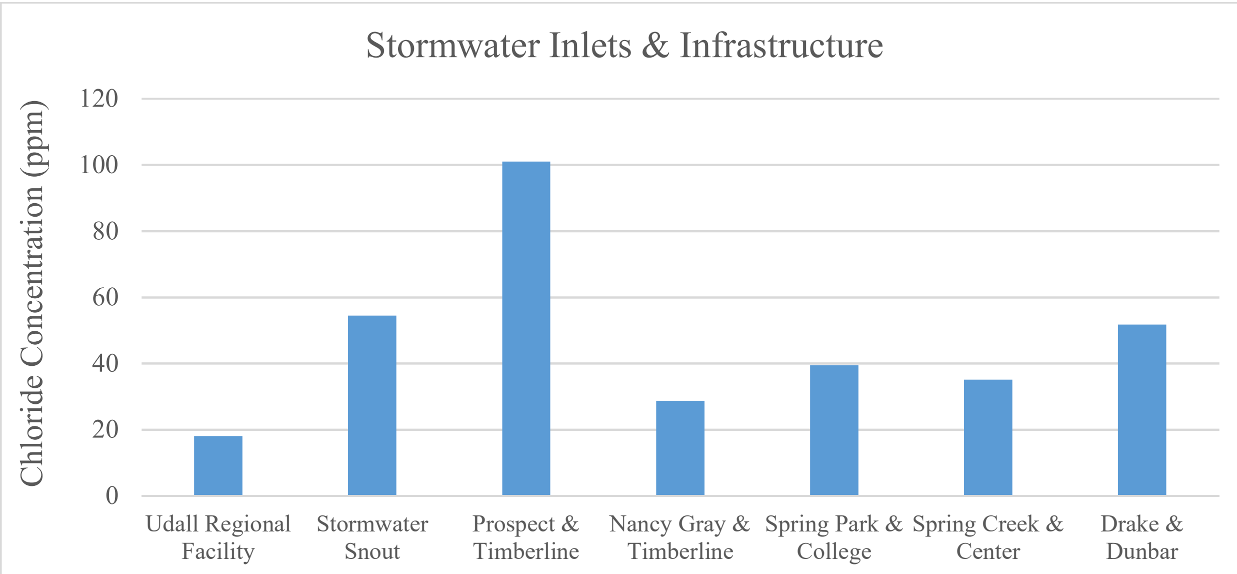

Figure 9: Results of the stormwater sewer solids analysis showing chloride content of the sampled solids

Roadside Solids

The second potential fate investigated involved chloride that could end up in soils next to the roads receiving deicers. The thought behind this potential fate was based on operations of plows that could push water, snow, and ice which contained deicers, off the roadway and into the nearby roadside. For this analysis, two soils from natural areas were sampled as well as three soils next to major roadways receiving deicer. The two natural soils were analyzed to determine the baseline chloride concentration and the three roadway samples were examined to explore if elevated chloride levels existed in roadside levels.

Results of this analysis (Figure 10) demonstrate high concentrations found in roadside solids, which can be considered a potential fate of chlorides and one explanation for the discrepancy between the applied and delivered chlorides. However, there was a large variation among roadside soils with some roadsides having small chloride concentrations and others having vary large concentrations. Some factors that could explain the variation of chloride concentrations include the presence of curbs, the speed of snowplows and the amount of deicer applied at that particular stretch of roadway.

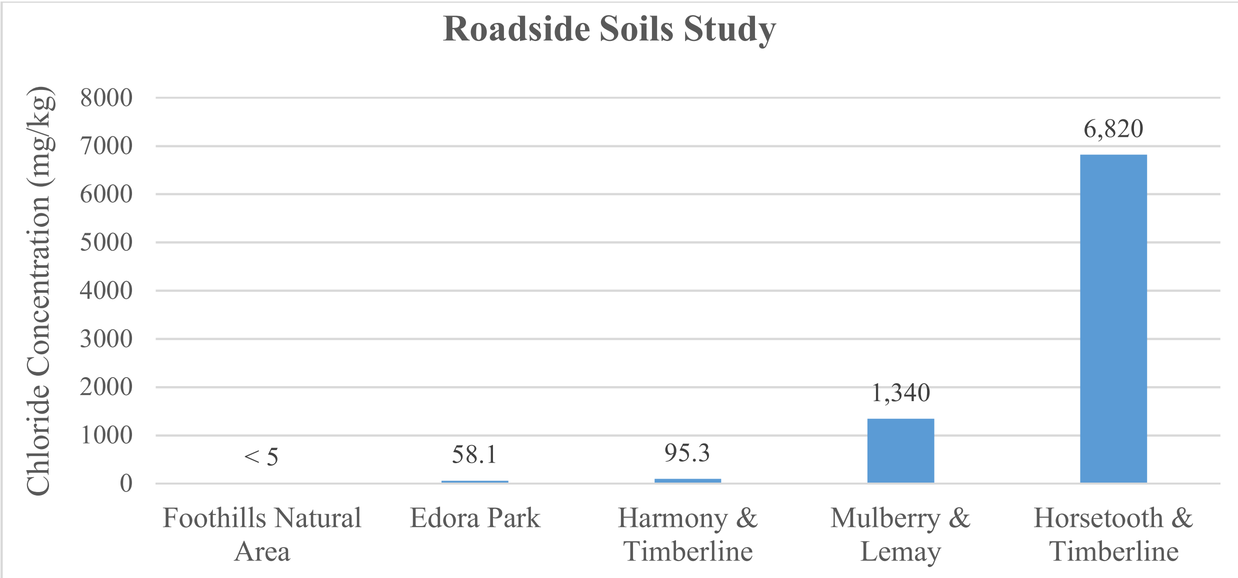

Figure 10: Results of the analysis of chloride concentrations of roadside solids

Groundwater Analysis

The third and final potential fate investigated for this study was the interaction between groundwater and surface water occurring along the Spring Creek. This interaction was initially assumed to be the highest likelihood for the fate of chloride from deicers. The main evidence given for this was the lack of chlorides that were present at the Timberline monitoring location.

The Timberline station should have had the highest chloride loads and concentrations but conversely, was found to exhibit some of the lowest. Timberline was consistently found to have smaller loads than the College site upstream of it. This demonstrates that there must be an interaction between the groundwater and surface water as that was the only potential outflow from this portion of Spring Creek.

To investigate the interaction of the groundwater and surface water, four groundwater wells, 3, 2, 1 and 5 were located 15', 30', 50' and 70', respectively, away from Spring Creek, and were used to collect grab samples after winter runoff events to see if there were elevated levels of chlorides compared to the stream at the same time. Elevated chloride levels would establish that chloride was leaving the surface water and entering the groundwater system along the stream. Results from the groundwater analysis are shown in Figure 11. Figure 11 displays chloride concentrations in order of each groundwater well's geographical location compared to Spring Creek.

