The Fate and Transport of Chlorides in a Constructed Stormwater Wetland

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ABSTRACT

Road de-icing salt is one contaminant of concern in stormwater runoff, as it has been shown to have negative effects on plant and animal species, decrease biodiversity, and degrade environmental quality. It has been assumed that road de-icing salt would wash through watersheds with spring rains, as road salt (usually NaCl) is soluble, and chloride (Cl^-) has long been considered a conservative tracer. However, many recent studies suggest that significant proportions of chloride mass may be retained within a watershed and that chloride levels resulting from winter salting activities may remain elevated late into summer months. Stormwater control measures (SCMs) have been praised for both volume reduction and improved water quality, but recent studies are showing that certain SCMs may increase the negative effects of road salting on the surrounding environment, such as contamination of groundwater, trace metal leaching, stratification in ponds, toxic effects, and reduced biodiversity. Because chloride poses a possible threat to downstream waters, a study was performed to study the fate and transport of chloride through one SCM, a constructed stormwater wetland (CSW), on Villanova's campus.

The study had three main goals: i.) to determine if effluent concentrations of chloride from the CSW meet recommended EPA standards for both chronic and acute criteria; ii.) to compare total dissolved solids (TDS), conductivity, and chloride concentration data in order to further validate the data sets and also quantify correlations between each parameter; and iii.) to perform a mass balance of chloride to study the fate and transport of chloride upstream, within, and downstream of the CSW. Chloride concentrations and TDS/conductivity/chloride correlations were analyzed over a period of four years, from December 2011 - November 2015 and a mass balance was conducted with flow data for 2013 and 2014.

BACKGROUND AND METHODS

Villanova's Constructed Stormwater Wetland (CSW) is the headwaters of Mill Creek (Figure 2), a high-priority stream on the perimeter of Philadelphia, Pennsylvania, situated in the Schuylkill watershed. The drainage area is an 18.2-ha suburban watershed, 9.7 ha of which are impervious surfaces and turfed pervious areas. The design consists of a large inlet forebay, three meanders, each separated by a sluice gate, an outlet forebay, and a small flow path that leads from the outlet forebay to the same outlet structure used in the original design (Figure 1). Both baseflow and storm events were sampled for water quality at the CSW over the study period, one of each event per month.

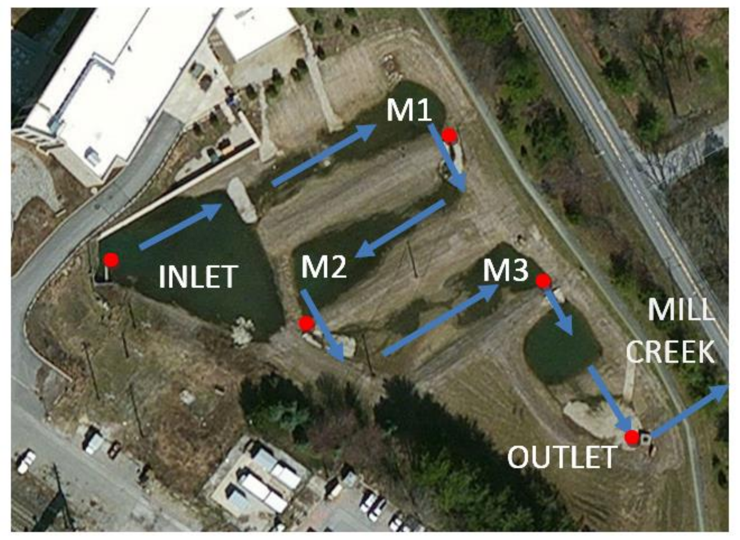

Figure 1: Villanova's Constructed Stormwater Wetland (CSW); flow path shown by blue arrows, sampling locations marked with a red circle; credit Google Maps

