DEPARTMENT OF TRANSPORTATION

Study of De-icing Salt Accumulation and Transport Through a Watershed

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University of Minnesota

December 2017

Research Project
Final Report 2017-50

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16. Abstract (Limit: 250 words)

The accumulation of chloride in surface waters and groundwater from road deicing and other sources is a growing problem in northern cities of the U.S., including the Minneapolis-St. Paul metro area. To inform mitigation efforts, the transport of chloride in surface waters of a metro-area watershed (Lake McCarrons) was studied in this project to characterize chloride transport by surface runoff, the residence time of chloride in surface water, and how variations in weather influence chloride transport and accumulation processes. Monitoring work over three winters showed that the residence time of chloride in small, sewered watersheds varied from 14 to 26 days, depending on winter weather conditions, with 37 to 63% of chloride applied as de-icers exported in snowmelt and rainfall surface runoff. In contrast, a monitored highway ditch exported less than 5% of chloride applied to the adjacent road. Stormwater detention ponds were found to act as temporary storage for chloride, with persistent layers of high chloride content at the bottom. Chloride monitoring data and runoff simulations were used to explore the possibility of snowmelt capture as a chloride pollution mitigation strategy. We found that capturing snowmelt runoff close to source areas (roads and parking lots) yields the highest chloride concentrations and removal potential.

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STUDY OF DE-ICING SALT ACCUMULATION AND TRANSPORT THROUGH A WATERSHED

FINAL REPORT

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EXECUTIVE SUMMARY

Background

Road salt (sodium chloride) is widely used as a pavement de-icer in the U.S. and other countries, and it is an increasing source of concern as it accumulates in the environment. In the Twin Cities (Minneapolis-St. Paul, MN) metropolitan area, data have been compiled showing that chloride levels are exceeding state and federal water-quality standards in some lakes and streams and are several times higher in shallow groundwater of the metro relative to rural areas. Although there is a growing body of monitoring data quantifying chloride accumulation in surface and groundwater, there is a lack of information on the transport and retention processes that lead to excessive chloride levels in surface and groundwater. The aim of this project was to measure the transport and accumulation of chloride from road de-icers by surface water runoff in a metro-area watershed, including runoff from source areas (roads and parking lots), transport in ditches and sewer networks, and retention in and release from detention ponds and wetlands. The project focused on field monitoring, but a computer modeling component was also included in this study to help generalize the monitoring results.

The monitoring work performed in this study focused on measuring the seasonal transport of chloride from source areas through small watersheds in the Lake McCarrons watershed, located in Roseville, MN, a suburb of the Twin Cities metropolitan area. Discharge and conductivity of surface runoff were monitored nearly continuously (year-round) from March 2015 through August 2017 at two roadway source areas (a sewered, curb-and-gutter roadway and a vegetated highway ditch), and at the inlet and outlet of two detention ponds. Water samples from each site were used to relate water conductivity to chloride concentration. Conductivity was found to be strongly and linearly related to chloride concentration at the roadway runoff sites, but at the pond outlets, variability and lower slopes in the chloride-conductivity regressions were caused by the presence of other ions. This contribution of other ions may be seasonal, and further study is warranted to improve chloride-conductivity relationships in future research.

Monitoring Results

In this report, *retention* is defined as the fraction of chloride applied as road salt that is temporarily or permanently retained in a watershed via infiltration to soils and groundwater, and therefore not observed in surface runoff. *Residence time* is defined as the time delay between road salt application and salt appearance at the watershed outlet. Overall, substantial retention of chloride was observed over the study, with some variability among sites and between years. Monitoring of runoff from the vegetated highway ditch (Highway 36) showed that over 95% of the chloride applied to the contributing highway infiltrated from the ditch into the soil, and less than 5% was exported from the site in surface runoff (Table E-1). Interestingly, substantial chloride export from the ditch was observed in November rainfall runoff prior to application of any new road salt for the upcoming winter, suggesting long-term storage in soils and groundwater in and near the ditch. Accordingly, estimated residence time of chloride in the ditch was significant at 172 days (Field Season 2). Monitoring of runoff from a 0.5-mile stretch of curb-and-gutter roadway with a storm sewer (County Road B) showed more variable results, as chloride residence time varied from 14 to 26 days, and chloride retention varied from 37% to 66% (Table E-1). The high retention in the County Road B watershed is noteworthy, as no stormwater Best Management Practices (BMPs), such as rain gardens or ponds, were present in the watershed. Chloride presumably infiltrated in pervious areas adjacent to the streets after being plowed or splashed over the curb by traffic. Significant amounts of chloride were exported from the County Road B watershed during winter (December through March), primarily in snowmelt (Figure E-1). At a third site (Alameda Pond Inlet), a larger, sewered, residential watershed, chloride retention of 29% - 50% and residence time of 158 days (Field Season 2) were observed. Several ponds and wetlands present in the drainage network of this watershed likely increased the chloride retention and residence time relative to the County Road B site, leading to chloride export months after spring snowmelt (Figure E-1). In all three winters, the hydrologic events that contributed the most to chloride export in surface runoff at all sites were rain-on-snow events (e.g., Feb 19, 2016, and Dec 25, 2016), as well as the first major, prolonged thaw in each season (early March 2015, late February 2016, and mid-January, 2017).

Several *detention ponds* of different sizes and landuse settings were also monitored. The chloride in runoff inputs to the detention ponds in winter tended to be at relatively low flow rates (from snowmelt events) with high chloride concentrations (up to 12,000 mg/L) accumulating at the pond bottom and causing strong stratification that persisted through winter and into most of the open water season. In contrast, the export of chloride from detention ponds was found to occur over the entire open water season (roughly April – November), with a relatively steady, low concentration (50-150 mg/L) outflow similar to that observed near the pond surface. This suggests a slow erosion of the saline layer at the pond bottom and vertical diffusion of chloride caused by inflows and other disturbances (e.g., wind). The residence time of chloride was estimated to be about 270 days in the Alameda Pond over the study, and about 217 days in the William Street Pond in Field Season 3.

Limitations of Chloride Transport Models

The modeling effort in this study led to the recognition that commonly used hydrologic runoff models such as the Environmental Protection Agency's Stormwater Management Model (SWMM) and the Hydrologic Simulation Program - FORTRAN (HSPF) have limitations for modeling chloride transport in surface waters, both in dealing with source areas (roadways, parking lots) and in intermediate storage areas (detention ponds, wetlands). HSPF was found to be the most usable modeling package for modeling chloride transport, with the capabilities to model both surface and subsurface transport of chloride. However, the model lacked the ability to simulate the transport of salt from roads to adjacent pervious areas (e.g., by snow plowing or spraying by vehicles) and was unable to match observed retention due to its simple handling of ponds and wetlands as well-mixed reactors. The inability to model salinity stratification in detention ponds and wetlands is a common limitation of available hydrologic modeling packages, including HSPF.

Table E-1. Summary of chloride inputs and outputs, residence time, and retention measured at the three surface runoff monitoring sites. The data from the Alameda Pond Inlet represent the watershed contributing to the Alameda Pond, not the pond itself.

	Field Season 2 (11/20/15 – 11/30/16)			Field Season 3 (12/1/16 – 8/1/17)		
	Hwy 36 Ditch	County Road B	Alameda Pond Inlet	Hwy 36 Ditch	County Road B	Alameda Pond Inlet
Cl Input (Applied de-icer, lbs)	6,233	3,595	19,130	9,012	4,726	21,864
Runoff Cl (lbs)	375	1,212	6,705	556	2,968	17,654
Chloride Retention (%)	94	66	65	94	37	19
Residence time of Cl (days)	172	26	158	5	14	3
Mean runoff conc. (mg/L)	43	42	26	117	182	103

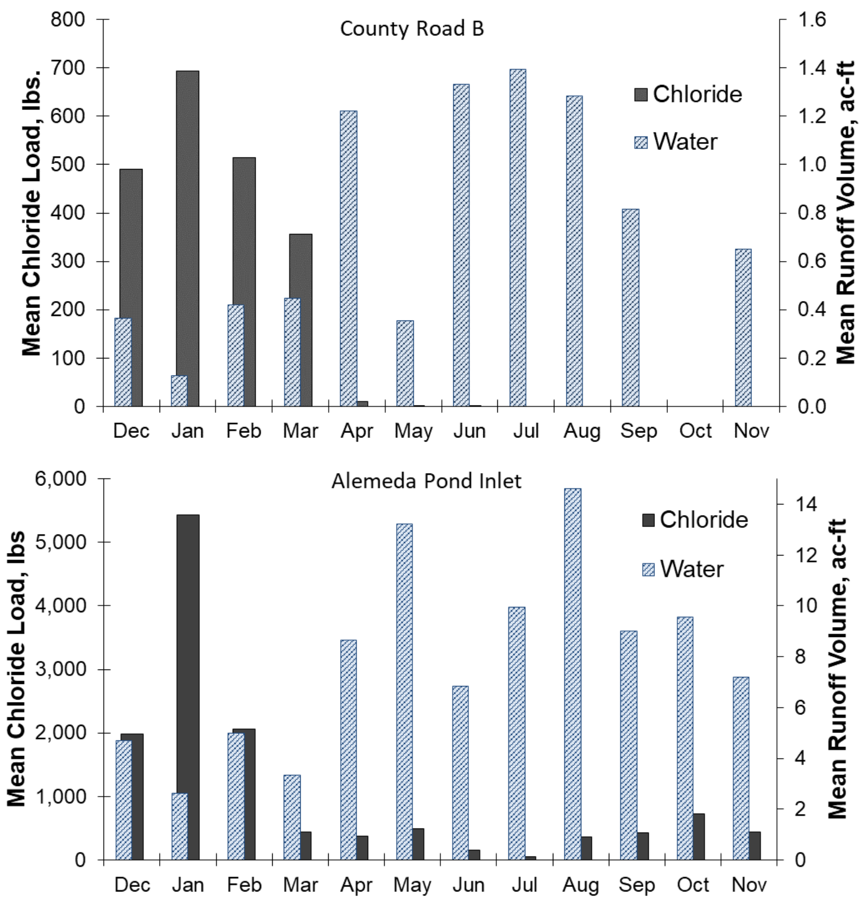


Figure E-1. Mean monthly water volume and chloride mass exported from the County Road B site (upper panel) and the Alameda Pond inlet site (lower panel) averaged over two years of monitoring (August 1, 2015, to July 31, 2017).

Chloride Management and Mitigation Strategies

The monitoring data and output from a pond model (CE-QUAL-W2) were used to examine chloride management strategies, primarily based on snowmelt runoff capture. Chloride removal by diversion and capture of saline surface water runoff was found to be most effective (in terms of mass of chloride removed per volume of water) in small catchments, because the runoff has the highest concentration of chloride near its sources. Several snowmelt capture strategies were examined, including capturing low flows, seasonal runoff capture, and capture based on salinity. Two examples of chloride capture strategies for the sewered roadway (County Road B) monitoring site are:

- Capturing all runoff (rain and snow) in December through March would, on average, capture 97% of all chloride exported in runoff. The total associated volume of water would be 16% of the total annual runoff.
- Capturing all runoff with chloride concentration greater than 350 mg/L would capture 90% of all chloride, with an associated volume of water of only 4% of the total annual runoff.

The withdrawal of saline water from the bottom of a pond was found to be less effective than removal of runoff at street-level because of dilution of flow once it enters the pond. Capturing chloride in snowmelt runoff, by itself, would be relatively ineffective for roadways with pervious ditches, since most of the snowmelt volume and chloride is infiltrated. Capturing chloride in runoff from roadways with pervious ditches may require, for example, a system of underdrains or lining of the ditch. Although this study gives information on the capture volume required to reduce chloride loading, major challenges exist with respect to the storage, treatment, and reuse of captured snowmelt runoff. No effort was made to estimate cost, which could be considerable, or feasibility of diversion practices.

Questions for Future Work

The results of this study raised several questions about the transport and retention of chloride from de-icers in small watersheds, which may guide future research. This study did not consider the transport of chloride in groundwater, and the results of this study reinforce the idea that a large fraction of road de-icers end up in groundwater. The fate of infiltrating chloride requires future study, to determine, at different spatial scales, what fractions of infiltrated chloride are retained in soils, reappear in baseflow to streams and rivers, or are transported to deeper groundwater aquifers. A more specific question raised by this study concerns the mechanisms by which chloride is infiltrated in sewered (urban) watersheds, and how de-icing and snow removal practices affect these processes. Several snowmelt capture strategies are described in this study as a means to reduce chloride loading to the environment; however, further work is needed on methods to separate snowmelt runoff from stormwater, and on strategies for the storage, treatment, and reuse of captured snowmelt. In parallel, work is needed on methods to reduce infiltration of chloride-laden snowmelt, including methods to selectively bypass infiltration practices.

1 INTRODUCTION

1.1 TRANSPORT AND FATE OF CHLORIDE IN THE ENVIRONMENT

Chloride from de-icing salt (NaCl) applied to roads, parking lots, and sidewalks can follow a multitude of pathways through the environment (Figure 1-1) by some combination of surface runoff, infiltration, sub-surface and groundwater flow. While sodium from road de-icing salt tends to bind to soil particles, chloride readily dissolves in water and is conservative, i.e., it is stable, unreactive, and persistent. The transport of chloride can be substantially delayed by weather (e.g., freezing conditions), by retention in surface waters such as lakes, ponds and wetlands, retention in unsaturated soils, and storage in groundwater.

In the Minneapolis-St. Paul metropolitan area (also referred to as the Twin Cities Metro Area, or TCMA), previous studies found that approximately 25% of the chloride applied as road de-icer is exported from the region via the Mississippi River, while the remainder accumulates in surface waters, soils, and groundwater (Stefan et al., 2008; Novotny et al., 2009). Recent studies have provided evidence of the considerable extent to which chloride is accumulating in both surface water and groundwater. For example, in 2013 the Minnesota Pollution Control Agency (MPCA) found that 27% of shallow groundwater wells surveyed in the 7-county Minneapolis-St. Paul metro area were above 250 mg/L (the drinking water standard for taste in the U.S.), and that median concentrations in urban wells were 5 times higher than in rural wells in Minnesota (MPCA, 2013). Similarly, across the northern United States, the USGS found in a recent study that concentrations of chloride in urban groundwater wells and public drinking water wells were significantly higher than concentrations in wells of forested and agricultural watersheds (Mullaney et al., 2009). With respect to surface water, the same USGS study of the northern U.S. found higher baseflow chloride concentrations in urban streams relative to those in less-developed watersheds. In addition, the MPCA found elevated chloride concentrations in roughly 22% of the 340 lakes, streams, and wetlands surveyed in the Minneapolis-St. Paul metro during the development of the Twin Cities Metropolitan Area Chloride Management Plan (MPCA, 2016a). Total Maximum Daily Loads (TMDL) have been determined for the 39 most impaired of these assessed water bodies (MPCA, 2016b).

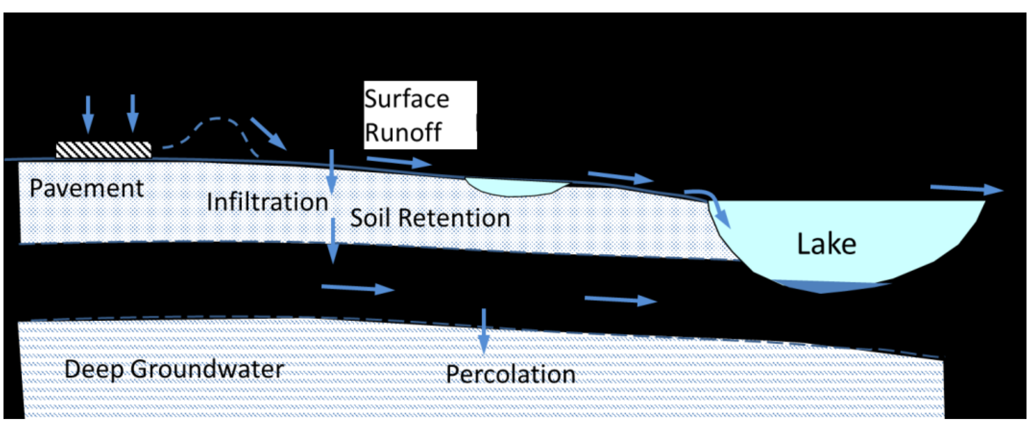


Figure 1-1. Schematic diagram of important surface and subsurface processes that transport chloride. Soils, surface ponds and lakes, and groundwater can all store (and release) chloride at different time scales.

1.2 ADVERSE EFFECTS OF CHLORIDE ON THE ENVIRONMENT

The accumulation of chloride in lakes, soils, and groundwater is a cause for concern in Minnesota and other northern states (Erickson et al., 2014; MPCA, 2016a). With respect to water used for human consumption, impacts of chloride to groundwater are of concern in Minnesota because roughly 75% of residents use groundwater as a drinking source (MPCA, 2013). The U.S. EPA recommends a chloride concentration threshold of 250 mg/L for drinking water (MPCA, 2016a), a standard based on taste rather than on harmful effects to humans. In addition to the potential impact to drinking and irrigation water resources, chloride from road salt and other sources can impact terrestrial and aquatic biota. In soils, chloride concentrations as low as 215 mg per kg of soil can be lethal to sensitive terrestrial plants (ECHC, 1999). Chronic exposure to chloride at levels from 210 to 240 mg/L have been shown to be lethal to aquatic life, with lower concentrations capable of disrupting the structure of aquatic food webs through impacts to survival of macroinvertebrates and juvenile organisms (ECHC, 1999). In Minnesota, the MPCA has adopted the EPA's chloride standards for aquatic life of 860 mg/L for acute events (one hour exposure) and 230 mg/L for chronic levels (4-day exposure; MPCA 2016a, Minnesota R. Ch. 7050 and 7052). Of the 340 lakes, wetlands, and streams that the MPCA sampled during its chloride assessment, 39 were found to exceed either the acute standard (two exceedances in a three-year period) or the chronic standard (one exceedance), with another 38 considered at high risk of impairment, having one sample within 10% (207 mg/L) of the chronic standard (MPCA, 2016a).

Sodium and chloride can also increase the mobility of toxic metals in soils (Amrheln et al., 1992, Norrstrom, 2005) and impact soil structure and permeability (ECHC, 1999). Chloride induced density stratification of the water above a lakebed may reduce mixing and oxygenation, impacting aquatic life and potentially increasing phosphorus release from sediments (Novotny and Stefan, 2012).

1.3 RESEARCH OBJECTIVES

Although there is a growing body of monitoring data that has quantified chloride accumulation in surface and groundwater since road salt applications became an integral part of winter road maintenance (especially in urban areas), there is a lack of information on the transport and retention processes that lead to excessive chloride levels. The aim of this project was to measure the transport and accumulation of chloride from de-icers (NaCl) in an urban watershed, including runoff from source areas (primarily roads), transport in ditches and sewer networks, and retention in and release from detention ponds and wetlands. The watershed of Lake McCarrons, an urban lake in Roseville, MN, considered at "high risk" of future chloride impairment based on the MPCA's assessment (MPCA, 2016a), was selected for the study (Figure 1-2). Both field monitoring and computer models were employed to estimate chloride residence times in different parts of the watershed, the seasonal timing of chloride transport events, and typical chloride concentration ranges for snowmelt and stormwater transport. This knowledge was then used to explore possible mitigation of chloride using, for example, snowmelt runoff capture. This project focused on surface waters and did not directly address the transport of chloride in soils or in groundwater. However, the fraction of applied de-icers that were infiltrated near road source areas was estimated for several sub-watersheds of the study area.

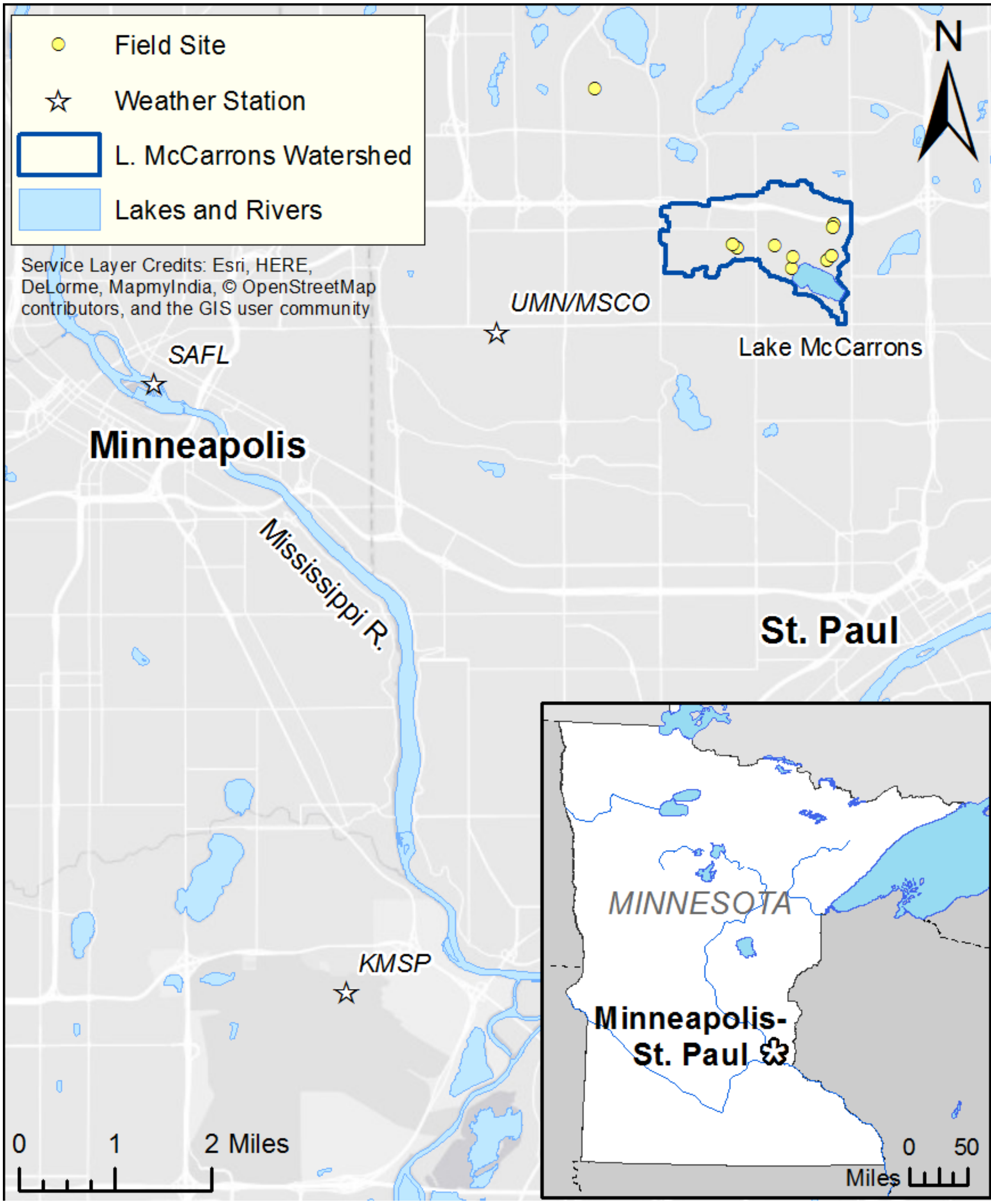


Figure 1-2. Locations of interest for the project, including primary field monitoring sites, weather stations (KMSP: Minneapolis-St. Paul Airport, UMN/MSCO: University of Minnesota / Minnesota State Climatology Office, SAFL: St. Anthony Falls Laboratory), and the watershed of Lake McCarrons, located within the Minneapolis-St. Paul metropolitan area, Minnesota, USA.

2 FIELD DATA COLLECTION

Field data collection efforts focused primarily on continuous monitoring of discharge and specific conductivity of surface runoff from road salt source areas (roadways) and small watersheds (primarily residential), as well as of inflow and outflow of stormwater detention ponds. Field sites, most of which were located within the watershed of Lake McCarrons in the Minneapolis-St. Paul metro area (Roseville, MN), are shown in Figure 2-1. Supplemental data collection included periodic monitoring of runoff from parking lots, measurements of temperature and conductivity profiles within detention ponds during ice-cover periods, water level monitoring in ponds and in shallow piezometers in a highway ditch, and water sample collection for chloride analysis, which was used for developing chloride-conductivity relationships to calculate chloride loads at each monitoring site.

The collection of continuous runoff and conductivity data, particularly of low flows from small watersheds during snowmelt, was crucial for determining chloride retention in elements of an urban drainage network, especially as very little data of this kind exists for the Minneapolis-St. Paul (Twin Cities) metro area. Data collection at ponds served two purposes: (1) inflow monitoring provided quantification of runoff from small watersheds and parking lots, and (2) in-pond and outflow monitoring provided residence times and seasonal timing of chloride transport in a common feature of urban drainage.

In general, monitoring efforts were focused on winter and spring snowmelt periods, with sites maintained year-round to observe warm season chloride transport and allow annual chloride budgets to be calculated for several sites. As much as possible, instrumentation was chosen that could tolerate cold weather and freeze/thaw conditions; however, some data gaps and loss occurred due to equipment failure in harsh conditions, and intentional removal during extreme cold or freeze-thaw periods to prevent damage to more sensitive instrumentation. Gaps and periods of poor data quality are noted in the instrumentation timelines for each site (Section 2.3).

Field efforts were carried out from January 2015 through July 2017, and consisted of three field seasons organized around three winter periods: Field Season 1 (January – October, 2015), Field Season 2 (November 2015 – November 2016), and Field Season 3 (December 2016 – July 2017). Note that the length of each field season is inconsistent among seasons due the timing of the project, and because the start and end dates for the latter two field seasons are related to when salt was first applied for the winter (late November in 2015, early December in 2016). A separate field plan was developed for each of the three field seasons, with plans for the latter two seasons modified based on results from the previous season. Sites were added or removed based on difficulties with monitoring or the need to shift priorities to other sites, and instrumentation was sometimes added, moved or modified to improve data collection efforts (see Section 2.5).

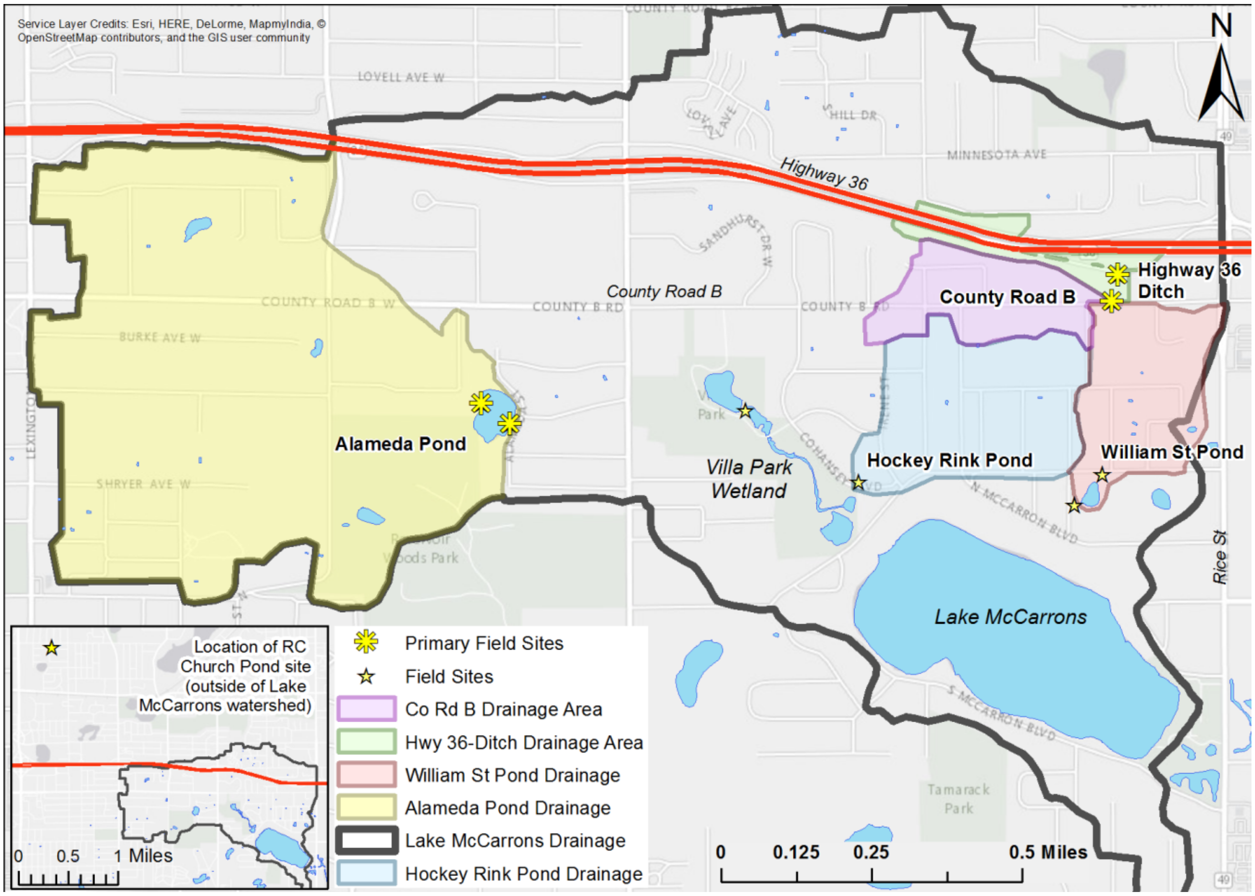


Figure 2-1. Map of the Lake McCarrons watershed in Roseville, MN, showing the locations of field and pond monitoring sites. Note that the Roseville Covenant Church Pond site was located in Roseville, MN, but outside of the lake's watershed.

2.1 ROADWAY RUNOFF MONITORING SITES

These sites were monitored to understand magnitude and timing of chloride loading from major road salt application areas (a major city street, and a highway with a vegetated ditch). Watershed drainage areas are provided in parentheses.

(1) County Road B: (28 ac) 30-inch diameter concrete pipe that discharges to the west end of the infiltration area at Highway 36 – Rice Street. Drainage area includes roughly 0.5-miles of County Road B as well as a few residential side streets in Roseville, MN (Figure 2-2). Discharge and conductivity monitored during all 3 field seasons.

(2) Highway 36 Ditch: (12 ac) 30-inch diameter concrete pipe that discharges to the north end of the west infiltration area. Drainage area consists primarily of ditches/swales adjacent to Highway 36 and its eastbound off-ramp to Rice Street (Figure 2-2). Discharge and conductivity monitored during all three field seasons.

(2b) Highway 36 Ditch Piezometers: piezometers, driven roughly 3 feet into the ground, were used to monitor shallow groundwater levels at three locations within the Ditch site drainage area during Field Season 3 (Figure 2-3). The purpose of these installations was to examine the possibility that seasonally variable shallow groundwater or interflow contributes to export of water (and thus potentially of chloride) from the ditch.

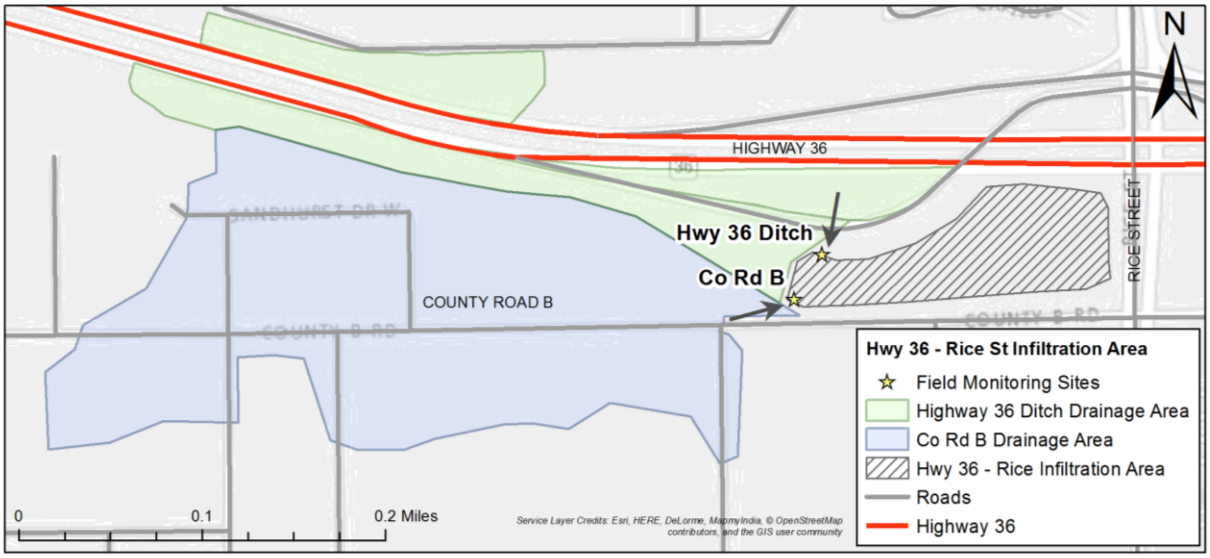


Figure 2-2. Map of runoff monitoring sites located at the Highway 36 – Rice Street infiltration area. Drainage areas are shown for the "roadway" site (Co. Rd. B), and for the "ditch" site (Hwy 36 Ditch), as well as for the main infiltration area to which these two sites discharge.

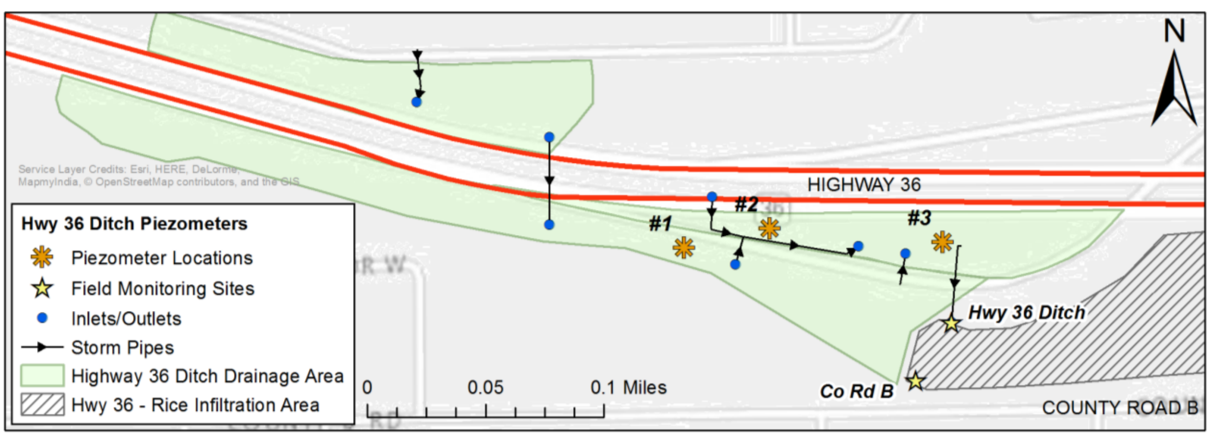


Figure 2-3. Location and ID # of piezometer installations within the monitored ditch site (Highway 36). Note that only data from Piezometer #1 and #2 were usable; location of Site #3 is shown for reference only.

2.2 POND, WETLAND, AND SMALL RESIDENTIAL WATERSHED MONITORING SITES

These sites were instrumented to quantify chloride loading from small urban watersheds and parking lots to detention ponds, and to understand residence times and seasonal timing of chloride export from these watersheds and ponds. Pond drainage areas are provided in parentheses.

(3) William Street Pond: (38 ac) Stormwater detention pond that discharges through a submerged pipe, with an iron-enhanced sand filter overflow bench. Outlet is connected to Lake McCarrons, and drainage area is entirely low-density residential development (Figure 2-4). Conductivity at the inlet, and depth and conductivity near the outlet were monitored during all 3 field seasons.

(4) Alameda Pond: (285 ac) A natural pond/wetland located just upstream of where the B-Dale watershed flows into the upper end of the Villa Park Wetland system (Figure 2-5). Drainage area is mostly residential land use with some areas of commercial and institutional development. The pond has a single inflow (40-inch diameter pipe), and the single outflow is a solid rectangular weir in an outlet structure. Monitoring included water level and conductivity near the outlet (all 3 field seasons) and discharge and conductivity at the inlet (primarily in Field Seasons 2 and 3).

(5) MnDOT Water's Edge Pond: Detention pond collecting runoff from roughly half of the parking area at the MnDOT Water's Edge Building in Roseville, MN, as well as snowmelt from the area used to store snow plowed from the entire parking lot. Water level in the pond was monitored as well as conductivity in the single outlet, a roughly 12-inch diameter pipe that discharges to an adjacent lake when the pond level rises significantly. Monitored during Field Seasons 1 and 2.

(6) Villa Park Sedimentation Basin: (612 ac) A detention pond at the upstream end of the Villa Park Wetland system, collecting runoff from 3 major inlet pipes including the Alameda Pond / B-Dale watershed (labeled "Villa Park Inlet" in Figure 2-1). The drainage area is a mixture of land uses, dominated by residential. Water level and conductivity at the outlet of the pond were monitored periodically during Field Seasons 1 and 2.

(7) Hockey Pond Inlet: (56 ac) A 44-inch diameter concrete pipe located at the inlet to the "Hockey Rink Pond" near the downstream end of the Villa Park wetland system (Figure 2-1). The drainage area is primarily single-family residential use. Monitored for discharge and conductivity during Field Season 2.

(8) Roseville Covenant Church Pond: (4.5 ac) A man-made detention pond located at the end of the church's parking lot. The drainage area is primarily the parking lot and the church grounds. Being studied as part of a different project; discharge, water level, and conductivity at the inlet pipe (18" RCP) and at the outlet (submerged pipe and sump with 12" RCP connection to downstream) were monitored during Field Season 3.

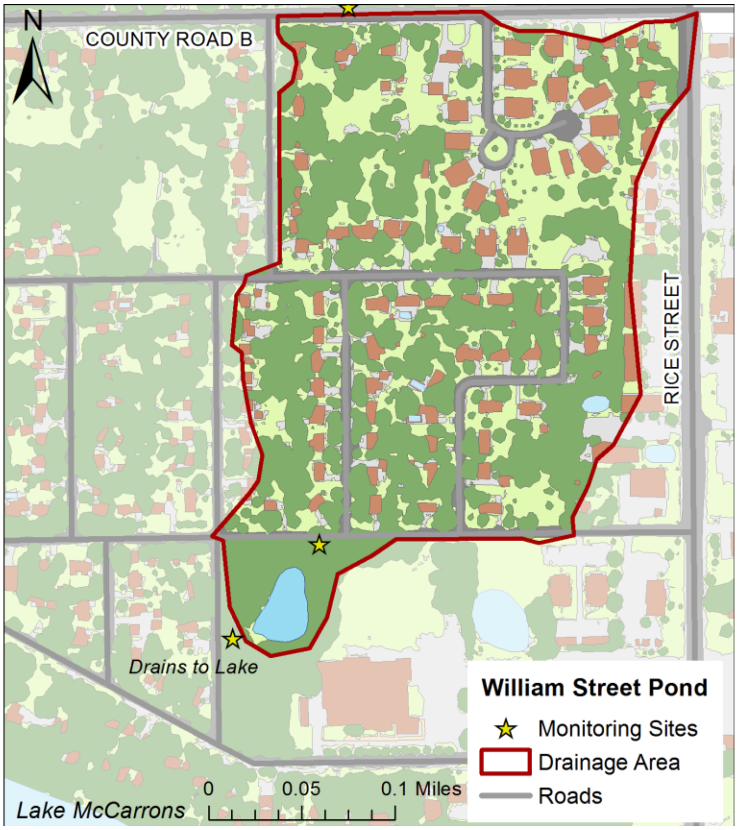


Figure 2-4. William Street Pond drainage area and monitoring sites at the pond inlet and outlet.

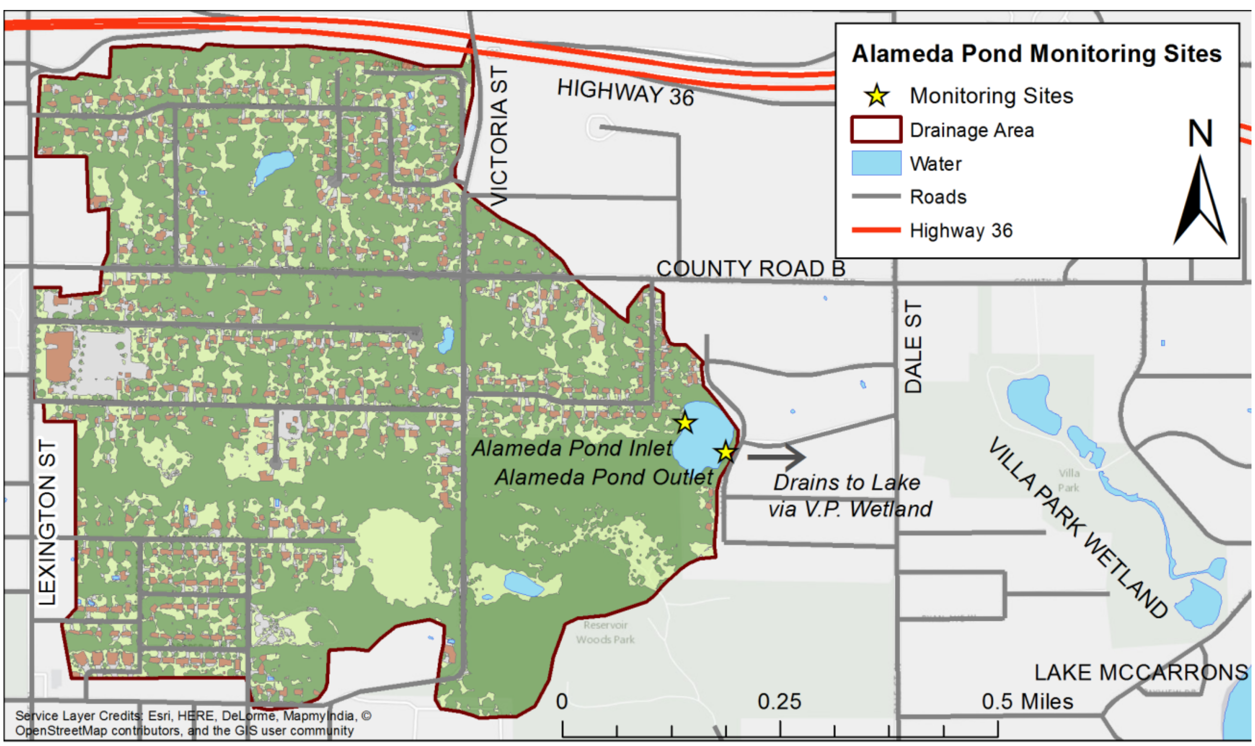


Figure 2-5. Location of the Alameda Pond and monitoring sites.