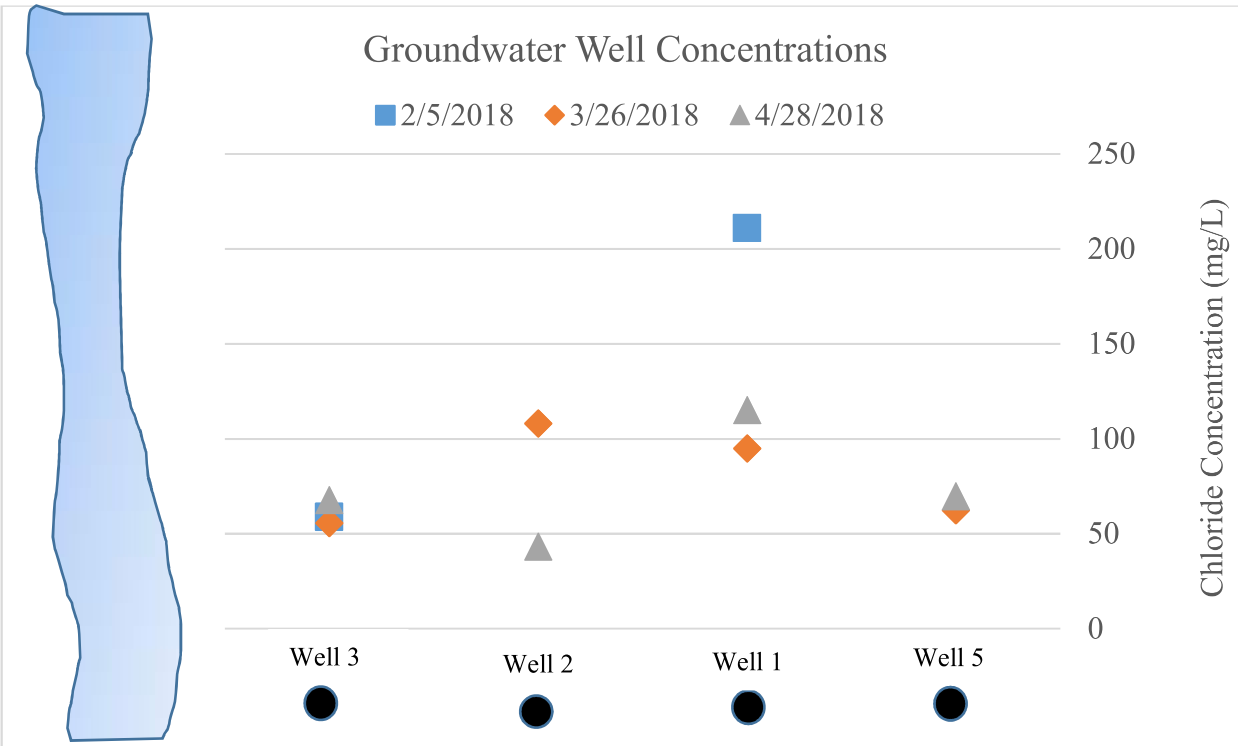

Figure 11: Chloride concentrations in groundwater after winter runoff events

The pulse that appears to be present after storms occur demonstrates the transport of chlorides between groundwater and surface water. Future analysis would include more detailed sampling of groundwater to accurately determine the timing of the pulse in order to quantify the magnitude of transfer taking place. It may be necessary to place a water quality sonde into the groundwater well to collect timeseries of the chloride concentration within the groundwater well.

Chloride Concentrations Analysis

Two different aspects of chloride concentrations were evaluated as a part of this study. The first aspect included the effects of chloride concentration on aquatic life based on previous studies. For this analysis the measured chloride concentrations were compared to USEPA recommendations and lethality measures. The second aspect included an analysis of baseline concentrations. According to previous studies steadily rising baseline chloride concentrations have been observed. If this trend continues what may not be problems now could become problems as the "normal" chloride concentrations rise above certain limits.

Chloride Impacts on Aquatic Life

Cl^- is known to be detrimental to aquatic life at certain concentrations. In 1988, the USEPA established ambient water quality criteria for Cl^-. The criteria maximum concentration (CMC) of 860 mg/L and the criterion continuous concentration (CCC) of 230 mg/L are expected to be protective of the "vast majority" of aquatic organisms throughout the U.S. if they are not exceeded for more than one hour and more than 4 hours, respectively (Benoit 1988). These guidelines, however, are non-regulatory and not enforceable unless adopted as a water quality standard by the state. Currently, the State of Colorado has not adopted a Cl^- standard for aquatic life protection (CDPHE 2011).

Lewis (1999) performed toxicity testing of magnesium Cl^- deicer on three aquatic species important to Colorado streams; the boreal toad, rainbow trout and ceriodaphnia, or water flea. Lewis calculated LC50 (lethal concentration required to produce 50% mortality) values for 24-, 48- and 96-hour periods and reported the results in terms of the required dilution (Table 5) of the deicing material. Lewis did not speculate as to what specific constituent(s) in the deicing materials may have contributed to species lethality, however for this study the conservative assumption was made that lethality was primarily due to Cl^-. The deicing material used in the study had a Cl^- concentration = 210,000 mg/L, which were used to extrapolate LC50 Cl^- concentrations from the LC50 dilutions (Table 5).

Table 5: Results of biotoxicity testing of deicing materials on aquatic species common in Colorado streams (adapted from Lewis 1999)

Species	24-hr LC50		48-hr LC50		96-hr LC50	
	Dilution	Cl^- (mg/L)	Dilution	Cl^- (mg/L)	Dilution	Cl^- (mg/L)
Boreal Toad	2.2%	4620	1.8%	3780	0.32%	672
Rainbow Trout	2.5%	5250	1.8%	3780	1.4%	2940
Ceriodaphnia	0.26%	546	0.19%	399	-	-
Notes: Deicing material used in testing had Cl^-concentration = 210,000 mg/L						

The Cl^- concentrations measured at each site during each runoff event were averaged over 1-hr, 24-hr, 48-hr and 96-hr periods. The maximum value of the averaged concentrations was then compared against the various criteria discussed in the previous paragraph to determine if deicing materials are applied at rates that exceed such criteria.

Table 6 provides a summary of the maximum average Cl^- concentration computed over relevant time periods and indicates when certain aquatic life criteria were exceeded during this study. The results show that Cl^- concentrations in Spring Creek do exceed some criteria established for protection of aquatic life. The CCC, or chronic toxicity level, is most frequently exceeded, both spatially (among different sites) and temporally (among different events). The CMC and LC50 criteria for ceriodaphnia were also exceeded at times.

Table 6: Maximum average Cl- concentration Computed Over 2017-2018 Monitoring and the Aquatic Life Criteria Exceeded During That Event

Event Start Date	Mass Cl^- Applied (lbs)	Maximum Average Cl^- Concentration (mg/L)				Criteria Exceeded?				
		1-hr	24-hr	48-hr	96-hr	CMC	CCC	BT	RT	CD
Drake										
12/21/2017	12,387	753	191	147	135					
12/31/2017	5,902	374	149	148	130					
1/15/2018	6,823	605	194	156	157					
1/21/2018	12,635	666	263	231	175					
2/1/2018	8,150	860	429	294	198	X				
2/9/2018	16,775	819	305	244	182					
2/19/2018	11,576	-	-	-	-					
2/23/2018	11,779	1,332	294	206	157	X				
Center										
12/21/2017	21,458	999	235	174	147	X				
12/31/2017	10,171	180	119	117	112					
1/15/2018	8,444	709	195	167	178					
1/21/2018	17,240	1,594	416	295	218	X				
2/1/2018	12,952	688	321	273	197					
2/9/2018	25,256	421	223	213	176					
2/19/2018	14,812	470	231	228	241		X			
2/23/2018	18,032	1,170	375	282	199	X				
College										
12/21/2017	18,852	872	258	187	157	X				
12/31/2017	9,739	160	121	118	113					
1/15/2018	8,016	749	245	192	206					
1/21/2018	15,650	1,667	496	352	253	X	X			
2/1/2018	11,257	947	390	325	225	X				
2/9/2018	19,610	461	267	243	194					
2/19/2018	13,000	700	313	302	302		X			
2/23/2018	14,020	1,660	478	344	235	X	X			
Timberline										
12/21/2017	57,957	333	215	172	151					
12/31/2017	23,461	139	126	124	120					
1/15/2018	18,125	305	206	176	149					
1/21/2018	54,512	749	453	350	254		X			
2/1/2018	22,330	469	337	290	215					
2/9/2018	60,688	283	234	215	186					
2/19/2018	26,805	-	-	-	-					
2/23/2018	19,065	741	466	364	257		X			

Results identify a few instances where the USEPA recommendations were exceeded, but there were no instances in the 2017-2018 winter when lethal concentrations were exceeded for three Colorado aquatic species. This illustrates that even though rising chloride levels may be a concern, they are not rising to the extent that water habitat or supply is severely threatened as of yet.

Baseline Concentrations

Baseline concentrations have been increasing overtime. The change in baseline conditions for the 2012, 2017, and 2018 winters are displayed in Figure 12. Assuming baseline chloride concentrations continue to rise at the observed rate, it would take the Drake, Center, College, and Timberline subwatersheds 13.3 years, 5.3 years, 6.7 years, and 22.2 years to reach the chronic toxicity level of 230 mg/L, a level set by the Colorado Department of Public Health and Environment for water to be used as a drinking water source.

Rising baseline concentrations may be evidence toward rising concentrations of chlorides in groundwater. Many communities, particularly farming communities in eastern Colorado are growing concerned by rising groundwater salinity levels. One potential source for these rising levels could be RDO from cities along the Front Range. When several thousand pounds of salts are added to the groundwater system in each city each year, the baseline salinity would naturally increase. This could result in higher salinity in farming soils if that groundwater is pumped and used for irrigation. For this reason, potential partners in the agricultural community are becoming available to further investigate methods for improving RDO.