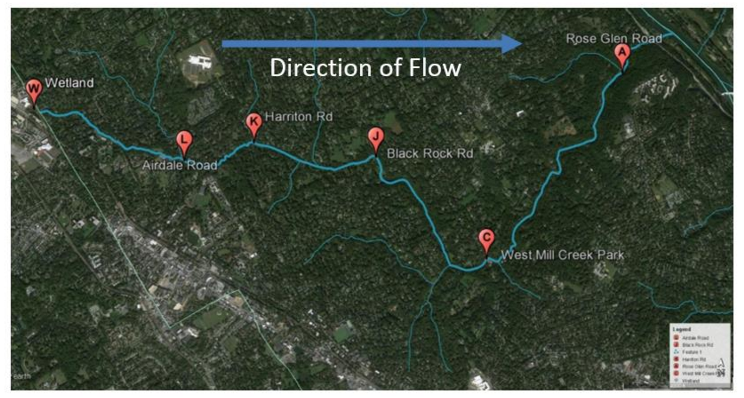

Figure 2: Map of Mill Creek and Five Sampling Sites from CSW to the Inlet at the Schuylkill River; the Villanova CSW is denoted with a capital W and the word "Wetland"

Data for the CSW, including total dissolved solids concentration (TDS) (mg/L), conductivity (μS/cm), and chloride concentrations (mg/L) were determined in the Villanova Water Resources Lab and volume data was calculated through a MATLAB code used in conjunction with a Microsoft Access database using volume data collected by flow meters at the CSW inlet and outlet. Discharge and chloride concentration data for the Mill Creek sampling locations were provided by the Department of Geography and the Environment.

Salt usage data from Villanova facilities was used to compare to the mass balance of chloride in the CSW (Figure 3). This data was used to estimate that approximately 39,800 kg in 2013, 76,000 kg in 2014, and 34,000 kg in 2015 were applied to the drainage area of the Villanova CSW during the winter months.

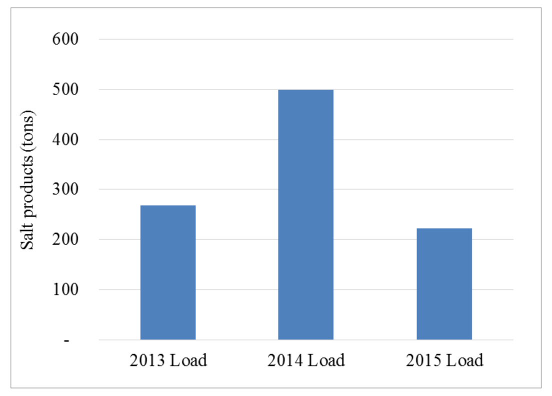

Figure 3: Tons of Salt Products Purchased over the Study Period; including all types; 2012 data was not available

RESULTS

Chloride data was plotted over time between Dec 2011 and Nov 2015 and compared to the EPA fresh water criteria (230 mg/L chronic and 860 mg/L acute) (Figure 4). For both storm and baseflow events, high spikes of chloride can be observed in the winter months when de-icing salts are traditionally applied. Chloride concentrations during storm events suddenly decrease to low levels, while base flow concentrations seem to decrease more slowly over time.

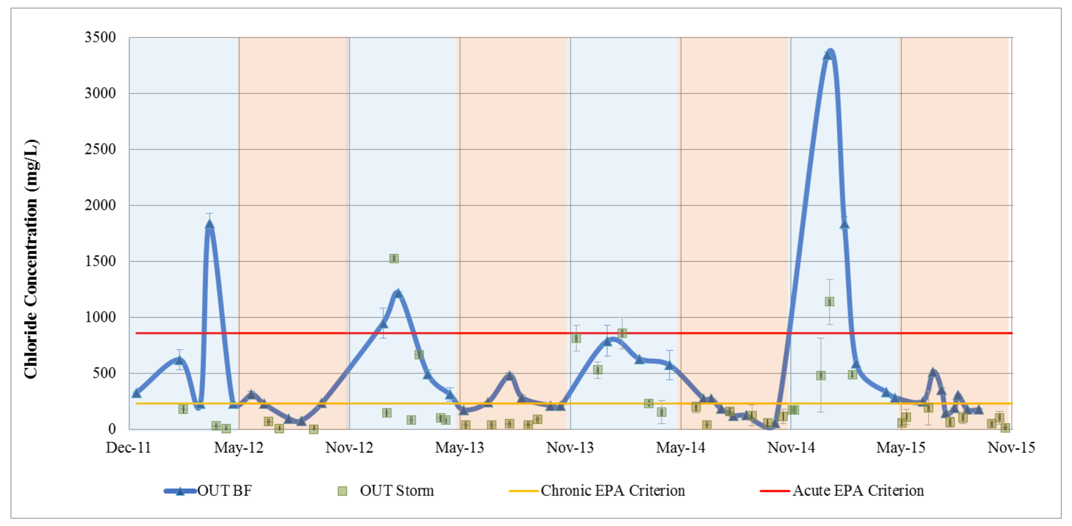

Figure 4: Chloride Concentrations for Baseflows and Storms at the CSW outlet against EPA Chronic and Acute Criteria; OUT baseflow in blue line; OUT Storm in green squares; Chronic Criteria (230 mg/L) in yellow line; Acute Criteria (860 mg/L) in red line