2.3 INSTRUMENTATION AND MONITORING DATA COLLECTION SUMMARY

This section describes the instrumentation used in monitoring and field data collection at each site, with a summary of the type and timing of data collected during the study. A summary of field sites, instrumentation, and type of data collected is shown in Table 2-1 below.

Table 2-1. Summary of parameters measured and instrumentation used by field site during the study. The first three sites listed, County Road B, Highway 36, and Alameda Pond, were considered the primary (high priority) field sites. For sites with an asterisk (*), ISCO monitoring equipment was installed in late 2016 as part of a separate project, with collected data made available for this project. Instrumentation and data collection timelines for each site are shown in detail in this section.

Site Name	Site Type	Hydrology		Conductivity
		Parameter	Method/Equipment	
County Road B	Road Runoff	Discharge	Weir (Massa Sonic)	Y
Hwy 36 - Ditch	Ditch Runoff	Discharge	Weir (Massa Sonic)	Y
Piezometers	Groundwater	Water Level	Pressure Logger	--
Alameda Pond	Pond/Watershed	Water Level	Pressure Logger	--
Inlet		Discharge	ISCO A/V probe & logger	Y
Outlet		Discharge	ISCO A/V probe, Weir (Pressure)	Y
William St Pond*	Pond / Watershed	Water Level	Pressure Logger	--
Inlet		Discharge	ISCO A/V probe & logger	Y
Outlet		Discharge	ISCO A/V probe & logger	Y
RC Church Pond*	Pond / Parking Lot	Water Level	Pressure Logger	--
Inlet		Discharge	ISCO A/V probe & logger	Y
Outlet		Discharge	ISCO A/V probe & logger	Y
Villa Park Sed. Basin	Pond Outlet / Wetland Inlet	Water Level	Pressure Logger	Y
MnDOT Water's Edge Pond	Pond / Parking Lot	Water Level	Pressure Logger	Y
Hockey Rink Pond	Pond / Watershed	Discharge	ISCO A/V probe & logger	Y

2.3.1 Site 1: County Road B

Equipment: A V-notch weir attached to a steel ring expanded against the walls of the pipe was installed at this storm drain outfall to monitor discharge (see photo on right). Water level in the pipe was measured with an ultrasonic distance gauge (Massa M150) mounted to an arm attached to the top of the steel ring, with flow rate calculated based on a weir equation (see Section 3.1). This setup was useful for snowmelt monitoring, as V-notch weirs are accurate for low flows, and the ultrasonic distance gauge could be used without being immersed in water, preventing damage from being frozen in ice. Conductivity was measured using a Sensorex CS150TC probe mounted to the bottom of the pipe downstream of the weir. A Campbell Scientific CR-10X data logger was used to record the level and conductivity measurements at 10-minute intervals. In November 2016, a second conductivity logger (Onset Hobo U-22) was installed in the same location as the Sensorex probe for redundant measurements (Field Season 3). Approximate intervals of data collection and quality are shown in the timeline below (Table 2-2).

Table 2-2. Timeline of instrumentation used and data collection and quality by month at County Road B over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 1								Field Season 2												Field Season 3										
	Year:	**2015**												**2016**												**2017**						
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
CR-B	Primary Hydro (Weir, Level)		X							X	X											X	X									
CR-B	Primary Conductivity (Sensorex)		X												X																	
CR-B	Backup Cond. (Onset Hobo)																															

2.3.2 Site 2: Highway 36 Ditch/Swale

Equipment: Instrumentation is the same as installed at the County B site (Site 1), and consists of a V-notch weir with an ultrasonic level gauge (Massa M150) to measure water level, and a Sensorex CS150TC probe for measuring conductivity. A Campbell Scientific CR-10X data logger recorded the level and conductivity measurements at 10 minute intervals. An Onset Hobo conductivity probe was added in November 2016 to provide redundant conductivity measurements during Field Season 3. Intervals of data collection and quality are shown in the timeline below (Table 2-3a).

In addition to monitoring the watershed outlet, piezometers were installed in mid-November 2016 at three locations within the ditch site and instrumented with Solinst pressure loggers to monitor shallow groundwater levels. The timeline of data collection and gaps is shown in Table 2-3b.

Table 2-3. Timeline of instrumentation used and data collection and quality by month at the Highway 36 Ditch, (a) main monitoring site and (b) piezometer sites, over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

(a)	*Season:*	Field Season 1								Field Season 2												Field Season 3										
	Year:	2015												2016												2017						
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
HWY 36	Primary Hydro (Weir, Level)												X																			
HWY 36	Primary Conductivity (Sensorex)												X	X																		
HWY 36	Backup Cond. (Onset Hobo)																								X							

(b)	*Season:*	Field Season 1								Field Season 2												Field Season 3										
	Year:	2015												2016												2017						
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
HWY 36	Piezometer #1 (Solinst Level)																															
HWY 36	Piezometer #2 (Solinst Level)																															
HWY 36	Piezometer #3 (Solinst Level)																								X	X	X	X	X	X	X	X

2.3.3 Site 3: William Street Pond

Equipment: A conductivity logger (Onset HOBO U22) was installed in the inlet pipe to the pond to monitor conductivity of inflows. A piezometer was installed near the outlet of the pond to measure the level (Onset pressure logger) and conductivity (Onset HOBO U22) of water leaving the pond through a submerged outlet pipe. ISCO 6712 automatic water samplers with area-velocity probes were installed at both the inlet and outlet of the pond as part of a separate project in November 2016, which provided additional flow data for these sites. Intervals of data collection and quality are shown in Table 2-4.

Table 2-4. Timeline of instrumentation used and data collection and quality by month at William Street Pond over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 1								Field Season 2												Field Season 3										
	Year:	**2015**												**2016**												**2017**						
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
Inlet	Primary Hydro (ISCO 6712)																															
Inlet	Conductivity (Onset Hobo)																										X	X	X	X	X	X
Outlet	Primary Hydro (ISCO 6712)																															
Outlet	Conductivity (Onset Hobo)																															
Outlet	Water Level (Solinst)																															

2.3.4 Site 4: Alameda Pond

Equipment: At the inlet, a conductivity logger (Onset HOBO U22) was used to monitor conductivity of inflows, and an ISCO 4150 data logger with an area-velocity probe mounted in the pipe roughly 50 ft. upstream of the outfall measured discharge. A Solinst pressure logger was installed in the pipe in Dec 2016 to provide a redundant level measurement in the case of data logger failure or poor depth data from the ISCO system. A piezometer was installed near the outlet structure of the pond to measure level (Onset pressure logger) as well as conductivity (Onset HOBO U22) of water leaving the pond over the top of a rectangular weir. Outflow was calculated using a weir flow equation, which was checked against measurements from an area-velocity probe installed in the outflow pipe in July 2017 (see Section 3.2). Intervals of data collection and quality are shown in Table 2-5.

Table 2-5. Timeline of instrumentation used and data collection and quality by month at Alameda Pond over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 1								Field Season 2												Field Season 3										
	Year:	**2015**												**2016**												**2017**						
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
Inlet	Primary Hydro (ISCO 4150)													X											X				X	X		
Inlet	Conductivity (Onset Hobo)											X	X	X												X						
Inlet	Backup Water Level (Solinst)																									X						
Outlet	Conductivity (Onset Hobo)																									X						
Outlet	Water Level (Solinst)																															

2.3.5 Site 5: MnDOT Water's Edge Building Pond

Equipment: A conductivity logger (Onset HOBO U22) was installed in the outlet pipe (12" RCP) of the pond. A piezometer with a level logger (Solinst) was used to measure the water level in the pond. The timeline of data collection and quality is shown in Table 2-6. Note that the piezometer and level logger were lost at this site in February or March 2016, likely due to theft. The conductivity logger was removed at the end of Field Season 2 and installed at a different site.

Table 2-6. Timeline of instrumentation used and data collection and quality by month at MnDOT Water's Edge Pond over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 1								Field Season 2											
	Year:	**2015**												**2016**							
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
Pond	Water Level (Solinst)											X	X	X	X						
Outlet	Conductivity (Onset Hobo)									X	X	X									

2.3.6 Site 6: Villa Park Sedimentation Basin

Equipment: A pressure transducer (Solinst Levelogger 3001) was periodically installed in an existing piezometer at the outlet of the pond to measure water level, which could be converted to discharge using Capitol Region Watershed District's rating curve for the site. A conductivity probe (Onset HOBO U22) was installed at the standpipe that serves as the primary outlet from the pond. The timeline of data collection and quality is shown in Table 2-7. Instrumentation was removed from this site at the end of Field Season 2.

Table 2-7. Timeline of instrumentation used and data collection and quality by month at Villa Park Sedimentation Basin over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 1								Field Season 2											
	Year:	**2015**												**2016**							
Location	**Instrumentation** *Month:*	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
Outlet	Water Level (Solinst)																				
Outlet	Conductivity (Onset Hobo)																				

2.3.7 Site 7: Hockey Rink Pond Inlet (Hockey Pond)

Equipment: Flow was monitored using an ISCO area-velocity probe and a model 4150 flow logger. Conductivity was measured with an Onset HOBO U22 logger. The timeline of data collection and quality is shown in Table 2-8. This site was used only for Field Season 2.

Table 2-8. Timeline of instrumentation used and data collection and quality by month at Hockey Rink Pond inlet over the entire field data collection period. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 2											
	Year:	**2015**				**2016**							
Location	**Instrumentation** *Month:*	9	10	11	12	1	2	3	4	5	6	7	8
Inlet	Hydro (ISCO 4150)			X	X								
Inlet	Conductivity (Onset Hobo)												

2.3.8 Site 8: Roseville Covenant Church Pond (RC Church Pond)

Equipment: A conductivity logger (Onset HOBO U22) and Solinst level logger were installed in the outlet sump of the pond, with another set of probes installed in the inlet pipe, in mid-December 2016, prior to the first major snowmelt for the winter season. In January 2017, ISCO 6712 automatic water samplers with area-velocity probes (for measuring discharge) were added to the site for another project; these data were available for this project's use but were not included in this report due to time constraints. The timeline of data collection is shown in Table 2-9.

Table 2-9. Timeline of instrumentation used and data collection and quality by month at Roseville Covenant Church Pond during field season 3. Shading indicates intervals of collected data, 'X' indicates poor quality data or gaps, and blanks indicate periods when equipment was not installed.

	Season:	Field Season 3										
	Year:	**2016**				**2017**						
Location	**Instrumentation** *Month:*	9	10	11	12	1	2	3	4	5	6	7
Inlet	Primary Hydro (ISCO 6712)											
Inlet	Conductivity (Onset Hobo)											
Inlet	Backup Water Level (Solinst)											
Outlet	Primary Hydro (ISCO 6712)											
Outlet	Conductivity (Onset Hobo)											
Outlet	Backup Water Level (Solinst)											

2.4 ANCILLARY DATA: WATER SAMPLES, WATER COLUMN PROFILES, CLIMATE, AND ROAD DE-ICER APPLICATION DATA

2.4.1 Water Sampling

Water samples were collected periodically during snowmelt and warm season rainfall-runoff from all sites. Samples were measured for conductivity in a laboratory at the University of Minnesota using a Hach HQ40D water quality meter, then filtered (0.7 um GF/F), frozen, and analyzed later for chloride concentration. The purpose of these analyses was to provide calibration points for the field conductivity probes and loggers, and also to develop chloride-conductivity relationships (linear regression) for each site that would be used to convert continuous conductivity measurements into chloride concentrations. Discharge data could then be used with the chloride concentrations to provide chloride load estimates for the sites. Developing independent relationships for each site, rather than using one relationship for all sites, allowed for more accurate chloride load estimations, as ions other than chloride (e.g. sulfate, nitrate, sodium, magnesium, calcium) potentially present in relatively high concentrations at some sites (e.g. ponds) would result in different slopes or offsets in the chloride-conductivity regressions.

153 samples were collected across sites during the study. A subset of 65 samples taken primarily from the primary monitoring sites (County Road B, Highway 35 Ditch, Alameda Pond inlet/outlet, and William Street Pond inlet/outlet; roughly 8-10 samples per site) were selected to be analyzed for chloride concentration by Metropolitan Council Environmental Services (MCES). Samples were chosen, as possible, to represent a wide and evenly-spaced range in conductivity in order to make the regression equations applicable to a range of conditions. These raw data are shown in Appendix B; the resulting chloride-conductivity regressions are shown in Section 3.3.

2.4.2 Water Column Profiles of Conductivity and Temperature

Water column profiles of temperature and conductivity were measured periodically in several of the ponds during ice-cover conditions in all three winters of the study to estimate the accumulation of chloride in the ponds, and to provide calibration points and initial conditions for the pond models. Winter measurements (taken on 4, 2, and 5 dates during the three winter field seasons, respectively) were generally taken just after ice-in, roughly every few weeks during winter, and once right before ice-out. Profiles were also taken on 7 – 10 dates at three of the sites during the open water period of Field Season 3. Measurements were made at a point near the center of the ponds (presumed to be the deepest point), using either a Hach WQ40D water quality meter or a YSI Exo-Sonde, and taking readings every 10 in (25 cm) from the ice or water surface to the pond bottom. The timeline of data collection is shown in Table 2-10; data are shown in Section 3.7and Appendix B.

Table 2-10. Timeline of pond water column temperature/conductivity profiling by site and measurement date across the three field seasons. Ice cover periods were approximately Jan 1, 2015 – Mar 20, 2015 (Field Season 1), Jan 1, 2016 – Feb 19, 2016 (Field Season 2), and Dec 10, 2016 – Mar 24, 2017 (Field Season 3). * This column shows the number of dates on which profiles were taken during open water conditions in spring and summer of Field Season 3 (between 5/22/17 and 8/23/17).

Field Season:	1				2		3				
Year:	**2015**				**2016**		**2016**	**2017**			
Location *Date:*	1/15	2/24	3/8	3/13	1/22	2/11	12/12	1/17	2/3	2/17	May - Aug*
William Street Pond	x	x	x	x	x	x	x	x	x	x	8
Alameda Pond	x	x	x		x	x	x	x	x	x	10
Villa Park Sedimentation Basin	x	x	x	x							
Villa Park Detention Pond	x	x	x								
RC Church Pond							x	x	x	x	7
MnDOT Water's Edge Pond						x					

2.4.3 Soil Sampling and Extraction

A small number of soil samples were collected from near the locations of piezometer installations in the Highway 36 ditch site (Figure 2-3). Samples were collected in November 2016, before first de-icer application. The intention was to turn the soils into slurries following recommended procedures (e.g. Gelderman et al. 1998), with the resulting aqueous extractions filtered, measured for conductivity, and frozen for later chloride analysis. The purpose of this work was a preliminary investigation into soil chloride storage and retention. However, due to time constraints, this work was never completed, and a second set of soil samples that were planned for spring (post-snowmelt) of 2017 were never taken.

2.4.4 Climate Data

Climate data, including precipitation (separately as rainfall or snowfall), snow depth, air temperature, and atmospheric pressure, were necessary for data analysis and interpretation. In particular, precipitation and temperature data were used to define periods of runoff and snowmelt events at some sites, and also to provide context for comparisons across sites or between seasons. Atmospheric pressure was needed to convert pressure measured by the level loggers (pressure transducers) into water depth, for periods prior to installation of an atmospheric pressure logger in January 2017. Climate data were observed roughly 8 miles from the study sites at the Minneapolis-St. Paul airport (MSP; Figure 1-2), at both hourly and daily time scales, and were generally acquired from the Midwestern Regional Climate Center (http://mrcc.isws.illinois.edu/CLIMATE/).

For periods when localized rainfall may have influenced the monitoring sites (e.g. increased pond water levels or runoff events observed at monitoring sites during periods of little or no rainfall at MSP), rainfall data were taken from a station located at the Minnesota State Climatology Office on the University of

Minnesota's St. Paul campus (station UMN/MSCO; Figure 1-2), which was located closer to the study sites (roughly 2 miles away) than the MSP airport. These data were acquired from Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu). As the rain gauge at this site is not heated, data were considered reliable only during warm weather periods (i.e. air temperatures above freezing). Therefore, the UMN/MSCO data were used only to confirm the likelihood of a rainfall-runoff event during non-freezing periods. Finally, solar radiation data used in running hydrologic models were taken from a station roughly 6 miles away at the St. Anthony Falls Laboratory at the University of Minnesota (SAFL; Figure 1-2).

2.4.5 Road De-icer Application Data

The timing and amount of de-icer applied (as sodium chloride) by the primary road management organizations (state, county, and city) in the study watersheds was necessary to estimate chloride retention and residence times. These data were acquired from the responsible agencies: MnDOT, Ramsey County, and the city of Roseville. The temporal and spatial resolution of the provided application amounts varied by applicator. For example, MnDOT provided a *single season* total for each winter for a 44.3 lane-mile section of Highway 36 that included the monitored ditch; Ramsey County provided *weekly* totals for several watersheds that were slightly larger than those that were monitored; and Roseville provided *event* totals for the monitored sub-watersheds. The methods used to scale the application totals to the study watersheds and to estimate their distribution in time over the season are described in Section 0.

2.5 MONITORING DIFFICULTIES IN FREEZE-THAW CONDITIONS

A primary focus of the project was to understand chloride transport in snowmelt and runoff from small watersheds, and relatively discrete elements of urban drainage networks (e.g. detention ponds, highway ditches, parking lots). The major difficulty in monitoring flows from small watersheds is the low flow rates, lack of baseflow, and/or proximity to the cold ground surface, which makes such sites prone to thawing and refreezing during low-volume snowmelt events (see Figure 2-6 below).

Many of the gaps in the data record, in particular at the storm drain sites (e.g. County Road B, Highway 36, Alameda inlet) occurred because of build-up of ice in the storm drains during periods of daily thawing and refreezing of snowmelt. Some sensors used in this project, such as area-velocity probes, level loggers, and conductivity probes, had to be submerged in flows in order to take readings, and would be damaged by being frozen in ice. Therefore some instrumentation had to be removed from flows prior to refreeze to prevent damage, contributing to gaps (typically in January and February). Furthermore, regular visits to the sites (sometimes several times a week) were required in order to remove ice or debris to allow water to continue to drain through the outfalls and prevent dams from forming, though this approach was not always successful.

Figure 2-6. Examples of ice dams forming at the outlets of the monitoring sites for County Road B (top) and Highway 36 Ditch (bottom) during early February freeze-thaw in Field Season 1.

3 DATA COLLECTED AND DATA ANALYSIS

In this section, we present plots and summaries of the data collected in this study, and interpret results of the analysis of these data. We also provide descriptions of the methods that were used to prepare, clean, and calibrate data so that useful outputs (time series of water discharges and volumes, chloride concentrations, and chloride loads) could be determined as accurately as possible. The quantities of particular interest calculated from these outputs, such as road salt (chloride) retention percentages and chloride residence times in the study watersheds, are summarized in this section along with time series of runoff and chloride loading at the monitoring sites.

3.1 WATER LEVEL AND DISCHARGE CALCULATIONS

At some sites, measured quantities such as water levels and discharges had to be determined by calculations made from the raw measurements of other parameters collected at the sites. These raw data included: (1) pressure measurements in the piezometers installed at the pond sites and at the ditch site, which needed to be converted to water levels; and (2) water level measurements at the Alameda Pond outlet piezometer and (3) in the storm sewer outfalls at the two roadway sites (Highway 36 and County Road B), which were converted to water flow rates using separate weir equations for (2) and (3).

3.1.1 Pond Water Level

The pressure transducers installed in the piezometers at the pond and the ditch sites, measured absolute pressure, or atmospheric pressure + pressure of the overlying water. Since the pressure due to water was the quantity of interest (and is easily converted to depth using the temperature-dependent specific weight of water), atmospheric pressure had to be subtracted from the raw pressure data. Atmospheric pressure was measured locally by a pressure logger placed above ground at the Highway 36 monitoring site, beginning Jan 16, 2017. Prior to this date, hourly atmospheric pressure data were taken from the nearest airport, Minneapolis-St. Paul (MSP), roughly 8 miles from the study sites. Under most weather patterns, atmospheric pressure does not vary much over distances of several miles, but it can be spatially variable during storms caused by intense low-pressure systems.

3.1.2 Weir Outflow – Alameda Pond

At Alameda Pond, a rectangular weir regulates the outflow from the pond. Water level in the pond can therefore be used to estimate discharge using the Francis equation for a rectangular weir:

$$\boldsymbol{Q = 3.33(L - 0.2h)h^{3/2}} \qquad \text{[Equation 3-1]}$$

where Q = discharge in cfs, L = width of the weir (6 feet in this case), and h = head of water above the weir, in feet. This approach to estimating flow is somewhat crude, given that rectangular weirs are not as accurate at low flow as compound or V-notch weirs (Gulliver et al. 2010), and most outflow from Alameda Pond occurred for low values of h.

3.1.3 Pipe Discharge – Highway 36 Ditch and County Road B

At the two sites using V-notch weirs, Highway 36 and County Road B, the water depth on each weir was determined by recording the distance through the air from a fixed overhead probe to the water surface; the water depth needed to be converted to a flow rate. This was done using an equation developed for V-notch weirs by Franzini and Finnemore (1997), as recommended by Gulliver et al. (2010):

$$Q = \frac{8}{15} C_d \left[tan \frac{\emptyset}{2} \right] \left(\sqrt{2g} \right) h^{5/2} \quad \text{[Equation 3-2]}$$

where Q = discharge in cfs, C_d = discharge coefficient (0.60), ϕ = angle of the V-notch (90˚), g = gravitational constant = 32.2 ft/s^2, h = head of water above the bottom of the notch in the weir in feet.

Two 0.5-in. diameter drain holes located near the bottom of the weir plate and intended to allow water to drain from behind the weir plate, in order to prevent build-up of ice and sediment, provided additional outflow. Since flow rates were low during snowmelt, the flow contribution from these drain holes was not negligible. A simplified version of Bernoulli's equation was used to estimate this flow rate,

$$Q = C_d A \sqrt{2gd} \quad \text{[Equation 3-3]}$$

where C_d = orifice contraction coefficient (0.60), A =area of the drain holes, and d = depth of water above the holes.

3.2 DATA CLEANING AND CALIBRATION

3.2.1 Calibration of Primary Measurements

Monitoring data were cleaned, calibrated, and inspected manually for outliers and consistency. Notes specific to each measurement type are given below.

Conductivity: The Sensorex probes originally used at the Highway 36 and County Road B sites tended to drift considerably during near-freezing temperatures (i.e., probe measurements were much different than calibrated values during these periods) and required frequent correction. Due to difficulties with these probes, Onset Hobo conductivity loggers were installed at both sites for Field Season 3, and were used as the primary source of conductivity data. Onset probes were used at the other sites, and generally did not exhibit much drift during the field season. Conductivity measurements made with these probes were calibrated to lab-measured conductivity using linear regression equations (slope-intercept) developed from all pairs of lab- and field- measured conductivities at a site (see example for William Street Pond Outlet, Figure 3-1 below). Correlation coefficients (R^2) were generally > 0.97.

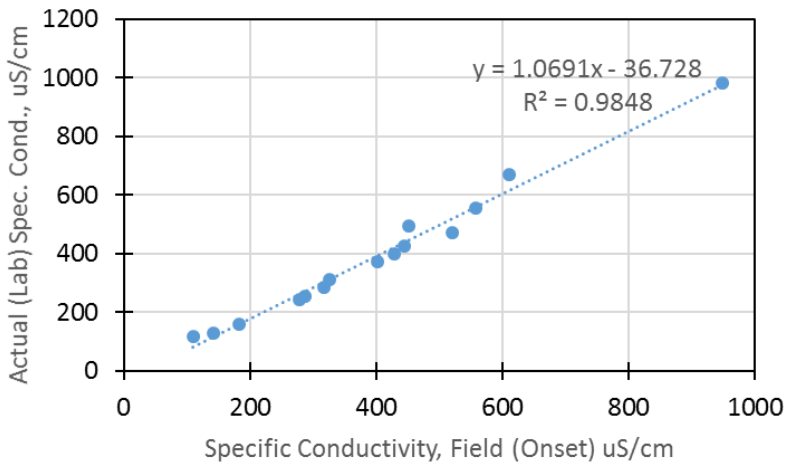


Figure 3-1. Linear regression equation used to calibrate the raw specific conductivity measurements made by the conductivity logger installed at the William Street Pond Outlet.

Pond water level: Logged values were corrected for drift via linear interpolation (in time) between direct depth/stage measurements, which were recorded on most trips to the sites. Since all of the water level loggers were the unvented type, they had to be corrected for atmospheric pressure. For the period January 16 – August 31, 2017, a pressure logger was installed above ground at the Highway 36 site to provide a local reference for atmospheric pressure (Figure 2-1); during all prior periods, atmospheric pressure was taken from the Minneapolis-St. Paul Airport (Figure 1-2).

Water depth (weir): Actual water depth above the V-notch in the weir was recorded when trips were made to the Highway 36 and County Road B sites during runoff events. These measurements were used to check (and calibrate, if needed) the water depth measured by the Massa Sonic distance gauges. Only small corrections (less than 1 cm) were ever needed.

Flow depth and velocity (ISCO 4150 & area-velocity probes): When possible, water depth was measured at sites using ISCO 6712 auto-samplers with area-velocity probes (Alameda, William Street, and Roseville Covenant Church ponds) or ISCO 4150 data loggers (Alameda Inlet until July 2017), and adjustments were made within the ISCO program during site visits. Velocity data were inspected for missing, erroneous, or extreme values, and were corrected by linear interpolation (during events) or by zeroing out the velocity (in the case of low or zero flows, confirmed by checking concurrent depth measurements and measured precipitation at MSP or the closer station at UMN/MSCO; Figure 1-2).

3.2.2 Site-specific Data Cleaning and Calibration

Depth corrections for ice or debris build up in pipes: At the County Road B site, debris accumulated behind the weir, along with ice during cold snowmelt periods. At Alameda Pond Inlet, ice would also build up in the storm sewer pipe at the location where the sensors were installed. To correct for ice and debris in the pipes, the depth of debris first had to be identified, which was done by applying baseflow separation to the raw observed (total) water depth (i.e. the debris or ice tended to show up in the time series as a slowly-varying component of the water depth; see Figure 3-2). The likelihood of ice build-up or thaw was checked against field photos and notes, and air temperature data from the MSP airport. Net flow was then calculated as the difference between flow calculated for the total depth, and flow calculated for the debris depth: q(net) = q(total_depth) – q(debris depth). When ice built up over the probes and runoff began flowing over the ice rather than under it (most common at Alameda Inlet), conductivity of grab samples was used in place of the probe conductivity.

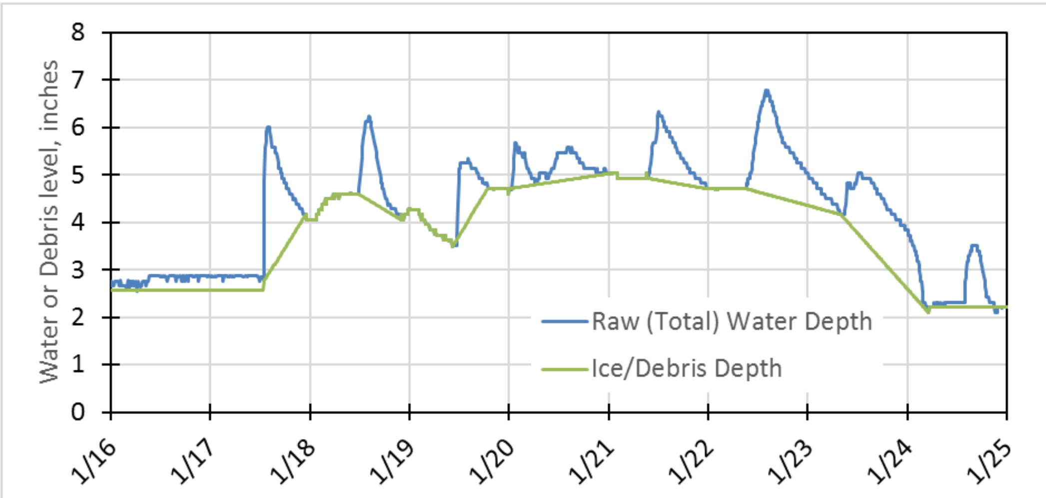
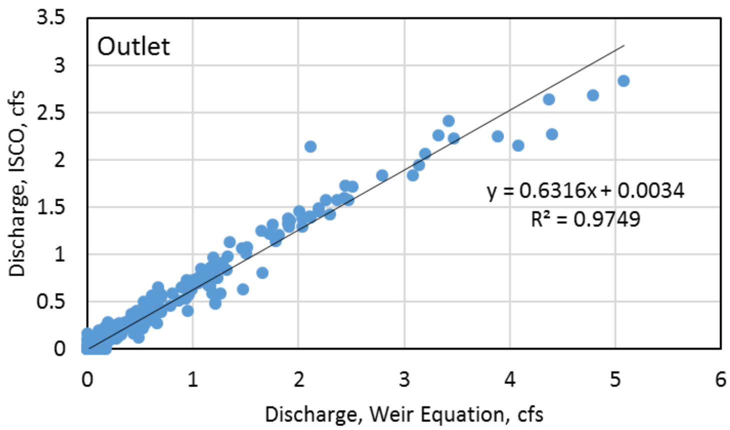


Figure 3-2. January freeze-thaw at the County Road B site, showing the graphical separation method used to subtract ice/debris depth from the total measured water/ice/debris depth in the pipe.

Correction for discharge calculations at the Alameda Pond Outlet weir: Results for the Alameda Pond from the previous field seasons had shown that far more water (~50%) was leaving the pond than was entering it through the monitored inlet. This suggested that either large inputs of groundwater were present, or more likely, that the inlet flows were underestimated or the outlet flows were over-estimated. In July 2017, ISCO 6712 auto-samplers were installed at both the Inlet and Outlet sites as part of a separate project, providing a second discharge measurement at both sites for a 24-day period (July 17 – Aug 10) in which several storms occurred. For the Inlet, the discharge calculated from the backup water level logger and a depth-velocity rating curve agreed to within 14% of the discharge measurements made by the ISCO samplers (area-velocity probe and ISCO 750 flow meter; Figure 3-3); no correction was made to the Inlet discharge. At the Outlet, the discharge estimated by the weir equation was roughly 37% higher than the discharge measured by the ISCO 750 flow meter and area-velocity probe; discharge estimated by the weir equation was corrected with the linear regression equation for the Outlet site (Figure 3-3). The need for a correction of the flow measured by a weir was attributed to the rough surface and ~6-inch depth of the weir crest (which was not “sharp” as assumed by the nominal value of the weir discharge coefficient, C_d, in the weir equation (Section 3.1.2), as well as to the occasional presence of debris on the weir.



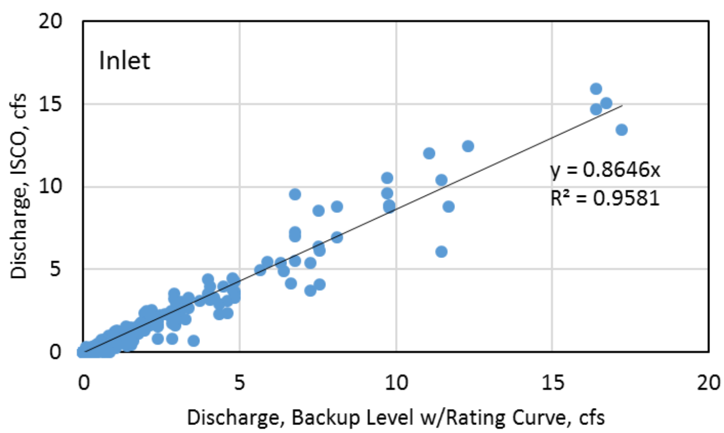


Figure 3-3. [top] Alameda Pond Outlet: Comparison of hourly discharge estimated by a weir equation (x-axis) and that measured with an ISCO area-velocity probe in the pipe downstream of the weir (y-axis); [bottom] Alameda Pond Inlet: discharge measured with an ISCO area-velocity probe vs. discharge estimated with backup water level and a depth-velocity rating curve for the pipe, for July 17 – Aug 10, 2017.

Estimation of outflow conductivity at Alameda Pond, January 2017: The conductivity logger reached end-of-file on Jan 6, 2017, but was not checked until Jan 25. Some outflow was measured from Jan 18 – Jan 25. To estimate outflow conductivity during this period, the measured conductivity at William Street Pond (WSP) Outlet over the interval was used to project the temporal variation in conductivity over this melt event. Three grab samples collected from Alameda Pond Outlet during this event were used to adjust the WSP Outlet values using the ratio of the two (starting at a conservative value of 1.0 at the start of the melt event on Jan 18, increasing via linear interpolation to a value of 1.65 at the first grab sample on Jan 22, then to a value of 1.57 for the second grab sample on Jan 23, then to a value of 1.35 for the grab sample on Jan 26). The time series of conductivity for both sites is shown in Figure 3-4. The consistency of the ratio between conductivity observed at WSP Outlet and that measured in the three grab samples at Alameda Outlet suggests that this simple method provides a sufficiently accurate estimate of outflow conductivity for the pond.

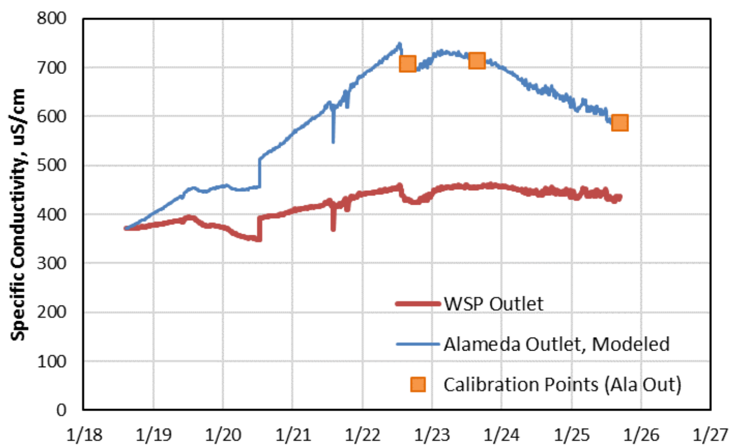


Figure 3-4. Estimated specific conductivity of outflow from the Alameda Pond (blue line) from Jan 18 – Jan 25, obtained from measured outflow conductivity at William Street Pond (red line) with adjustment by conductivity measured in three grab samples collected during the melt event at Alameda Outlet.

3.3 DETERMINING CHLORIDE LOADING FROM ELECTRICAL CONDUCTIVITY

Chloride loading was calculated as the product of observed runoff volume for a measurement interval (generally 10 or 15 minutes) and average chloride concentration during that interval, which was estimated from conductivity measured concurrently at the study sites. A chloride-conductivity relationship, which was critical for translating conductivity time series into approximate time series of chloride concentration, was developed separately for each monitoring site.

3.3.1 Chloride-conductivity relationships

Conductivity is proportional to the total dissolved ions in the water, with ionic strength varying amongst the types of ions present (e.g., chloride, nitrate, sulfate, sodium, magnesium, etc.). In this study, variation in chloride concentration is dominant and controls variation in conductivity (except at low conductivity) due to relatively high concentrations and ionic strength of chloride, and therefore a strong (usually linear) relationship between chloride and conductivity can be used to convert the time series of conductivity measurements into a time series of approximate chloride concentrations.

Of the 153 water samples collected across monitoring sites during the study, 65 samples were analyzed for chloride concentration by Metropolitan Council Environmental Services in order to develop the chloride-conductivity regression equations for each site. Sample selection was focused on the primary monitoring sites (Highway 36 Ditch, County Road B, Alameda Pond Inlet and Outlet) as well as on the pond outlet sites, in which ions other than chloride from road salt were expected to be present in similar concentrations to chloride during summer and fall.

Chloride-conductivity regressions are shown in Figure 3-5 for the primary monitoring sites, plus William Street Pond Inlet and Outlet. A line for a pure sodium chloride (NaCl) solution is also shown in each plot. This line, which is the chloride-conductivity relationship for NaCl dissolved in deionized water (i.e. no other ions present) fits the following equation:

$$\boldsymbol{Chloride}\ [\mathbf{mg/L}] = \mathbf{0.346} * \boldsymbol{Specific\ Conductivity}\ [\mathbf{uS/cm}] - \mathbf{22.0}$$ [1] **[Equation 3-4]**

This equation is used as a reasonable upper limit of chloride concentration for a given conductivity, i.e. as if all ions contributing to conductivity were solely from dissolving NaCl in a deionized water sample. In a natural water sample, other conductive ions are usually present and therefore chloride concentration is less than that predicted by the above equation. Any data points plotting above this line indicated erroneous measurements either in chloride concentration or in specific conductivity, and were therefore excluded from the fitting of the regression lines.

Especially for the road runoff sites (Alameda Inlet, County Road B, and to some extent Highway 36), the slopes of the regression equations were similar to the pure sodium chloride solution line, suggesting that the variability in road salt (NaCl) content is controlling the variation in conductivity of the runoff. Sites with a slope lower than that of the NaCl line, such as at the pond Outlet sites, reflect the relatively constant presence of other ion(s), e.g. from groundwater or from the pond sediments. In these cases, while the other ion(s) are present at high enough levels to impact the regression coefficients, the relationship of conductivity and chloride is still strong enough ($R^2 > 0.85$) that the use of these regression equations for estimation of chloride concentration should not be in doubt. Finally, for some sites such as Highway 36 ditch and Alameda Inlet, the large offsets in the regressions (i.e. non-zero specific conductance observed when extrapolating the regressions to zero chloride concentration) are further evidence of the presence of non-chloride ions at these sites.

Temporal variability in the chloride-conductivity regressions is not apparent in this dataset, though a larger sample size may be necessary to reveal seasonal patterns. Most analyzed samples in the data set were taken during winter or spring (defined here as November – April), though the few taken during summer or fall (May – October) are noted in the plots in Figure 3-5. However, substantial scatter in the data for the Alameda Pond Outlet (Figure 3-5) is worth noting. Specifically, two points from spring/summer samples (May 2017 and September 2016) plot well below the other points. These data points were omitted from the regression due to their leverage on the relationship, but they suggest that in future analyses, seasonally-variable chloride-conductivity relationships may be necessary to accurately determine chloride loads. This scenario may be especially important for ponds, where background sources of conductivity from other ions, e.g. by groundwater, sediment, or stormwater inputs, may vary in strength over the year.