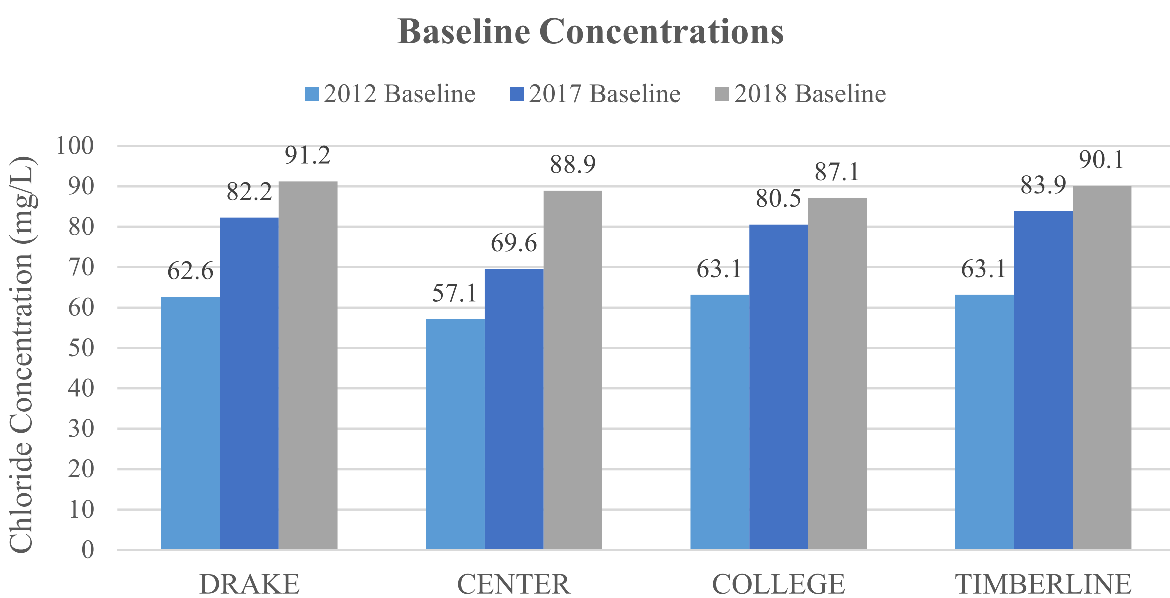

Figure 12: Baseline Concentrations at each monitoring location based on the 2012, 2017 and 2018 winters

Another important idea to consider when looking at rising baseline concentrations, is the timeframe for which results are being observed. There is a general lack of understanding if rising baseline concentrations are a result of high application of deicers from the current year or from the precious 20 years, or if it is a continual leaching process. Because the natural system appears to have the capacity to retain large amounts of chloride as evident by the lack of chlorides being delivered, it is unknown what changes to the RDO program would accomplish in the short-term.

PAVEMENT PERFORMANCE ANALYSIS

Finally, an analysis of pavement performance as a result of RDO was conducted. Evaluating pavement performance is a critical component to this study for two reasons. First, any recommendations that are made concerning the application of deicers from a water quality perspective must be given with roadway safety in mind. The ideal solution from an environmental perspective would be to quit using deicers completely. However, this is not a feasible solution as deicers are necessary to provide safe roads for general and emergency transportation. Thus, suggestions to change the rate of application of deicers should also consider any trade-offs in roadway performance.

The second reason pavement analysis was conducted was not necessarily to consider how RDO operations could be changed but examining to what levels are current operations achieving roadway performance. For this analysis a few different measures of roadway performance were considered, the primary measure being time required to remove ice and snow from roadways and have “bare roads”. To evaluate the roadway performance of current RDO, two studies were completed. The first involved establishing a metric for roadway performance based on literature, weather, and pavement data. The second analysis attempted to determine if, and to what extent, current RDO is resulting in better performing roads.

When considering the performance of pavement there is one factor that is largely considered, the level of grip. This metric essentially is a measure of the coefficient of friction of the roadway. Roads with low levels of grip have little friction which is what is necessary for vehicles to stop. Usually, decreased levels of grip are a result of the presence of water, snow, or ice on the road surface. Based on discussions with the Streets Department, the level of grip of dry pavement is 0.82, but that value can drop as low as 0.12 in slick conditions. A level of grip of 0.6 has been determined by the Streets Department to provide appropriate friction for safe stopping and is the level of performance that is sought during a snow and ice event.

Data for pavement performance was provided by cameras and sensors that are placed at the roadway of intersections. These pavement performance sensors (PPS) provide several datasets including the level of grip, snow, ice and water accumulation, and pavement temperature. Many of these sensors also have weather monitoring equipment to provide localized weather information important for determining metrics about the storm severity such as humidity, air temperature, and wind speed. The map shown above in Figure 2 shows the locations of these PPSs in the Spring Creek watershed. Figure 13 shows a picture of one of the sensors at Overland and Prospect in Fort Collins, CO.

Figure 13: Pavement performance sensor recording performance for the southbound lane of Overland Trail just south of the intersection with Prospect in Fort Collins, CO.

Performance Ratings and Application Rates

Using the information from both the AVL data and the PPS, roadway performance was evaluated. The first method that was used to evaluate roadway performance considered three metrics: the severity of the storm; the second was a metric based on storm severity and the time for the pavement to recover to the specified 0.6 level of grip; and the third metric was the amount of chlorides used to provide that performance. For this study one storm, which occurred from 12/21/2017 through 12/24/2017 was analyzed for performance.

Storm Summary

On December 21st 1.5 inches of snow fell starting around 3:30am. Roads were dry leading up to the storm event. Because conditions allowed, anti-icing was performed the day before the storm arrived. Air and pavement temperatures were around or below 32°F leading up to the beginning of precipitation. Air temperatures dropped quickly after snow began to fall, with temperatures bottoming out around 18°F on the 21st. Road conditions deteriorated with the grip level dropping below 0.6 by 4:40am and bottoming out at 0.16 at 5:00am. Despite precipitation continuing until 12:30pm, road conditions recovered to a level of grip above 0.6 after 8:30am. A small ice buildup, maxing out at 0.25mm and a snow accumulation (water equivalent) of 0.6mm were recorded at 7:50am. Pavement temperatures dropped to a low of about 25°F during precipitation.

Snowfall occurred again on December 23rd around 5:00pm with temperatures at or around 32°F and remaining below 25°F through December 24th. The low temperatures through the event made

Roadway Deicing Operations more difficult. Grip levels dropped to 0.14 by 6:20PM on December 23rd and had recovered and were maintained above 0.6 by 9:50PM. On December 24th, while battling refreezing due to very cold temperatures, the grip on the roadway was maintained above 0.6 for the entire day through repeated application of liquid and solid deicing agents about every 1-2hrs.

Performance Metrics

Three main metrics were used to evaluate the performance of RDO, the first was the Storm Severity Index (SSI) which is a metric used to normalize roadway performance and to recognize that some storms have higher snowfalls and windspeeds, and lower temperatures which can increase the difficultly of achieving a level of grip of 0.6. The SSI was calculated using Equation 3, based on a method developed by the Colorado Department of Transportation (CDOT) and Vaisala. General guidelines for the SSI value are; normal frost events 0-10, normal snow events 20-80, and severe weather 80-500.

Equation 3

$$Storm\ Severity\ Index = Max\ wind\ speed\ (mph) + Max\ layer\ of\ thickness\ (mm) + \left(\frac{300}{Min\ Surface\ Temp(°F)}\right)$$

The SSI value is used to normalize the loss of grip during the storm for the second metric, the Winter Performance Index (WPI). The WPI was calculated by determining the time, in hours, where the pavement grip was below 0.6 and then dividing by SSI, Equation 4. WPI is typically within a range of 0-1, with lower values indicating better performance. Figure 14 shows a rough outline for what the WPI means. Table 7 shows the values used from all PPSs to determine the SSI, and WPI at each sensor.

Equation 4

$$Winter\ Performance\ Index = \frac{Time\ Below\ 0.6\ Grip}{SSI}$$

Winter Performance Index Legend

0	Successfully treated
0.00 - 0.30	Significantly accelerated grip recovery
0.31 - 0.49	Some success at grip recovery
0.50 - 0.69	Very little success at deicing
0.70 -	Limited maintenance or no deicer success

Figure 14: Outline displaying the ranges of WPI and what they mean

Table 7: Storm information, SSI, and WPI at each PPS for the December 21, 2017 storm

Sensor	Max Wind Speed (mph)	Max Thickness (mm)	Min Surface Temp (F)	Time Below 0.6 Grip (hr)	Storm Severity Index	Winter Performance Index
Prospect @ BRT	30.00	1.43	12.00	7.83	56.43	0.14
Prospect & Overland	36.20	1.42	7.90	18.83	75.59	0.25
Horsetooth & Stover	27.70	1.43	9.90	19.50	59.43	0.33
Taft & Elizabeth	25.90	2.08	6.40	14.33	74.86	0.19
Timberline - Nancy Gray	32	1.18	10	10.50	63.18	0.17
Timberline Bridge	26.80	1.42	5.90	4.50	79.07	0.06
Timberline County Road	38.00	1.57	9.10	17.17	72.54	0.24
Harmony & Taft	36.20	1.01	9.10	14.67	70.18	0.21
Harmony @ BRT	30.00	2.24	12.70	11.00	55.86	0.20
I-25 & Harmony	34.40	1.09	8.80	4.00	69.58	0.06
Trilby Road	30.00	1.67	5.00	4.00	91.67	0.04
Average	**31.56**	**1.50**	**8.80**	**11.48**	**69.85**	**0.17**

For two of the PPS, an analysis of the chlorides that were applied based on AVL data was conducted. The sensors that were considered included Prospect @ BRT and Timberline – Nancy Gray. The SSI rating for the storm at the Prospect pavement sensor was found to be 56.4, and 63.2 for the Timberline pavement sensor. The WPI index value for the Prospect pavement sensor was found to be 0.14, and 0.17 for the Timberline pavement sensor. During this storm event 134,581lbs of chloride were applied to the roadway in the Spring Creek Watershed. For the Prospect @ BRT sensor 2,783lbs of chloride were applied for 0.8 miles of roadway, and 6,704lbs were applied on Timberline – Nancy Gray for 1 mile of roadway. The total application of chloride for 1 mile of roadway for Timberline Road was found to be 6,704 lbs/mile, and 3,479 lbs/miles at Prospect. Figure 15 shows the combination of all three metrics for the two sensors.