This data was used to estimate the percent of time that the CSW might meet or exceed criteria, but can only serve as a rough estimate (Table 1).

n = 69	Percentage of Time, estimated
Meets both Criteria	39%
Exceeds Chronic Criteria	61%
Exceeds Both Criteria	12%

Table 1: CSW Criteria Assessment; % of Time (Estimated) Meeting/Exceeding Criteria

Chloride data was separated into "Salt Application" (December -May) and "Non-Salt Application" periods (June – November) in order to compare different trends. Salt Application concentrations (median~ 550 mg/L) were generally much higher than during the Non-Salt Application period (median~ 150 mg/L) (Figure 5). Base Flow chloride concentrations (median~ 270 mg/L) were also generally higher than Storm chloride concentrations (median~ 100 mg/L) (Figure 6).

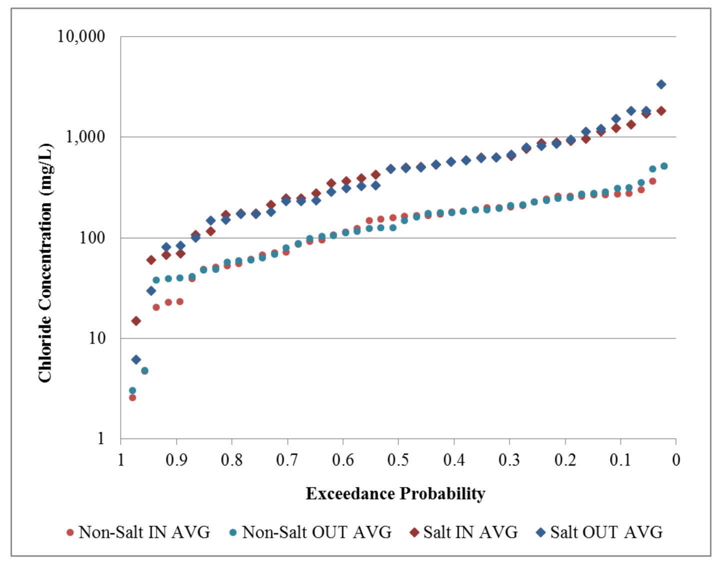

Figure 5: Chloride Exceedance Probability Distribution Salt and Non-Salt Application Period IN and OUT samples over the full 4 year study period; y-axis on a base 10 log scale

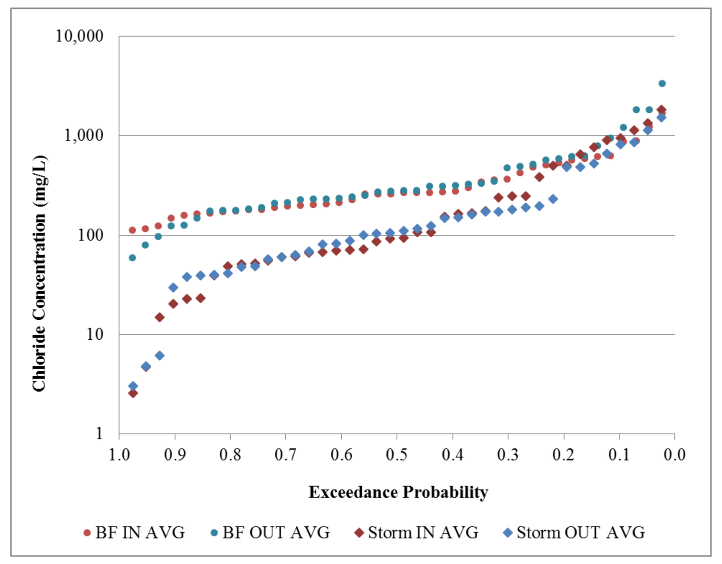

Figure 6: Chloride Exceedance Probability Distribution Baseflow and Storm IN and OUT samples over the full 4 year study period; y-axis on a base 10 log scale