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[1] http://vernier.com/booklets/cond.pdf

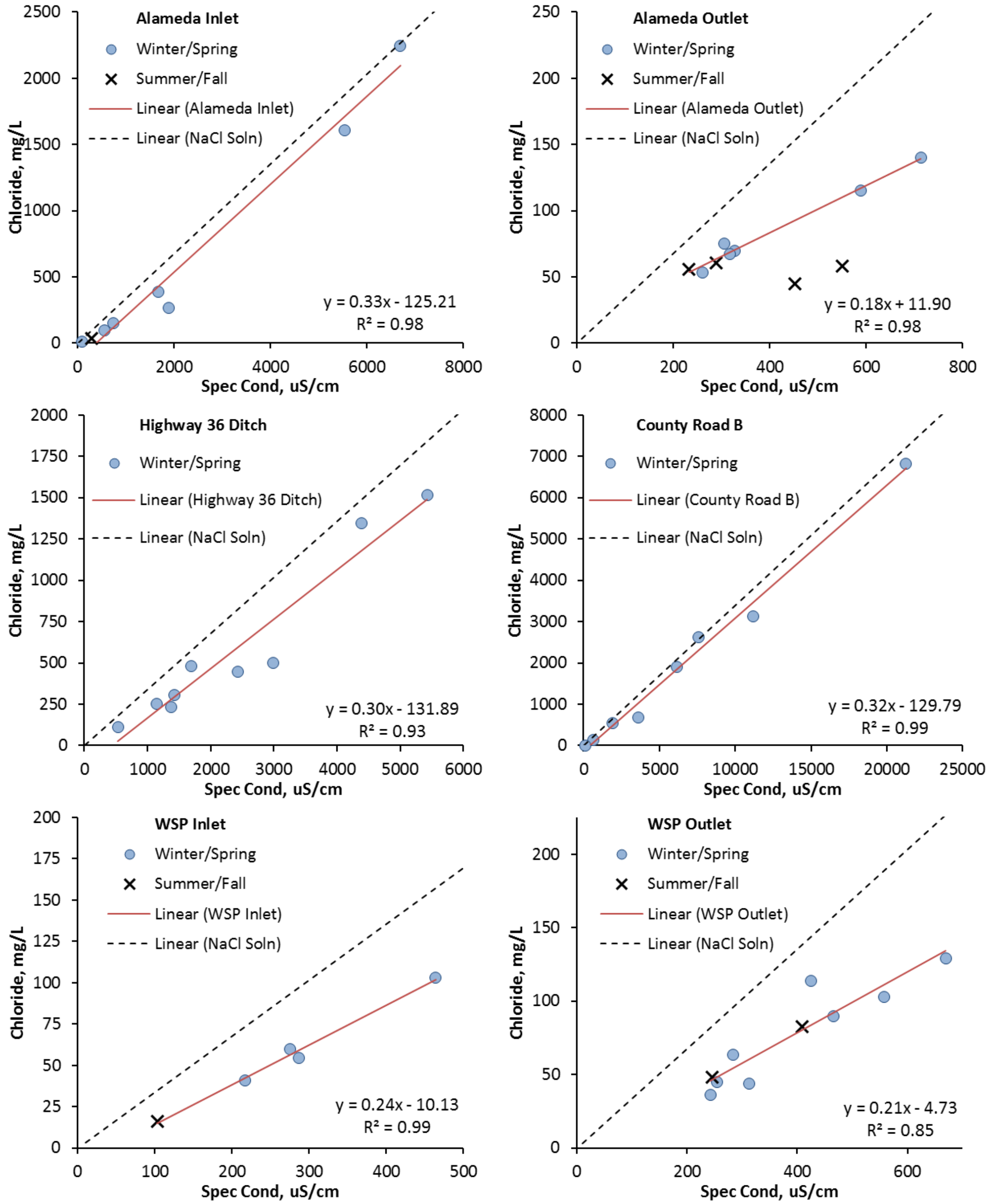


Figure 3-5. Linear regression of chloride concentration vs. specific conductivity obtained by laboratory measurements of water samples collected at six monitoring sites. The dashed black line in each plot is the chloride-conductivity relationship for sodium chloride dissolved in deionized water, and serves as an upper limit for chloride concentration for a given conductivity reading. For these plots, "Winter/Spring" is Nov – Apr, and "Summer/Fall" is May – Oct. All samples regardless of season are included in the line fits, with the exception of the Alameda Pond Outlet, for which the two outlying Summer/Fall samples were omitted.

3.4 ESTIMATING ROAD SALT INPUTS TO WATERSHEDS

Road salt amounts applied to the study watersheds were provided at different spatial and temporal resolutions by the organizations responsible for winter road maintenance (MnDOT, Ramsey County, and city of Roseville). Scaling of these amounts to boundaries of monitored watersheds was necessary to estimate road salt inputs (needed to calculate retention in the watershed; see Section 3.5). Partitioning of totals in time within the field seasons was needed to estimate chloride residence time (Section 3.5).

Roseville provided records of *daily* total NaCl applied in each watershed for the three field seasons. Ramsey County provided records of *weekly* totals over each field season, for County Road B from Rice Street to Dale Street, and for the entire Lake McCarrons watershed; these totals were scaled down to the relevant watersheds (County Road B, Alameda Pond) proportional to lane-miles, and partitioned in time based on Roseville's application schedule. MnDOT provided a single season total amount of NaCl applications in each winter for a 44.3 lane-mile stretch of Highway 36 that included the monitored ditch (1.37 lane-miles); this total was scaled down to that of the ditch site proportional to lane-miles, and partitioned in time proportional to Roseville's application schedule. This somewhat crude approach contributed some error to the exact timing of the road salt applications within the season, but was sufficient for an estimate of chloride residence time and for a chloride budget on a seasonal time scale (Section 3.5. A short section (196 m) of Capitol View Road drains to the north end of the ditch system at the Highway 36 monitoring site; salt applications by Roseville were estimated for this section by scaling the provided amounts for the Roseville side streets along County Road B, proportional to lane-miles. This amount was minor, roughly 7% of MnDOT applications to the 1.37 lane-mile stretch of Highway 36 in Field Season 2, for example.

Since all road salt applications were provided in terms of NaCl, they were scaled to mass of chloride by multiplying by 0.393, the molar ratio of Cl (22.99 g/mol) to NaCl (58.44 g/mol), before comparison to chloride concentrations and amounts observed in runoff.

3.5 DATA ANALYSIS: CHLORIDE MASS BUDGETS AND RESIDENCE TIMES

The chloride-conductivity relationships (Section 3.3.1 and time series of conductivity and discharge were used to calculate a time series of chloride loading for each site. These chloride loads were summed over field season periods corresponding to road salt application (see Section 3.6, and compared to the chloride in the salt applied as road de-icer over the corresponding field season. Two important parameters, **chloride retention** and **chloride residence time**, were determined from these data.

***Chloride retention** is defined as the fraction (or percentage) of chloride applied as road de-icer that does not exit the watershed or pond in surface runoff prior to application of road salt in the following winter*:

$$\boldsymbol{Retention = 1 - \frac{Mass\ of\ chloride\ in\ surface\ runoff}{Mass\ of\ chloride\ applied\ as\ road\ salt}} \quad \text{[Equation 3-5]}$$

For example, if 2,000 lbs. of chloride is applied to roads as de-icer over a winter, and 1,500 lbs. of chloride is observed in runoff over the year starting with the first de-icer application, the retention percentage is 25%. This retained chloride has generally entered the soil and groundwater of the watershed through infiltration from the surface (in ditches, curbside boulevards, rain gardens, or infiltration areas connected in-line with the drainage network), but the specific fate of the chloride is not known. It may be stored temporarily in soil or shallow groundwater, or enter sub-surface flow paths that were not observed or modeled in this study, from where it may enter lakes, streams, or deeper aquifers.

Residence time of chloride *in the surface runoff of the study watersheds or ponds is the time between road salt application and salt appearance at the watershed outlet.* Residence time was determined for both ponds and watersheds by computing the difference in travel time between mass centroids of the observed chloride mass time series, a method often applied to tracer injection studies in streams. Specifically, this is the difference in time between the centroid of chloride in road salt applied in the watershed (Section 0and the centroid of chloride observed in runoff at the outlet from the watershed (3.3. This definition of chloride residence time requires that the time period for centroid analysis begin with the first road salt input to the watershed. The method is also relatively insensitive to any inaccuracies in the determination of chloride from conductivity because the relationship is linear. For pond sites, such as Alameda Pond, residence time was determined using an approach similar to a standard method for hydraulic residence time in which the pond's volume is divided by the mean outflow rate. For chloride, the total inflow chloride load in a season (lbs) was divided by the mean outflow rate of chloride over the season (lbs/d) to provide a residence time in days.

A drawback of the centroid method for residence time analysis is that all residence times will be less than a year because of the interval used for the analysis (one field season), even if the actual residence time is greater than a year. Furthermore, this residence time only applies to chloride in surface runoff; it does not explicitly take into account chloride transported by sub-surface processes, which would be expected to greatly increase residence times. Alternate methods of estimating residence time, which were not attempted in this study, include observation of a conservative tracer (e.g., dye, bromide) applied with road salt, or modeling surface and sub-surface chloride transport in a watershed.

3.6 RESULTS BY SITE: RUNOFF LOADING TIME SERIES, CHLORIDE BUDGETS, AND RESIDENCE TIMES

This section describes the data analysis results, which are presented for the primary monitoring sites (County Road B, Highway 36 Ditch, Alameda Pond Inlet and Outlet) as well as for William Street Pond. Results include the following:

- Amount of road salt applied (lbs) and observed chloride in runoff (lbs) and volume of runoff(ac-ft) for Field Season 2 and Field Season 3;
- Chloride retention (%) for Field Season 2 and Field Season 3;
- Chloride residence time (days) for Field Season 2 and Field Season 3;
- Plots of seasonal chloride export (mean monthly chloride loads), averaged over two years of continuous monitoring (Aug 1, 2015 – July 31, 2017);
- Plots of monthly chloride loading by water source (snowmelt vs. rainfall-runoff, with rain-on-snow considered rainfall-runoff), averaged over two years of monitoring (Aug 1, 2015 – July 31, 2017);

- Mean runoff chloride concentration (mg/L) and Water yield (ac-ft of runoff per in. of precipitation);
- Date of the center of mass (centroid) for road salt application, chloride export, and runoff volume.

Mean monthly chloride loads have been averaged over a two-year period of continuous monitoring at the primary sites, Aug 1, 2015 – July 31, 2017, in order to generalize the seasonal timing of chloride and water export. Snowmelt events are defined by a daily maximum air temperature above 20°F (the approximate effective melt temperature of ice and snow treated with sodium chloride), lack of rainfall, and a non-zero snow depth observed at the MSP airport.

Chloride retention and residence times are presented by field seasons, which are defined based on the timing of road salt application in each winter rather than on an arbitrary date. This was done in order that cumulative chloride loads would most likely reflect export of the most recent winter's salt application, which was a useful interpretation of the chloride retention and residence time. The first application of road salt for winter 2015-2016 (Field Season 2) was on Nov 20, 2015, and for winter 2016-2017 (Field Season 3) on Dec 1, 2016. **As a result of year-to-year variability in timing of salt applications, the field seasons do not have consistent lengths**:

- Field Season 1 (Nov 10, 2014 – Nov 19, 2015) *Note that monitoring did not begin until March 2015*
- Field Season 2 (Nov 20, 2015 – Nov 30, 2016)
- Field Season 3 (Dec 1, 2016 – Aug 31, 2017)

Any results from Field Season 1 are presented primarily for reference, as monitoring for this season was incomplete due to (1) the initial monitoring difficulties at some sites and (2) the late start of the monitoring in the middle of winter 2014-2015. Field Season 3 results are also incomplete for sites with year-round chloride export, but are shown for comparison to Field Season 2. Plots of daily time series of precipitation, road salt applications, chloride export, and water export are shown in Appendix A. Tables of monthly chloride and water loads by site are given in Section 5.2.

3.6.1 Weather

The timing of snowmelt, rain-on-snow, and rainfall events is very important for chloride (road salt) transport. Plots of daily mean air temperature, precipitation depth (snowfall and rainfall), and snow depth observed at the Minneapolis-St. Paul Airport (MSP) during the three field seasons are shown in Figure 3-6 to Figure 3-8. Major chloride export events are described briefly for each field season below. Air temperature and precipitation characteristics of the three field seasons (winters) are summarized in

Table 3-1. Note that monitoring for the project did not begin until early 2015, and that Field Season 3 does not span an entire year. All three winters experienced snowfalls that were far below the 1981-2010 average (54.4 in.) at MSP airport, while mean air temperatures and total precipitation (rain + snow) were above the 30-year average (45.0° F and 30.6 in., respectively).[2]

[2] http://www.dnr.state.mn.us/climate/twin_cities/normals.html

Table 3-1. Total snowfall, precipitation, and mean air temperature observed at Minneapolis-St. Paul Airport (MSP) over the three field seasons in this study, with 30-year annual climate normals for reference. Note difference in field season lengths. *Monitoring for Field Season 1 did not begin until March 2015 at most sites; temperature and precipitation shown for entire winter season for comparison to other field seasons.

Period	Start	End	Days	Total Precip (in)	Snowfall (in)	Mean Daily Air Temp (F)
Field Season 1*	11/10/2014	11/19/2015	374	35.0	32.4	47.2
Field Season 2	11/20/2015	11/30/2016	376	41.2	39.0	50.0
Field Season 3	12/1/2016	8/1/2017	243	21.0	29.7	45.5
1981-2010 Annual Mean (MSP):			*365*	*30.6*	*54.4*	*45.0*

Field Season 1 (Nov 10, 2014 – Nov 19, 2015). Monitoring for this season was incomplete (beginning in in early March at most sites), but a few events are worth noting:

(1) A short thaw around Jan 20, 2015 (similar in timing to Field Season 3, but much shorter in duration);
(2) A major snowmelt from Mar 8 – 12, by far the latest of any of the field seasons;
(3) A series of storms from Nov 11 – 18, 2015 that produced roughly 4 in. of total rainfall (at MSP), producing substantial chloride export at the Highway 36 ditch site when no salt had been applied since the previous winter.

Field Season 2 (Nov 20, 2015 – Nov 30, 2016). Major chloride export events:

(1) A mid-December rainfall event (0.75 in. on Dec 13-14), following a few small snowfall/road salt application events, produced early winter chloride export at some sites;
(2) A brief thaw on Feb 6-7, 2016, which was preceded by a major snowstorm on Feb 2;
(3) A substantial melt event occurred a couple of weeks later from Feb 19 – 28 beginning with a small rain-on-snow event on Feb 19, resulting in the greatest seasonal chloride export at most sites;
(4) A 0.85-inch rainfall (MSP) that occurred on Mar 16, which produced large chloride loads.

Field Season 3 (Dec 1, 2016 – Aug 1, 2017). Major chloride export events:

(1) About half of the winter's snow fell in December, such that a 1-inch rainfall event that occurred on Dec 25 resulted in a large export of chloride at most sites;
(2) Additional snowfall occurred in early January, followed by a prolonged period of above-freezing temperatures from Jan 17 – 25 that resulted in the winter's major snowmelt event, occurring much earlier than in previous years;
(3) A ~ 0.75-inch rainfall event on Feb 20 also caused significant chloride export at some sites, although little snowfall (or de-icer application) had occurred since the January thaw;
(4) A small snowfall event on Mar 12, preceded by fresh de-icer applications and followed by two days of warm weather, also caused substantial chloride export at some sites;
(5) Later in the season, frequent rainfall in April and May led to flushing of chloride from the pond sites.

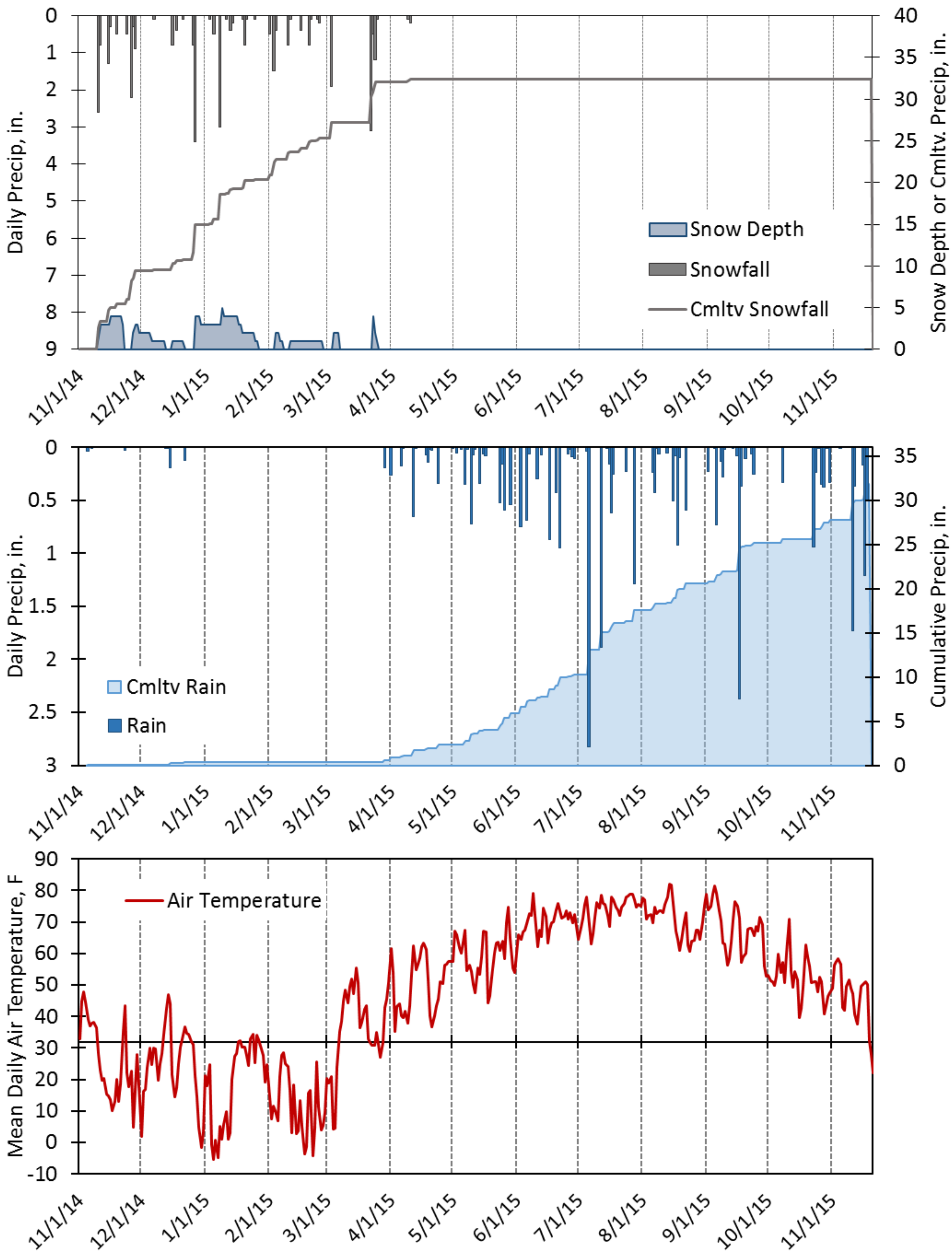


Figure 3-6. Time series of daily snowfall, snow depth, total precipitation and mean air temperature observed at Minneapolis-St. Paul Airport (MSP) during Field Season 1 (Nov 10, 2014 – Nov 19, 2015).

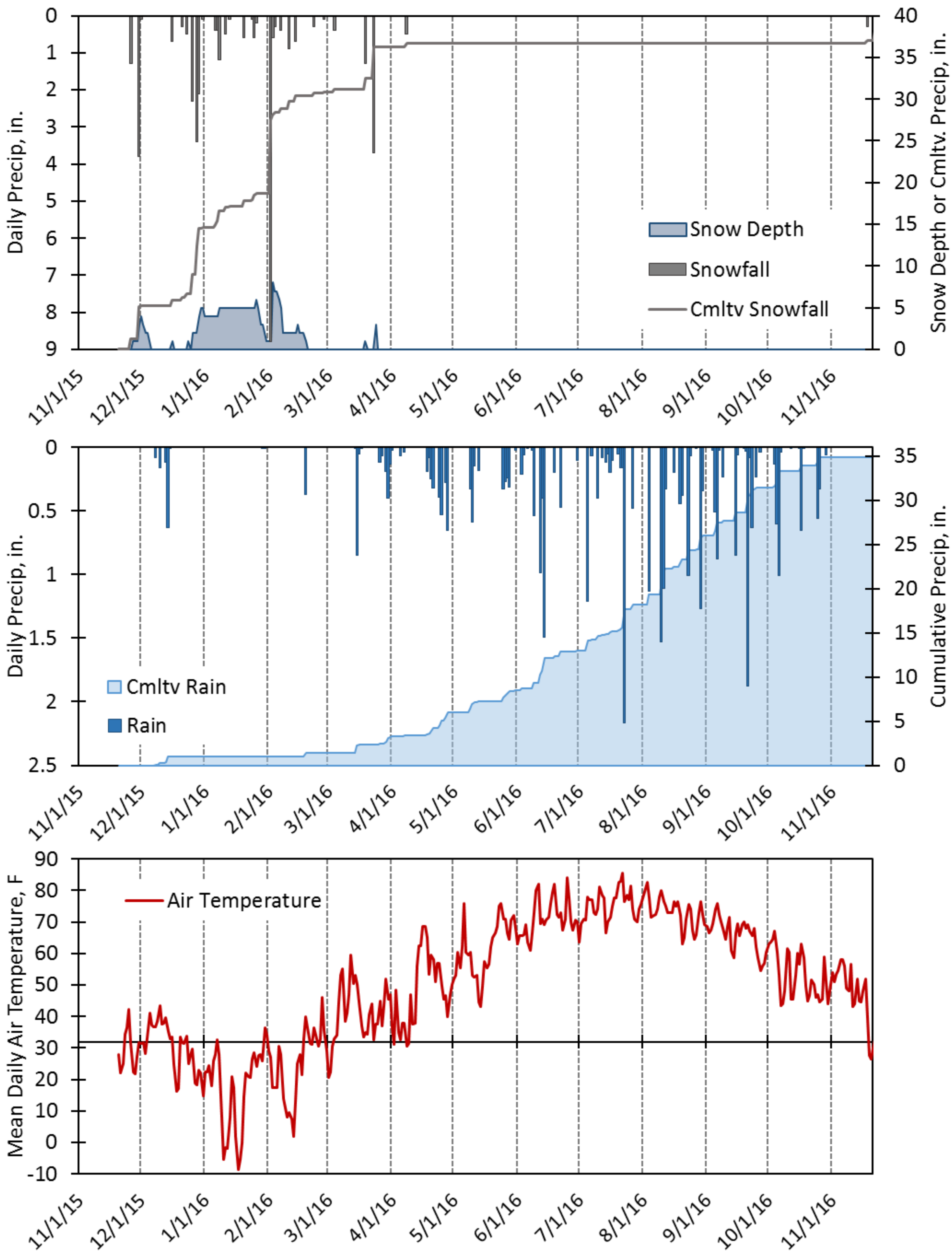


Figure 3-7. Time series of daily snowfall, snow depth, total precipitation and mean air temperature observed at Minneapolis-St. Paul Airport (MSP) during <u>Field Season 2</u> (Nov 20, 2015 – Nov 30, 2016).

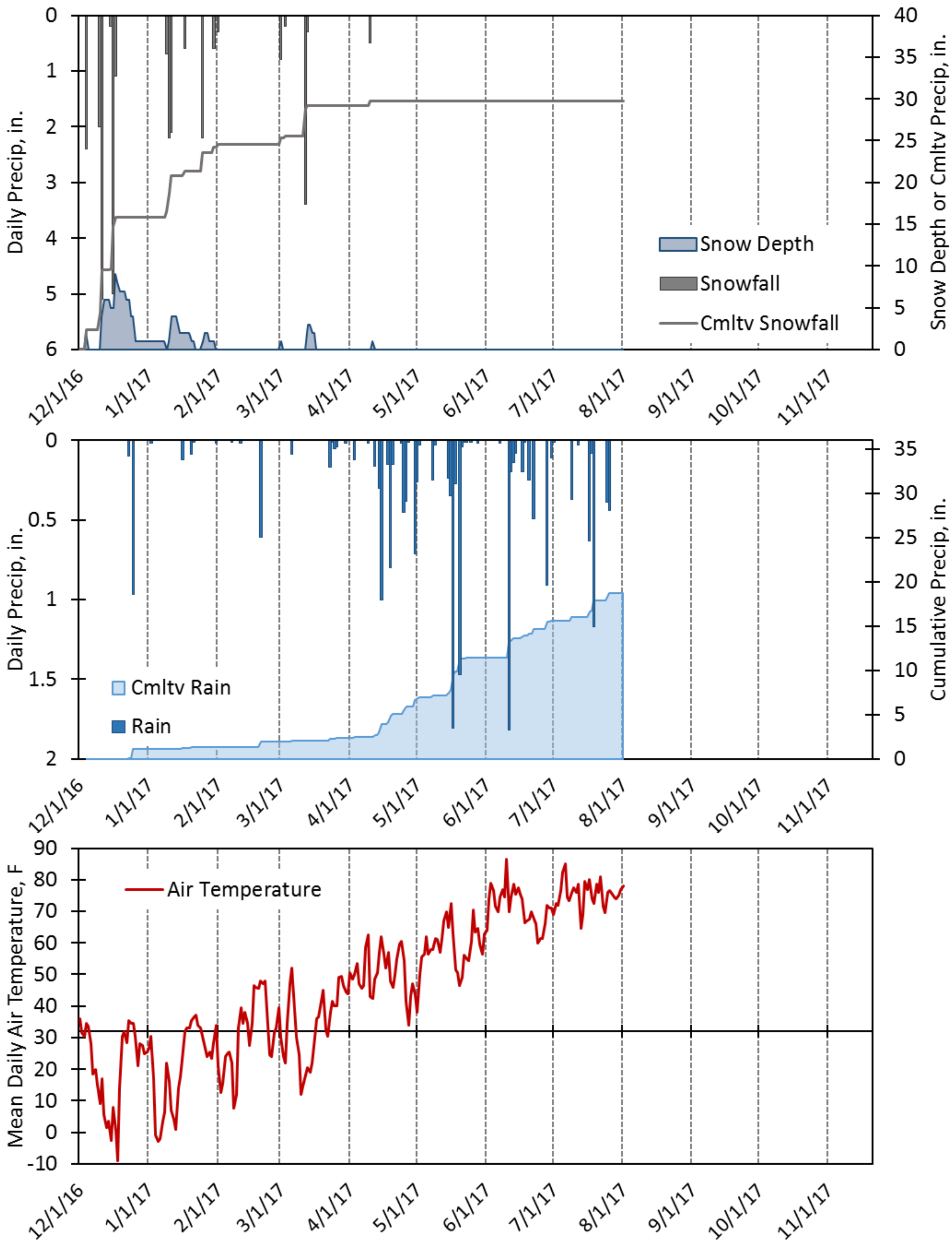


Figure 3-8. Time series of daily snowfall, snow depth, total precipitation and mean air temperature observed at Minneapolis-St. Paul Airport (MSP) during Field Season 3 (Dec 1, 2016 – Aug 1, 2017).

3.6.2 Data Analysis Results: County Road B

Monthly mean chloride and water loading for the County Road B site over two years of monitoring (Aug 1, 2015 – July 31, 2017) is shown in Figure 3-9, with monthly chloride loads by flow type (snowmelt vs. rainfall-runoff) shown in Figure 3-10. Chloride residence times and retention percentages, season totals, and other relevant outputs for Field Seasons 2 and 3 are shown in Table 3-2. Raw time series of precipitation, road salt application, chloride export, and water loading, with locations of time series centroids, are shown in Appendix A for Field Seasons 2 and 3.

Over the study period, high chloride export was observed during winter and spring at the County Road B site (Figure 3-9), and particularly during snowmelt (71% of total chloride loading was observed in snowmelt; Figure 3-10). Less chloride export occurred by rainfall (and rain-on-snow) events overall (29%), but was observed in all months of the winter (Nov – Apr). In Field Season 2, most chloride export occurred during the two major snowmelt events in February, while in Field Season 3, a majority of chloride export was associated with the three major snowmelt events (Dec 25 rainfall, late January thaw, and mid-March snowfall; see raw time series in Appendix A). Chloride loading became negligible by April (Figure 3-9 and Figure 3-10), shortly after the final road salt applications, as expected for a watershed consisting of a short (0.5-mile) section of roadway with no surface water storage by BMPs or surface features. Accordingly, in both field seasons, chloride residence times were relatively short in surface runoff (~14 - 26 days based on lag of road salt and runoff chloride centroids; Table 3-2). As expected, water yield (0.31 – 0.37 ac-ft per in. of precipitation; Table 3-2) was several times higher for this sewered, curb-and-gutter site than the vegetated ditch site (Highway 36; Table 3-3).

However, chloride retention was unexpectedly high given the lack of surface water storage in the watershed: roughly 66% of applied road salt in Field Season 2 was retained, with a much lower but substantial retention of 37% in Field Season 3. Potential mechanisms of chloride retention (i.e. loss to sub-surface storage in soil or groundwater, or transport not associated with surface runoff) could not be identified, but could include transport by wind or by vehicles, or infiltration of snowmelt from snow piled onto curbside areas by snowplows. The cause of the difference in retention between seasons is not apparent, but may be related to higher frequency of rainfall and snowmelt during Field Season 3 (see time series plots in Appendix A), which may have prevented chloride from infiltrating in roadside areas.

Table 3-2. Summary of chloride loading observed at the County Road B monitoring site during Field Season 2 (Nov 20, 2015 – Nov 30, 2016) and Field Season 3 (Dec 1, 2016 – Aug 1, 2017). Residence times were determined from centroids of time series. Retention is the fraction of applied road salt that is not observed in surface runoff.

	Field Season 2 (2015-16)			Field Season 3 (2016-17)		
	Road Salt Cl	Runoff Cl *observed*	Runoff Volume	Road Salt Cl	Runoff Cl *observed*	Runoff Volume
Total Mass or Volume	3,595 *lbs*	1,212 *lbs*	10.6 *ac-ft*	4,726 *lbs*	2,968 *lbs*	6.0 *ac-ft*
Yield (ac-ft/in. precip)	--	--	*0.31*	--	--	*0.37*
Chloride Retention (%)	--	66%	--	--	37%	--
Mean Conc (mg/L)	--	41.9	--	--	182.4	--
Centroid Date	1/10/16	2/5/16	6/15/16	1/11/17	1/26/17	6/11/17
Residence time, Cl (days)	26			14		

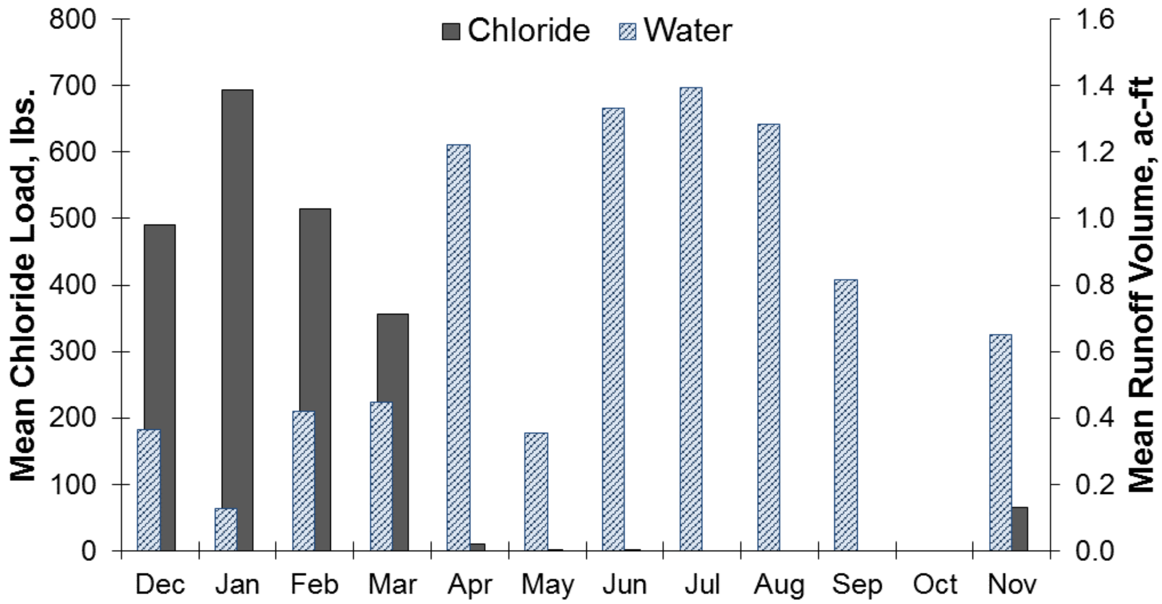


Figure 3-9. Mean monthly loading of chloride (lbs.; left axis) and water (ac-ft; right axis) observed at *County Road B* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017. The lack of October runoff data is due to temporary removal of the weir for site maintenance.

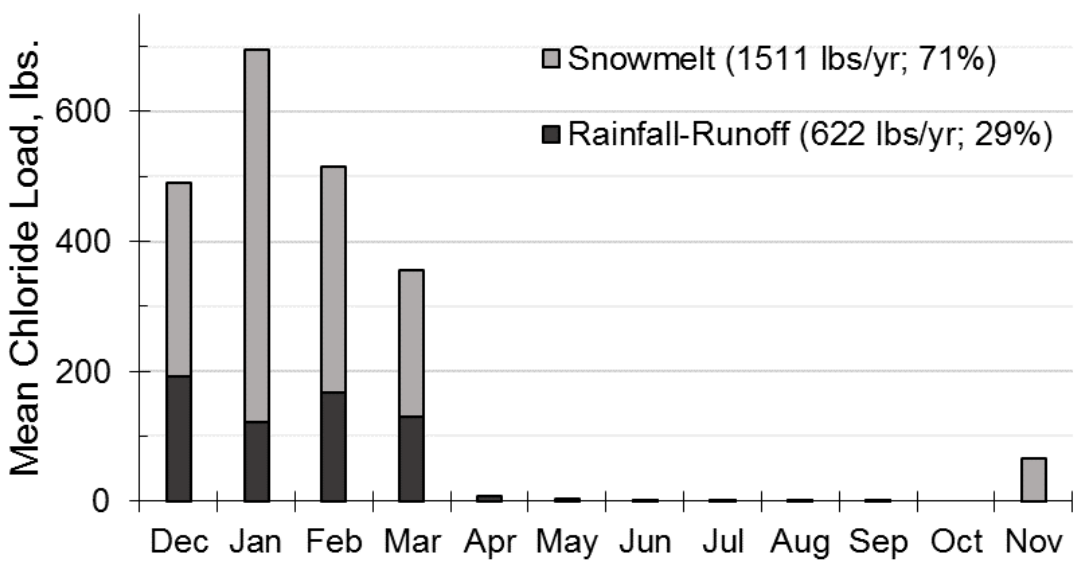


Figure 3-10. Mean monthly loading of chloride (lbs.) by flow regime (snowmelt vs. rainfall-runoff) observed at *County Road B* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017. Note that rain-on-snow events were considered rainfall-runoff.

3.6.3 Data Analysis Results: Highway 36 Ditch

Monthly mean chloride and water loading for the Highway 36 Ditch over two years of monitoring (Aug 1, 2015 – July 31, 2017) is shown in Figure 3-11, and monthly chloride loads by flow type (snowmelt vs. rainfall-runoff) are shown in Figure 3-12. Chloride residence times and retention percentages, season totals, and other relevant outputs for Field Seasons 2 and 3 are given in Table 3-3. Raw time series of precipitation, road salt application, chloride export, and water loading, with locations of time series centroids, are plotted in Appendix A.

Several features of the results at the Highway 36 Ditch site are noteworthy:

(1) Chloride export from the ditch was very low compared to estimated road salt inputs along the highway (~6% in both field seasons; Table 3-3);

(2) Export of chloride occurred during winter and spring snowmelt and rainfall, as at other sites, but was highest in late autumn rainfall, prior to salt application for the upcoming winter (Figure 3-11);

(3) Chloride residence time in surface runoff was unexpectedly long, at 172 days (Field Season 2;Table 3-3);

(4) In contrast to the curb-and-gutter roadway site (County Road B), most chloride export occurred in rainfall-runoff (73%) as opposed to snowmelt (23%; Figure 3-12);

(5) Similarly, little runoff occurred from the site in general except during very rainy periods (e.g., May 2017, July and Aug 2016; see time series in Appendix A), and water yield (0.10 – 0.12 ac-ft per in. of precipitation, Table 3-3) was roughly one-third that of the sewered County Road B site.

Together these results suggest substantial infiltration of runoff in the ditch system in general, resulting in very high retention of chloride (>94%). The importance of rainfall-runoff and rain-on-snow events for chloride export from the ditch (Figure 3-12), suggests that low-energy flows like snowmelt tend to infiltrate in the ditch. However, large volumes of snowmelt, such as were observed during prolonged thaws in January 2016 and January 2017, led to appreciable chloride export from the ditch (Figure 3-11, Figure 3-12).

While chloride export was minimal during summer, fall was especially important: in Field Season 1, two large storms in mid-November (~4” rain total at MSP), which produced less runoff than some earlier storms in July, still resulted in similar chloride export as all of Field Season 2 (Appendix A). A similarly large export event occurred also during fall of 2016 (Field Season 2). In both cases, no road salt had been applied on the roadway since the previous winter. These patterns suggest that the infiltrated chloride may be stored in the ditch soils or shallow groundwater until fall, when the water table may rebound from lack of evapotranspiration by growing vegetation and/or inputs from large storms (for which infiltration rates are higher than in summer storms due to reduced evaporation and interception), producing interflow rates high enough to flush chloride from the ditch soils.

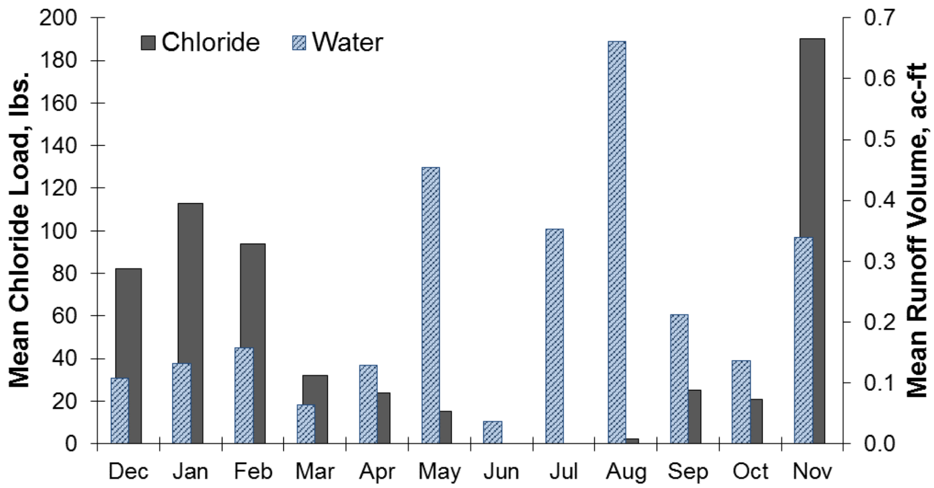


Figure 3-11. Mean monthly loading of chloride (lbs.; left axis) and water (ac-ft; right axis) observed at *Highway 36 Ditch* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017.

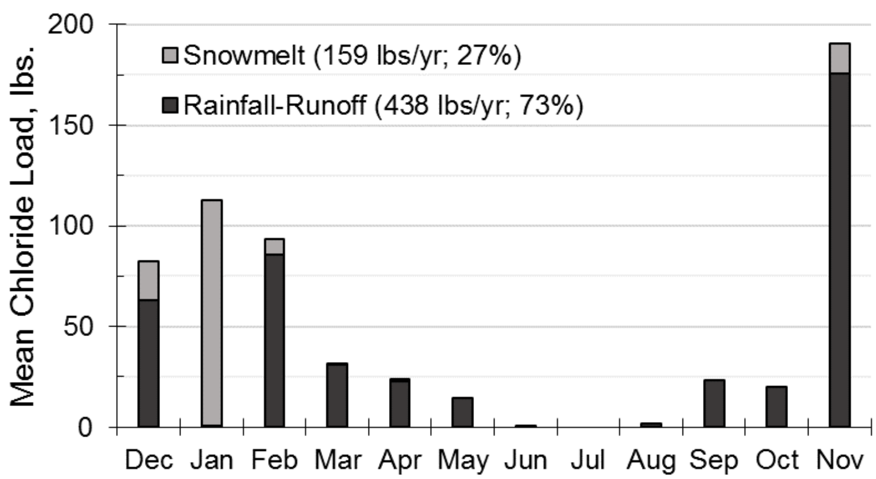


Figure 3-12. Mean monthly loading of chloride (lbs.) by flow regime (snowmelt vs. rainfall-runoff) observed at *Highway 36 Ditch* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017. Note that rain-on-snow events were considered rainfall-runoff.

Table 3-3. Chloride loading observed at the Highway 36 Ditch site during Field Season 2 (Nov 20, 2015 – Nov 30, 2016) and Field Season 3 (Dec 1, 2016 – Aug 1, 2017). Residence times determined from centroids of time series. Retention is the fraction of chloride in applied road salt not observed in surface runoff from the watershed.

	Field Season 2 (2015-16)			Field Season 3 (2016-17)		
	Road Salt Cl	Runoff Cl *observed*	Runoff Volume	Road Salt Cl	Runoff Cl *observed*	Runoff Volume
Total Mass or Volume	6,233 *lbs*	375 *lbs*	3.2 *ac ft*	9,012 *lbs*	556 *lbs*	1.8 *ac ft*
Yield (ac-ft/in. precip)	--	--	0.10	--	--	0.12
Chloride Retention (%)	--	94.0%	--	--	93.8%	--
Mean Conc (mg/L)	--	43	--	--	117	--
Centroid Date	1/8/16	6/29/16	6/29/16	1/24/17	1/29/17	4/5/17
Residence time, Cl (days)		**172**			**5**	

Ditch Piezometers

Two piezometers installed in the ditch were instrumented to record water level during a portion of Field Season 3 in order to assess the role of interflow or groundwater input contributing to chloride export from the site. Piezometer #1 was located roughly 100m upstream from the outlet of the ditch, and Piezometer #2 was located in a portion of the ditch connected to the main ditch by a culvert (Figure 2-3). Data from piezometer #3 were unusable, as the data logger had been accidentally removed during a site visit. Water level data are shown in Figure 3-13 as depth-to-water (depth below ground surface). The screen level in the piezometers is approximately 4.5 feet below ground surface (the greatest depth achievable with hand installation), so gaps in the time series indicate that water level was deeper than screen depth. Given that the monitored storm pipe exiting the ditch was at a greater depth than the screen, water moving (undetected) through soil beneath the screen depth could still be intercepted and exported by this pipe.