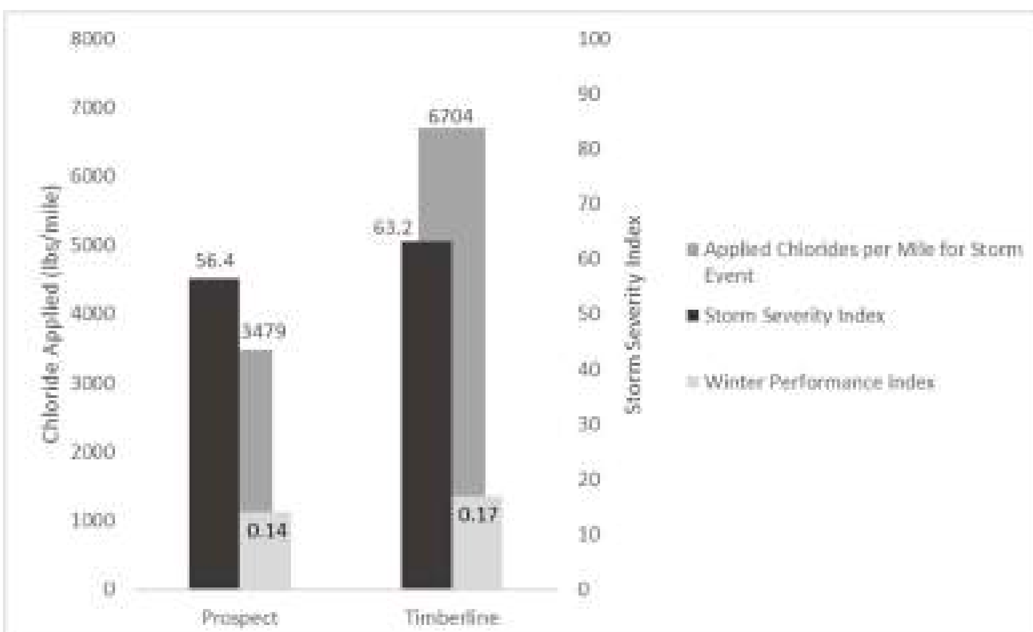

Figure 15: Application Rate, Storm Severity Index, and Performance for Prospect and Timberline

Performance of Roadway Deicing Operations for the December 21-24, 2017 storm event indicates that anti-icing, response time, and reapplication of de-icing materials in a timely fashion can affect the performance and improve roadway conditions. The differences noticed for deicing operations at Prospect and Timberline were that Prospect saw smaller repeated applications of de-icing agents, recovered faster than Timberline, and had anti-icing material applied the day before. No dramatic differences in winter performance index were observed between the two streets, with Prospect receiving a rating of 0.14 and Timberline a rating 0.17. Timberline also had a higher storm severity index value associated with the conditions of the road. The most notable difference between the two streets is that Prospect had 3,479lbs of chlorides applied per mile stretch of road (anti-icing included) while Timberline had 6,704lbs of chloride applied per mile stretch of road. Even with about double the amount of chloride applied to Timberline, WPI was not significantly different from Prospect which received much less. Therefore, the importance of response time, reapplication of smaller amounts of deicing agent, and anti-icing were seen to reduce the amount of chloride application to achieve similar, if not better, roadway performance.

Pavement Performance Data

The first analysis explored the overall performance of RDO for an entire storm. A second analysis was done at various sites to determine how RDO performed throughout the storm. This was done by looking at the timeseries of level of grip and comparing to the pavement temperature, snow, ice and water depth accumulation on the roadway, as well as the number of passes by a snowplow and the subsequent amount of deicing agents applied and the timing of application. Figures 16-20 each show the pavement performance at different intersections for different storms.

Each figure demonstrates that there are a number of factors that dictate roadway performance, particularly the recovery of the level of grip. One of the surprising factors was that there was not always an immediate response to passes on the plow. This is evident in Figure 16 where a plow delivered a large application of deicer, but there was no measured effect on the level of grip. Figure 17 shows an example of two passes that were done by snowplows where one of them had a minimal effect and another had a substantial effect. Also seen in Figure 17, there appeared to be additional influences causing fluctuations in level of grip to both decrease and increase, which brings the accuracy of AVL data into question and suggests there are times when a plow is making a pass that is not being recorded.

Figure 16: Roadway performance at Prospect and Overland for the 12/21/2017 winter event

Figure 17: Roadway performance at Prospect and BRT for the 12/21/2017 winter event

Figure 18 shows an example of anti-icing operations, the practice of applying deicing agents before the storm occurs. It appeared in this circumstance that anti-icing provided a significant benefit to the effectiveness of the first snowplow. However, with anti-icing it is important to note that it can only be used when there will not be any rain before the snow event or else the ant-icing agents are washed off rendering them ineffective.

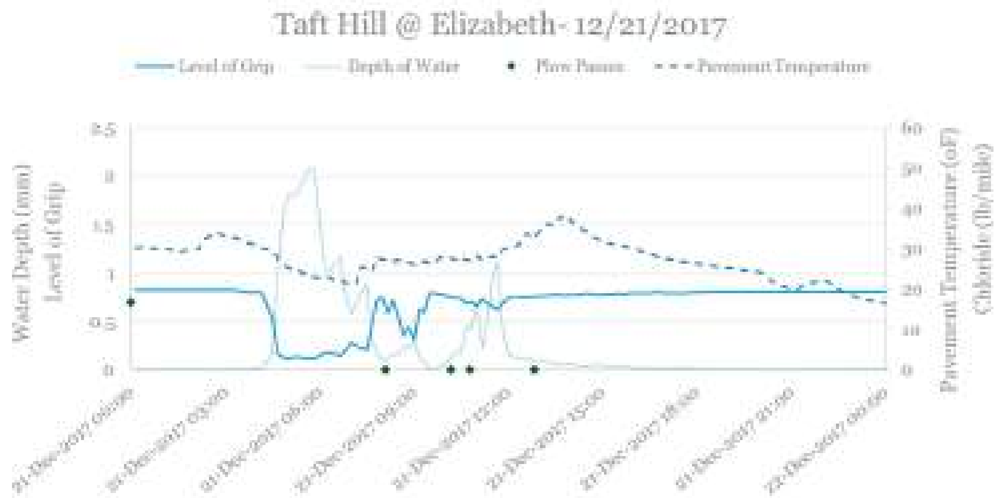

Figure 18: Roadway performance at Taft Hill and Elizabeth for the 12/21/2017 winter event

Figure 19, shows the variation of performance of deicing operations. In some circumstances the deicing agent and plow pass had a substantial improvement, but at other times it did not. This demonstrates that are additional factors that should be considered when wanting to optimize the performance of RDO. Finally, Figure 20 shows that large amounts of deicing application may not necessarily result in immediate performance improvement. This indicates that there may be times when deicing should not applied because it will not have any effect on roadway performance.