TDS, conductivity, and chloride concentration are all related. Correlations between each parameter were plotted in order to create specific correlations for the Villanova CSW and to check the accuracy of each data set. The TDS vs. conductivity curve is especially useful in water quality testing. While each of the correlations (chloride vs conductivity, chloride vs TDS, and TDS vs conductivity) were good, the TDS/Conductivity is most useful. The curve obtained from this dataset (Figure 7) has a high R2 coefficient (0.9698) and a linear correlation. The k constant obtained from this correlation is 0.57, within the expected range. This correlation can be used to estimate TDS from a conductivity reading in the future.

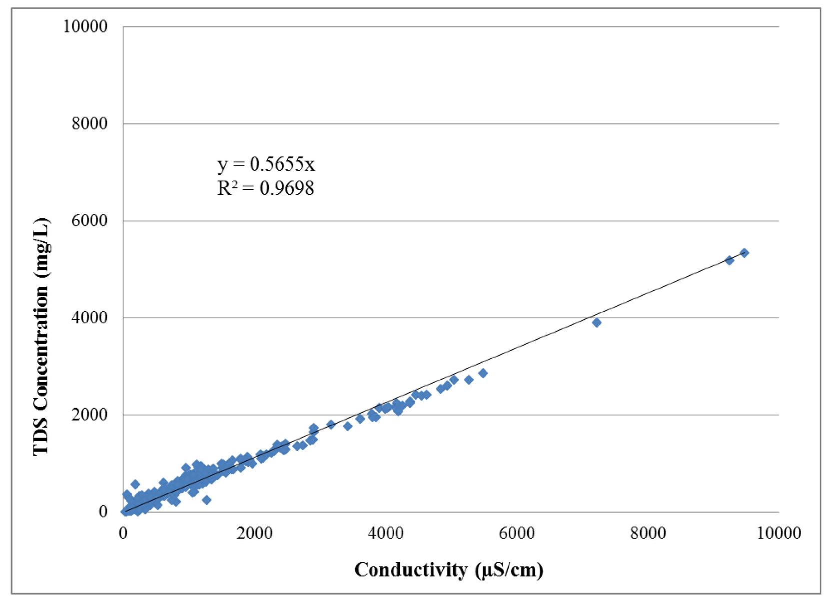

Figure 7: TDS vs. Conductivity Correlation at the CSW with linear trend line; n = 454

	Volume in (m³)	Volume out (m³)	Vol Retention	Median In (mg/L)	Median Out (mg/L)	Mass In (kg)	Mass Out (kg)	Mass Retention
All Salt	453,600	232,000	49%	523	552	237,400	128,100	46%
All Non-Salt	240,200	155,700	35%	149	125	35,700	19,500	45%
Sum	**693,800**	**387,700**	**44%**			**273,100**	**147,500**	**46%**
All Baseflow	269,500	128,200	52%	269	276	72,400	35,400	51%
All Storm	424,300	259,400	39%	107	120	45,400	31,200	31%
Sum	**693,800**	**387,700**	**44%**			**117,900**	**66,600**	**44%**
Total 2013-2014	**693,800**	**387,700**	**44%**	**227**	**196**	**157,200**	**76,000**	**52%**
Road De-Icing Salt						*116,200*		

Table 2: 2013 and 2014 Sum Baseflow and Storm Comparison in Calculating Mass of Chloride; Total Calculation over both years is included as well as total road de-icing salt chloride estimate

A mass balance was conducted between the inlet and outlet of the CSW (Table 2). The median chloride concentration was multiplied by the volume of water to obtain a mass of chloride. Approximately 40-50% volume was retained within the CSW, while median concentrations between the inlet and outlet did not change significantly. Data was analyzed for the full 2013-2014 year span, resulting in an estimate of 157,200 kg of chloride entering the CSW and 76,000 kg leaving during that 2 year period, with a 52% retention rate. The estimated total chloride mass applied to the CSW drainage area during that time was 116,200 kg. A mass balance was also conducted between the Villanova CSW and the Mill Creek sites.