A few remarks pertaining to the observed water levels in the piezometers (Figure 3-13):

(1) Shallow groundwater may be responsible for some export of chloride, particularly in late fall, as suggested by the presence of water in Piezometer #1 near the ditch outlet during chloride export associated with rainfall in November 2016, prior to application of road salt. Water may also be moving laterally towards the ditch outlet at a greater depth than observable by the piezometers, contributing to export of salt infiltrated in past events.
(2) Some chloride export from the ditch is likely associated primarily with surface runoff, such as during the December 25 rainfall, January snowmelt, and the February 20 rainfall events, as very small increases in water level were observed in the piezometers despite high fluxes of chloride from the ditch during these events.
(3) The increases in piezometer water level observed during and shortly after the major chloride exports events (e.g., in December, January, and February) as well as for a small snowmelt event (mid-March) during a dry spring period, may indicate infiltration of surface water. This water would have high concentration of chloride, and potentially contribute to chloride storage or delayed export from the ditch.
(4) Similarly, the decreases in piezometer water level after these flux events may indicate movement of water, either downward into deeper soil or laterally towards the outlet. Loss via evapotranspiration would be negligible during this time. This water would also likely have high chloride content and, particularly if moving downward, could represent a mechanism for chloride storage or (unobserved) loss to greater soil depth in the ditch.

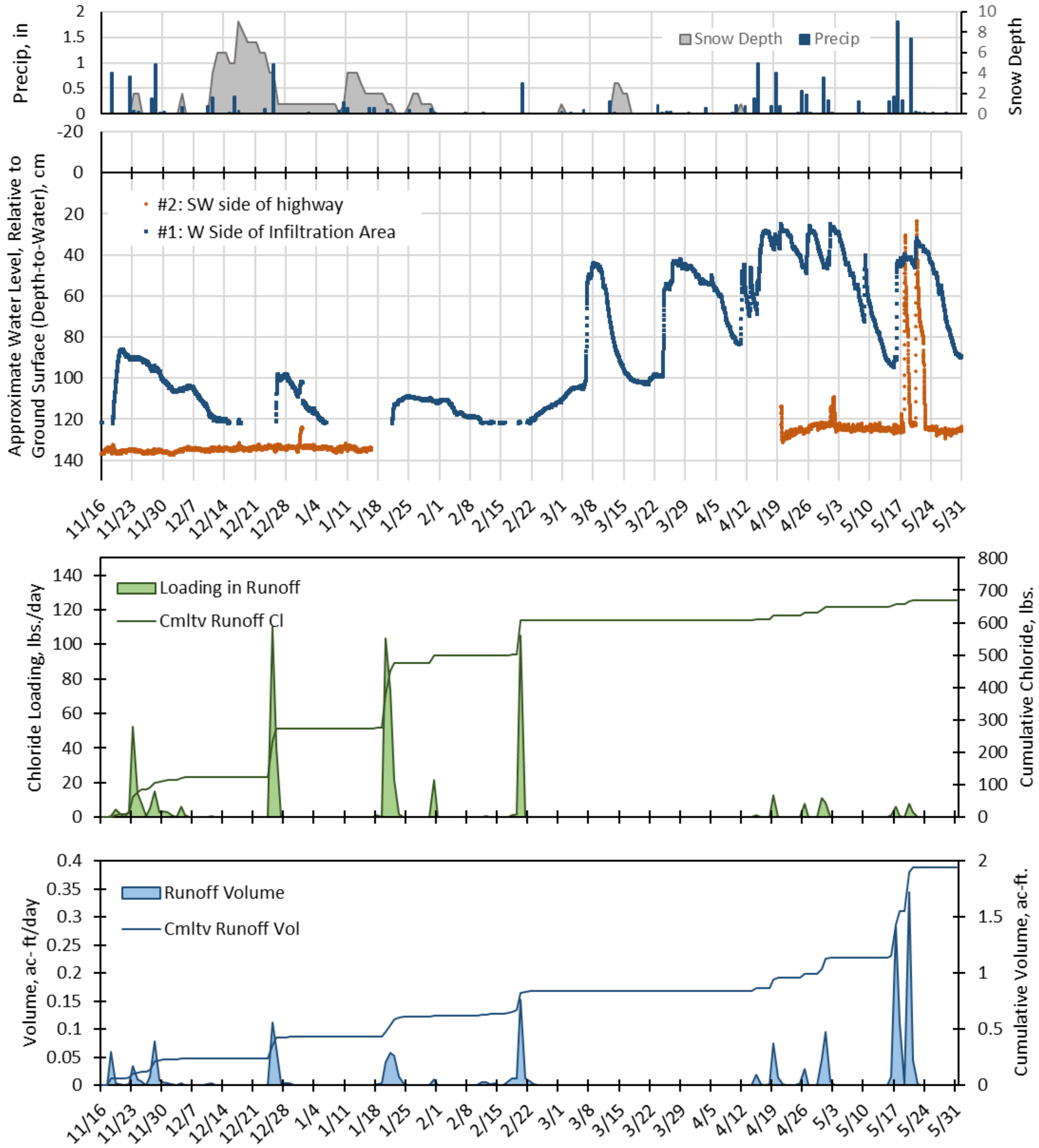


Figure 3-13. Time series of water level (depth-to-water) in two of the ditch piezometers at *HIGHWAY 36* from Nov 16, 2016 – May 31, 2017 (2nd plot), shown with precipitation and snow depth at the MSP airport (top plot), cumulative loading of chloride in runoff (green; 3rd plot), and of runoff volume (light blue; 4th plot) for reference. Gaps in depth-to-water time series indicate that piezometers were dry (i.e. water level was below screen level, which was approximately 4.5 feet below the ground surface).

3.6.4 Data Analysis Results: Alameda Pond

Monthly mean chloride and water loading for Alameda Pond Inlet and Outlet over two years of monitoring (Aug 1, 2015 – July 31, 2017) is shown in Figure 3-14, with monthly chloride loads by flow type (snowmelt vs. rainfall-runoff) shown in Figure 3-15. Approximate chloride residence times and retention percentages, season totals, and other relevant outputs for Field Seasons 2 and 3 are shown in Table 3-4 for both sites. Raw time series of precipitation, road salt application, chloride export, and water loading, with locations of time series centroids, are shown in Appendix A for the Inlet (Seasons 2 and 3) and the Outlet (Seasons 1 - 3).

Chloride retention in the Alameda Pond watershed was significant, with roughly 65% and 19% of applied road salt being retained in the watershed in Field Seasons 2 and 3, respectively, based on monitoring at the Inlet (Table 3-4). When considering the effect of the pond, chloride retention was lower (50% at the Outlet vs. 65% at the Inlet in Field Season 2), meaning that more chloride was exported from the pond than was observed flowing into it in surface runoff. This suggests that some chloride enters the pond in groundwater, or also that some uncertainty is associated with field measurements; for example, in Field Season 2 because of a crucial gap in monitoring data during early February snowmelt (Section 3.2.2), and in Field Season 3 because application amounts of road salt had to be estimated for Ramsey County (Section 2.4.5). In previous years, the County contributed approximately 50% of the road salt applied in this watershed. Regardless of these uncertainties, significant chloride retention was observed in the pond watershed, and is a sensible result given substantial upstream storage potential in the watershed due to the presence of wetlands connected to the storm drain network. The much lower retention in Field Season 3 (compared to Field Season 2), even despite being incomplete, is a pattern observed at the other sites as well, and may be related to earlier and more frequent snowmelt and rainfall events in Field Season 3.

Several observations suggest that Alameda Pond has a large capacity for chloride storage. First, slightly more than half (56%) of chloride loading to the pond (Alameda Inlet) from its watershed occurred during snowmelt (Figure 3-15a), and primarily during winter months (Nov – Feb). By contrast, chloride export from the pond (Alameda Outlet) was caused almost entirely by rainfall events (94%; Figure 3-15b), and was observed throughout the open-water season (roughly April to November). The highest chloride loads from Alameda Pond coincide with late spring rainfall after ice-out on the pond (April and May; Figure 3-14b), suggesting flushing of winter and spring chloride inputs, while chloride export during the rest of the season was associated with especially rainy periods, e.g. fall 2015 and 2016, or spring and summer 2017 (Appendix A). The persistence of chloride export from the pond (and of chloride loading to the pond) over the entire open water season suggests that residence time of chloride in the pond and its watershed is considerable, and that chloride may be stored year-to-year. Accordingly, residence time of chloride in Alameda Pond, as estimated from the definition of hydraulic residence time (see Section 3.5), ranged from 264 days (Field Season 2) to 278 days (Field Season 3). Water quality profiles measured in Alameda Pond suggest a strong and fairly stable density (temperature and salinity) stratification during most of the year. The role of this stratification on the timing and duration of chloride export is explored in Section 0

Chloride residence time in the Alameda Pond watershed was much longer than in the County Road B watershed and similar to the Highway 36 ditch site, based on the centroid difference estimate (158 days, Field Season 2; 3 days, Field Season 3). The apparent short residence time in Field Season 3 is due to two factors: (1) the two substantial chloride export events were very early in winter (December 25 rainfall and mid-January thaw), which resulted in much earlier chloride export than in previous field seasons; and (2) potentially substantial export from the watershed during fall, observed during both Field Season 1 and Field Season 2 (Appendix A), was not monitored in Field Season 3. The residence time would be expected to increase in Field Season 3 if monitoring had been continued through fall.

Table 3-4. Summary of chloride loading observed at the (a) ALAMEDA POND INLET and (b) ALAMEDA POND OUTLET monitoring sites during Field Season 2 (Nov 20, 2015 – Nov 30, 2016) and Field Season 3 (Dec 1, 2016 – Aug 1, 2017). Residence times are determined from centroids of chloride runoff or outflow time series, and with respect to the centroid of the time series of salt application in the connected watershed. Retention is the fraction of chloride in applied road salt that is not observed in surface runoff. *Residence time of chloride in the pond is estimated similarly to hydraulic residence time (inflow load / outflow rate).

(a) Alameda Pond Inlet	Field Season 2 (2015-16)			Field Season 3 (2016-17)		
	Road Salt Cl	Runoff Cl *observed*	Runoff Volume	Road Salt Cl	Runoff Cl *observed*	Runoff Volume
Total Mass or Volume	19,130 *lbs*	6,705 *lbs*	98.1 *ac-ft*	21,864 *lbs*	17,654 *lbs*	63.0 *ac-ft*
Yield (ac-ft/in. precip)	--	--	2.38	--	--	2.99
Chloride Retention (%)	--	65%	--	--	19%	--
Mean Conc (mg/L)	--	26	--	--	103	--
Centroid Date	1/12/16	6/18/16	7/28/16	1/24/17	1/28/17	4/8/17
Residence time, Cl (days)	**158**			**3**		

(b) Alameda Pond Outlet	Field Season 2 (2015-16)			Field Season 3 (2016-17)		
	Road Salt Cl	Runoff Cl *observed*	Runoff Volume	Road Salt Cl	Runoff Cl *observed*	Runoff Volume
Total Mass or Volume	19,130 *lbs*	9,570 *lbs*	93 *ac-ft*	21,864 *lbs*	15,422 *lbs*	55 *ac-ft*
Yield (ac-ft/in. precip)	--	--	2.26	--	--	2.60
Chloride Retention (%)	--	50%	--	--	29%	--
Mean Conc (mg/L)	--	38	--	--	104	--
Centroid Date	1/12/16	6/30/16	7/13/16	1/24/17	4/24/17	4/30/17
Residence time, Cl (days)	**170**			**90**		
Res. time of Cl in pond*, (days)	**264**			**278**		

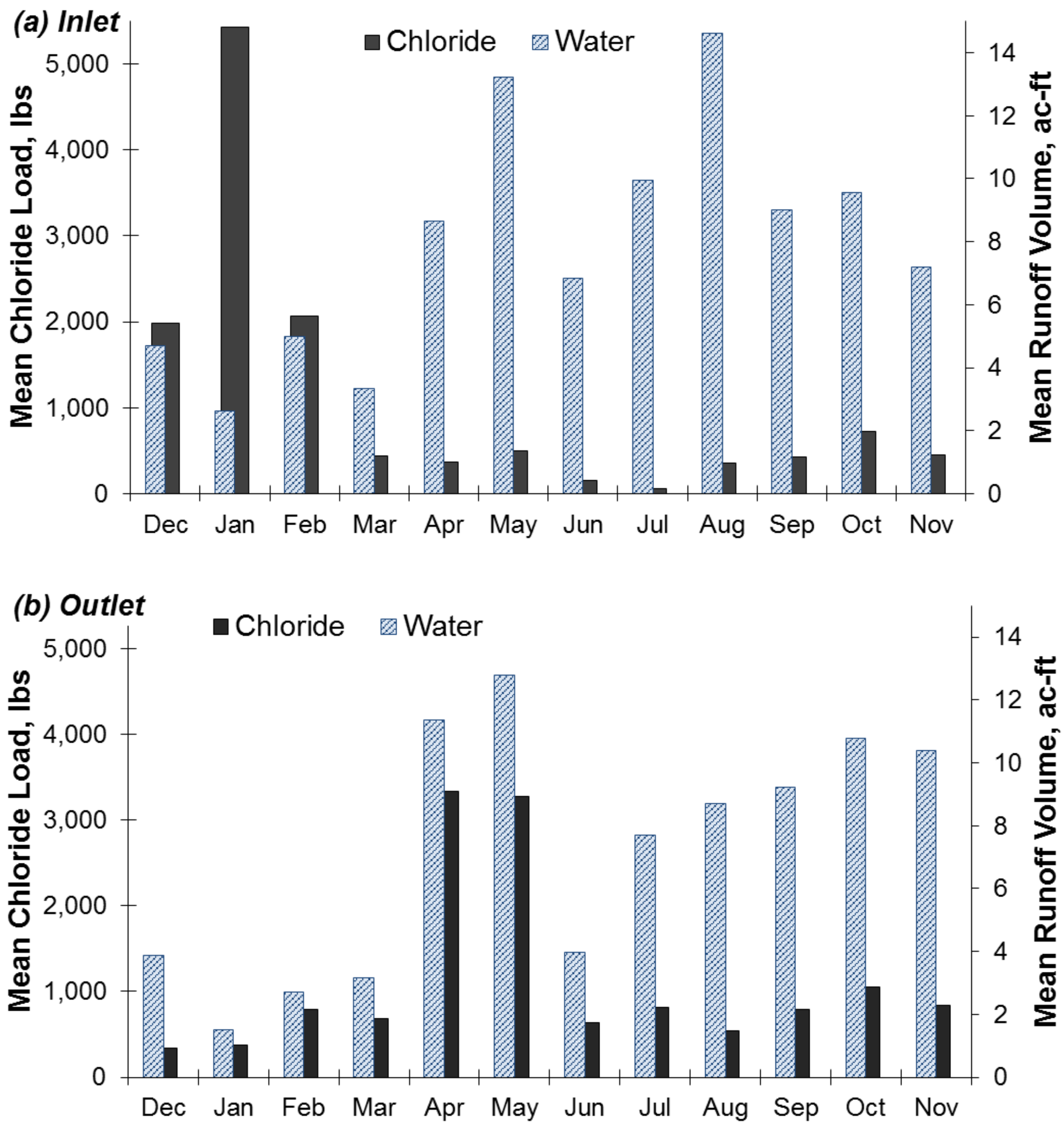


Figure 3-14. Mean monthly loading of chloride (lbs.; left axis) and water (ac-ft; right axis) observed at (a) *Alameda Pond Inlet* and (b) *Alameda Pond Outlet* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017. Vertical scales are identical between plots.

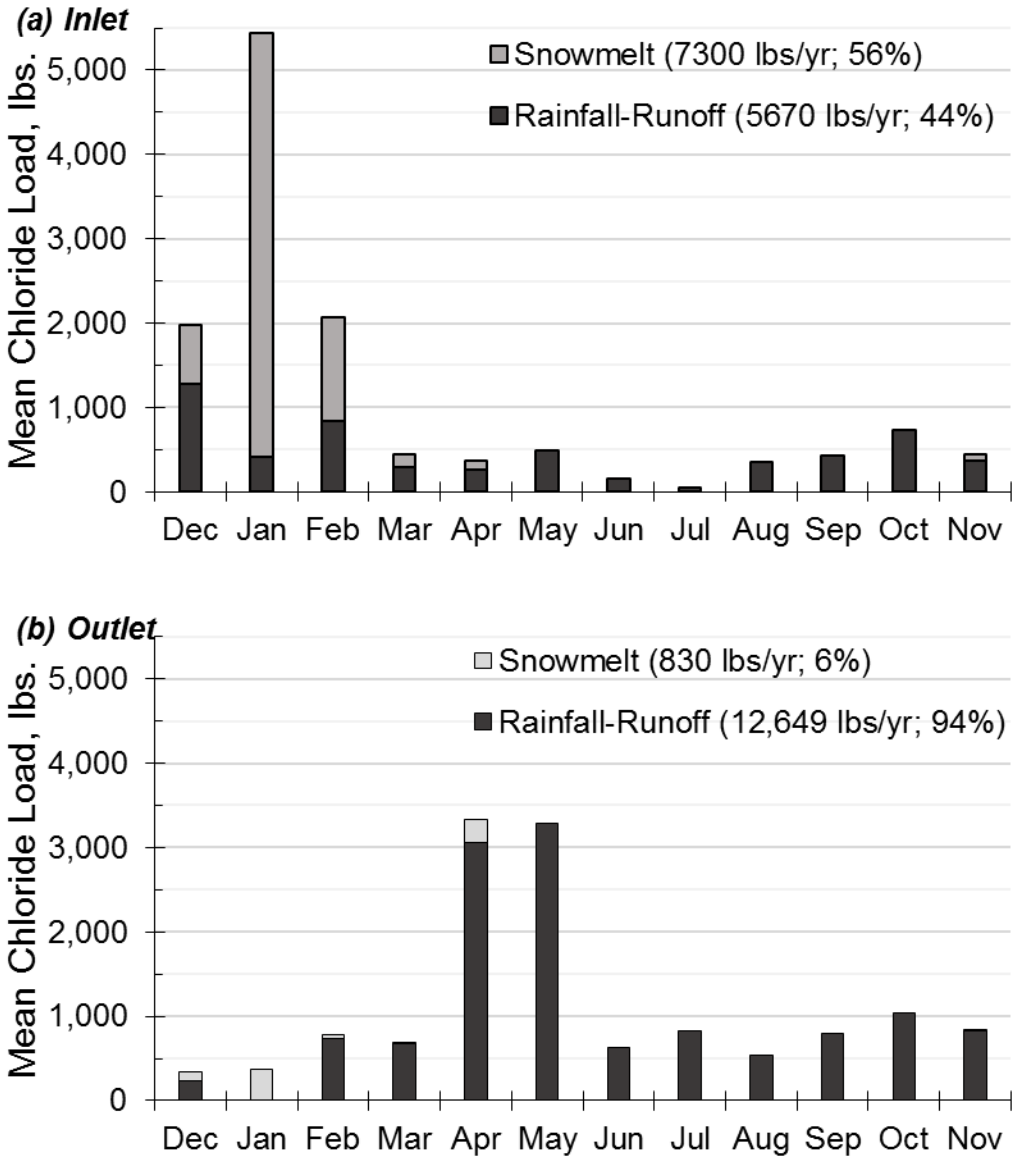


Figure 3-15. Mean monthly loading of chloride (lbs.) by flow regime (snowmelt vs. rainfall-runoff) observed at (a) *Alameda Pond Inlet* and (b) *Alameda Pond Outlet* over two years of continuous monitoring Aug 1, 2015 – Jul 31, 2017. Note that rain-on-snow events were considered rainfall-runoff. Vertical scales are identical between plots.

3.6.5 Data Analysis Results: William Street Pond

William Street Pond was considered a lower priority site than those presented above, and damage to a conductivity logger at the Inlet site in Field Season 3 prevented the estimation of a complete chloride budget for the pond. Data are incomplete for the other field seasons and are not shown.

Results for the Outlet site are shown here primarily for comparison to those from the Alameda Pond site, and include monthly loading of chloride and water for Field Season 3 (Figure 3-16), along with the breakdown of monthly chloride loads between snowmelt and rainfall-runoff (Figure 3-17). The water and chloride loading time series and centroids for William Street Pond Outlet are shown in Appendix A. Season totals, approximate chloride residence time and retention percentages, and other relevant outputs are given in Table 3-5. Note that the residence time is computed similarly to hydraulic residence time (inflow load / outflow rate; Section 3.5), using applied road salt chloride as the inflow load since an accurate inflow chloride load was not available.

The pond exports approximately 12% more chloride than was applied in road salt in the upstream watershed. This may indicate that outflow discharge measurements are positively biased, or that groundwater inputs (which are likely present at this pond), may be contributing chloride infiltrated in other parts of the watershed. The residence time of chloride in the pond, 216 days, was a bit shorter than that observed for the Alameda Pond (278 days) in Field Season 3. Chloride loading at the William Street Pond (WSP) Outlet (Figure 3-16) was similar in timing to that of the Alameda Pond (Figure 3-14): chloride export was associated primarily with rainfall events (93%) throughout the season, with the largest fluxes in May presumably resulting from flushing of the previous winter's road salt chloride during spring rainfall.

Table 3-5. Summary of chloride loading observed at the WILLIAM STREET POND OUTLET monitoring site during FIELD SEASON 3 (Dec 1, 2016 – Aug 1, 2017). Residence time is determined from the difference in centroids of the time series of chloride in outflow and of salt application in the connected watershed. Retention is the fraction of chloride in applied road salt that is not observed in pond outflow. *Negative retention indicates export of chloride from the pond was greater than that observed in road salt applications in the watershed.

	Field Season 3 (2016-17)		
	Road Salt Cl	Runoff Cl *observed*	Runoff Volume
Total Mass or Volume	3,113 *lbs*	3,490 *lbs*	16.1 *ac-ft*
Yield (ac-ft/in. precip)	--	--	0.88
Chloride Retention (%)	--	-12%*	--
Mean Conc (mg/L)	--	80	--
Centroid Date	1/17/2017	4/23/2017	4/26/2017
Res. time of Cl in pond, (days)	**216**		

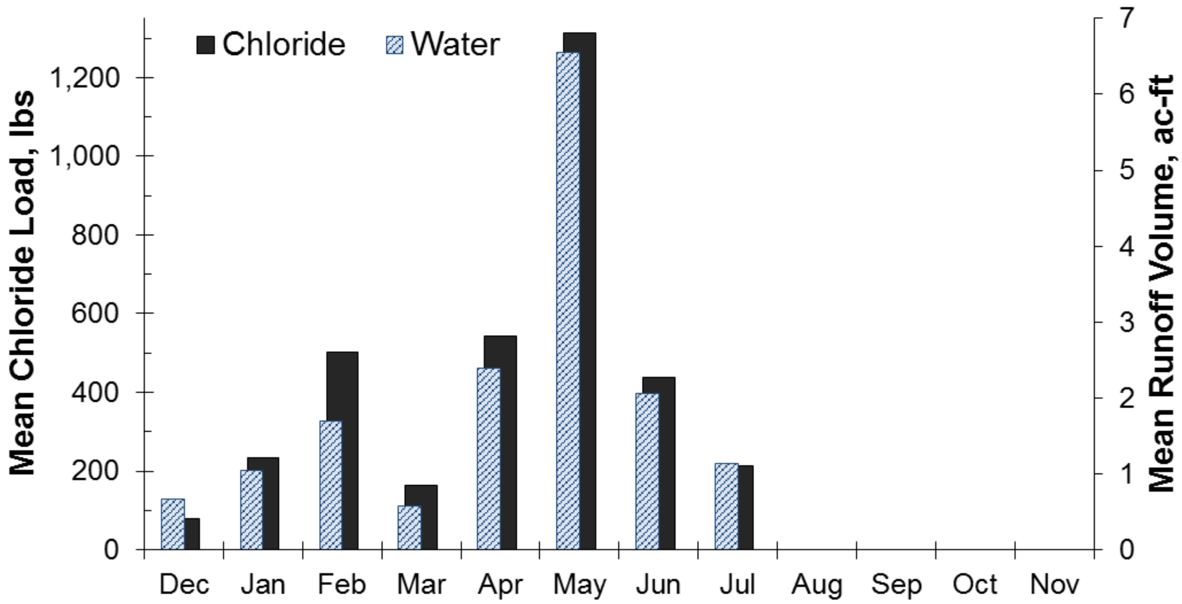


Figure 3-16. Monthly loading of chloride (lbs.; left axis) and water (ac-ft; right axis) observed at ***William Street Pond Outlet*** during ***Field Season 3*** (Dec 1, 2016 – Jul 31, 2017). Note that this plot differs from the similar plots shown above for the main field sites, which show monthly mean loads over two years of the study. Only one field season of data were available at this site.

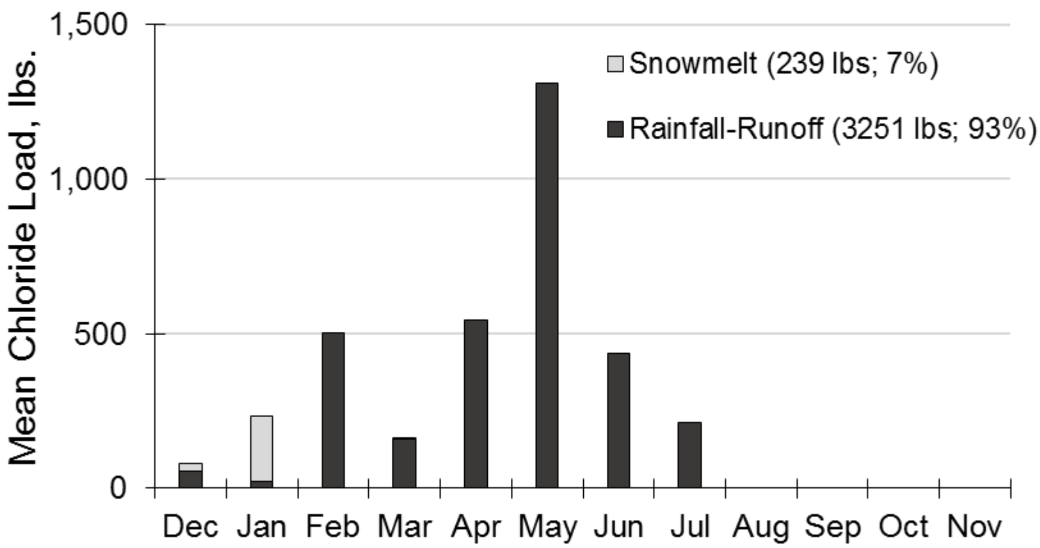


Figure 3-17. Monthly loading of chloride (lbs.) by flow regime (snowmelt vs. rainfall-runoff) observed at ***William Street Pond Outlet*** during ***Field Season 3*** (Dec 1, 2016 – Jul 31, 2017). Note that this plot differs from the similar plots shown previously for the main field sites, which show monthly mean loads over two years of the study. Only one field season of data were available at this site. Rain-on-snow events were considered rainfall-runoff.

3.7 CHLORIDE RETENTION AND EXPORT BY STORMWATER PONDS

Strong temperature stratification and salinity stratification were observed in several stormwater ponds during all three winters (ice cover periods) of the study. These ponds include the Alameda Pond, William Street Pond, Villa Park Sedimentation Basin, and Villa Park Detention Pond (Figure 2-1). Temperature and conductivity profiles for all sites are shown in Appendix B. In this section, water column profiles of conductivity and outflow conductivity time series are shown for the Alameda Pond and William Street Pond for Field Season 3, in which profiles were collected at more frequent intervals (weekly to monthly) during both ice cover and open water periods. These data show the persistence of stratification in these ponds during the spring and summer, which increases chloride retention and prolongs residence time in detention ponds.

3.7.1 Alameda Pond

Water column profiles of specific conductivity (and temperature) were measured in Alameda Pond during Field Season 3 on eight dates between Dec 2016 and July 2017 and are shown in Figure 3-18. The two plots, [top] representing the pond with ice cover and [bottom] the open-water period, clearly show a salinity stratification in the pond that varies seasonally. Beginning with a well-mixed condition of low salinity in mid-December, the salinity stratification at the bottom of the pond starts at the latest in December after road salt applications have begun and a few snowmelt events have occurred, reaches a maximum in February when the pond is ice-covered, and diminishes gradually throughout the open-water period (from May onward). From May to July, a well-mixed surface layer of nearly uniform salinity appears, i.e. the pond mixes from the top down in this period, and some salinity is lost by the outflow from the pond. This sequence suggests that Alameda Pond stores chloride from winter and spring inflows in water layers that have increasing salinity and hence density towards the bottom of the pond. The density gradient or stratification with depth hinders substantial interaction or mixing between layers except by diffusion or weak turbulence from inflow and outflow, convective cooling, or wind-mixing events.

The intense stratification and short lag time between water discharge and chloride centroids (~5 days; Appendix A) implies that concentration of chloride in the outflow from Alameda Pond did not vary greatly during open-water conditions. Accordingly, the daily mean conductivity (chloride) at the outlet was relatively constant over the open water season (after peaks in February and March), decreasing only slowly with time (Figure 3-19), and roughly matching conductivity observed in the top 75 cm of the pond's water column (Figure 3-18). The excursion in daily mean conductivity at the outlet on Feb 20, 2017 was likely caused by relatively low-chloride runoff from a rainfall event that day. The time series of conductivity at the outlet also showed much less seasonal variability than at the inlet site (Figure 3-19), illustrating the role of the pond in detaining chloride inputs from the watershed.

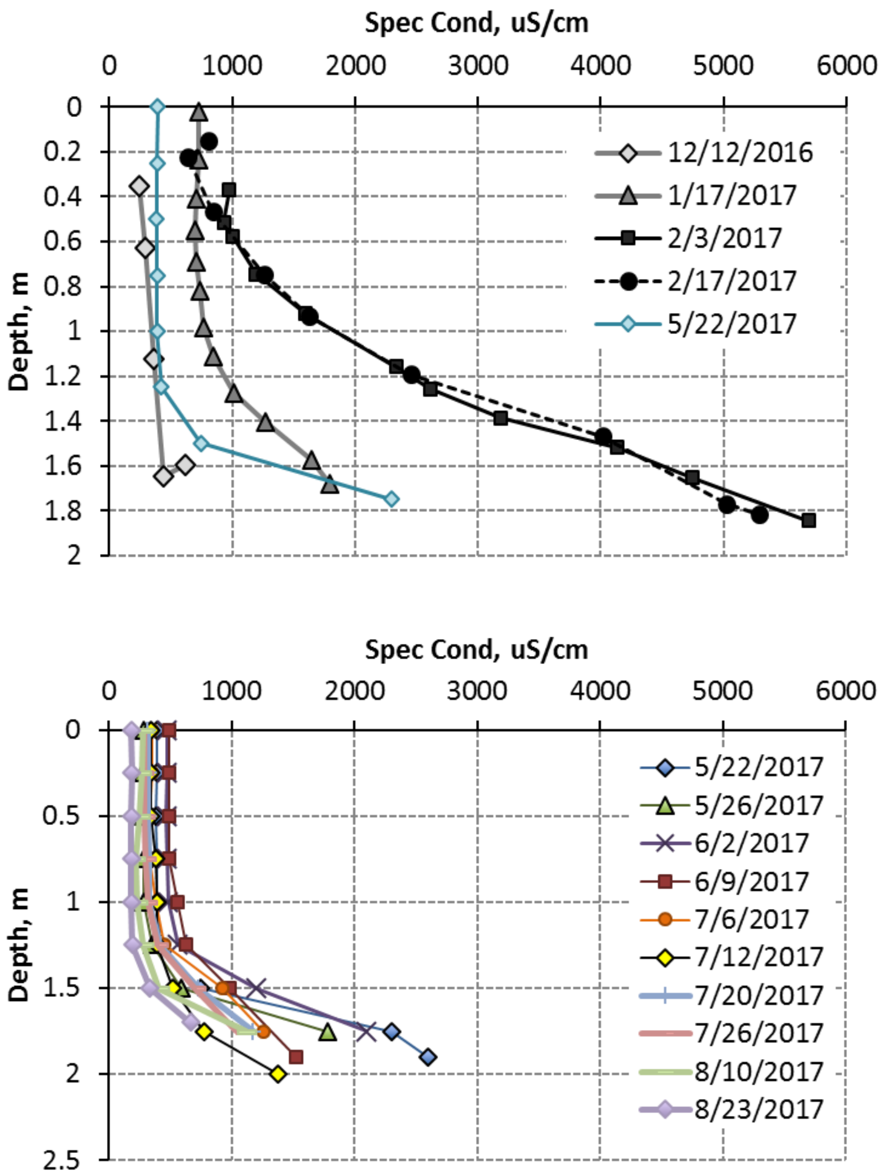


Figure 3-18. Water column profiles of specific conductivity observed at Alameda Pond during Field Season 3: [top] ice cover and [bottom] open-water periods. Note that the 5/22 profile was collected during open water and is shown on both plots for reference.

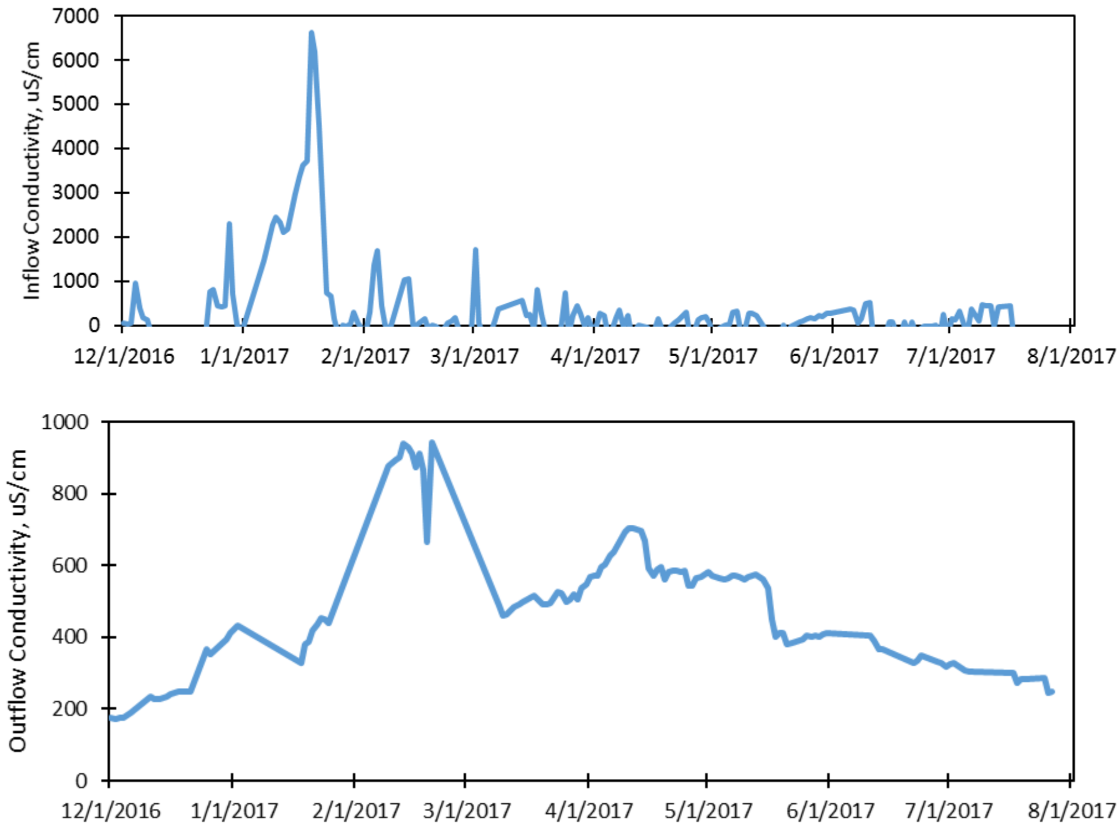
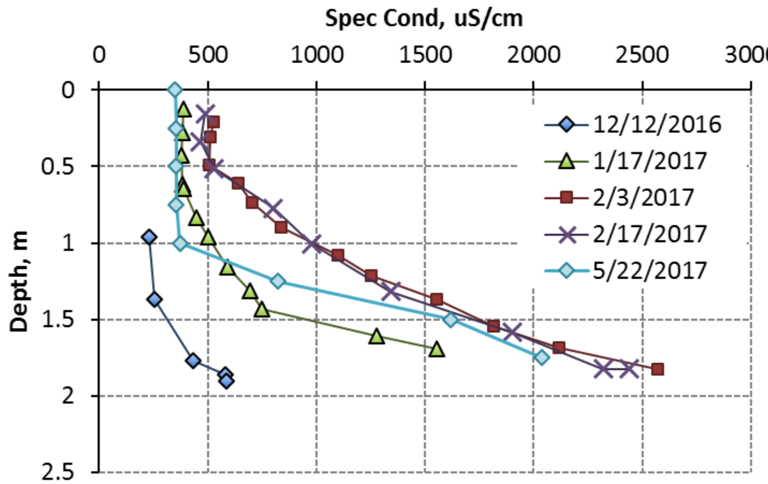


Figure 3-19. Time series of daily mean specific conductivity (uS/cm) of [top] inflow to and [bottom] outflow from the Alameda Pond from Dec 1, 2016 – Aug 1, 2017 (Field Season 3).

3.7.2 William Street Pond

As shown in Figure 3-21, outflow conductivity (chloride) from the William Street Pond was relatively consistent throughout the season, decreasing over time during the warm season and roughly matching conductivity of the middle 100 cm of the water column (Figure 3-20). This pattern may be produced by the subsurface withdrawal at the William Street Pond outlet (submerged pipe), such that water is taken from the middle of the water column (roughly 1m below the water surface), as opposed to the Alameda Pond, which has a weir at the outlet that causes more water from the top of the water column to be discharged. Conductivity observed at the outlet of William Street Pond also tended to increase after rainfall events (Figure 3-16 and Figure 3-21), while at Alameda Pond, conductivity was much steadier following rainfall events. This pattern, too, may be caused by the submerged withdrawal of water from lower in the water column in the pond: this level of the pond may receive chloride from groundwater or via diffusion from sediments or more saline water at the bottom of the pond. The generally higher conductivity measured at the bottom of William Street Pond (Figure 3-20) compared to Alameda Pond (Figure 3-18) later in the season suggests that William Street Pond may be receiving other chloride inputs (groundwater) or that inflows mix even more weakly in William Street Pond than in Alameda Pond, perhaps due to the much smaller surface area of WSP, resulting in more wind sheltering.



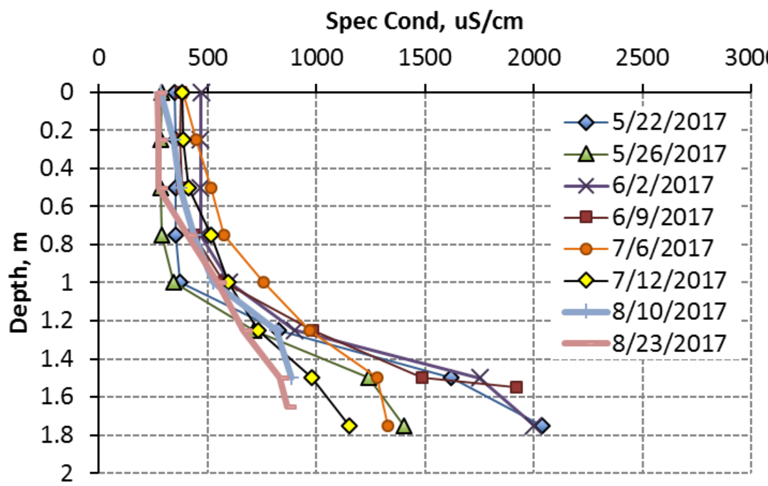


Figure 3-20. Water column profiles of specific conductivity observed at William Street Pond during Field Season 3: [top] ice cover and [bottom] open-water periods. Note that the 5/22 profile was collected during open water and is shown on both plots for reference.

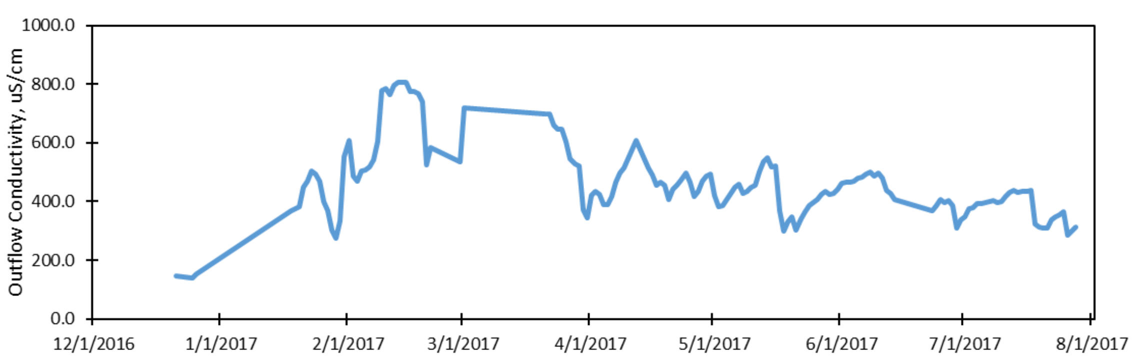


Figure 3-21. Time series of volume-weighted specific conductivity (uS/cm) of outflow from the William Street Pond from Dec 1, 2016 – Aug 1, 2017 (Field Season 3).

3.8 CUMULATIVE FREQUENCY OF CHLORIDE LOADING AT PRIMARY SITES

The three main monitoring sites, which included a ditch (Highway 36), a major roadway (County Road B), and a residential watershed (Alameda Pond inlet), exhibited differences in magnitude and timing of chloride transport. These differences can be illustrated by cumulative loading frequency plots (Figure 3-22) developed from observed hourly water and chloride loading in surface runoff for the two-year period of Aug 1, 2015 – July 31, 2017.