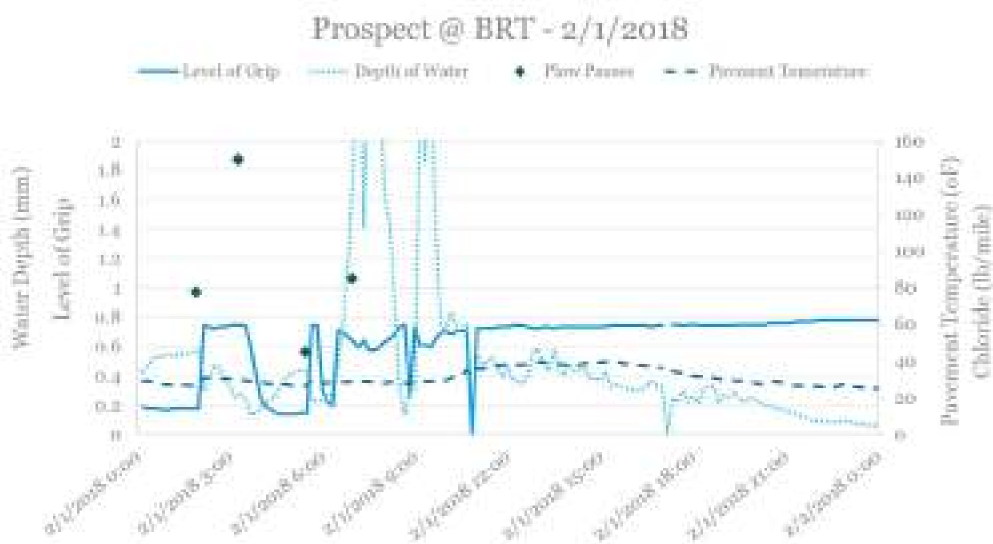

Figure 19: Roadway performance at Prospect and BRT for the 2/1/2018 winter event

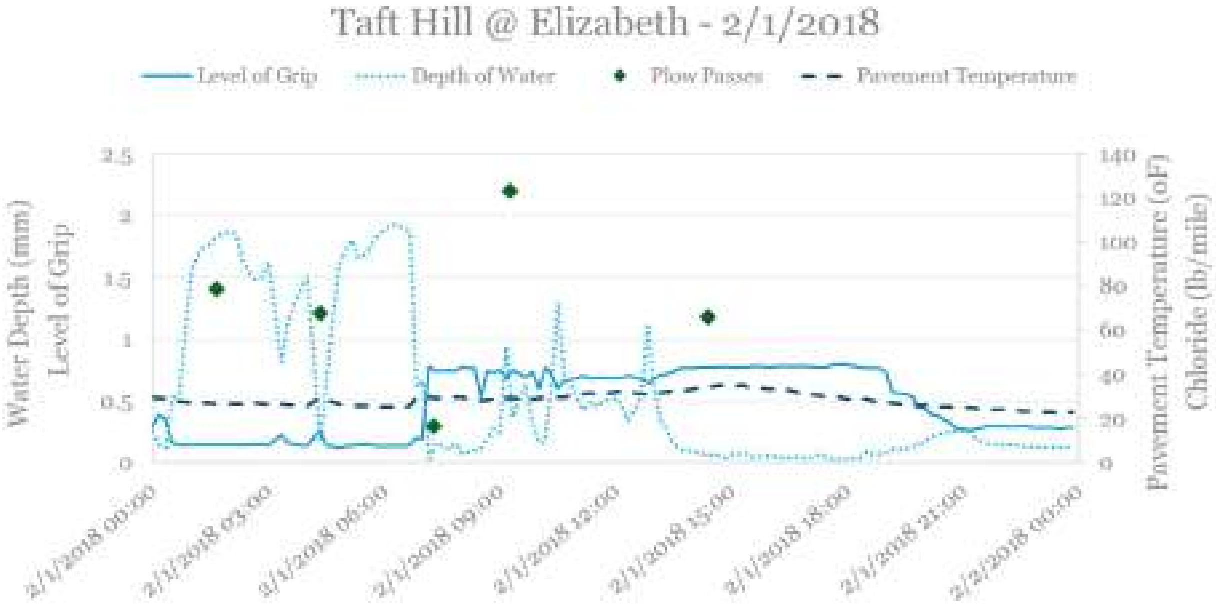

Figure 20: Roadway performance at Taft Hill and Elizabeth for the 2/1/2018 winter event

There other methods being considered to improve the analysis. The first is simply ensuring that the timing of the AVL data matches the timing on the pavement sensors. There were some instances where it appeared that the road improved before the plow arrived, but it is more likely that there is just a discrepancy in the time between the two different monitoring devices. Another way that the analysis can be improved is to not only consider the amount of chloride that is applied but evaluate the type and amount of deicer that is applied. The type and amount of application is the information needed in order to improve RDO. For the purpose of this study, the overall impact of chloride was considered, but to provide better recommendations to RDO for what applications strategies are effective, it would be important to know the type and amount of deicer to apply.

CONCLUSIONS

This study provided several key findings. The first of which was another confirmation that the amount of chlorides being applied for RDO within the Spring Creek watershed was not immediately reaching Spring Creek during the storm event. This indicates that the system is storing or exporting that chloride through another mechanism. In fact, it was determined that at the final in-stream monitoring location, Timberline, only 18% of the applied chlorides were delivered through the stream system. One result of the storage of chlorides could be the consistent increase in baseline chloride concentrations being experienced in Spring Creek. This is concerning because if these levels continue to increase at the present rate, within 6 years some of the monitoring locations would be surpassing some of the recommended instream chloride values provided by CDPHE(230 mg/L). This could have a detrimental impact on aquatic life throughout Spring Creek.

Potential fates of chloride were also investigated in this study and it was found that roadside deicers and groundwater interactions were the most probable reservoirs for the chloride that don't make it to the surface water during a storm event. Storm sewer solids were also investigated and found to have a minimal amount of chlorides. Other sources that could still be investigated are chlorides that may be present in the road surface material itself (e.g. concrete or asphalt) or chlorides that may be present in solids that are swept up after storms as part of the street sweeping practices used by the City of Fort Collins.

Not only is there the concern from increasing baseline concentrations, but there is also a concern from the measured spikes of chlorides that are present in winter runoff. When this study began, the State of Colorado did not have a chloride water quality standard for aquatic life, but has since adopted a chronic standard of 250 mg/L. Study results were compared to USEPA acute and chronic criteria and there were several instances of exceedances, demonstrating that aquatic life may have been impacted. Even though Spring Creek does not have a chloride impairment listed on the Colorado 303(d) list, Spring Creek and the Cache la Poudre River may be subject to future increased regulation. It is important to consider future regulatory implications as well as the long-term effects of RDO on aquatic life.

Finally, metrics to evaluate roadway performance were investigated for overall storms as well as during storms. This analysis suggests improvements can be made to RDO supported by evidence several sites that were analyzed where it was found that even when more chlorides were applied, a lower level of roadway performance was achieved. There were also several instances where roadway performance improved without the passing of a snowplow based on AVL data. This indicates that there are either gaps in the AVL data or other factors besides plows and deicer that can improve roadway performance.

Recommendations for Future Studies

This study focused on the results of the 2017-2018 winter, however multiple studies have been conducted for other years. After conducting the study for several years, there are elements that can be improved and further questions that should be addressed. From the last study it was suggested to begin collecting information about the type of chloride deicer that was being applied. By recording the type of deicer applied better estimates of the applied chloride from RDO were determined. This should be continued in all future studies. Also, the sample collection time was improved so that grab samples that occurred at peak chloride concentrations were easier to obtain allowing for a stronger correlation between specific conductivity and chloride concentrations. Future samples should continue to be collected at the improved times to provide similar results. Additional improvements were made for monitoring flow by installing a second pressure sensor at each in-stream location which collected more accurate water depths resulting in increased accuracy of flow records in Spring Creek.

Future questions that can be addressed continue to include the fate of chlorides and the discrepancy between the amount of chlorides that are applied and delivered to Spring Creek with an emphasis on groundwater interactions along Spring Creek and roadside solids. Groundwater interactions can be addressed by increased monitoring of groundwater wells near the Center monitoring location as well as groundwater modeling. Roadside solids can be further investigated by looking at how chloride concentrations vary in terms of depth of roadside solids, distance from roadway, as well as seasonality considerations.

Finally, the pavement performance analysis can be improved by first simply ensuring that the timing of the AVL data matches the timing on the pavement sensors. There were some instances where it appeared that the road improved before the plow arrived, but it is more likely that there is just a discrepancy in the time between the two different monitoring devices. Another area of improvement is to not only consider the amount of chloride that is applied, but to also evaluate the type and amount of deicer applied. For the purpose of this study, the overall impact of chloride was considered, but in order to provide more robust recommendations to RDO for what applications strategies are effective, it would be important to know the type and amount of deicer to apply. Finally, expanding this analysis to look at more storms and locations would also provide more details for how RDO can be improved.

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Appendix A – Chloride Concentration Plots

The chloride concentration timeseries for each location throughout the monitoring period including an estimate of precipitation.