Chloride transport from the ditch was proportional to flow (i.e. the chloride and volume loading lines have similar shapes); both low and high flows produced chloride export. This pattern suggests high levels of chloride storage in the ditch from infiltration of snowmelt; large runoff events do not dilute chloride but instead likely access shallow groundwater stores that are not hydrologically connected during small events (note, however, that the ~20% of volume associated with the highest flow rates is accompanied by very little chloride transport, so some dilution or depletion does occur). Similarly, for the residential Alameda Pond watershed, chloride loading follows roughly the same pattern as volume loading. This watershed has opportunities for storage or infiltration in wetlands located within the drainage network, and therefore the chloride transport observed in high flows (such as in summer and fall storms) may be the result of flushing from these in-line wetlands. Unlike the ditch site, this watershed does not appear to deplete or dilute its chloride source within events, but instead exports chloride at some level for a wide range of event intensities (flow rates). By contrast, at the roadway site (County Road B), most loading (~70%) occurred at flow rates between 0.01 cfs and ~0.2 cfs. Dilution or depletion of chloride sources occurred at high flows (e.g., in summer storms), while some low flows (e.g., during summer or fall, after road salt had been flushed from streets), had no chloride.

This cumulative frequency analysis was also used in the development of chloride runoff diversion strategies, which are described in more detail in Section 5.2.

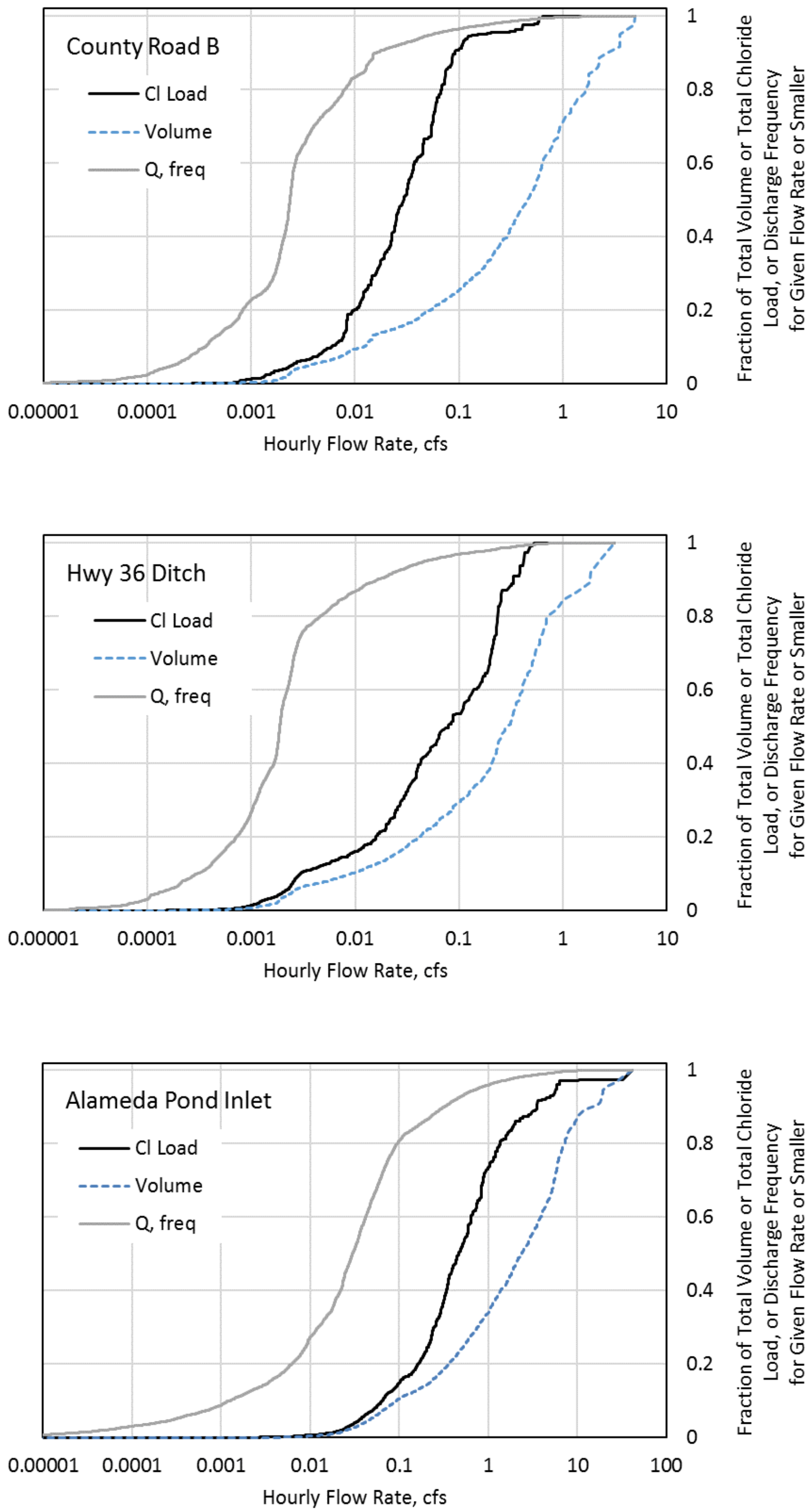


Figure 3-22. Cumulative frequency of flow rate, volume, and chloride loading observed in surface runoff from Aug 1, 2015 to July 31, 2017 at three primary monitoring sites: County Road B (top), Highway 36 ditch (middle), Alameda Pond watershed (bottom).

4 COMPUTER MODELS FOR CHLORIDE TRANSPORT

Computer models provide the opportunity to better understand the hydrologic and mass transport processes within a watershed, and to extrapolate existing monitoring data to other locations, time periods, or climate conditions. In this project, a modeling effort was included with the following goals:

(1) *Model evaluation*: Evaluate the ability of the existing hydrologic models SWMM, HSPF and GSSHA to handle snow accumulation, snowmelt, infiltration, and the associated chloride transport through urban watersheds.
(2) *Model testing*: Assemble and apply models to a study watershed to simulate chloride transport during both snowmelt and rainfall runoff events from source areas (roads) and through elements of the drainage network, including swales, storm sewers, detention ponds, and/or wetlands.
(3) *Model analysis*: Use simulation models to extend the analysis beyond the monitoring record of the project's field efforts: (a) Characterize the seasonality and year-to-year variation in chloride transport through the watershed, and (b) determine the residence time of chloride in different portions of the watershed's drainage network.
(4) *Evaluate mitigation strategies*: Use the models to investigate the effects of possible chloride mitigation scenarios, such as diversion and capture of high-chloride runoff.

4.1 MODELS FOR WATERSHED CHLORIDE TRANSPORT AND CHLORIDE SOURCE AREAS

Three widely-available hydrologic models were evaluated for application to modeling chloride transport: SWMM, HSPF, and GSSHA. SWMM (Stormwater Management Model) (Rossman 2015) is an EPA-supported hydrologic modeling tool, which is used extensively for modeling of rainfall runoff and nutrient transport in urbanized watersheds. The HSPF (Hydrologic Simulation Program – Fortran) modeling package (Bicknell et al. 2005) is a general purpose rainfall runoff model supported by the EPA. It runs using standard climate data and spatially variable soil and land cover parameters, and is capable of simulating fluxes of water and contaminants in surface water and groundwater. Compared to SWMM, it is more oriented towards modeling undeveloped watersheds, and is more detailed in its routing of water through the sub-surface. The GSSHA (Gridded Surface Subsurface Hydrologic Analysis) modeling package (Downer and Ogden 2006) is relatively strong in modeling surface/sub-surface interactions, and has been developed to model water and material transport through groundwater, soils, streams, and channels. Both overland flow and groundwater can be modeled in two dimensions. GSSHA is a grid-based, rather than catchment-based, hydrologic model.

Initially, the GSSHA model appeared to be the best candidate for modeling chloride transport, due to its ability to route temporally and spatially variable inputs of snow and chloride in surface and sub-surface water. However, a test application of GSSHA to a simple road-ditch system (Appendix C) found that the snowmelt routing model to be only partially developed, and not usable for systems including drainage pipes. In addition, model setup was found to be challenging without the use of a licensed pre-processor. Finally, GSSHA does not include the ability to model stratified water bodies, such as detention ponds with thermal or chemical stratification.

The SWMM model was also evaluated on a simple test case. SWMM has the ability to model snowmelt and the transport of chloride in surface runoff. SWMM also includes features for modeling snow plowing, e.g. moving snow from one area to another. However, a serious limitation was identified; although infiltration is simulated, the transport of chloride with the infiltrating water is not simulated. Hence, the partitioning of chloride between surface water and infiltrated water cannot be simulated using SWMM. Like GSSHA, SWMM does not have the ability to model stratified ponds and lakes.

Based on the limitations of GSSHA and SWMM described above, HSPF was used as the watershed model in this project. HSPF models were set up for two cases: 1) a simple road-ditch system, to simulate a typical chloride source area, and 2) a model of the watershed of the Alameda pond, within the Lake McCarrons watershed. HSPF was found to include most of the basic components for modeling chloride runoff and transport, including snow accumulation and melting, infiltration of water and dissolved substances, and routing of flow through open channels and closed pipes. HSPF also has some ability to route subsurface flow and dissolved substances, to simulate inflow and groundwater transport, but these features were not used in this study. Like SWMM and GSSHA, HSPF does not have the ability to model stratified ponds and lakes.

HSPF Chloride Source Model

The watershed model HSPF was set up for a sample source area, very similar to the GSSHA source model described in Appendix C. The test domain (Figure A-1.1) was a rectangular patch, 18m wide x 90m long, including one lane of highway and an adjacent ditch. Cross sectional geometry at the end points were taken from LiDAR elevations of eastbound Highway 36 near the Rice Street off-ramp (located within the monitored watershed), and mean slope was determined from these elevations as an input to the HSPF model. The domain was modeled as a single watershed, with 720 m^2 of impervious area (the lane of highway) and 900 m^2 of ditch.

The test simulation consisted of application of 1332 lbs chloride to the roadway, which corresponds to the seasonal road salt application by MnDOT to the site (scaled by lane-miles) during Field Season 1. This salt was distributed in time from November through March according to timing of applications by the city of Roseville, and for each event, salt was distributed evenly over the impervious portion of the domain. The simulation was run from Jan 1, 2015 to Sep 1, 2015 using climate data observed at the St. Anthony Falls Laboratory in Minneapolis, MN (SAFL; Figure 1-2). The simulation results showed that roughly 90.6% of rainfall was infiltrated in the ditch over the 9-month simulation period, along with 99.6% of the chloride applied to the roadway. This simulation was not calibrated, but appears to be usable as a chloride source model for a ditched roadway. Due to time constraints, the model was not applied to later field seasons or developed for the actual Highway 36 site.

HSPF Chloride Transport Model for the Alameda Pond Watershed

HSPF was used to model water and chloride transport in surface runoff in the Alameda Pond watershed, which is contained in the Lake McCarrons watershed (Figure 1-2). The HSPF model assembled for the Alameda pond watershed has 11 sub-watersheds, with a modeled drainage (channel) network corresponding approximately to the storm drain network (Figure 4-1). The model included two wetlands that are part of the drainage network – HSPF modeled the wetlands as well-mixed storage ponds. De-icer chloride was applied to impervious areas, and resulting simulated transport was tracked only in surface water (the remainder, which infiltrated in these wetland areas, was not tracked.) The model was assembled and tested with observed flow and chloride applications (July 2015 – June 2016), using estimated road salt input for winter 2015-2016 from the city of Roseville, Ramsey County, and MnDOT.

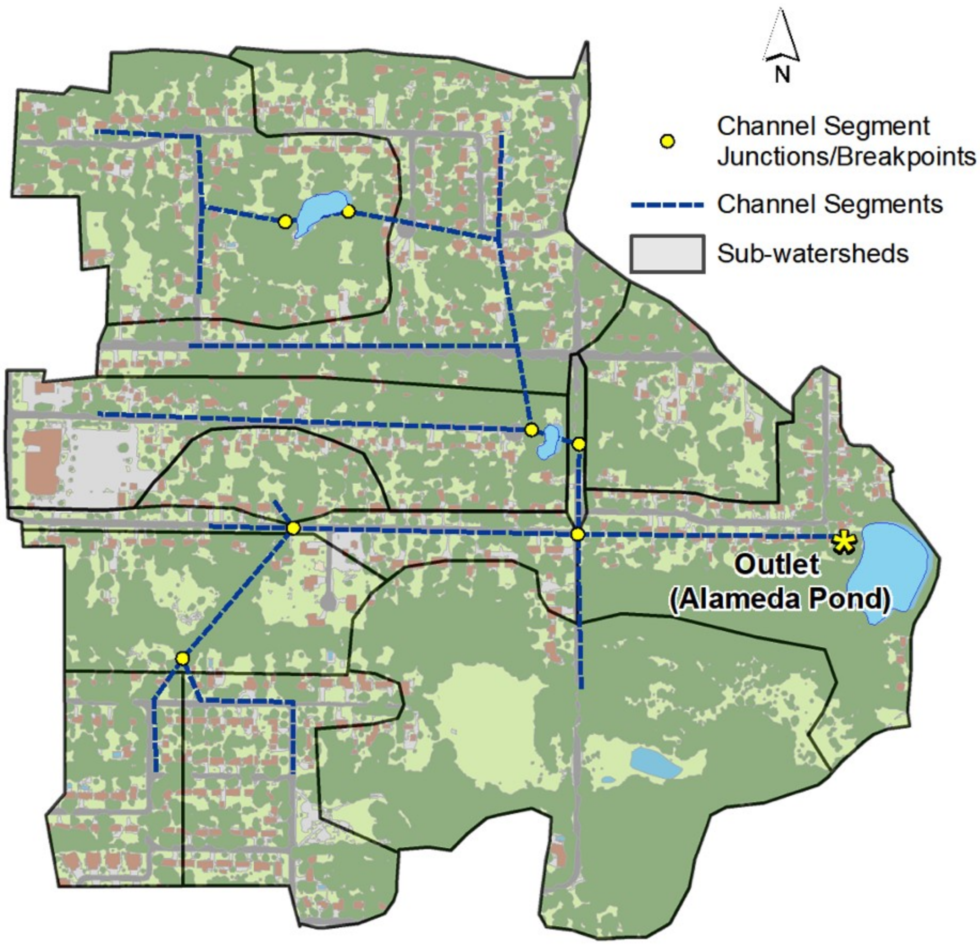


Figure 4-1. Illustration of the HSPF model application to the Alameda pond watershed, showing the 11 sub-watersheds, the junctions, and the drainage network (channels).

For the multi-year simulation, three winter seasons (2013-2014, 2014-2015, and 2015-2016) were simulated using observed weather data from the State Climatology station on the UMN St. Paul Campus (UMN/MSCO), with gaps in temperature, wind, and precipitation filled from the Minneapolis-St. Paul International Airport (MSP) and gaps in solar radiation data were filled from a station at SAFL (Figure 1-2). Actual salt application for the 2nd and 3rd years were used, along with a hypothetical amount for the first year based on amount applied per snowfall event from the first two years. The model was initialized for soil moisture and chloride storage by running the 3 years in succession, and then the same 3 years were run again to obtain the final output (monthly simulated chloride and water export from the Alameda Pond watershed, averaged over the period July 2013 – June 2016; Table 4-1).

Simulated chloride and water loading (export) for the Alameda Pond watershed are compared by month to observations at the watershed outlet (Alameda inlet monitoring site) for the period July 1, 2015 – June 30, 2016 (Figure 4-2). Results show some substantial differences with observations. Overall, HSPF over-predicted both volume and chloride for the 1-year comparison period (16% and 29% for volume and chloride, respectively; Figure 4-2). The largest over-predictions occurred in spring snowmelt (Feb – Apr), while observed loading during late summer (July – Aug) was much higher than in the simulations. This suggests that the model may be limited in its ability to simulate chloride storage within the watershed (e.g., in groundwater or wetlands), and thus may not be useful for determining the timing of removal until it could be improved through calibration. However, it may still be used to determine flow thresholds for diversions.

Table 4-1. Mean monthly loading of chloride and water by month, simulated for the period of July 2013 – June 2016 for the Alameda Pond watershed using HSPF.

ALAMEDA - MODEL	Chloride				Water			
month	lbs	lbs/ac	% Total	Conc, mg/L	cu ft	cfs	in	% Total
Jan	419	1.5	4%	928	0.2	0.003	0.01	0%
Feb	2,625	9.2	27%	535	1.8	0.032	0.08	3%
Mar	1,402	4.9	14%	219	2.4	0.038	0.1	4%
Apr	1,766	6.2	18%	80	8.1	0.137	0.34	13%
May	998	3.5	10%	55	6.7	0.108	0.28	10%
Jun	560	2	6%	16	12.5	0.213	0.53	19%
Jul	404	1.4	4%	16	9.2	0.149	0.39	14%
Aug	157	0.5	2%	10	5.8	0.094	0.24	9%
Sep	124	0.4	1%	8	5.6	0.095	0.24	9%
Oct	129	0.5	1%	7	6.3	0.103	0.27	10%
Nov	159	0.6	2%	15	3.8	0.065	0.16	6%
Dec	947	3.3	10%	134	2.6	0.042	0.11	4%
Total:	***9,690 lbs***				***65.0 ac-ft***			

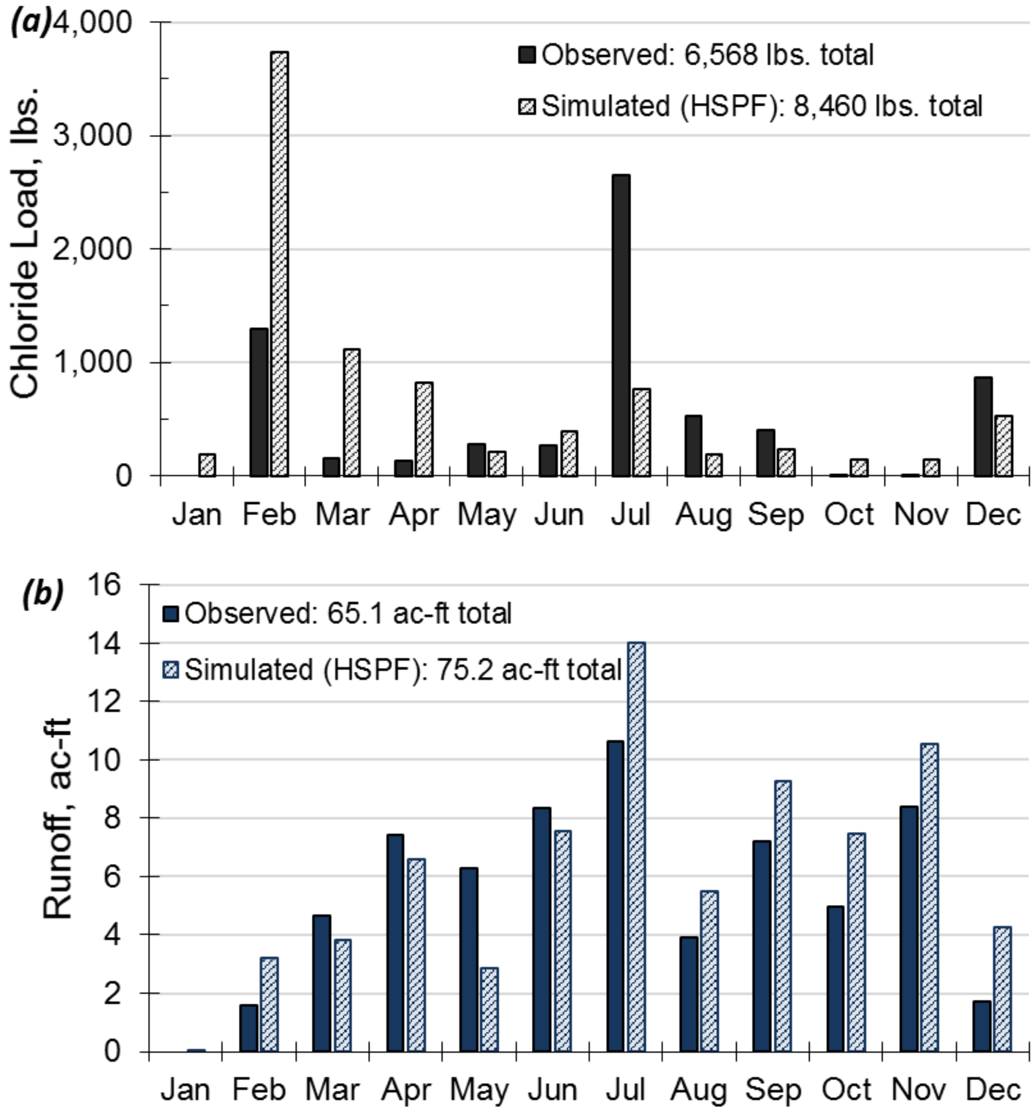


Figure 4-2. Observed and simulated monthly (a) chloride and (b) water export from the Alameda Pond watershed for the one-year period July 1, 2015 – June 30, 2016.

4.2 MODELING CHLORIDE RETENTION IN PONDS

Two modeling packages were evaluated for simulating stratified detention ponds: the US Army Corps of the Engineers CEQUAL-W2 model, and the Generalized Lake Model (GLM), created at and supported by the University of Western Australia. CEQUAL-W2 (Cole et al. 2015) is a two-dimensional water quality model intended for modeling reservoirs, but it can and has also been applied to rivers and lakes. The water budget, flow velocities, and water quality are simulated over depth and in the horizontal direction corresponding to the flow direction, assuming the water body is well-mixed laterally. CEQUAL-W2 includes models for atmospheric heat transfer and ice formation, and, importantly for this project, can simulate stratification due to temperature gradients or density changes due to salinity. A variety of hydraulic structures can be modeled, including weir and pipe outlet structures. Water withdrawals from a specific point in the model can also be modeled as a specified time series.

In addition to the CEQUAL-W2 modeling package, the GLM modeling package (Hipsey et al. 2013) was evaluated by creating a model for Alameda pond. GLM is a one-dimensional lake water quality model that simulates the variation of temperature, dissolved oxygen, and many other parameters over depth, assuming that the lake is laterally well mixed. GLM currently does not have provisions for simulating outlet structures, so that lake outflow is simulated as simple overtopping of the lake perimeter or as a specified outflow rate time series. Although a model for the Alameda pond was successfully assembled and run, the model was somewhat unstable, where modest changes in many of the model parameters for vertical mixing rates, etc. caused the model to crash. Like the CEQUAL-W2 model described below, the GLM model was run for a period of three years, with specified inflows of water and chloride and local climate data. In the limited model runs that were obtained, the simulated pond export of chloride were similar to the results obtained with the CEQUAL-W2 model. Due to the model limitations and problems described above, the pond modeling in this project focused on the CEQUAL-W2 model.

The CEQUAL-W2 model constructed for the Alameda pond is shown schematically in Figure 4-3. The model had 15 elements in the flow direction and 18 elements over depth, with each layer 0.18 m thick. The inflow time series (flow rate, chloride concentration, temperature) is specified using either field measurements or modeled time series from the HSPF model. Outflow rate and outflow chloride concentrations and several vertical profiles in the pond were saved at 15-minute increments.

The CEQUAL-W2 pond model was run for the period 7/1/2015 to 6/30/2016, using inflow rates and chloride concentrations measured at the inlet of Alameda pond (Figure 4-4). The simulated export of chloride at the pond outlet was then compared to the measured outflows for this period, shown in Figure 4-5. It is apparent that the pond model predicted a large chloride export in March 2016, whereas the observations showed a large export in May. This suggests that the model is under-predicting the retention time of the pond, and may not be capturing the degree of density stratification present in the pond. This is also apparent in Figure 4-6, which shows observed and simulated chloride profiles.

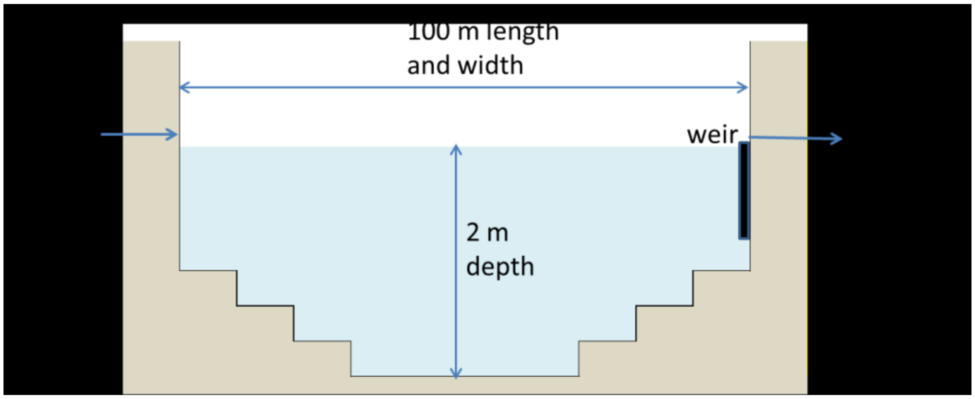


Figure 4-3. Schematic diagram of the CEQUAL-W2 model for the Alameda pond.

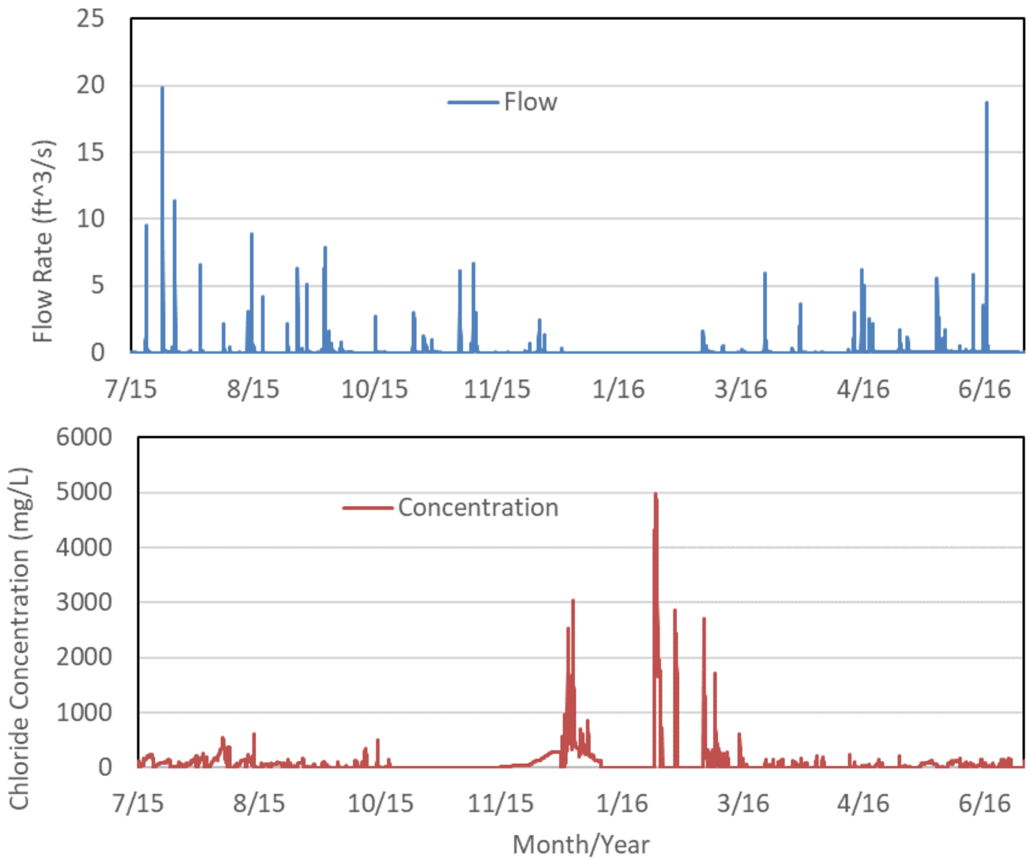


Figure 4-4. Time series of observed flow rate and chloride concentration input to Alameda pond, 7/1/2015 to 6/30/2016.

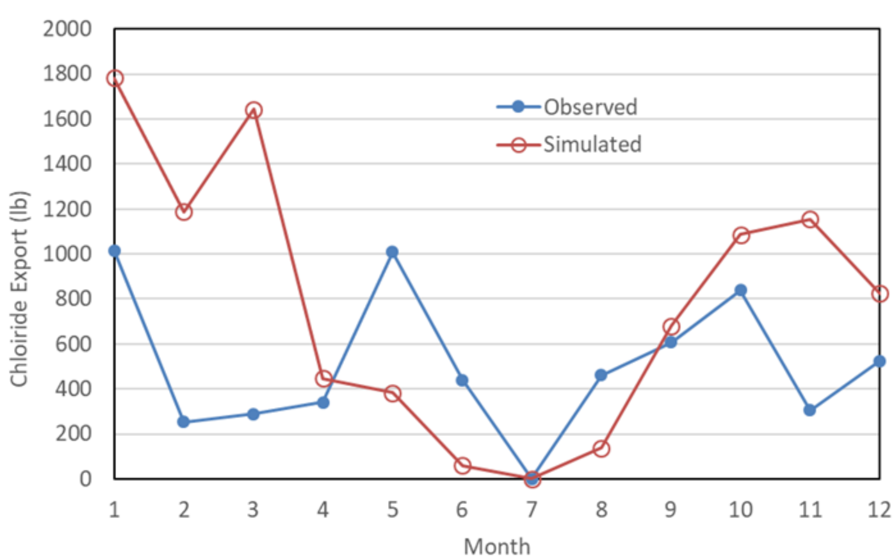


Figure 4-5. Observed and simulated monthly total chloride export from the Alameda pond for July 2015 through June 2016.

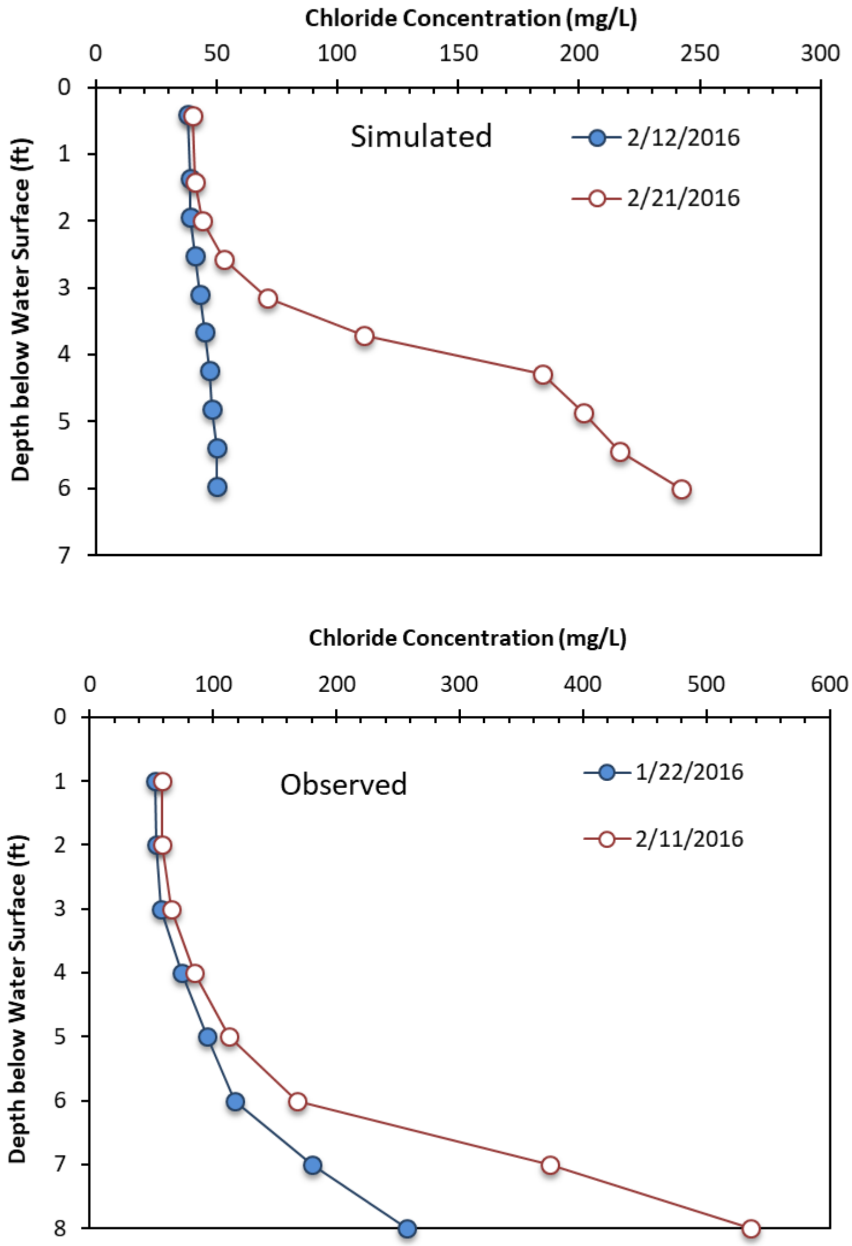


Figure 4-6. Simulated and observed chloride concentration profiles in Alameda pond in February 2016. The inflow event leading to the change in concentration in the observed profiles was not recorded at the pond inlet, so that a different modeling time period is used for comparison.

4.3 MODEL LIMITATIONS

Modeling the processes of chloride export from source areas, chloride transport via surface runoff, and retention of chloride in ponds with commonly available hydrologic models proved to be challenging. The challenges involve both limitations of the available models, and a lack of understanding and resolution of the processes at the chloride sources (roadways). As a result, this study was unable to completely address the original four objectives of the modeling task (see Introduction to Chapter 4).

Much of the effort for the project's modeling task became concerned with model selection and evaluation (Objectives 1 and 2). The limitations of the available and tested models (discussed in detail in Sections 4.1and 4.2 and summarized below) made it difficult to use the model(s) as intended to address the latter two objectives (3 and 4), which were concerned with model application and analysis: analyzing model output to investigate the effect of year-to-year climate variability on chloride export, and using models to assess chloride mitigation scenarios such as reduced road salt application or runoff diversions (see Section 5.2).

Specifically, the watershed chloride model (Section 4.1was unable to simulate the observed chloride retention nor the seasonality of chloride export from the Alameda Pond watershed. Therefore, the model was unsuitable for modeling the timing of chloride diversion strategies, or to investigate year-to-year variability of chloride transport as a function of weather or as a function of reduced road salt inputs. The pond models were unable to simulate the observed strength of stratification in the Alameda Pond, and thus the models under-predicted chloride residence time (i.e. projected larger chloride export earlier in the season). Despite this limitation, the pond model was used to assess a pond diversion strategy (Section 5.3).

4.3.1 Models for Chloride Source Areas

Models for the transport of chloride through watersheds begin at the roadways, sidewalks, and parking lots where de-icers are applied. The partitioning of applied de-icers between surface runoff and infiltration is a key component needed for modeling chloride source areas.

Major Roadway with a Vegetated Ditch: For ditched roadways, our field data collection effort at the ditch site (Highway 36) found that a high percentage of chloride (>90%) was lost to infiltration. We found the HSPF model was capable of simulating this case, giving a reasonable estimate of the amounts of chloride that are infiltrated and transported in surface runoff. Although we did not consider the effect of frozen soils on infiltration, HSPF does include provisions for modifying infiltration based either on soil temperature or the ice content of the snowpack.

Sewered, Curb-and-gutter Roadways: For a roadway with curbs and gutters connected to storm drains (County Road B), our field measurements found that 37% to 66%% of applied chloride was retained in the catchment, and presumably infiltrated. The processes by which chloride is retained in sewered catchments are not well understood, and hydrologic modeling tools such as HSPF lack the detailed processes that are likely to be involved: plowing snow over the curb, scattering by vehicles, airborne transport, storage in soils or groundwater, etc. SWMM, which was also considered as a chloride transport model, includes a snow plowing routine and could potentially route chloride to the vegetated area adjacent to the roadway, but the model lacked the ability to infiltrate chloride or track chloride in the sub-surface.

4.3.2 Models for Chloride Transport in a Sewered, Urban Watershed

The ability of a watershed transport model to accurately simulate chloride transport in a sewered, curb-and-gutter watershed was considered essential, as this configuration is characteristic of most urban areas. Given the limitations of HSPF (or other candidate models) to simulate chloride transport for curb-and-gutter watersheds, chloride retention in the Alameda Pond watershed was modeled in this study by specifying (a priori) the fraction of applied chloride that ended up in surface runoff, rather than the ideal case of being able to specify the total amount of applied road salt to the watershed and allowing the model to simulate the processes that partition the salt into surface runoff vs. infiltration to soils and groundwater.

Controlled experiments at a facility like MnROAD (Monticello, MN) may be required to better understand the retention of chloride in sewered watersheds. Modifications to the existing models or development of a new sub-model may be necessary to accurately simulate watershed-scale chloride transport.

4.3.3 Models for Detention Ponds and Wetlands

HSPF includes hydraulic storage elements that can be used to represent well-mixed detention ponds. We used these elements to represent several small wetland areas in the Alameda pond watershed, which were connected to the storm drain network and essentially behaved as detention ponds. These wetlands were not instrumented, however, there was evidence in the data from the outlet of this watershed that chloride is being retained in these wetlands and released later in the year. We found that the storage elements in HSPF were not able to reproduce this seasonal chloride storage and release, probably because the storage elements are well mixed, and do not consider stratification of temperature and chloride. Some degree of chloride stratification (higher concentration near the bottom) was observed in all sampled ponds in this study.

To delve into more detail on the retention of chloride in stratified ponds, we modeled the Alameda pond using the USACOE model CE-QUAL-W2. This model considers vertical stratification of temperature and salt (or other dissolved substances) by keeping track of density changes over depth. We found that CE-QUAL-W2 was capable of simulating stratification of temperature and chloride, and retention over periods of weeks. However, CE-QUAL-W2 appeared to underpredict the degree of stratification and the persistence of the stratification. In particular, the simulated density gradient in a pond due to chloride was found to diffuse upward and mix over the course of a week or two, even with ice cover, whereas profiles taken at the pond showed these density stratifications to be quite stable. Further investigation of strategies for modeling vertical mixing with temperature and salinity stratifications are needed.

5 CHLORIDE MITIGATION STRATEGIES

In this section, we describe potential strategies for reducing or mitigating the spreading of chloride from road salt applications by transport in surface runoff. The suggestions presented here are not exhaustive, as they are based on the results of the data analyses and model simulations conducted as part of this study. A brief literature review is presented first as an overview of the types of strategies that are currently being investigated or employed in other cold climate regions. This overview is followed by a more detailed description of potential mitigation strategies derived from knowledge gained in the current study.

5.1 PREVIOUS WORK

A literature survey was conducted to document existing chloride mitigation or management practices, as well as potential consequences or shortcomings of these strategies. We found few studies concerned with chloride removal from surface runoff; most studies focused on capturing or reusing runoff from salt or snow storage facilities.

It should be noted that we are not advocating the adoption of any of the management options summarized here. Some of these strategies are not suitable or feasible for implementation in the Twin Cities due to, for example, different climate conditions, available infrastructure, or cost. The following list gives an overview of the strategies employed in other states to address the difficulties in managing chloride in surface runoff.

- The state of Virginia has investigated the use of **captured runoff from salt storage facilities** as a component of brine mixtures to be used for later de-icing (Craver et al. 2005). The suspended sediment that also tends to be captured in such systems did not reduce the effectiveness of the brine mixture in field tests. Capture of runoff and snowmelt for re-use as brine was also recommended by Fay et al. (2013) and by Golub et al. (2008), particularly for salt- and snow-storage facilities.

- **Evaporation ponds**, which collect highly saline water runoff with high salt content during winter (primarily from truck washing and spillage at salt storage facilities) and promote evaporation during summer, have also been suggested by Fay et al. (2013) and by Golub et al. (2008). These ponds have impermeable liners to prevent loss by infiltration; the highly saline post-evaporation water in the ponds can be incorporated into brine for road pre-wetting in winter. Actual evaporation ponds studied were located in New Jersey (with other sites in Indiana, Montana, and Washington); climate conditions for promoting springtime evaporation may be more favorable in places like New Jersey or Indiana than in Minnesota.

- **Spray-freezing of meltwater from snow storage facilities** in Edmonton, Alberta, Canada was used to reclaim dilute salt from large snow piles (Tatarniuk et al. 2009). Chloride was concentrated via fractionation as the spray-freeze piles melted, and this runoff was re-incorporated into brine that could be used as road de-icer.

- A study at the University of Connecticut (Dietz and Clausen 2016) found that an **anion exchange resin used with a bioretention media** in a laboratory column study was able to capture chloride leached through the columns, even at very high concentrations (up to 15,000 mg/L). The mass of resin required to achieve removal was several times greater than the mass of chloride removed.
- A literature summary and lab experiment by Santiago-Martin et al. (2016) showed some potential for **chloride removal by certain species of macrophytes planted in constructed wetlands**; the plants take up sodium and chloride in influent runoff and soil water, and can be harvested in the fall to remove chloride. The effectiveness is highly dependent on water quality and quantity, and the vegetation did not prevent large fluxes of chloride from leaving wetlands in spring runoff, when the plants were dormant. The disposal or treatment of removed vegetation was not discussed.

5.2 RUNOFF CAPTURE

Capturing small amounts of snowmelt runoff at the street level, similar to capturing first flush stormwater, can reduce the amount of chloride reaching surface waters. Contaminants such as metals, dissolved nutrients, and sediment, are present in especially high concentrations early in rainfall/runoff events, and stormwater BMPs are already being used to capture this first flush runoff (as described, for example, by the New South Wales EPA[3] and Virginia DOT[4]). Ensuring the functionality of such practices during cold weather periods may allow them to be used to capture snowmelt water as well. However, we have made no effort to determine cost or feasibility of the systems needed to capture, store, or treat snowmelt runoff (or first flush runoff), which could be considerable. In addition, water volumes to be removed may be too large to be trucked out; syphons, pumps and pipes can handle larger water volumes but require a suitable storm drain (i.e. one that does not connect to a sensitive water body) into which to drain the highly saline water, and such a drain may not be available in proximity to the pond.