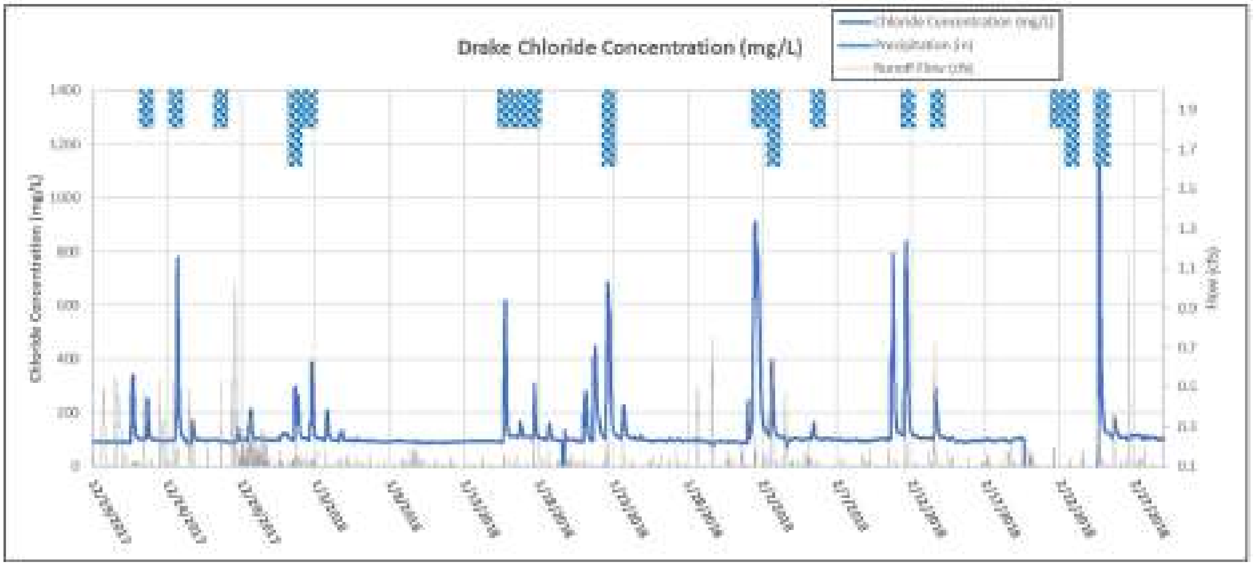


Figure A.1: Chloride concentrations at the Drake monitoring station

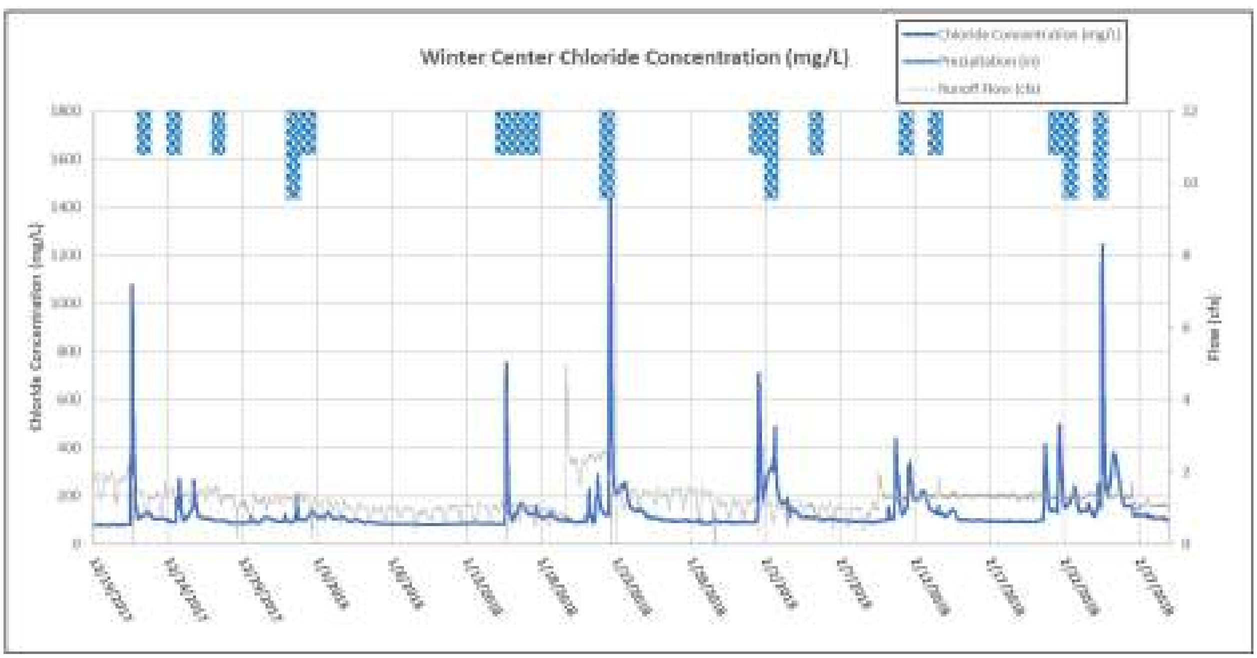


Figure A.2: Chloride concentrations at the Center monitoring station

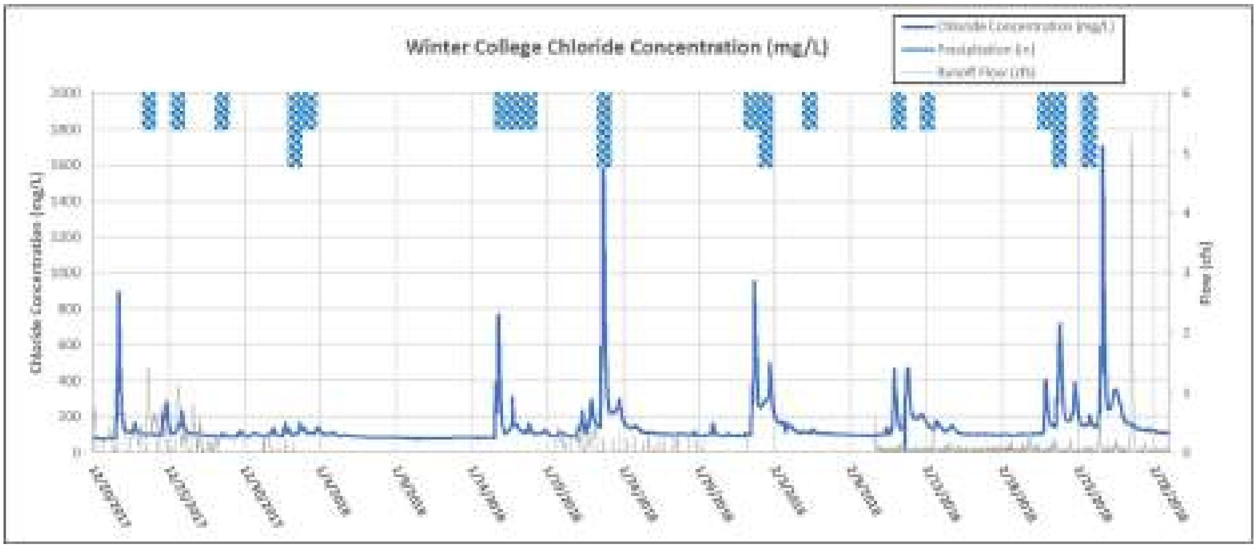


Figure A.3: Chloride concentrations at the College monitoring station

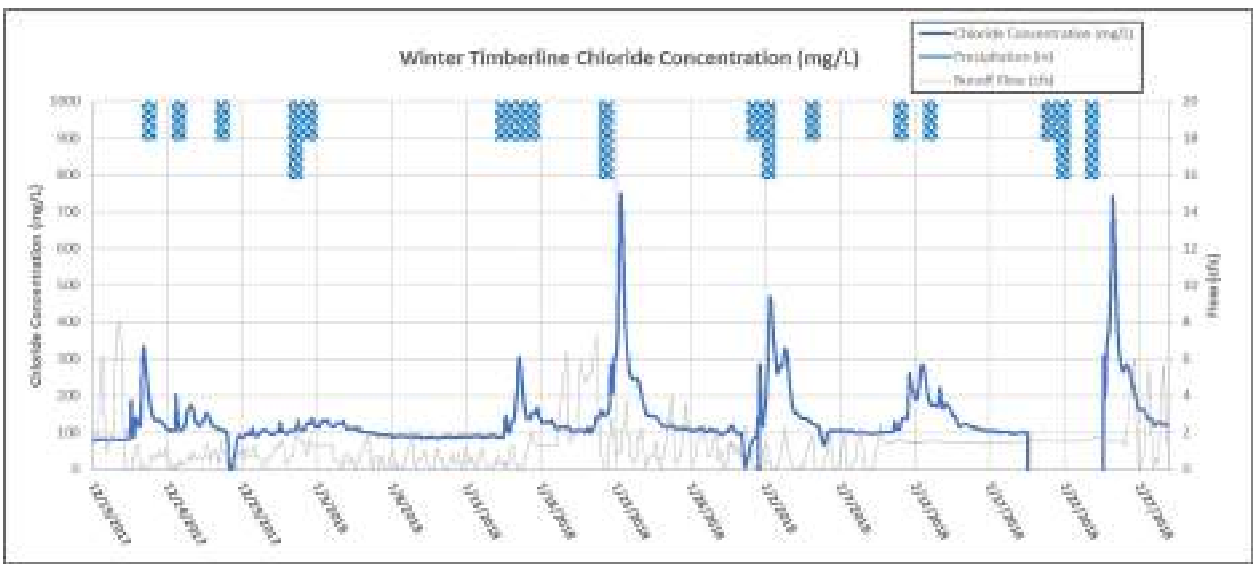


Figure A.4: Chloride concentrations at the Timberline monitoring station

APPENDIX B – CROSS-SECTION ANALYSIS

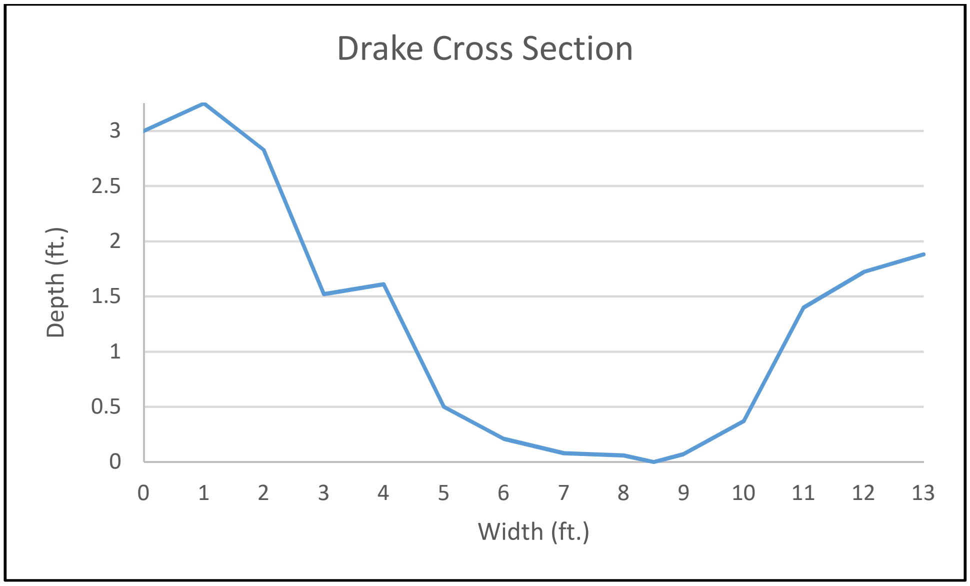
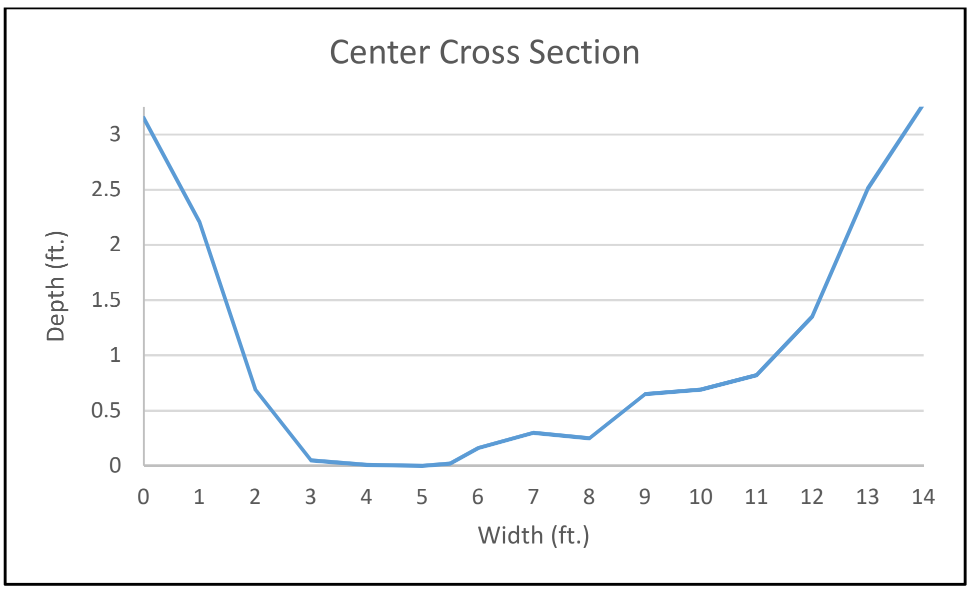


Figure B.1: Cross-section at the Drake monitoring site