5.2.1 Runoff Diversion Structures

Examples of structural diversion designs and practices are discussed briefly below; however, details or feasibility of implementation could not be assessed using field data or model analysis, and are left for future work. Chloride management strategies concerned with the diversion (capture) of runoff were explored in greater detail using field data collected in this project at the study sites, along with the associated chloride transport models for a watershed and a pond. These applications, which primarily concern the amount of runoff to divert and the timing of these diversions, are described in the next section.

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3 http://www.epa.nsw.gov.au/mao/stormwater.htm
4 http://www.virginiadot.org/business/resources/LocDes/BMP_Design-Manual/Chapter_14_Rainwater_Capturing_Systems.pdf

(1) *First flush / Snowmelt capture by curb and gutter:* Modification of curb-and-gutter systems to divert small flows into a separate drain system or holding tank may be an effective way to capture first flush of storm events as well as chloride in snowmelt. These systems may be most feasible at small scales when curbs and catch basins are rebuilt, and diversion pipes and holding tanks can be cost-effectively added.

a. One option is to place a diversion structure (e.g. pipe or orifice connected to a holding tank or sewer drain system) inside existing catch basins. At high flows, or when the tank is full, water can flow past this diverter into the main chamber of the catch basin. The system might be enhanced by cutting a small trench at the base of the curb that would carry small flows into catch basin diverters, with larger flows spreading across the width of the gutter.

b. Another option is to place secondary drains in gutters upstream of catch basins, connected to holding tanks or sewer drainage networks. The gutter and/or roadway could be raised just downstream of the alternate drain (similar to a speed bump) to promote ponding of first flush runoff and diversion into the secondary drains.

(2) *Capture of bridge runoff:* Bridge decks can be areas of intense salt application and are often located above surface waters, and thus may be of particular concern for chloride management. Drains on bridges could be designed to selectively divert (for example, based on time of year) stormwater or snowmelt water into alternate drains or to storage tanks. Modeling could be used to determine the required volume capture needed to meet a given chloride capture goal. Feasibility of alternative disposal of the runoff would be an important consideration, as would be the size and the height of a bridge above banks and river water levels for a storage tank or a diversion drain to be installed.

5.2.2 Diversion strategies: How Much and When to Capture Runoff

Low-flow capture could be an effective management goal for reducing chloride in surface runoff, for example at the small scale of the County Road B site. Two management scenarios, which differ on the threshold used for diversion (i.e. flow rate based, or chloride based) have been investigated by analyzing the cumulative chloride loading data for the three primary monitoring sites:

- Scenario 1: flow rate-based diversion, i.e. all flows below a certain discharge rate are captured;
- Scenario 2: chloride-based diversion, such that all flow rates for which chloride concentration (conductivity) exceeds a given level are captured.

Scenario 1: Flow rate-based diversion

In this scenario (1), all low flows below some threshold would be captured, similar to first flush diversion; for the purposes of this analysis, we make no distinction between snowmelt or the rising or falling limbs of summer storms, in which flow rates may be low enough to fall below the threshold even if they contain little or no chloride. To estimate the water volumes that would need to be extracted to achieve a given reduction of chloride in surface runoff, normalized cumulative loading plots can be used in which all intervals have been ordered on the x-axis from lowest to highest flow rates (Figure 5-1). For example, if 1 inch of runoff from the smallest flow events were diverted at all sites over 1 year (Scenario 1), this would result in capture of 55%, 60%, and 95% of observed chloride loading in surface runoff at the watershed site (Alameda Pond inlet), roadway site (County Road B), and ditch site (Highway 36), respectively. Alternatively, if a 60% reduction in surface chloride loading is desired, this would require diverting 0.6 in, 1.0 in, and 1.3 in of the smallest flow events at the Highway 36 ditch site, the County Road B site, and the Alameda Pond watershed site, respectively (Figure 5-1).

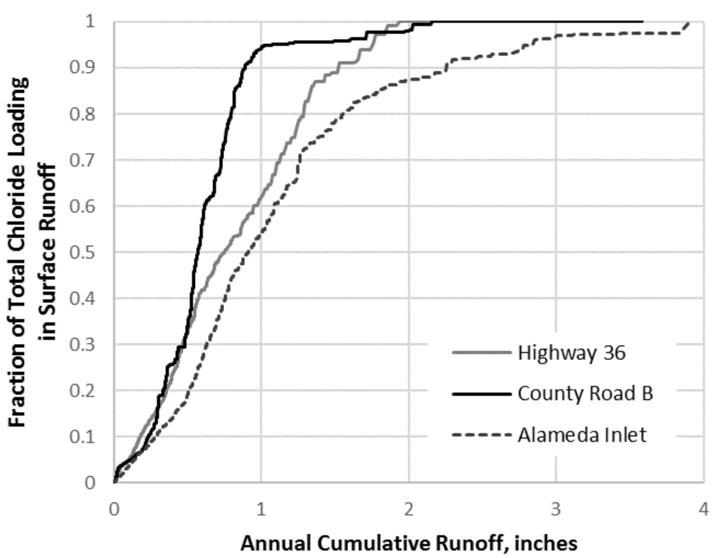

Figure 5-1. Fraction of annual chloride loading in surface runoff as a function of cumulative observed runoff yield (inches) as flow rate increases (i.e., x-axis is ordered left to right from lowest to highest flow rate). Results shown for three primary monitoring sites: County Road B, Highway 36 ditch, and Alameda Pond watershed. Note that chloride loading fraction concerns only that observed in surface runoff, and does not include chloride lost to infiltration.

Scenario 2: Chloride-based diversion

In this scenario (2), all flows that exceed a specified chloride concentration would be captured. In practice, this would require a conductivity sensor in the outflow that would trigger a diversion when flows exceed a conductivity value proportional to the chloride threshold. This method could be viewed as a best-case scenario (or upper bound) for chloride removal for a given capture volume, as it targets only the most saline runoff. This scenario is illustrated in a cumulative loading plot (Figure 5-2), ordered on the x-axis from high concentration to low concentration. Results are also summarized in Table 5-1 below, which illustrates the chloride captured, as fraction of surface runoff and as a fraction of road salt applied, for given runoff depth (and volume) diversions in this scenario (2). For example, capturing the most saline 0.1 inch of annual runoff at the roadway site (County Road B) would require diverting 10,218 ft^3 of runoff with a chloride concentration of 845 mg/L or higher, providing a reduction of 80% of the total observed surface runoff chloride load (roughly equivalent to 38% of the total chloride applied as road de-icer).

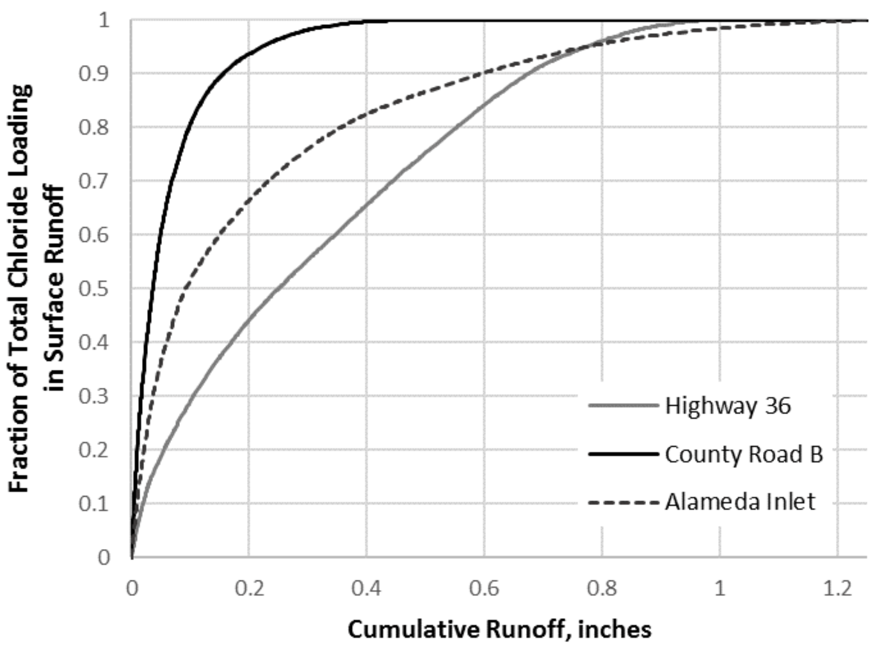

Figure 5-2. Fraction of chloride loading in annual surface runoff as a function of cumulative observed runoff yield (inches) as chloride increases (i.e., x-axis is ordered left to right from lowest to highest chloride concentration). Results shown for three primary monitoring sites: County Road B, Highway 36 ditch, and Alameda Pond watershed. Note that chloride loading fraction concerns only that observed in surface runoff, and does not include chloride lost to infiltration.

Table 5-1. Diversion (capture) volumes and chloride concentration thresholds for given annual capture depths (in inches of runoff) for the chloride-based diversion strategy, along with chloride captured as a fraction of observed surface runoff chloride load, and as a fraction of road salt applied to the watershed (based on mean retention % in Field Seasons 2 and 3). Observed annual chloride loads for the two-year study period coincident at the three sites (Aug 1, 2015 – July 31, 2017): Hwy 36 Ditch = 50.9 lb/ac, County Road B = 75.8 lb/ac, and Alameda Pond inlet = 42.1 lb/ac.

Cmltv Depth Captured, in.	**Hwy 36 Ditch** Capture Vol, ft3	Conc. Thresh., mg/L	Fract. of Runoff Cl	As Fract. of Applied Cl
0.02	853	926	0.1	0.01
0.04	1,706	545	0.16	0.01
0.06	2,559	494	0.21	0.01
0.08	3,412	445	0.25	0.02
0.1	4,265	422	0.29	0.02
0.15	6,398	345	0.37	0.02
0.2	8,531	277	0.44	0.03
0.25	10,663	253	0.5	0.03
0.5	21,326	206	0.75	0.04
1	42,653	5	1	0.06
Cmltv Depth Captured, in.	**County Road B** Capture Vol, ft3	Conc. Thresh., mg/L	Fract. of Runoff Cl	As Fract. of Applied Cl
0.02	2,044	3807	0.34	0.16
0.04	4,087	2685	0.53	0.25
0.06	6,131	1775	0.66	0.32
0.08	8,175	1204	0.74	0.36
0.1	10,218	845	0.8	0.38
0.15	15,328	385	0.89	0.43
0.2	20,437	211	0.94	0.45
0.25	25,546	138	0.96	0.46
0.5	51,092	4	1	0.48
1	102,185	0	1	0.48
Cmltv Depth Captured, in.	**Alameda Pond Inlet** Capture Vol, ft3	Conc. Thresh., mg/L	Fract. of Runoff Cl	As Fract. of Applied Cl
0.02	20,691	1399	0.18	0.11
0.04	41,382	962	0.32	0.19
0.06	62,073	686	0.4	0.23
0.08	82,764	572	0.47	0.27
0.1	103,455	369	0.51	0.29
0.15	155,183	273	0.6	0.35
0.2	206,910	220	0.66	0.38
0.25	258,638	173	0.72	0.42
0.5	517,275	66	0.87	0.5
1	1,034,550	18	0.98	0.57

The seasonal timing of chloride export and flow rates or volumes are also relevant to any discussion of management strategies involving diversion or capture of runoff. Table 5-2 shows mean chloride and volume loading at the three main monitoring sites by month and by flow type (snowmelt or rainfall runoff) along with the percent of total observed chloride loading for that interval. These are also shown as graphs in the Results (Section 3.6). This table might be used to illustrate when and how much flow to divert to achieve a given chloride load reduction. For example, at the County Road B site, if all February and March flows were diverted, roughly 41% of chloride loading observed in surface runoff at this site would be prevented from reaching downstream waters. This would require holding or diverting roughly 48,000 ft^3 of water (per year) with a mean flow rate of roughly 0.013 cfs. Note that the chloride reduction is for salt in surface runoff only, and does not reflect the large fraction (roughly 52% on average) of applied chloride that is lost to infiltration before reaching the monitoring site (Table 3-2).

The monthly summary in Table 5-2 also illustrates the differences in seasonal loading patterns across the watershed types. Nearly half of chloride loading at the highway site (48%; Table 5-2b), for example, occurs in November and December, while at the roadway site, 59% of observed loading occurred in the months of January and February during the study period. At the Alameda Pond watershed, which is much larger than the other two sites (285 ac, vs. 28 ac and 12 ac for the roadway and ditch, respectively), chloride loading occurs not just in snowmelt (especially in January in the study period), but is also distributed over the rest of the year, similar to the ditch site. This pattern suggests that diversion or capture of runoff at a watershed outlet, like the Alameda Pond, may not be as feasible or effective as diverting further upstream in the watershed (i.e. at the scale of a roadway like County Road B), because chloride loading is not necessarily confined to one or two months during the year in a larger watershed where storage and release of chloride may occur.

Table 5-2. Mean annual export of chloride and water by month, and overall by flow regime (snowmelt or rainfall-runoff ("stormflow")), as observed over two years of monitoring (Aug 1, 2015 to July 31, 2017) at the three main monitoring sites: (a) County Road B, (b) Highway 36 Ditch, and (c) Alameda Pond inlet.

(a) Co Rd B	Chloride				Water			
month	lb/yr	lb/ac/yr	% Total	Conc, mg/L	cu ft/yr	cfs	in/yr	% Total
1	694	24.7	33%	2,012	5,529	0.006	0.05	2%
2	515	18.3	24%	451	18,272	0.013	0.18	5%
3	356	12.7	17%	293	19,460	0.013	0.19	5%
4	9	0.3	0%	3	53,209	0.022	0.52	15%
5	2	0.1	0%	2	15,376	0.009	0.15	4%
6	1	0.0	0%	0	58,082	0.026	0.57	16%
7	0	0.0	0%	0	60,694	0.030	0.59	17%
8	0	0.0	0%	0	55,903	0.042	0.55	15%
9	0	0.0	0%	0	35,521	0.038	0.35	10%
10	0	0.0	0%	--	0	--	0.00	0%
11	65	2.3	3%	37	28,312	0.034	0.28	8%
12	491	17.4	23%	496	15,854	0.012	0.16	4%
Snowmelt:	1,511	53.7	71%	1,494	16,200	0.004	0.16	4%
Stormflow:	622	22.1	29%	28	350,012	0.012	3.43	96%

(b) Hwy 36	Chloride				Water			
month	lb/yr	lb/ac/yr	% Total	Conc, mg/L	cu ft/yr	cfs	in/yr	% Total
1	113	9.6	19%	314	5,741	0.005	0.13	5%
2	94	8.0	16%	219	6,834	0.005	0.16	6%
3	32	2.7	5%	184	2,751	0.005	0.06	2%
4	24	2.0	4%	68	5,595	0.010	0.13	5%
5	15	1.2	2%	12	19,785	0.048	0.46	16%
6	0	0.0	0%	5	1,591	0.019	0.04	1%
7	0	0.0	0%	0	15,389	0.147	0.36	13%
8	2	0.1	0%	1	28,797	0.058	0.68	24%
9	25	2.1	4%	44	9,199	0.016	0.22	8%
10	21	1.8	4%	58	5,951	0.011	0.14	5%
11	190	16.2	32%	207	14,740	0.017	0.35	12%
12	82	7.0	14%	282	4,673	0.008	0.11	4%
Snowmelt:	159	13.5	27%	261	9,208	0.003	0.22	8%
Stormflow:	438	37.3	73%	63	111,274	0.025	2.61	92%

(c) Alameda	Chloride				Water			
month	lb/yr	lb/ac/yr	% Total	Conc, mg/L	cu ft/yr	cfs	in/yr	% Total
1	5,434	19.1	45%	760	114,487	0.094	0.11	3%
2	1,394	4.9	12%	105	212,615	0.094	0.21	5%
3	443	1.6	4%	49	145,096	0.056	0.14	4%
4	372	1.3	3%	16	376,879	0.115	0.36	9%
5	498	1.7	4%	14	576,030	0.129	0.56	14%
6	155	0.5	1%	8	297,672	0.077	0.29	7%
7	57	0.2	0%	2	433,375	0.250	0.42	11%
8	359	1.3	3%	9	636,102	0.409	0.61	16%
9	431	1.5	4%	18	392,664	0.203	0.38	10%
10	422	1.5	4%	20	342,524	0.177	0.33	8%
11	446	1.6	4%	23	313,984	0.173	0.30	8%
12	1,984	7.0	17%	155	205,151	0.159	0.20	5%
Snowmelt:	7,297	25.6	56%	340	343,752	0.077	0.33	8%
Stormflow:	5,672	19.9	44%	24	3,781,785	0.258	3.66	92%

5.3 SELECTIVE WITHDRAWAL FROM DETENTION PONDS

Monitoring of two detention ponds in this study has shown that ponds accumulate a large amount of salt during winter and spring snowmelt, and become strongly stratified with a dense layer of highly saline water (from dissolved NaCl) on the bottom of the ponds. These ponds continue to export salt throughout the warm season; this occurs by entrainment and flushing of portions of the saline bottom layer (hypolimnion) by storm runoff and wind mixing events in the warmer season, and by chloride inputs from wetlands and ponds in the upstream watershed (as observed for the Alameda Pond) or from groundwater inputs. Ponds present several chloride management options:

(1) Selective withdrawal: after snowmelt, when the largest chloride loading occurs, the high-chloride water on the bottom of the pond could be pumped or siphoned out, or diverted through an outlet structure or underdrain that is only open during this period. The pond model developed in this study can be used to determine how much withdrawal is needed, and when it is needed, to achieve a given removal amount. Another option would be to draw down the pond in the fall prior to freeze-up, to allow chloride-laden runoff to accumulate on top of the ice during the winter and spring[5]. This runoff could then be diverted prior to ice-out, when the pond would mix.
However, disposal of diverted pond runoff is a complicated and potentially costly issue; in addition to the concerns with diversion at street level (cost and feasibility of runoff storage, treatment, or transport), other contaminants commonly found in pond sediments (PAH's, heavy metals, etc.) may also be present in the saline water, and would have to be handled appropriately.

(2) Combination outlet structure: Knowing that a saline (chloride) layer develops on the bottom of a pond may be motivation to use an outlet structure capable of removing water from a submerged outlet as well as from an overflow/weir. A submerged outlet (pipe or orifice) withdraws water from lower in the water column, and is typically used for several reasons: to reduce peak flows, to prevent floating debris or vegetation from exiting the pond, and to create cooler outflows. A submerged outlet, however, may promote export of denser, chloride-laden water in early summer season storms. A combination submerged outlet and weir might provide a way to attenuate the chloride export over the warm season, especially if the submerged outlet could be closed during spring snowmelt to prevent export. This structure would not reduce the amount of chloride exported from the pond, but could serve to dilute outflows from the pond. This scenario could also be simulated with this project's pond model.

(3) Skimmer wall / forebay: some pond designs include a forebay to collect inflows to the pond, separated from the main pond body by a berm, weir, or skimmer wall structure. This feature is intended to promote settling of grit and sediment in the forebay, in order to reduce sedimentation in the main pond. Forebays may also provide temporary chloride retention during snowmelt, as highly saline inflows may be dense enough to plunge to the bottom of the forebay. Chloride could

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[5] https://stormwater.pca.state.mn.us/index.php/Cold_climate_impact_on_runoff_management

then be prevented from downstream transport if this saline water could be pumped or diverted prior to being flushed into the main pond by spring and summer storms.

The CEQUAL-W2 model for Alameda pond was used to explore the feasibility of using bottom withdrawal from a detention pond to remove chloride from the system. The pond model is described in more detail in Appendix C. The pond model was run for a three year time period, using loading inputs of water and chloride generated from the previously described HSPF model. A nominal run was made using no bottom withdrawal, and then two model runs were made with different rates of bottom withdrawal (Table 5-3). There are many possible strategies for setting the timing of bottom withdrawal; for this exercise, the timing of bottom withdrawal was set based on the simulated chloride concentration. Withdrawal was turned on at a fixed rate for a period of time when the bottom concentration exceeded 200 mg/L (Figure 5-3) in the nominal pond simulation.

Based on the model simulations, water withdrawn from the pond bottom has a chloride concentration of about 200 mg/L. At the lower withdrawal rate (0.01 cfs, or 0.3 L/s), removing 0.6% of the total runoff volume resulted in the removal of about 3% of the total chloride input to the pond (Table 5-3, Figure 5-3). Increasing the withdrawal rate to 0.035 cfs (1 L/s) reduces the chloride average concentration of the withdrawal to 180 mg/L, resulting in 8.3% of the chloride removed with 2.1% of the runoff volume (Table 5-3, Figure 5-3). Figure 5-4 shows a simulated time series of chloride load coming out of the Alameda pond outlet with and without bottom withdrawal. The highest chloride export in a month (May 2015) was reduced 44% with bottom withdrawal, while the peak exports in the other two years were reduced only by 10-15%.

Based on the results of the pond withdrawal analysis, a substantial volume of water needs to be withdrawn from a pond to remove a significant fraction of chloride loading in a watershed. However, there is some indication that the CEQUAL-W2 model may be underpredicting the stratification of salinity in a pond. If the pond bottom chloride concentrations are higher and more persistent, then chloride may be withdrawn at a higher concentration, yielding more chloride per withdrawal volume. Based on analysis of diverting surface runoff at select times (e.g. prior to the detention pond), it may be advantageous to divert captured high concentration chloride runoff to a separate holding tank or pond, to minimize the volume of water that needed to be handled.

Table 5-3. Summary of simulated results for chloride removal via bottom withdrawal from a detention pond.

Case	Withdrawal Rate (cfs)	Average Annual Withdrawal Volume (ft^3)	% Total Runoff Volume Captured	Average Annual Chloride Mass Captured (lbs)	% Inflow Chloride Captured
1 (nominal)	0	0	0	0	0
2	0.011	53,330	0.6	701	2.8
3	0.035	177,500	2.1	2,060	8.3

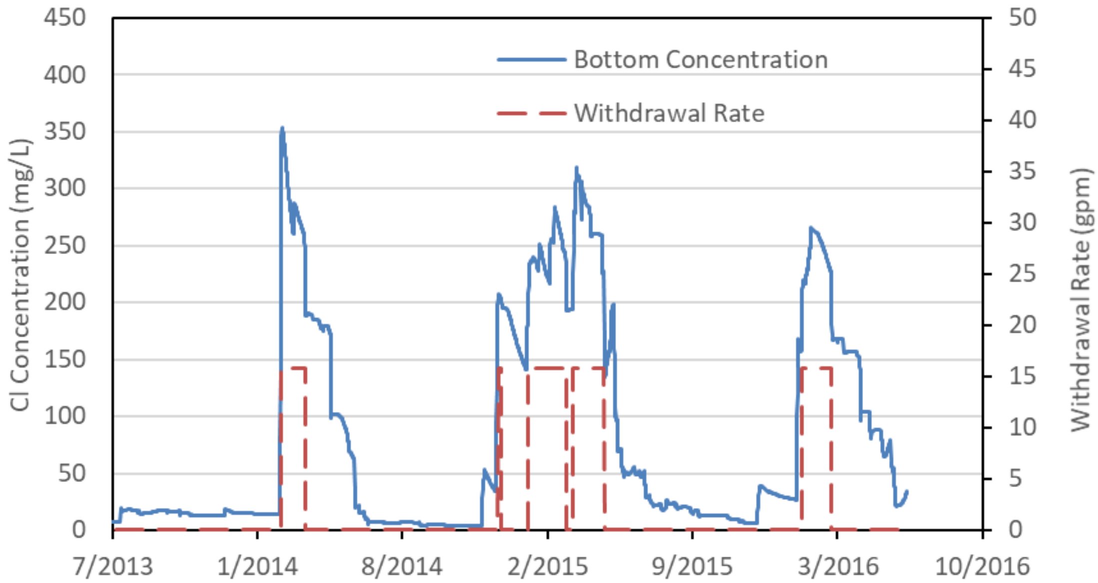

Figure 5-3. Time series of the simulated water withdrawal rate for model Case 3, which used the 0.035 L/s withdrawal rate and based timing of withdrawal on the bottom chloride concentration exceeding 200 mg/L.

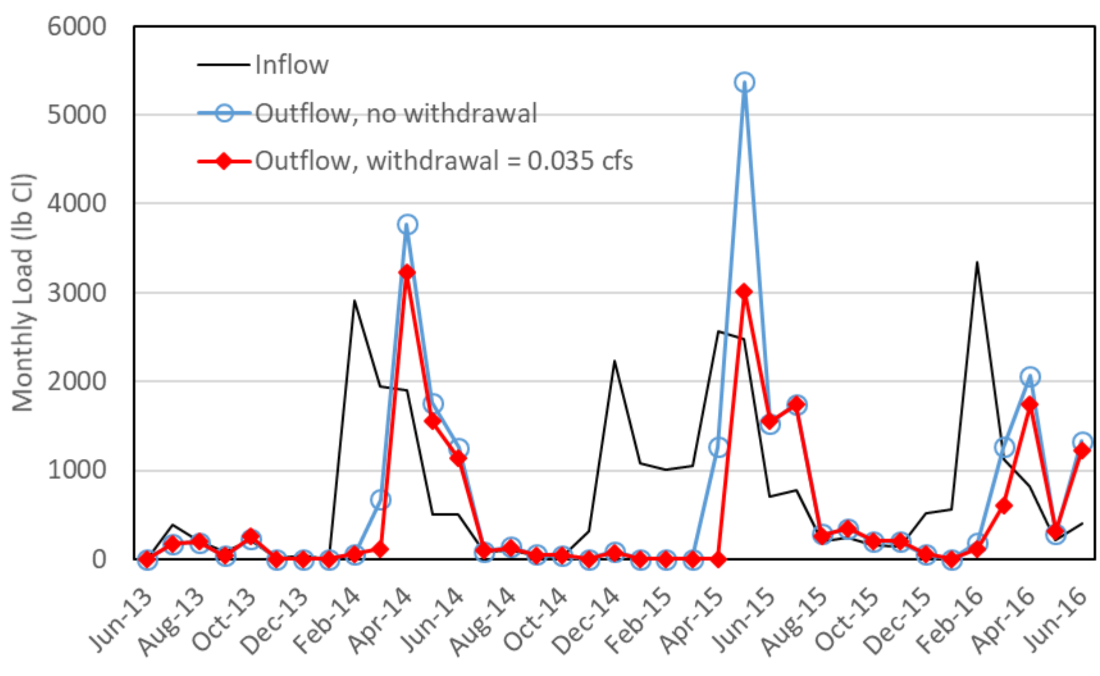

Figure 5-4. Simulated monthly loads of chloride in and out of the Alameda Pond. Outflow chloride shown both for a case with a bottom withdrawal rate of 0.035 cfs, and for a case of zero bottom withdrawal.

5.4 INFILTRATION BMPS

Increasing infiltration to reduce water loss from rainfall to surface runoff has been a primary objective of many stormwater best management practices (BMPs), e.g., rain gardens, infiltration ponds, vegetated swales. However, higher infiltration increases chloride transport into the subsurface, potentially enriching aquifers with chloride. Alternative strategies that prevent water loss to infiltration during snowmelt are necessary for chloride management. Striking a balance between stormwater runoff volume reduction and chloride reduction in infiltrating water is difficult. Capturing first flush runoff or snowmelt water is one approach to dilemma. The recommendations below attempt to address also the high chloride loss from surface runoff observed in the watersheds monitored in this study.

(1) *Curb/Ditch underdrains:* Similar to those used in some rain gardens or in agricultural tile drain systems, underdrains could be placed in ditches and roadside (curb-and-gutter) boulevards. Outlets would connect directly to storm drains or to gutters through holes in curbs, to move recently infiltrated water from roadside areas back into storm drains and gutters. During the warm season, leachate from the underdrain systems would potentially export nutrients such as phosphorus and nitrogen (in particular from lawn areas), which would be undesirable; therefore the ability to close them off during the warm season would potentially be necessary. This system would reduce the amount of chloride infiltrated in roadside areas, but would be expected to increase downstream loading of chloride annually; if combined with a capture strategy, a net reduction of both groundwater and surface water chloride could be achieved.

(2) *Seasonal bypass of infiltration BMPs:* Saline runoff could be prevented from reaching infiltration BMPs by installing a mechanism upstream of the BMPs to allow flows to bypass the infiltration area and be routed to the downstream pipe network. This mechanism could be a valve or diversion weir installed in an upstream storm pipe, operated seasonally to route inflows into an alternate pipe that circumvents the infiltration area.

(3) *Narrowing of streets or boulevards to reduce salt and snow:* If substantial chloride infiltration occurs in roadside boulevard areas, then another potential strategy is to design narrower streets and remove street parking, which could reduce the amount of salt that is needed to de-ice the roadways, as well as reduce the amount of snow and salt that gets plowed onto boulevards. A related option might be to narrow the boulevards and slope them towards the street in order to direct snowmelt and runoff from the plowed snowpack towards the gutters.

6 CONCLUSIONS

The monitoring work described in this report focused on the seasonal transport of chloride from road salt in small urban watersheds, from source areas (roads) where it is applied as de-icer, dissolved in surface water runoff, and transported through the urban drainage network from where it may be lost to groundwater or accumulate temporarily in ponds or wetlands. Chloride loading, retention, and approximate residence times observed at the primary monitoring sites are summarized for Field Seasons 2 and 3 in Table 6-1.

6.1 CHLORIDE RETENTION AND RESIDENCE TIME IN URBAN WATERSHEDS

In this report, *retention* was defined as the fraction of chloride applied as road salt that is temporarily or permanently retained in watershed via infiltration to soils and groundwater, and therefore not observed in surface runoff. *Residence time* was defined as the time between road salt application and salt appearance at the watershed outlet. In this study, we observed substantial retention of road salt chloride, with some variability among sites and between years. Monitoring of runoff from a vegetated highway ditch showed that roughly 94% of the chloride applied to the highway was infiltrated in the ditch, with only ~6% exported from the site in surface runoff. This result was consistent between field seasons, and agreed with previous studies showing very high infiltration rates in ditches (Garcia-Serrana et al., 2017). Estimated residence time of chloride in the ditch was significant, at 172 days (Field Season 2). For a small, sewered, curb-and-gutter watershed (County Road B), results were more variable between field seasons, with chloride retention of 66% and 37% in Field Season 2 and Field Season 3, respectively. The residence time of chloride in the County Road B watershed was much shorter than for the ditch, and varied from 14 to 26 days. The high retention (37-66%) of the chloride applied for de-icing in the County Road B watershed was noteworthy, as no stormwater BMPs (such as rain gardens or ponds) were present in the watershed. Chloride presumably infiltrated in pervious areas adjacent to the streets after being plowed or splashed over the curb by traffic. Chloride retention of 29% - 50% was observed in the Alameda Pond watershed, a larger, sewered, residential watershed with a residence time of 158 days. Several ponds and wetlands present in the drainage network of this watershed likely increased the chloride retention and residence time, especially as some chloride was exported months after spring snowmelt.

In all three winters, the hydrologic processes or events that contributed to the greatest chloride export in surface runoff tended to be rain-on-snow events (e.g., Feb 19, 2016 and Dec 25, 2016), as well as the first major, prolonged thaw in each season (early March 2015, late February 2016, and mid-January 2017). Chloride retention across sites was generally lower in Field Season 3 compared to Field Season 2, even though monitoring in Field Season 3 was incomplete (i.e., less than a full year). The lower retention in Field Season 3 is attributed to the more frequent mid-winter rainfall events (e.g., Dec 25, 2016, and Feb 20, 2017) than in Field Season 2, and prolonged periods of thaw (e.g., mid-January 2017) that may have resulted in more surface runoff and less opportunity for chloride to infiltrate. Surprisingly, wet periods in November 2015 and 2016 also resulted in substantial chloride export from the ditch and Alameda Pond Inlet sites, even though no new road salt had been applied since the previous winters.

This pattern suggests that chloride stored in soils, wetlands and shallow groundwater from infiltration early in the season may be flushed out during these late season rainfall events when evapotranspiration rates are lower and water tables rebound.

The results of this study on the retention of chloride in small urban watersheds were consistent with results from previous studies. For example, Novotny et al. (2009) found 56% - 85% road salt retention in watersheds of major tributaries to the Minnesota and Mississippi Rivers in the Minneapolis-St. Paul metro, and a study in Toronto, Canada (Howard and Haynes, 1993) found roughly 65% retention in a 40.2 mi^2 (104 km^2) urban watershed. However, the watersheds in these previous studies were generally much larger than the ones included in our study, and the variability in retention observed across site types in our study suggests that chloride retention may be quite variable within watersheds, even if overall retention is similar. For example, highways are areas of intense salt application, and loss of chloride to infiltration is apparently very high in vegetated swales next to highways. However, highways are a small part of the road network; the bulk of roadways are more similar to the residential curb-and-gutter roadways in our study watersheds, where retention of chloride is lower (though overall salt amounts may be similar to highways). The retention of chloride at the scale of large, urban watersheds may therefore be related to the balance of roadway types present (e.g., highway vs. residential) and to the size and number of BMPs (such as detention ponds or wetlands).

Monitoring of several detention ponds of different sizes showed consistent results. The inputs to the detention ponds over winter tended to be at relatively low flow rates (from snowmelt events) with high chloride concentrations (up to 12,000 mg/L). They tend to accumulate at the pond bottom, similar to how chloride-rich meltwater accumulates in lakes (Novotny et al., 2008, Weiss et al., 2010). In contrast, the export of chloride from detention ponds was found to occur over the entire open water season (roughly April – November), with a relatively steady, low concentration (50-150 mg/L) similar to that observed near the pond surface. This suggests a slow diffusion from or erosion of the saline layer at the pond bottom by inflows and other disturbances (e.g., wind). Chloride residence time in the Alameda Pond was around 7 months using a method similar to computing hydraulic residence time in a stratified waterbody. The persistence of chloride outflow from the pond over the entire open-water season also suggests a long residence time. The ponds in our study appeared to mostly delay, rather than prevent, the transport of chloride out of the pond, as Alameda Pond exported ~40% more chloride than flowed into it (Field Season 2), with a similar pattern observed for William Street Pond (Field Season 3). In both ponds, additional chloride may be contributed by shallow groundwater inputs, or by release from storage in sediments of chloride applied in previous years.

Finally, calculation of chloride loads in surface runoff in this study relied heavily on the regression equations relating chloride concentration to specific conductivity. The advantage of conductivity is that it can be measured continuously and accurately, and at considerably less cost than direct measurements of chloride. Chloride-conductivity relationships in runoff from the roadway and watershed sites closely resembled that of pure sodium chloride dissolved in water, especially in the slope of the relationships, suggesting a strong influence of road de-icer (sodium chloride) on the conductivity of runoff from these watersheds. However, the pond outflow sites showed some variability and lower slopes in the chloride-conductivity regressions, which was most likely related to the presence of other ions in concentrations similar to that of chloride. For the Alameda Pond outlet in particular, these deviations from the sodium chloride solution line may be a function of season, as two summer and fall samples were major outliers. Given that the ponds may have both surface and sub-surface water and nutrient sources, and internally process nutrients and metals (in contrast to, for example, the roadway sites), the significant and seasonal contribution of other ions to conductivity can be expected.

6.2 LIMITATIONS OF AVAILABLE MODELS FOR SIMULATING CHLORIDE TRANSPORT IN URBAN WATERSHEDS

The modeling effort in this study revealed that commonly used hydrologic runoff models such as SWMM and HSPF have limitations for modeling chloride transport in urban watersheds, both in dealing with source areas (roadways, parking lots) and in intermediate storage areas (detention ponds, wetlands). HSPF was found to be the most usable modeling package for chloride transport, with the capabilities to model both surface and subsurface transport of chloride. HSPF was applied to the sewered Alameda Pond watershed. However, the model lacked the ability to simulate the movement of salt from where it is applied on roadways to pervious areas above curbs (i.e., the transport associated with snow plowing or spraying by vehicles). This was primarily a problem for simulating transport in the Alameda Pond watershed; the model was able to simulate the chloride transport from a hypothetical vegetated ditch. Furthermore, HSPF also utilized a simple approach to surface water BMPs (ponds or wetlands), modeling them as completely mixed reactors with a specified infiltration rate. This approach does not reflect the reality of strongly and persistently stratified ponds observed in this study, and may have contributed to the model's inability to simulate late-season (summer and fall) transport of chloride in the Alameda Pond watershed.

With respect to the other models, SWMM includes a street plowing component that could have been used to route chloride onto boulevards, but it lacked the ability to infiltrate or track chloride in the sub-surface, and therefore was unsuitable for this study. GSSHA, another hydrologic model evaluated in this study, has the ability to simulate surface and sub-surface chloride transport and includes several different snowmelt routines, but the model was complex to set up, and several routines appeared to be incomplete or non-functional.

A common limitation of all watershed-scale hydrologic modeling packages is the inability to model salinity stratification in detention ponds and wetlands. The lake/reservoir modeling packages CEQUAL-W2 and GLM were both used separately from the runoff models to simulate salinity stratification in a detention pond. Both packages were found to be capable of modeling salinity stratification and the corresponding effect on the retention of chloride in a pond; however, the degree of stratification and the length of the chloride retention time may be under-predicted by these models.

6.3 CHLORIDE MITIGATION BY RUNOFF DIVERSION AND SELECTIVE WITHDRAWAL

The chloride management strategies examined in this study focused primarily on snowmelt capture, with the idea that capturing small amounts of snowmelt runoff with high chloride concentrations may be a relatively efficient method to mitigate chloride spreading from de-icers in the environment.

However, we have made no effort to estimate the cost of snowmelt runoff capturing systems and the associated systems needed to store and treat the captured saline runoff. Because snowmelt runoff capture systems could be expensive, and space or infrastructure could be limiting, such systems could be designed to be dual purpose, i.e., (1) to capture high chloride concentration snowmelt water and (2) to capture first-flush runoff from summer rainfall events with high contaminant concentrations. Ultimately, the cost of mitigating chloride pollution by de-icers needs to be weighed against the environmental costs of no treatment, or against the costs of reducing the use of sodium chloride based de-icers.

A few results of the runoff diversion analysis, which was carried out using monitoring data as well as the output from the pond chloride model, are worth highlighting:

- Chloride removal by diversion of saline runoff will be most effective (in terms of mass of chloride removed per volume of water) if implemented at the scale of a roadway, before runoff enters the drainage network (e.g., at County Road B). This is illustrated by the larger volumes of water required to remove a similar amount of chloride at the outlet of the Alameda watershed compared to the roadway site (County Road B). For example, a diversion of 0.1 inches of the most saline runoff at the County Road B site would remove 80% of surface runoff chloride from the site (requiring diversion of roughly 10,000 ft^3 of water), while a diversion of 0.1 inches of the most saline runoff at the Alameda Pond inlet would remove only 51% of chloride in surface inflows to the pond (requiring diversion of 103,455 ft^3 water; Table 5-1)).
- Similarly, withdrawal of saline water from the bottom of a pond (as simulated for Alameda Pond in Section 4.3) was found to be less effective than removal at street- or even watershed-level due to dilution of inflow once it enters the pond. For example, diverting 177,500 ft^3 of water from the bottom of Alameda pond would remove 8% of chloride entering the pond (Table 5-3), whereas capturing only 103,000 ft^3 of the most saline runoff at the pond's inlet could remove ~51% of potential influent chloride (29% of the salt applied in the watershed; Table 5-1). However, the pond models used to generate these numbers may be underpredicting salinity stratification, so that further study of pond withdrawals is warranted.
- Seasonal diversion may also be effective, and potentially simpler to implement than the concentration-based diversions described above. For example, at Country Road B, 97% of the chloride in surface runoff could be removed if it was possible to divert or capture all flows during winter (December – March; Table 5-2). This would represent 16% of the annual runoff volume, or 1.10 inches of runoff.
- Capturing chloride in snowmelt runoff, by itself, would be relatively ineffective for roadways with pervious ditches, since most of the snowmelt water volume and the chloride it contains is infiltrated. Capturing chloride in runoff from roadways with pervious ditches may require a system of underdrains.

6.4 QUESTIONS FOR FUTURE STUDY

The results of this study provide information on the transport and retention of chloride from road de-icers in small urban watersheds. The results also raise additional questions, which could be addressed in future studies. The more important unresolved issues include:

- *Fate and transport of infiltrated chloride*: This study did not consider the transport of chloride in the sub-surface, and the results of this study reinforce the idea that a large fraction of road de-icers end up in soil and groundwater. The fate of infiltrating chloride is a good candidate for future study, to determine, at different spatial scales, what fractions of infiltrated chloride are retained in soils, reappear in baseflow to streams and rivers, or are transported to deeper groundwater aquifers.
- *Chloride retention in curb-and-gutter watersheds*: A more specific question raised by this study concerns the mechanisms by which chloride is infiltrated in sewered, curb-and-gutter watersheds, and how factors such as traffic or de-icing and snow removal practices affect these processes. A controlled field study of these processes or a synthesis of previous work is likely needed to develop a predictive model that could be used to predict chloride loss in roadside areas.
- *Seasonal variability of chloride-conductivity in surface water*: The variability and lower slopes present in the chloride-conductivity regressions at the pond outlet sites was likely related to the time-varying presence of other ions (e.g., nutrients, metals, salts) in concentrations similar to that of chloride. A much larger sampling dataset, ideally for a range of pond types and ages, would be useful to better understand the seasonality of the chloride-conductivity regressions. Such information would improve the chloride loading predicted from conductivity time series.
- *Variability of chloride retention across types of watersheds or salt source areas:* The contrast in retention between the vegetated ditch and the curb-and-gutter roadway suggests chloride retention is spatially variable across the urban landscape, and potentially related to type of roadway, presence/absence of sewers, or connectedness of ponds. Similarly, we were unable in this study to complete a chloride budget for a typical parking lot – pond system, which is another common, and under-studied, salt source area in cities. Future work could investigate chloride retention across several source areas within a watershed.
- *Large-scale chloride budget*: Results from this study could potentially be scaled up to larger watersheds where relevant data are available (road salt application, chloride and discharge at the watershed outlet), to understand if the results are useful in a predictive application.

Table 6-1. Summary of chloride and water (volume) loading, chloride residence time, and volume-weighted concentration at the primary monitoring sites for (a) Field Season 2 and (b) Field Season 3. Note that the "Alameda Inlet" column refers to the drainage area upstream of the Alameda Pond; the "Alameda Pond" column refers to the difference in loading between the inlet and outlet sites. *Field Season 3 residence time is likely inaccurate for these sites because the season's monitoring ended in August. **Residence time is of chloride within the pond, based on the method for hydraulic residence time: inflow load / outflow rate).

(a) Field Season 2 (11/20/2015 – 11/30/2016)	**Hwy 36 Ditch**	**County Road B**	**Alameda Inlet**	**Alameda Outlet**	**Alameda Pond**
Cl Input (Road Salt or Inflow)	6,233 *lbs*	3,595 *lbs*	19,130 *lbs*	19,130 *lbs*	6,705 *lbs*
Runoff or Outflow Cl	375 *lbs*	1,212 *lbs*	6,705 *lbs*	9,570 *lbs*	9,623 *lbs*
Chloride Retention	94%	66%	65%	50%	-44%
Residence time of Cl	172 *days*	26 *days*	158 *days*	170 *days*	264 *days***
Runoff/Outflow Volume	3.2 ac-ft	10.6 ac-ft	98.1 *ac-ft*	93.0 *ac-ft*	--
Mean Conc in Runoff	43 *mg/L*	42 *mg/L*	26 *mg/L*	38 *mg/L*	--
(b) Field Season 3 (12/1/2016 – 7/31/2017)	**Hwy 36 Ditch**	**County Road B**	**Alameda Inlet**	**Alameda Outlet**	**Alameda Pond**
Cl Input (Road Salt or Inflow)	9,012 *lbs*	4,726 *lbs*	21,864 *lbs*	21,864 *lbs*	17,654 *lbs*
Runoff or Outflow Cl	556 *lbs*	2,968 *lbs*	17,654 *lbs*	15,422 *lbs*	15,422 *lbs*
Chloride Retention	94%	37%	19%	29%	13%
Residence time of Cl	5 *days**	14 *days*	3 *days**	90 *days**	278 *days***
Runoff/Outflow Volume	1.8 ac-ft	6.0 ac-ft	63.0 *ac-ft*	54.6 *ac-ft*	--
Mean Conc in Runoff	117 *mg/L*	182 *mg/L*	103 *mg/L*	104 *mg/L*	--

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APPENDIX A
TIME SERIES PLOTS OF PRECIPITATION, ROAD SALT APPLICATION, CHLORIDE EXPORT, AND WATER EXPORT OBSERVED AT PRIMARY MONITORING SITES DURING FIELD SEASONS 1 – 3

A-1. TIME SERIES PLOTS – COUNTY ROAD B

Note: no results shown for Field Season 1.

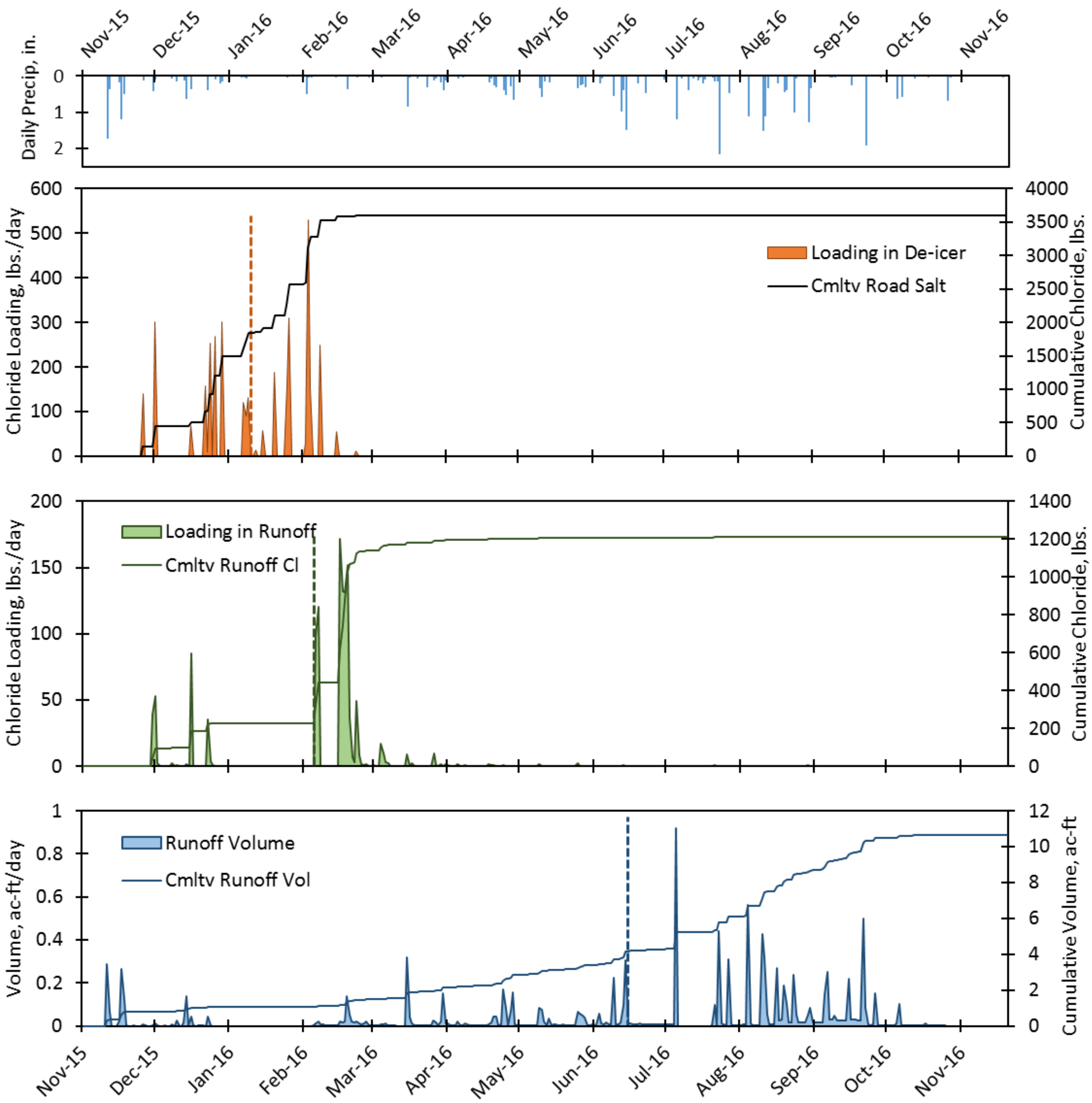


Figure A-1-1. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *County Road B* from Nov 20, 2015 – Nov 30, 2016 (*Field Season 2*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

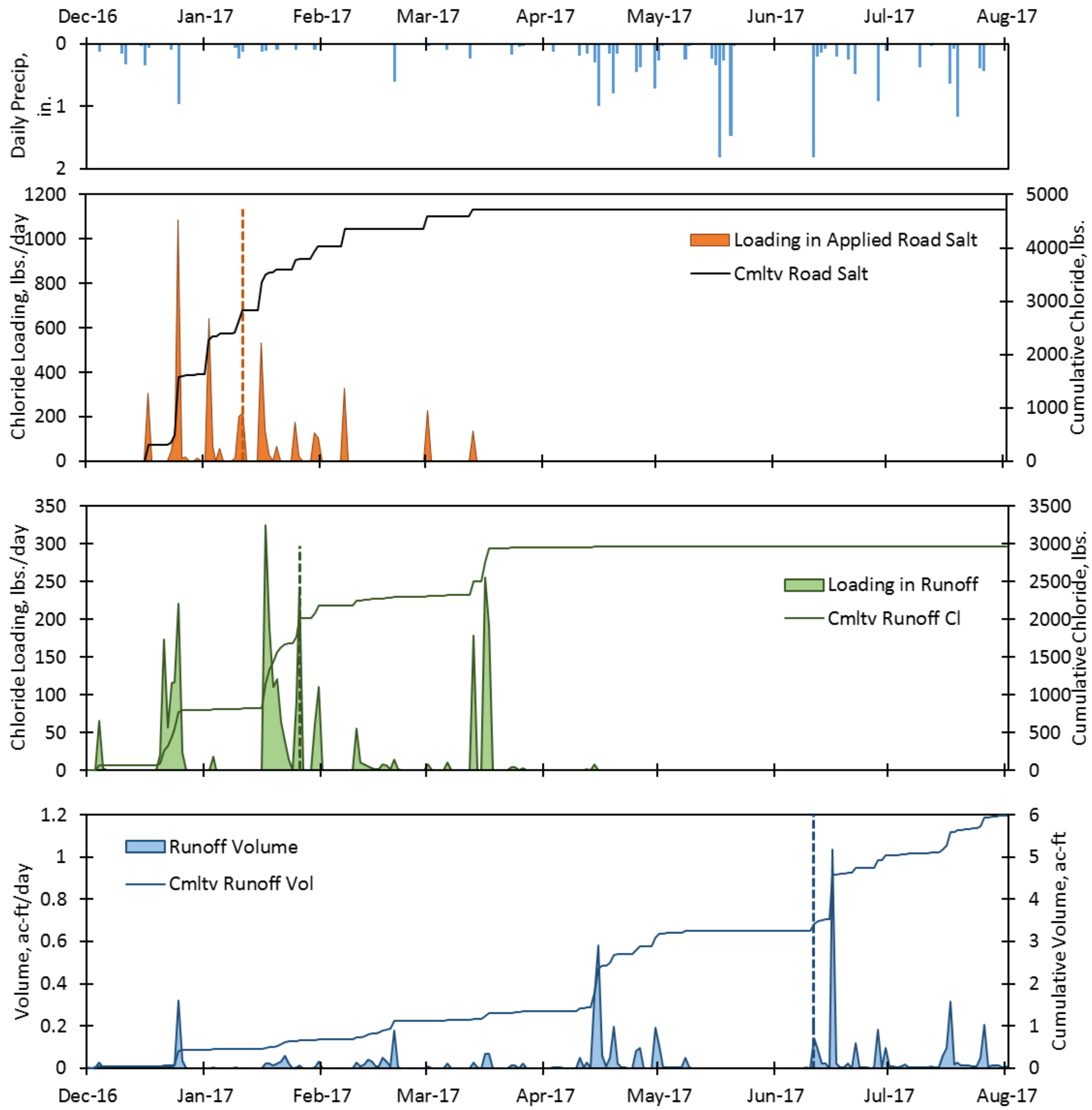


Figure A-1-2. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *County Road B* from Dec 1, 2016 – Aug 1, 2017 (*Field Season 3*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

A-2. TIME SERIES PLOTS – HIGHWAY 36 DITCH

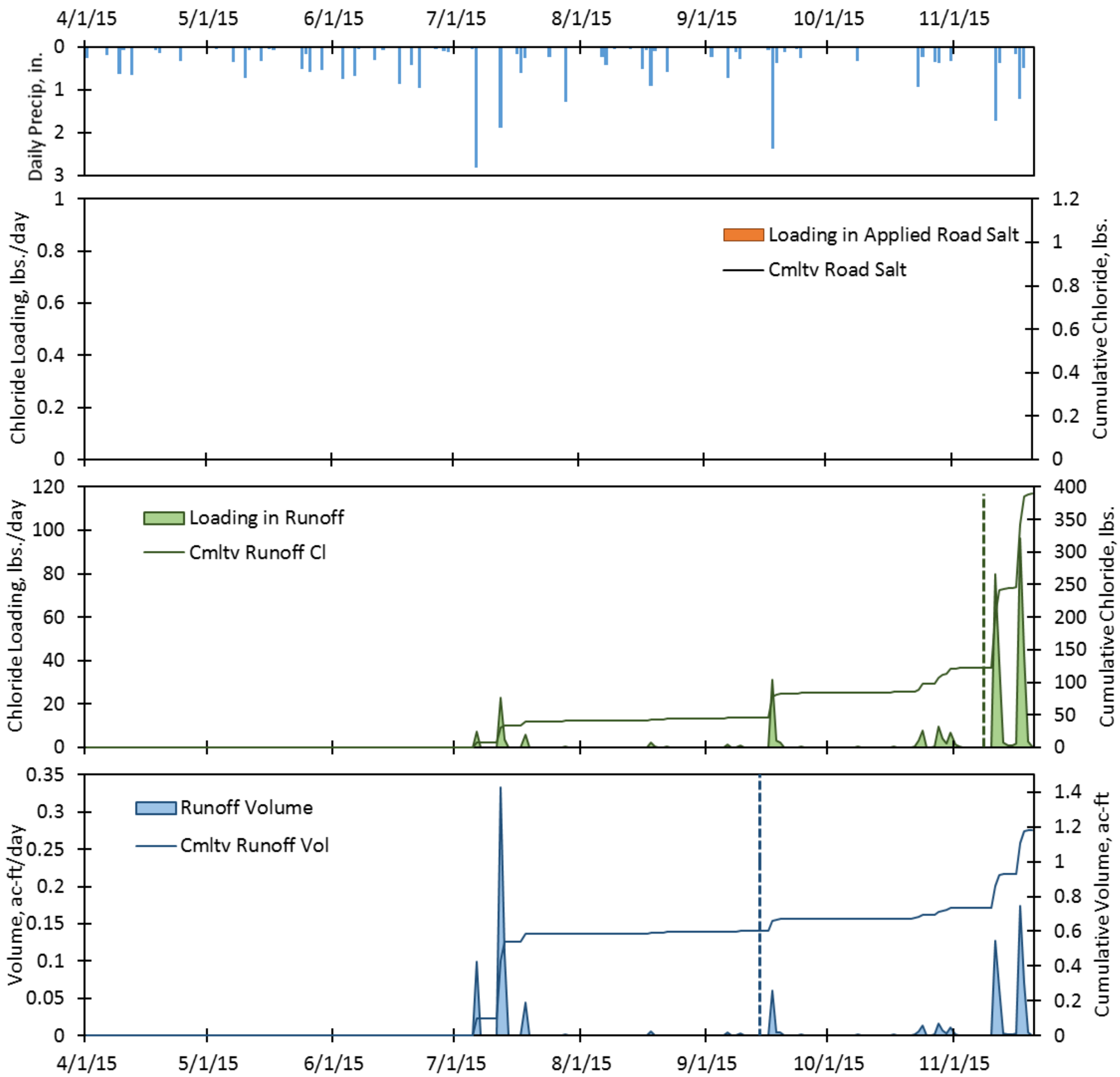


Figure A-2-1. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *HIGHWAY 36 DITCH* from Jul 1, 2015 – Nov 19, 2015 (*FIELD SEASON 1*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

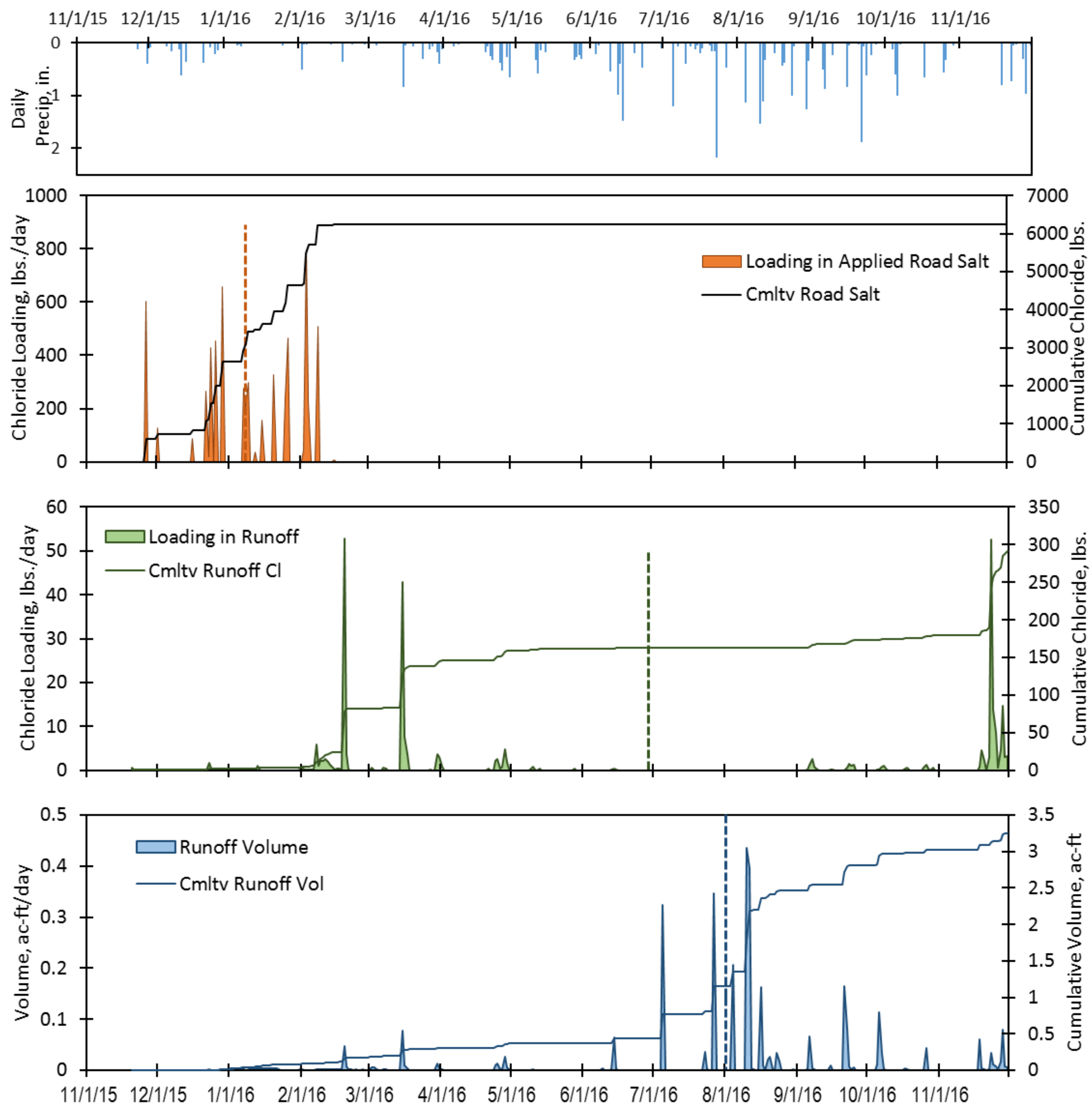


Figure A-2-2. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *HIGHWAY 36 DITCH* from Nov 20, 2015 – Nov 30, 2016 (*FIELD SEASON 2*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

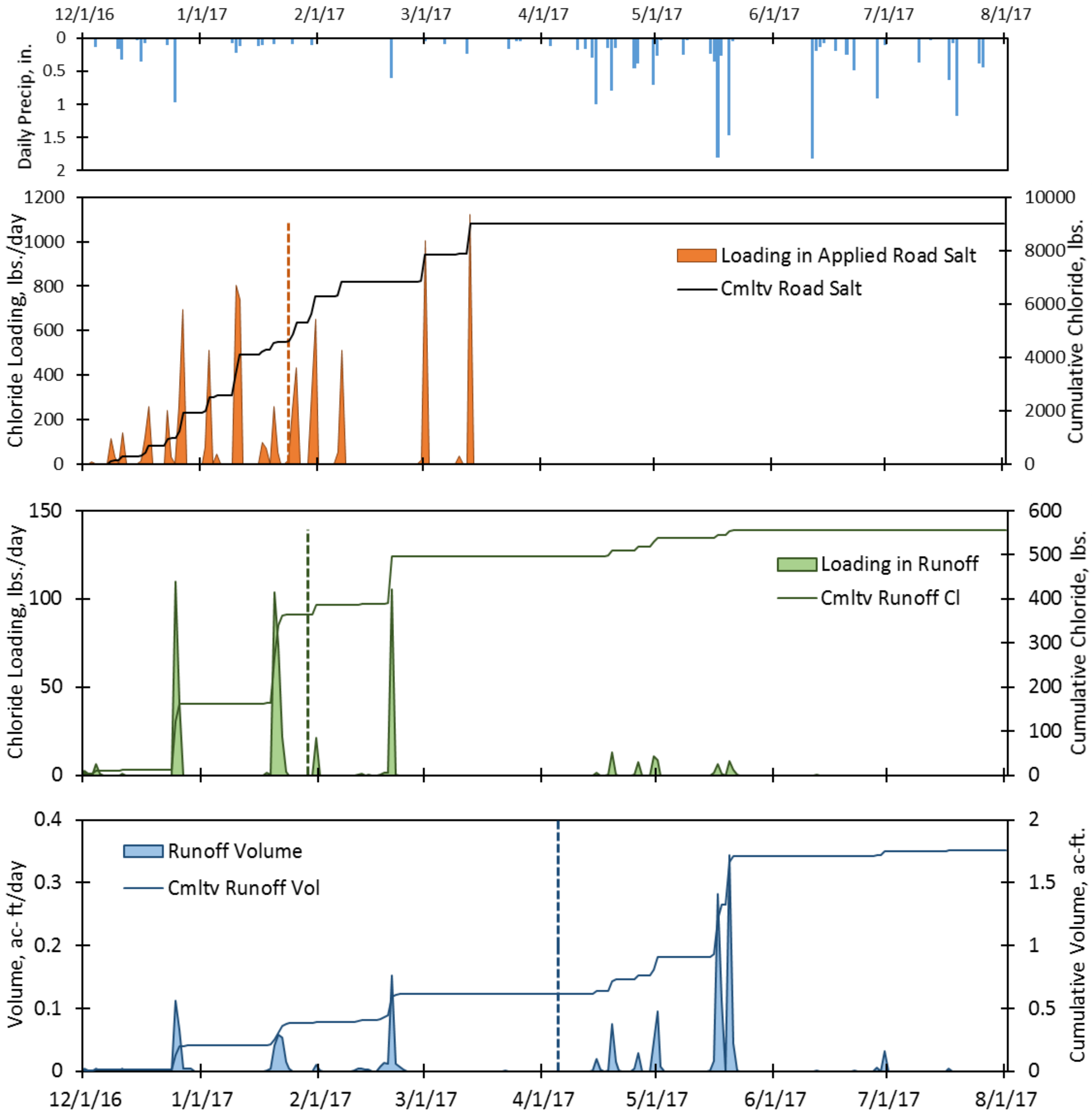


Figure A-2-3. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *HIGHWAY 36 DITCH* from Dec 1, 2016 – Aug 1, 2017 (*FIELD SEASON 3*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

A-3. TIME SERIES PLOTS – ALAMEDA POND INLET AND OUTLET

Note: no results shown for outlet site for Field Season 1.

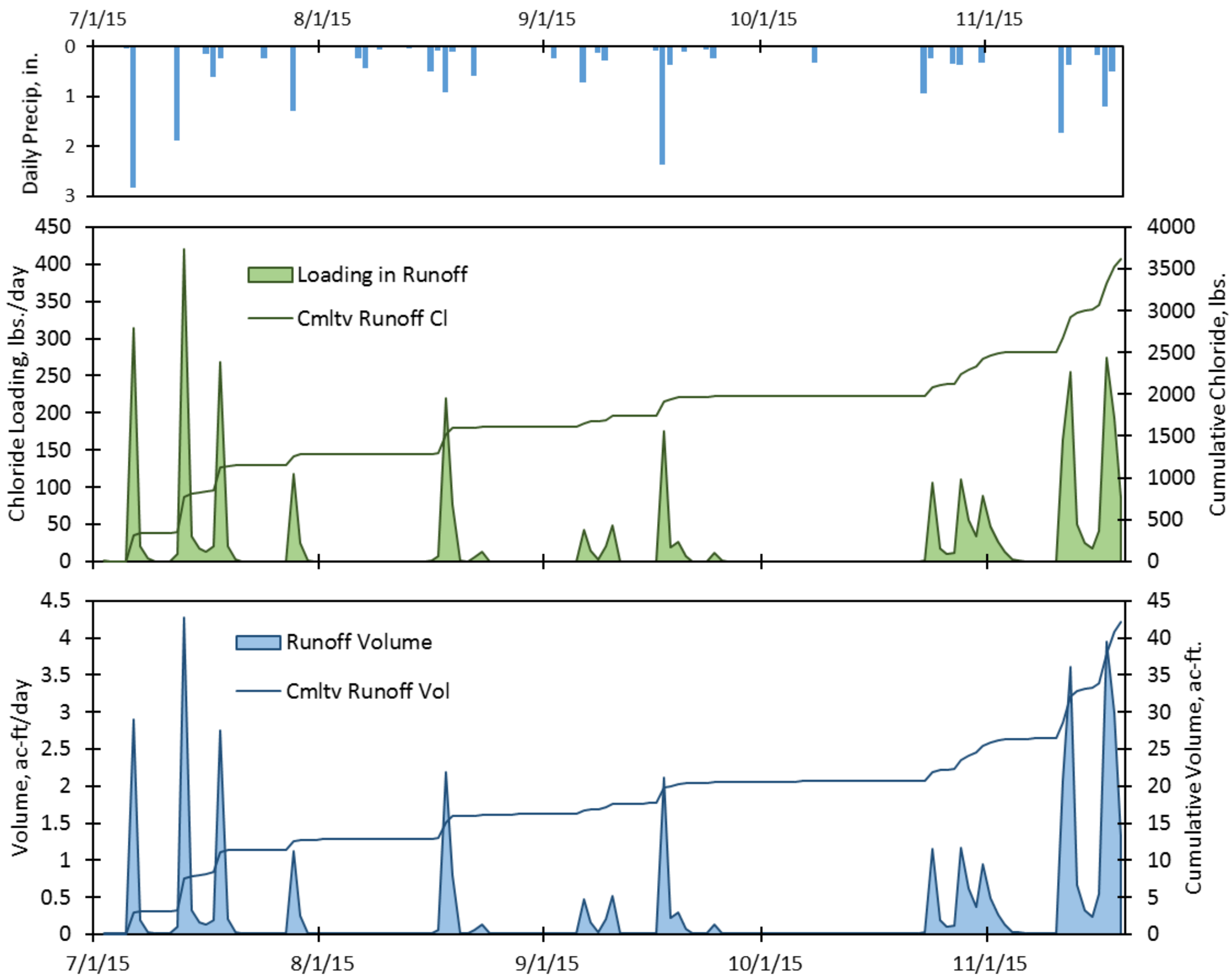


Figure A-3-1. Time series and cumulative loading of chloride in runoff (green; middle plot), and of runoff volume (blue; bottom plot) at *ALAMEDA POND INLET* from July 1, 2015 – Nov 19, 2015 (*FIELD SEASON 1*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top.

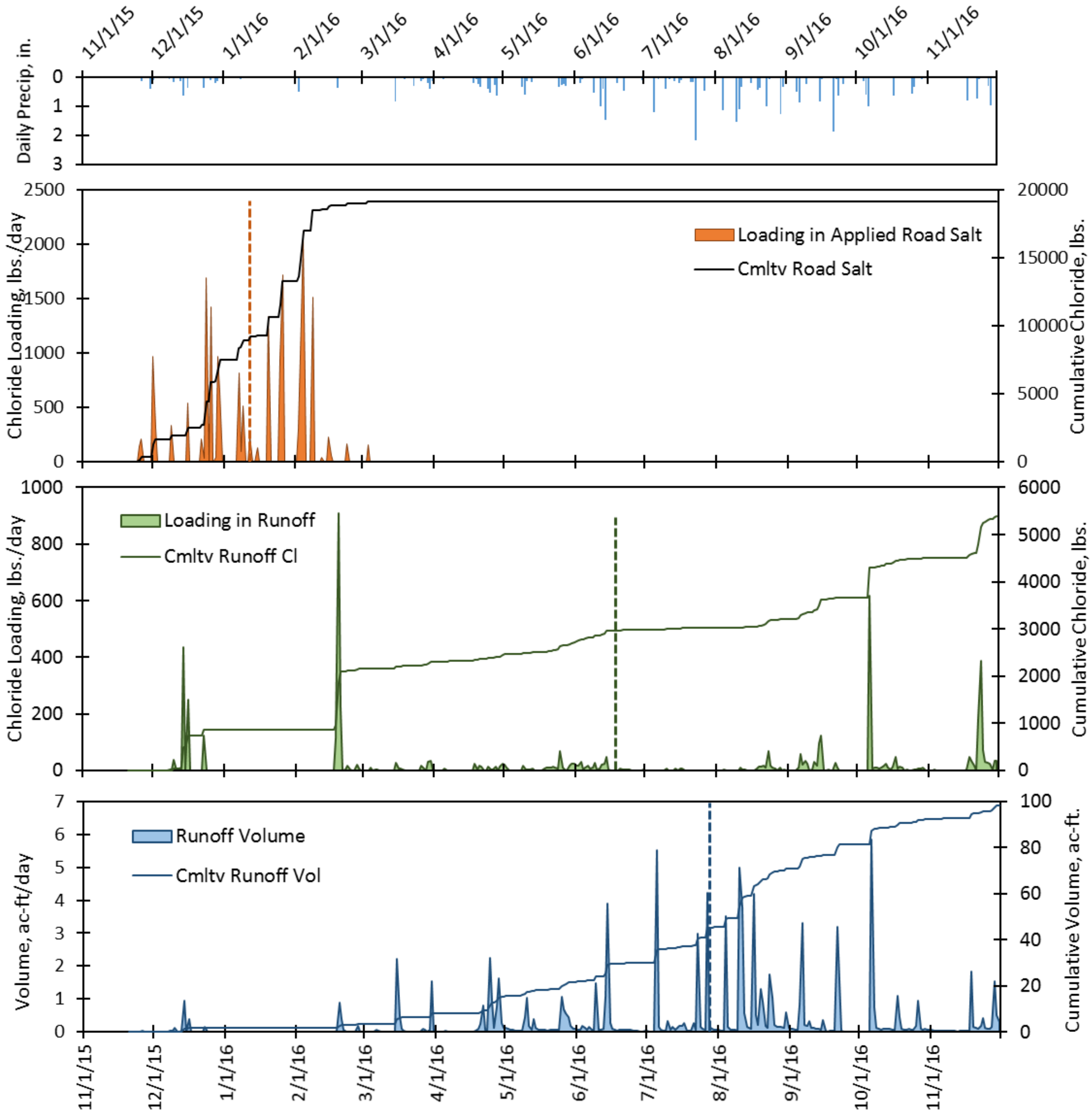


Figure A-3-2. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *ALAMEDA POND INLET* from Nov 20, 2015 – Nov 30, 2016 (*FIELD SEASON 2*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

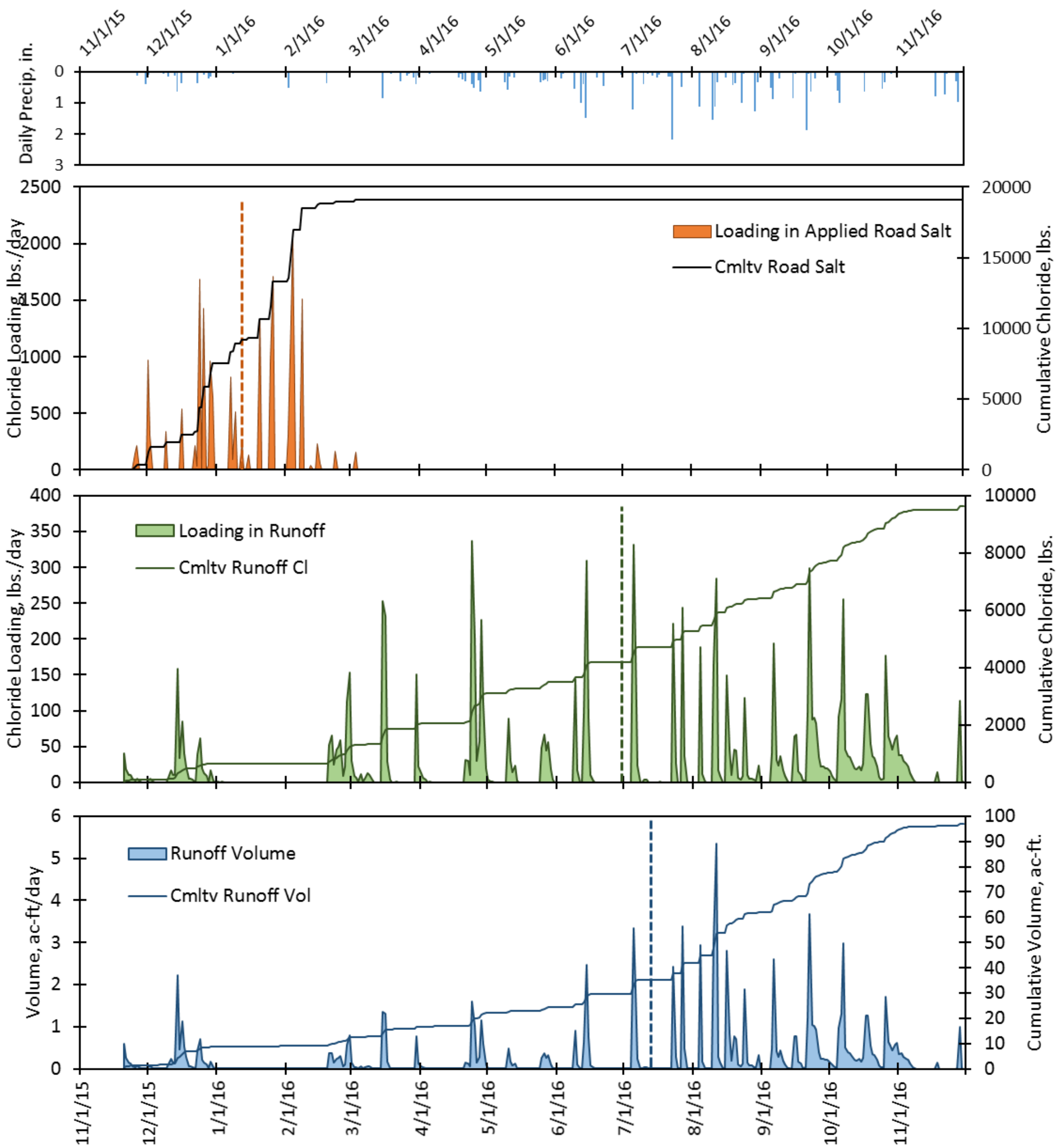


Figure A-3-3. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *ALAMEDA POND OUTLET* from Nov 20, 2015 – Nov 30, 2016 (*FIELD SEASON 2*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

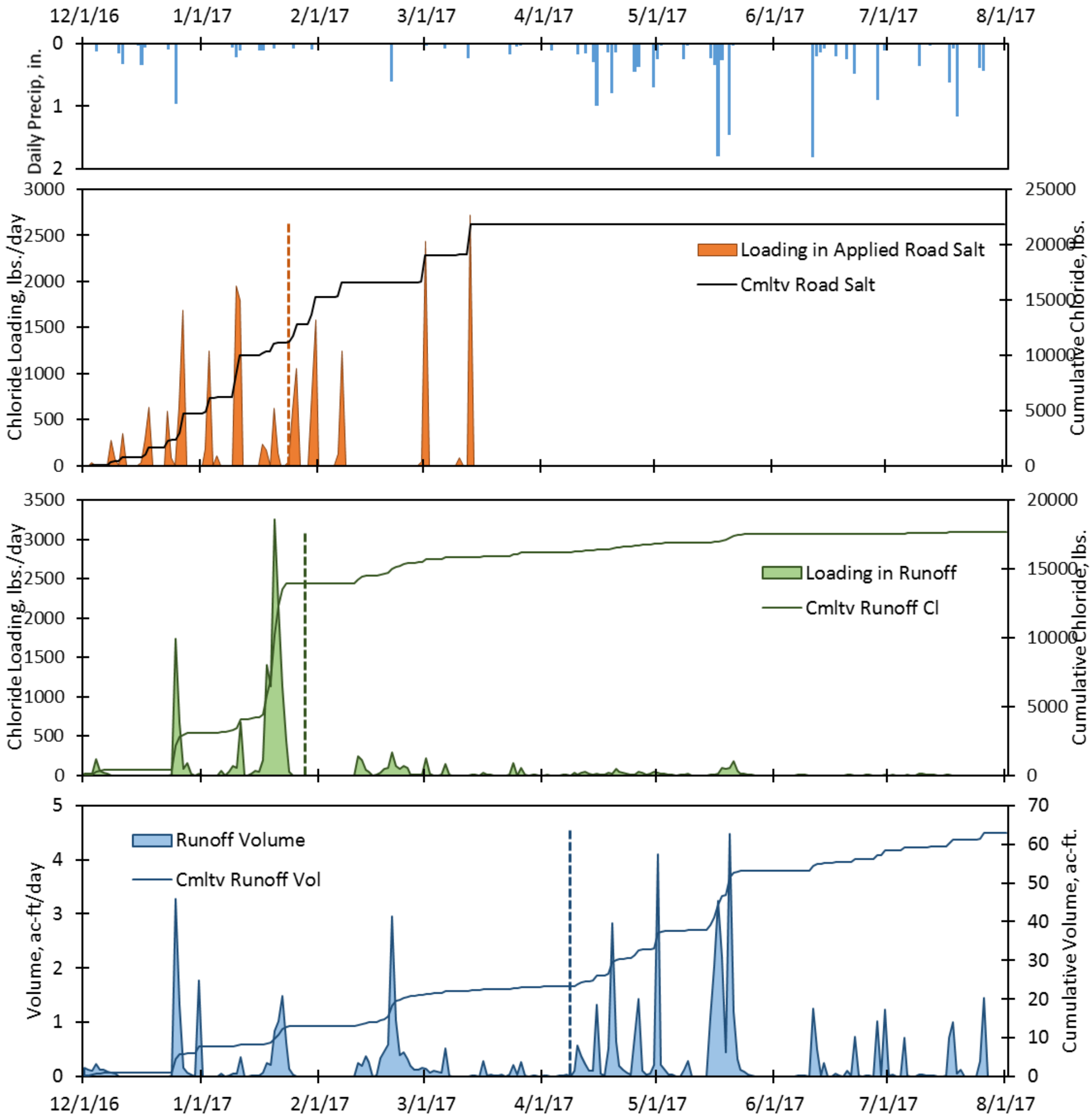


Figure A-3-4. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *ALAMEDA POND INLET* from Dec 1, 2016 – Aug 1, 2017 (*FIELD SEASON 3*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

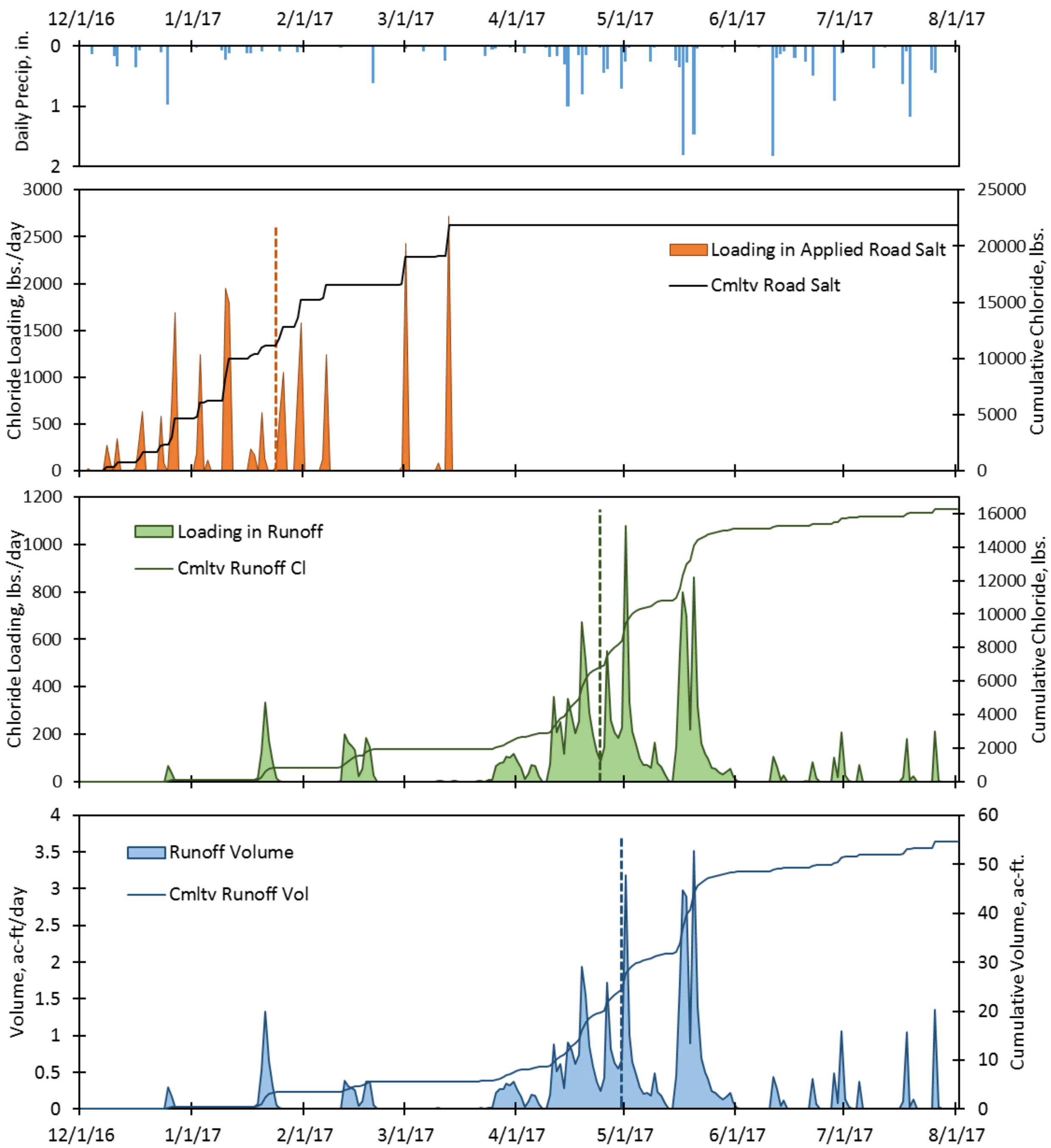


Figure A-3-5. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *ALAMEDA POND OUTLET* from Dec 1, 2016 – Aug 1, 2017 (*FIELD SEASON 3*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

A-4. TIME SERIES PLOTS – WILLIAM STREET POND OUTLET

Note: results only shown for Field Season 3 at William Street outlet.