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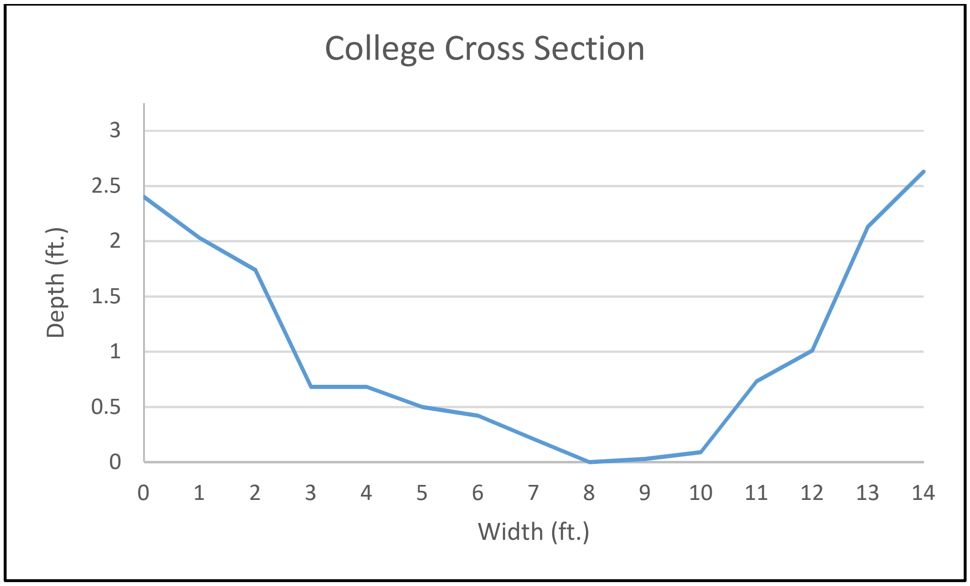

Figure B.3: Cross-section at the College site

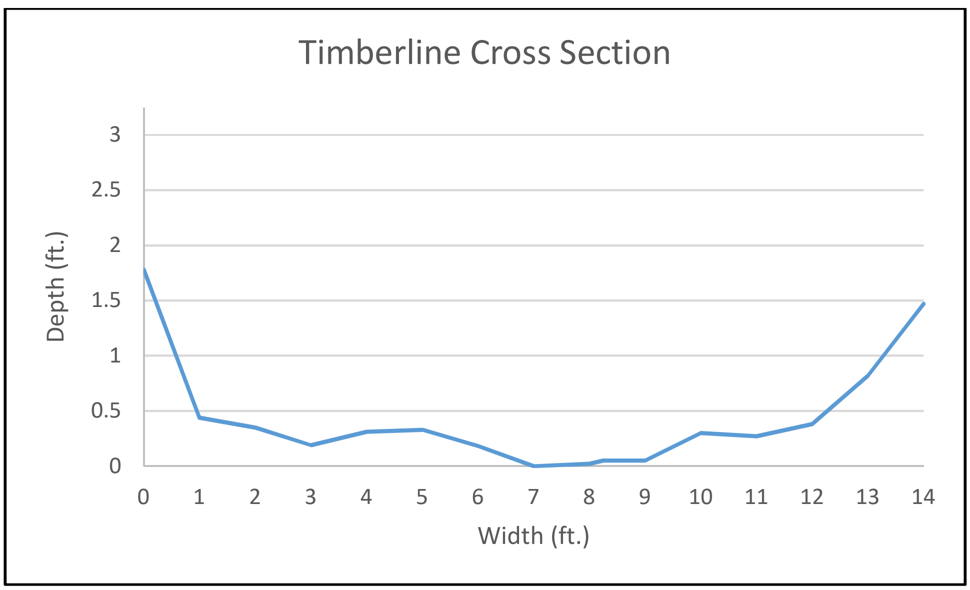

Figure B.4: Cross-section at the Timberline site

Table B.1: Cross-section parameters for Manning's equation

Cross-Section	Manning's n	Slope
Drake	0.035	0.008
Center	0.035	0.009
College	0.035	0.005
Timberline	0.035	0.004

Appendix C – Chloride Mass Plots

The following figures display the chloride mass plots depicting the chloride that is applied within each subcatchment through RDO as well as what is quantified as delivered to each monitoring station.

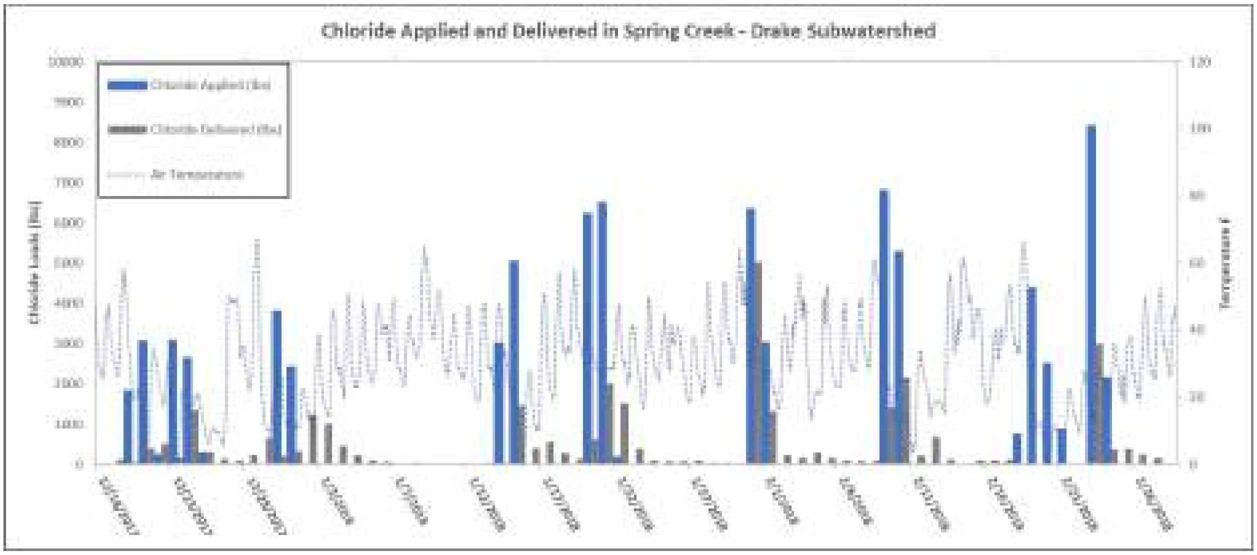

Figure C.1: Mass of chloride applied and delivered for the Drake subwatershed and monitoring location

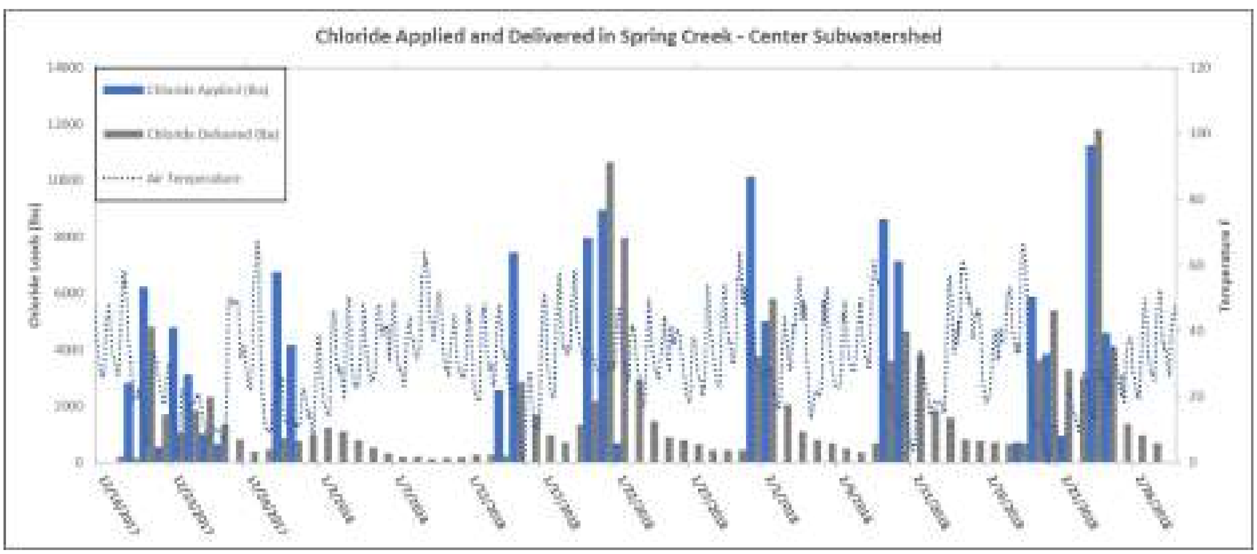

Figure C.2: Mass of chloride applied and delivered for the Center subwatershed and monitoring location

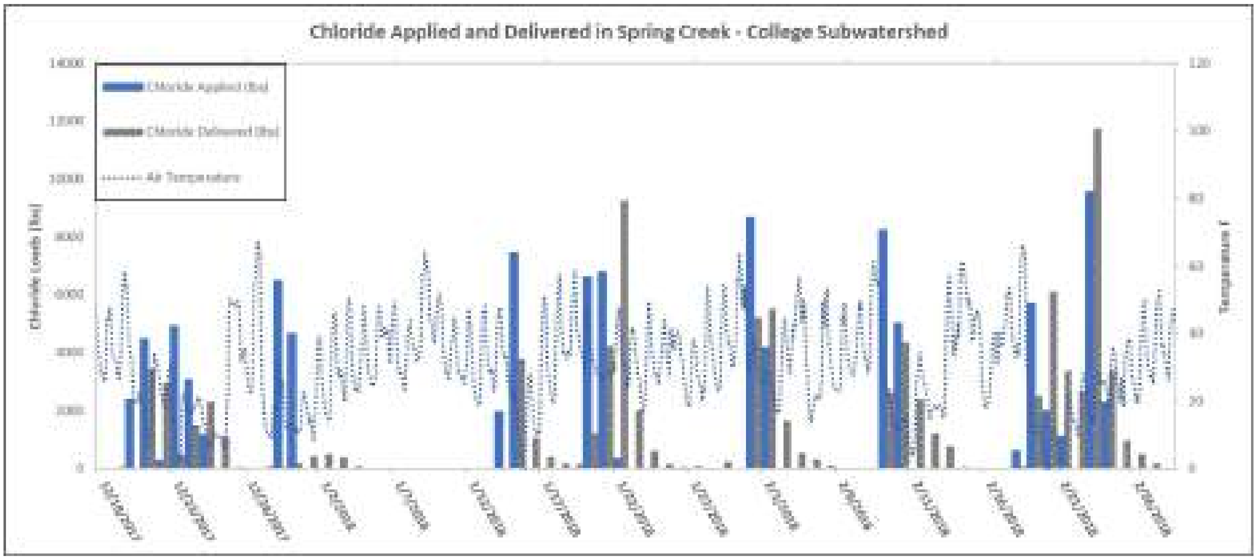

Figure C.3: Mass of chloride applied and delivered for the College subwatershed and monitoring location

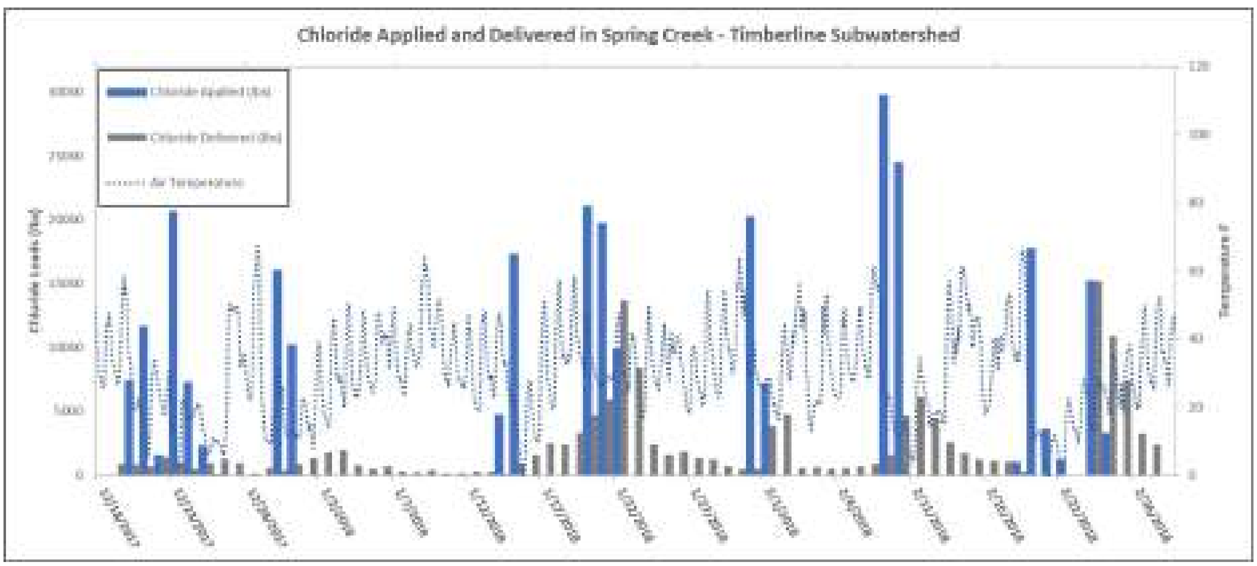

Figure C.4: Mass of chloride applied and delivered for the Timberline subwatershed and monitoring location