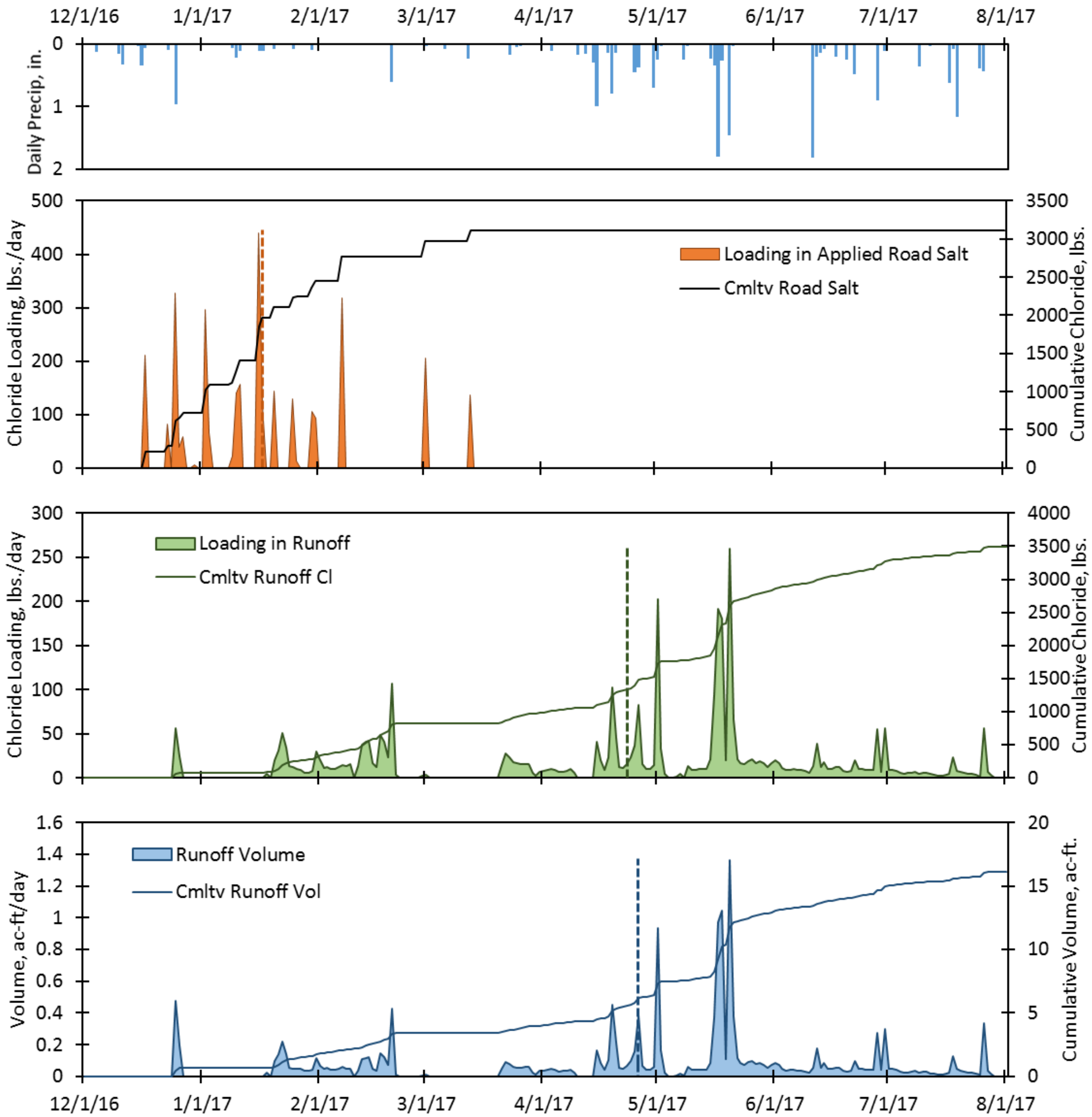


Figure A-4-1. Time series and cumulative loading of chloride in applied road salt (orange; 2nd plot), of chloride in runoff (green; 3rd plot), and of runoff volume (blue; 4th plot) at *WILLIAM STREET POND OUTLET* from Dec 1, 2016 – Aug 1, 2017 (*FIELD SEASON 3*). Daily precipitation as snow or rain (in inches of water) observed at KMSP shown at very top. Vertical dashed lines are locations of mass centroids (chloride or water).

APPENDIX B
ANCILLIARY DATA: CHLORIDE CONCENTRATIONS FROM WATER SAMPLING, AND POND WATER COLUMN PROFILES OF TEMPERATURE AND SPECIFIC CONDUCTIVITY

B-1. CHLORIDE CONCENTRATION DATA

Table B-1. Water samples from monitoring sites that were selected for analysis of chloride concentration by MCES. Samples selected from snowmelt and stormwater events, and pond water columns. Conductivity and temperature of samples were measured in the laboratory.

Sampling Point	Sampled Date	Spec Cond *uS/cm*	Temp *C*	MCES Chloride		Analysis Date
Alameda Inlet	7/1/15 12:40	292	6.6	32.1	mg/L	Jul-2016
Alameda Inlet	12/21/15 11:30	734	8.3	150.1	mg/L	Jul-2016
Alameda Inlet	1/7/16 11:30	555	13.8	93.1	mg/L	Jul-2016
Alameda Inlet	1/28/16 10:00	19620	7.1	7663.4	mg/L	Jul-2016
Alameda Inlet	2/7/16 16:20	5540	6.5	1610	mg/L	Jul-2016
Alameda Inlet	2/22/16 13:52	1668	9.2	385	mg/L	Jul-2016
Alameda Inlet	4/21/16 12:25	97	7.3	12.6	mg/L	Jul-2016
Alameda Inlet	1/20/17 13:00	6690	13.5	2247	mg/L	Aug-2017
Alameda Inlet	1/25/17 11:30	1892	13.7	263	mg/L	Aug-2017
Alameda Outlet	5/27/15 14:00	289	25.3	60.5	mg/L	Jul-2016
Alameda Outlet	6/19/15 15:30	233	7.6	55.9	mg/L	Jul-2016
Alameda Outlet	2/22/16 13:30	261	9.5	53.3	mg/L	Jul-2016
Alameda Outlet	3/22/16 14:20	306	8.3	74.9	mg/L	Jul-2016
Alameda Outlet	3/30/16 10:50	318	14.4	67.3	mg/L	Jul-2016
Alameda Outlet	4/21/16 12:00	397	7.2	188.2	mg/L	Jul-2016
Alameda Outlet	4/28/16 9:35	328	13.4	69.4	mg/L	Jul-2016
Alameda Outlet	9/22/16 14:35	551	9.3	58.0	mg/L	Aug-2017
Alameda Outlet	1/23/17 15:35	713	13.9	140.0	mg/L	Aug-2017
Alameda Outlet	1/26/17 10:00	589	11.8	115.2	mg/L	Aug-2017
Alameda Outlet	5/18/17 11:35	452	4.4	44.6	mg/L	Aug-2017
Alameda Pond Center	2/3/17 14:15	2430	12.4	451.1	mg/L	Aug-2017
County Road B	1/26/15 14:55	3620	7.2	682.6	mg/L	Jul-2016
County Road B	3/6/15 15:50	11200	13.2	3135.8	mg/L	Jul-2016
County Road B	3/9/15 14:58	1932	13.6	537.4	mg/L	Jul-2016
County Road B	1/7/16 14:00	24000	13.1	9277.7	mg/L	Jul-2016

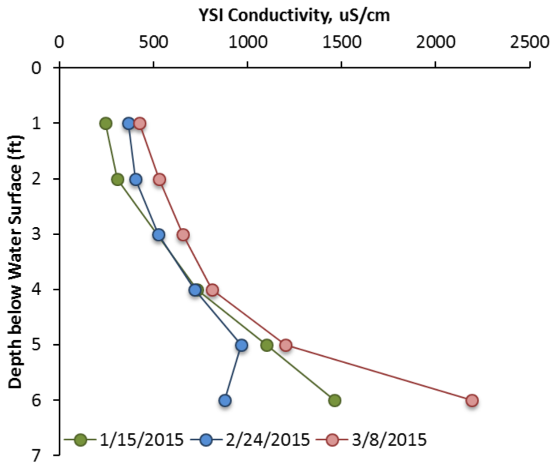
County Road B	1/28/16 11:00	21260	6.4	6814.9	mg/L	Jul-2016
County Road B	2/7/16 16:00	6160	7.1	1904	mg/L	Jul-2016
County Road B	2/19/16 10:55	623	12.4	143.2	mg/L	Jul-2016
County Road B	4/21/16 11:25	99	7.5	8.3	mg/L	Jul-2016
County Road B	1/20/17 11:35	7580	15.7	2613	mg/L	Aug-2017
Hockey Pond	1/7/16 12:30	20900	12.7	8616.8	mg/L	Jul-2016
Hockey Pond	5/17/16 13:56	1472	19.5	261.3	mg/L	Jul-2016
Hockey Pond	12/21/15 10:45	89	20.9	17.8	mg/L	Jul-2016
Hwy 36 - N Swale	11/20/15 9:40	1368	13.4	232.7	mg/L	Jul-2016
Hwy 36 - N Swale	12/21/15 13:30	2430	22.2	446.3	mg/L	Jul-2016
Hwy 36 - N Swale	12/23/15 10:30	1421	15.4	305.1	mg/L	Jul-2016
Hwy 36 - N Swale	2/7/16 16:10	4390	9.1	1345.6	mg/L	Jul-2016
Hwy 36 - N Swale	2/19/16 11:00	1686	11.9	482.2	mg/L	Jul-2016
Hwy 36 - N Swale	2/22/16 15:18	1145	7.3	254	mg/L	Jul-2016
Hwy 36 - N Swale	3/30/16 10:18	529	12.9	109.6	mg/L	Jul-2016
Hwy 36 - N Swale	1/22/16 13:00	2990	7.6	500.1	mg/L	Aug-2017
Hwy 36 - N Swale	1/20/17 11:50	5430	12.5	1514.2	mg/L	Aug-2017
MnDOT Pond	10/21/15 15:45	213	8.5	40.2	mg/L	Jul-2016
MnDOT Pond	2/16/16 17:00	1867	10.9	4233.8	mg/L	Jul-2016
MnDOT Pond	5/17/16 14:50	808	20.4	484.9	mg/L	Jul-2016
RC Church Pond Center	2/3/17 13:15	1723	13.7	386.3	mg/L	Aug-2017
RC Church Pond Inlet	1/22/17 13:15	2140	14.3	473.9	mg/L	Aug-2017
RC Church Pond Outlet	4/26/17 10:50	565	8.7	136.7	mg/L	Aug-2017
RC Church Pond Outlet	5/1/17 0:00	388	12.1	91.8	mg/L	Aug-2017
William St Pond Center	2/3/17 14:40	1213	12.3	249.4	mg/L	Aug-2017
William St Pond Inlet	3/22/16 16:00	287	8.1	54.4	mg/L	Jul-2016
William St Pond Inlet	3/30/16 10:30	275	13.9	59.8	mg/L	Jul-2016
William St Pond Inlet	4/28/16 9:45	48	14.4	25.7	mg/L	Jul-2016
William St Pond Inlet	1/22/17 0:00	464	13.8	102.9	mg/L	Aug-2017
William St Pond Inlet	2/13/17 15:30	217	9.4	41.0	mg/L	Aug-2017
William St Pond Inlet	5/15/17 0:00	103		16.0	mg/L	Aug-2017

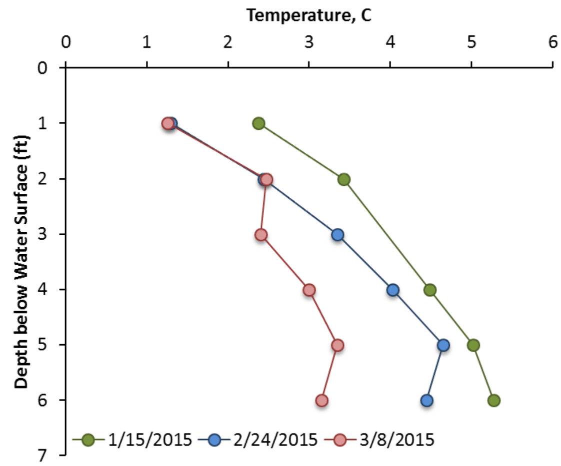
William St Pond Outlet	5/8/15 14:00	409	6.6	82.8	mg/L	Jul-2016
William St Pond Outlet	6/19/15 15:00	245	8.4	48.3	mg/L	Jul-2016
William St Pond Outlet	1/22/16 12:30	242	7.9	36	mg/L	Jul-2016
William St Pond Outlet	2/19/16 11:30	312	10.7	43.7	mg/L	Jul-2016
William St Pond Outlet	3/22/16 15:55	254	9.3	44.9	mg/L	Jul-2016
William St Pond Outlet	3/30/16 10:37	284	14.1	63.6	mg/L	Jul-2016
William St Pond Outlet	4/21/16 11:45	425	6.8	114	mg/L	Jul-2016
William St Pond Outlet	3/23/17 13:05	557	10			Aug-2017
William St Pond Outlet	3/21/17 12:50	669	9.7			Aug-2017

B-2. POND PROFILE DATA

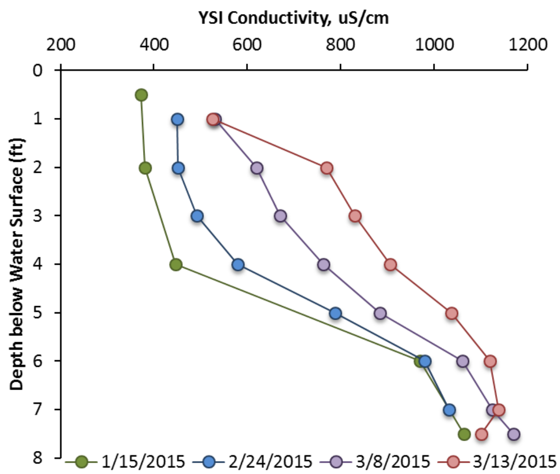
Profiles of pond water chemistry (specific conductivity, uS/cm, and temperature, C) measured over the three field seasons are shown here for the Alameda Pond and William Street Pond, and for the Villa Park Sedimentation Basin for Field Season 1.

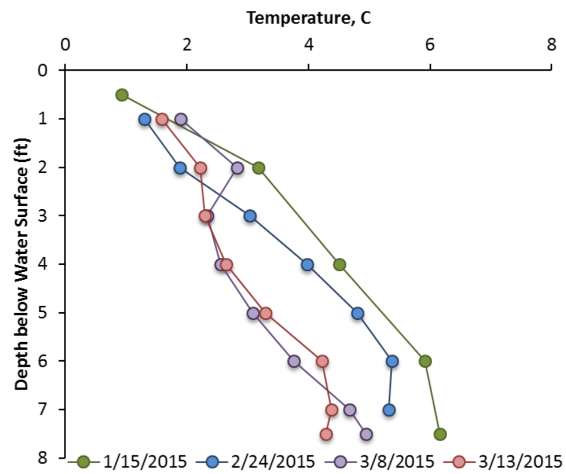
Alameda Pond – Field Season 1



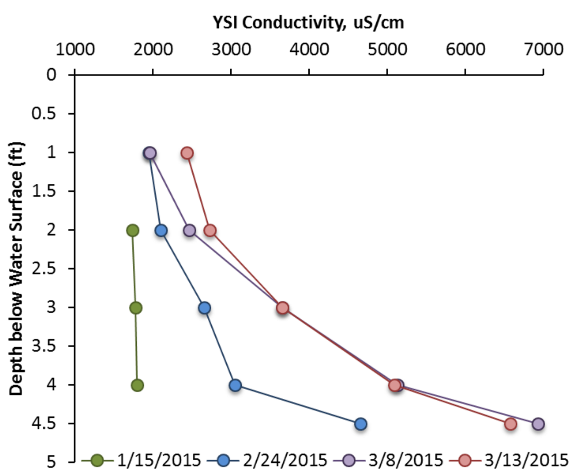


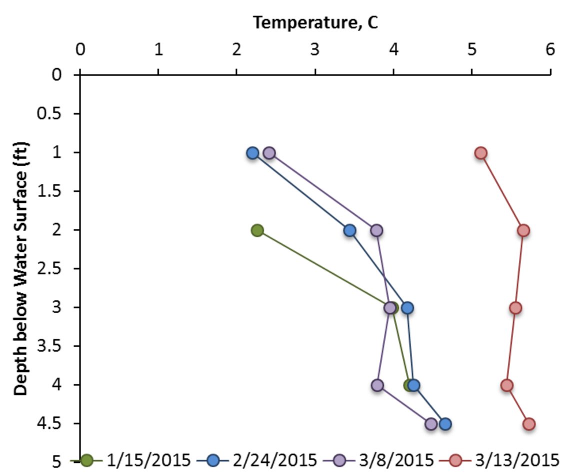
William Street Pond – Field Season 1



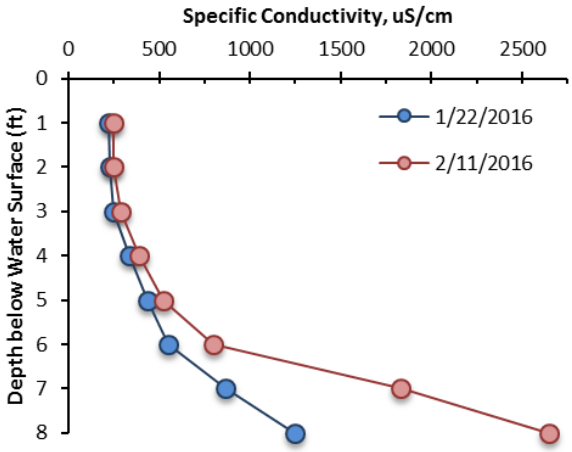


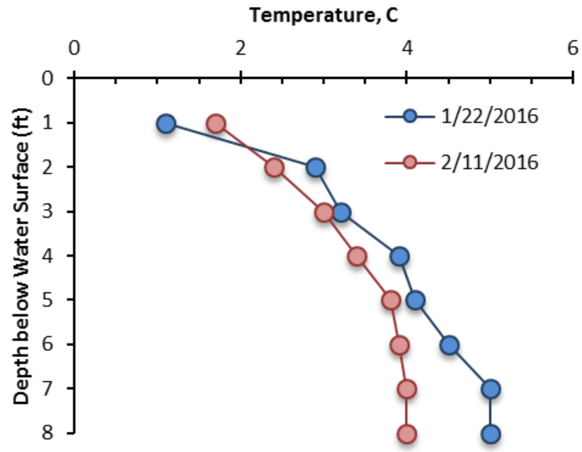
Villa Park Sedimentation Basin – Field Season 1



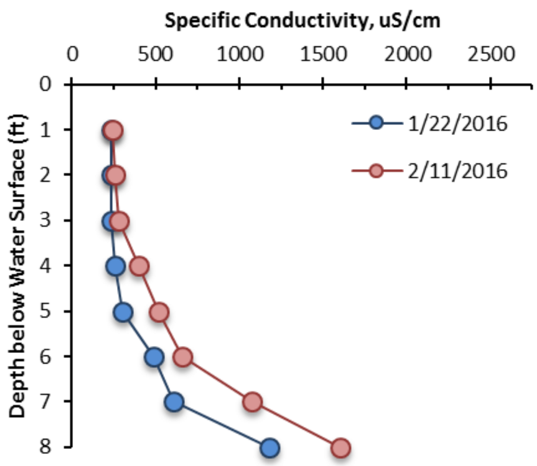


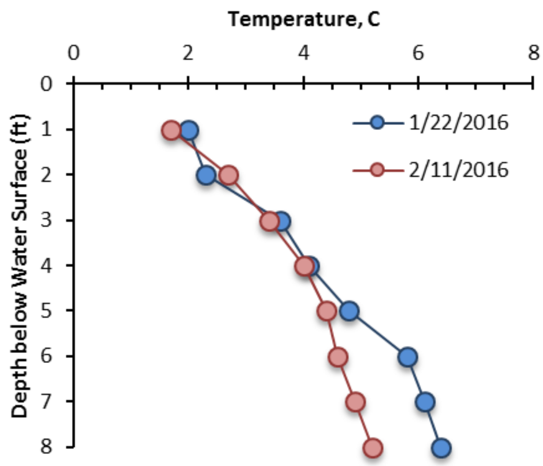
Alameda Pond – Field Season 2



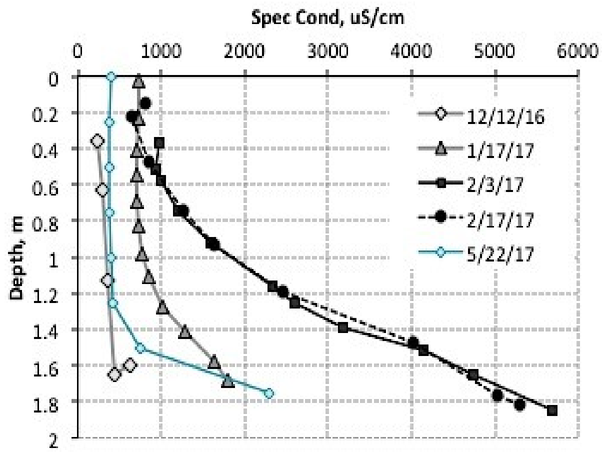


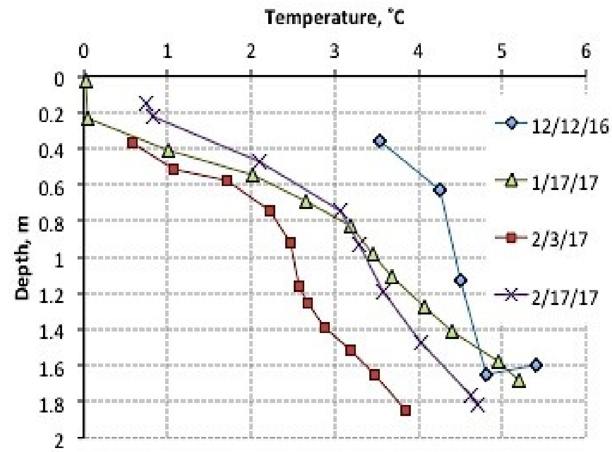
William Street Pond – Field Season 2



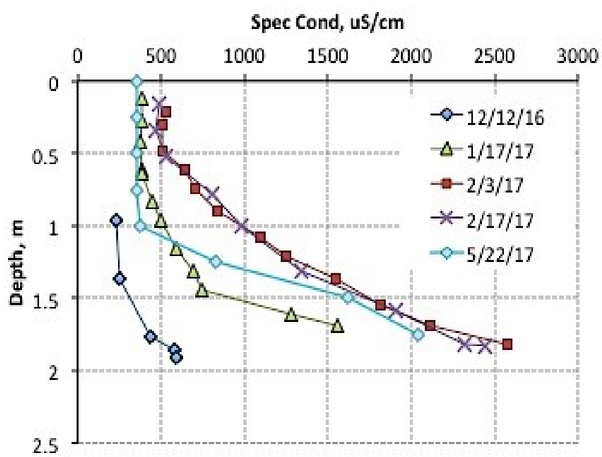


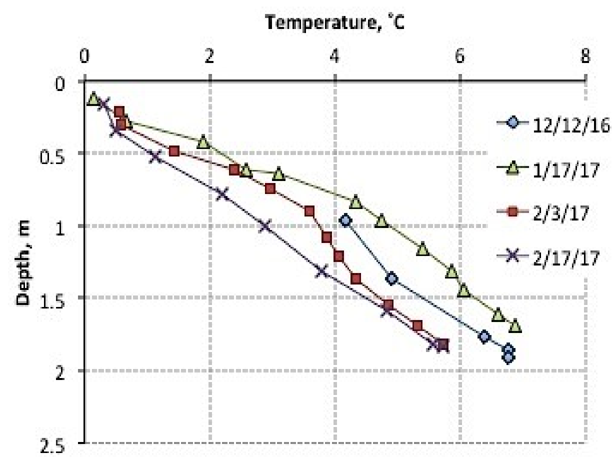
Alameda Pond – Field Season 3





William Street Pond – Field Season 3





APPENDIX C
SETUP AND EVALUATION OF THE GRIDDED SURFACE-SUBSURFACE HYDROLOGIC APPLICATION (GSSHA) MODEL

Model Setup

GSSHA was set up for a relatively idealized test case to assess and evaluate the feasibility of using it to model highway-ditch runoff, i.e. runoff of melting snow and ice from a highway or road surface on which road salt is or has been applied, to a ditch that collects and conveys the runoff away from the road. The test domain (Figure C-1.1) was a rectangular grid 18m wide x 90m long with a cell size of $1m^2$, which represents a 90m long stretch of highway (one lane) and an adjacent ditch. Cross sectional geometry at the end points (x=1m and x = 18m) were taken from LiDAR elevations of eastbound Highway 36 near the Rice Street off-ramp (located within the monitored watershed), and elevations at the intermediate cells were determined by linear interpolation between the end-points to create a uniform horizontal (east-west) slope. The depth of soil simulated in the model was 1m.

Soils were determined to be sandy loam based on a SSURGO soil map, and soil (infiltration) properties were set accordingly. For the purpose of assessing model performance, hydraulic conductivity was set artificially low (~0.01 cm/h) in the ditch to produce surface runoff; much of the surface runoff had infiltrated in early simulation runs with sandy-loam soil.

GSSHA includes a channel model for 1-D routing of runoff water in streams and open channels. A channel model was placed in the test domain at the lowest elevation of the ditch (running from west-to-east in Figure C-1.1[top]), and given a cross-sectional geometry corresponding roughly to the ditch. Flow through culverts and storm sewer pipes can also be simulated in GSSHA with the channel model; it was therefore worthwhile to test this functionality of the model as well.

Climate data needed to run the GSHHA model, including precipitation as snow or water, solar radiation, air temperature, wind speed, and humidity, were taken for the month of March 2015 from a weather station at the St. Anthony Falls Laboratory at the University of Minnesota. This period was chosen because it provided a convenient test of the snowmelt and rainfall-runoff components of GSSHA: snow depth was approximately zero at the beginning of the month, and a small snowfall (3”) occurred on March 3, followed by several days of warm weather (March 8 – 13) during which nearly all accumulated snow melted. Several small rainfall events (and one with wet snow) occurred during the rest of March.

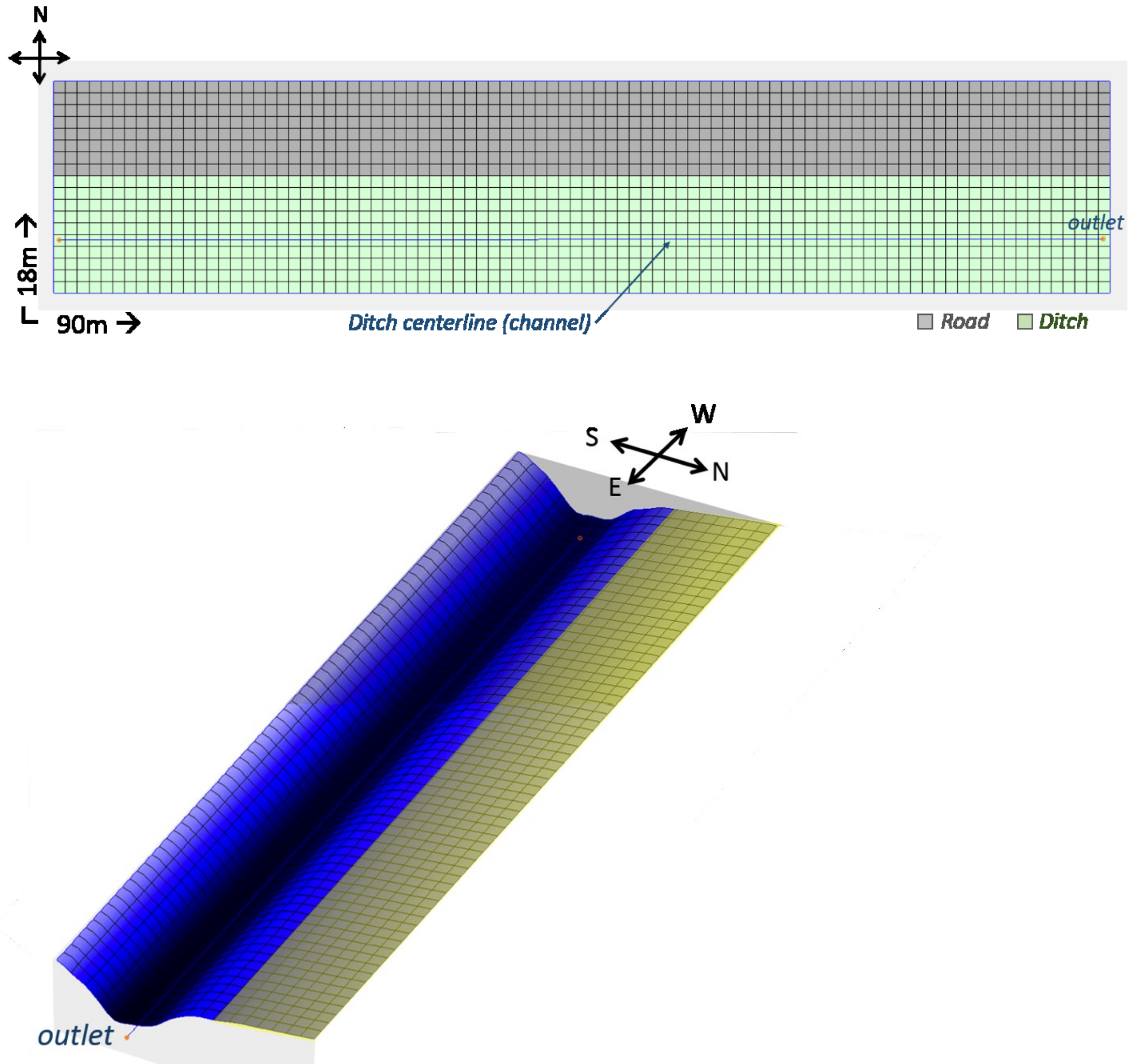


Figure C-1.1. Rectangular test domain used for assessing the grid-based GSSHA model's suitability as a Highway-Ditch chloride source model: [top] Plan view showing 18m (North-South) x 90m (East-West) grid with land cover, and [bottom] 3-D representation of the test domain showing elevation. The lighter-colored area is the road.

Simulation Plan and Results

The test model was assembled and tested in stages, as prescribed by the GSSHA User's Manual (gsshawiki.com). The development and simulation plan proceeded using the following steps or cases:

Overland runoff simulation for a uniform intensity rainfall event (1"/hr). This simulation was used to test that the overland runoff routine was working correctly. The channel model was not included, and no weather data was needed because evapotranspiration was not being calculated. No snowmelt was simulated. Model time step was initially set to 5 minutes but decreased to 5 seconds to remove oscillations in water depth profiles in the ditch. Simulation times were on the order of 1-2 minutes. No issues or concerns were raised by the results of this simulation.

Long-term simulation of real rainfall events. This simulation was used to test the soil moisture and evapotranspiration components, which use the climate data as input. The rainfall events in March 2015 were used in this simulation set, but no snowfall or snowmelt events. No issues were encountered, and results seemed reasonable.

Long-term simulation with a channel sub-model. Adding the channel sub-model to the domain without the aid of a user interface was a tedious and time-consuming process. The real rainfall events from Case #2 were simulated. No snowfall was included at this time. Simulation times increased substantially from a few minutes to nearly an hour (the model automatically decreases time step to compensate for instabilities; the time step was on the order of 0.1sec), but results were very similar to those of Case #2 (without the channel), and no serious issues were encountered.
Conclusion: Major hydrologic components (overland runoff, infiltration, evapotranspiration, and soil moisture effects) appear to be modeled appropriately, but issues may emerge with channel routing.

Long-term simulation with channel and culvert. A 12-foot long culvert was added to the ditch in the middle of the test domain to evaluate the effect of this feature on the model results; this test was necessary because culverts are frequently used in highway drainage such as shown in Figure A-1.1, e.g. at the Hwy 36 runoff monitoring site. With the culvert installed in the ditch simulations would often not be completed due to instabilities, even with an extremely short time step (0.01 sec). A very short rainfall event was successfully simulated, but the required simulation time was unreasonably long (on the order of 3 hours).
Conclusion: GSSHA is not suitable to simulate pipes or culverts in the study watershed (Fig. C-1.1).

Snowmelt simulation with overland runoff only. The first two weeks of March 2015 were simulated using the actual climate data (snowfall on Mar 3 followed by snowmelt on Mar 9-13). No channel model. Results seem reasonable, with snow melting first on the highway and the north side of the ditch, producing some runoff, although most melt water infiltrated or evaporated. Tweaking of snowmelt parameters has some effect on runoff volumes and runoff timing.

Snowmelt with channel model. Same as Case #5 but with the channel model added to the ditch. Simulation proceeds without error but produces no runoff in the channel or at the outlet grid cell (which

by design does not export flow if a channel model is present). Inspection of results shows ponding of runoff in outlet grid cell, where it persists for days while it slowly infiltrates or evaporates, but never gets routed into and out of the channel.
Conclusion: After much trouble-shooting it appears that a bug in the snowmelt routine may prevent snowmelt from being routed into the channel sub-model. The channel model will not be usable for snowmelt, meaning GSSHA can only be used as a source model (providing input to the watershed model) and not as a routing model.

Chloride on roadway followed by rainfall event. To test the contaminant transport feature, chloride was placed on the roadway with an initial concentration of 0.03 kg per cell, or 22 kg total, consistent with MnDOT application rates along Hwy 36 for a single event during winter 2014-2015). A March rainfall event was specified and chloride transport results were reasonable; all chloride was removed from the roadway, and partitioned into ditch runoff and infiltration.

Chloride application on roadway followed by snowmelt event(s). Same scenario as Case #7 but using the first two weeks of March climate as in Case #5 to simulate a real snowfall-snowmelt event sequence (results shown in Figure C-1.2). Initial total amount of chloride on the roadway surface, was 22 kg as in Case #7. Simulation results are reasonable, although some tweaking of the uptake coefficient was necessary (chloride mass budget errors appeared when the coefficient was set above 0.1 m/d). Minor mass budget issues were present (see next section), especially when the GSHHA model was run with several events (rain or snowfall) in succession.
Conclusion: GSSHA is suitable only for simulating chloride transport from a single snowmelt event (or from a single initial input of chloride).

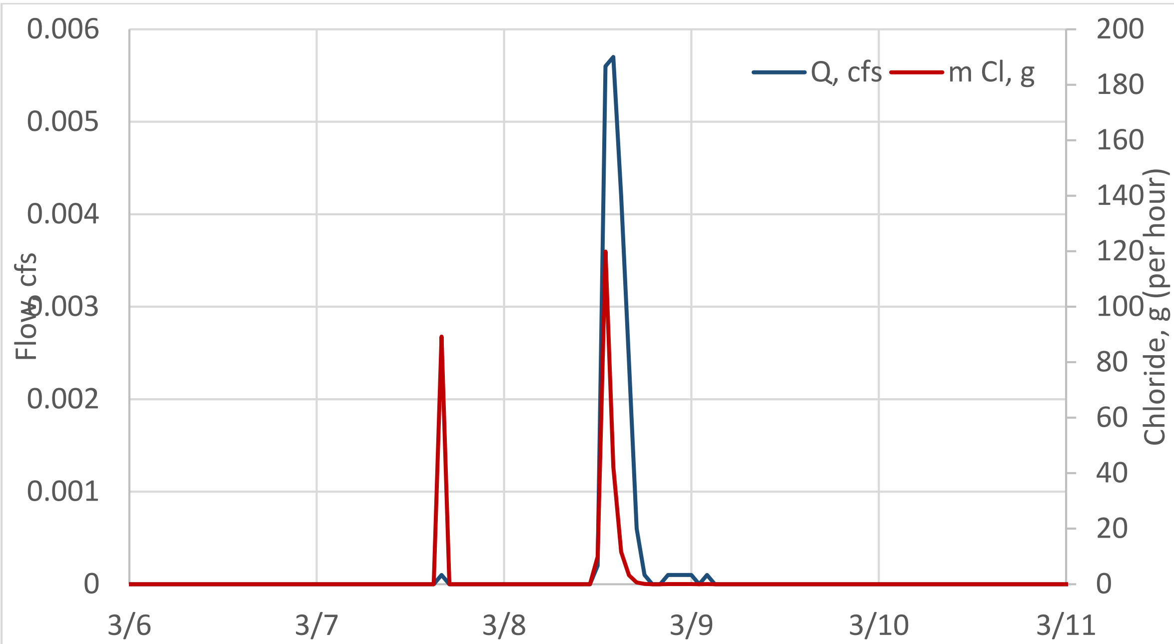


Figure C-1.2. Simulated snowmelt runoff and associated chloride mass loading from the outlet of the ditch in the test domain (Fig. C-1.1), simulated by GSSHA using observed snowfall and climate data from the UofM St. Anthony Falls Laboratory for March 1-14, 2015. Above-freezing temperatures persisted from late March 7 through March 11, melting all snow. Of this melt volume, a small percentage (16.2%) became surface runoff (89 ft^3), 80% was infiltrated (341 ft^3) and 3.8% evaporated (16 ft^3). Initial condition was 22 kg chloride distributed evenly on the road surface on March 1; 98.5% of this chloride (21.7 kg) was lost to infiltration in the simulation, even with low hydraulic conductivity in the ditch.

Potential Problems with the GSSHA Model

Several problems were identified in the applications of the GSSHA model, version 6.2, that prevent its intended use in the current study. These problems are:

The channel routing model does not seem to work with the snowmelt routine in version 6.2 of the GSSHA model. Without the channel model, GSSHA will only be useful as a small-scale source model, and will not be suitable for extensive ditch or pipe routing. This is one reason for using HSPF as the watershed model instead of GSSHA.

It is cumbersome to determine the chloride mass at the ditch outlet. With a channel model in place, GSSHA automatically provides time series for water flow, chloride mass and concentration at any point in the channel, including the outlet. However, without the channel model, only a time series of water flow rate is provided at the outlet cell. Time series domain maps of surface chloride concentration and flow rate by cell can be produced by the model; a script was written to parse these files to produce a time series of chloride mass and flow rate at the outlet cell. However, the time scale of these maps is coarser than that of the simulated outlet hydrograph (1-2 hours vs. 5-10 minutes) because of the amount of data produced by the maps of output at high temporal resolution; as a result, the masses calculated from the maps often do not match the results shown in the model run's summary file (which provides a summary of water volume and chloride mass in the various hydrological components over the course of a model run). The difference between the output summary and the mapfile estimates can be as high as 20% in some cases.

In its currently available form, the GSSHA model is unable to incorporate time series of point source inputs. A strength of the GSSHA model was its alleged ability to specify temporally and spatially variable inputs of snowfall and chloride, which would be crucial for simulating inputs of road salt associated with snowfall events. However, documentation on this particular aspect of the model is sparse and no tutorial or examples could be found to aid in setup of this feature. At this time we have been unable to get time series inputs of chloride working, and have to specify it as an initial condition instead. Thus the model can only simulate a single snowmelt event (or transport of a single road salt input during several subsequent events).

Indeterminate units in the chloride mass maps. With the need to run the model on an event basis, the output of one model run (event) needs to serve as the input to the next model run (event). GSSHA has no built in functions for specifying maps of snow depth or chloride mass at the end of each run to be used as startup files in the next run, as it does for runoff depth and flow rate. An R script was written to parse the output map files to produce startup files for snow depth and surface chloride mass. However, the units of mass in the chloride output maps are unclear; it is not absolute mass, as the total mass on the surface at the end of the model run exceeds the total chloride input by an order of magnitude or more. When normalized by water depth or snow water equivalent, the mass budget still incurs significant errors. The latter three issues in particular prevent GSSHA from being operated in a continuous mode as originally intended, and combined with the first issue, make it unsuitable for use as a source model or as a watershed model.