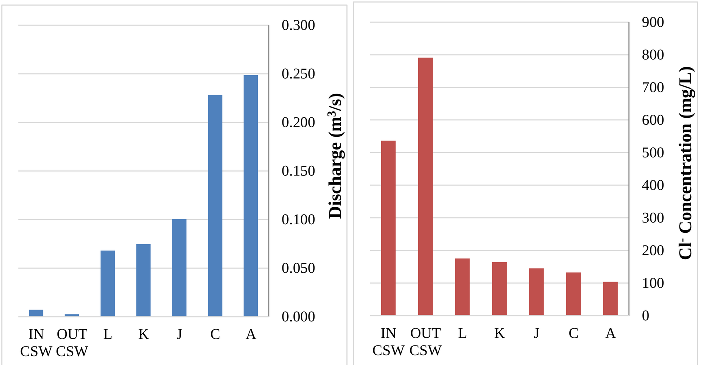

Figure 8: On the left: Discharge in units of m3/s; On the right: Chloride Concentration in units of m3/s

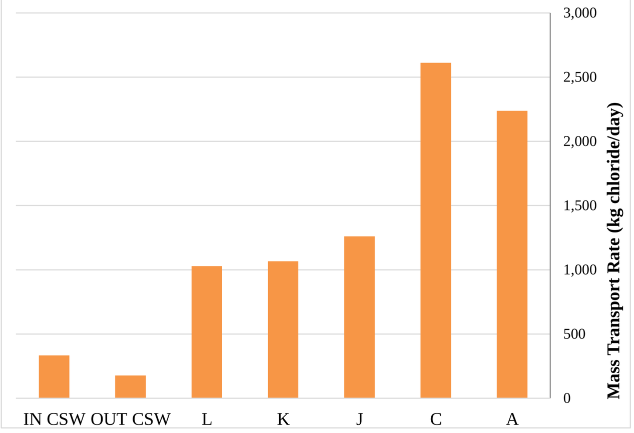

Figure 9: Chloride Mass Transport for the CSW Inlet and Outlet as well as along Mill Creek (L-A) during a January Baseflow Event; in units of kg chloride/day

The Mill Creek discharge data was multiplied by the chloride concentration data to obtain a mass of chloride moving through the system. Figures 8 and 9 show a snapshot in time of a January 25th base flow event. Mass in the Villanova CSW inlet and outlet are plotted alongside the Mill Creek data. Mass generally increases as you move downstream and while mass does decrease within the CSW, it increases at each Mill Creek sampling site, implying additional inputs of chloride downstream of the CSW.

CONCLUSIONS

High chloride spikes were observed during the Salt Application period, between December and May, and heightened baseflow chloride concentrations lasted through summer months, even when storm event concentrations were low approaching > 10 mg/L. In using EPA freshwater quality criteria of chronic (230 mg/L) and acute (860 mg/L) toxicity as benchmarks, it was found that the CSW effluent concentration was below chronic only 33% of sampled baseflow events (10% exceeded acute) and 77% of sampled storm events (12% exceeded acute). On a yearly basis, it was estimated that the CSW effluent is below chronic criteria only 39% of the year, exceeds the chronic criterion 61% of the year, and exceeds the acute criterion 12% of the year. Because this study was unable to assess the precise EPA criteria definitions (based on 1 and 4-day averages), this serves only as an estimate of the CSW's performance.

Chloride/TDS/conductivity correlations were created between each parameter and the Villanova CSW had a TDS/conductivity k constant of 0.57 (mg/L)/(μS/cm).

A mass balance of the Villanova CSW showed that about 40-50% of volume is reduced between the inlet and the outlet, and an equal, if not slightly greater percentage of chloride mass is retained within the CSW as well. In comparison to road de-icing salt application estimates, there is evidence that there is a greater amount of chloride mass entering the CSW than from impervious surfaces alone. This leads to questioning the possibility that groundwater flow interacts with the CSW and carries additional chloride mass from upstream locations. Analysis of discharge and chloride concentration data of Mill Creek, the natural water body immediately downstream of the CSW, showed that a large amount of chloride mass is added to Mill Creek after the CSW. This indicates that the CSW is not the only source of chloride loading to Mill Creek and that it is only a small percentage of the total chloride loading throughout the creek. Of the available dataset, Mill Creek chloride concentrations were below 230 mg/L for all sampling events but one that occurred in mid-winter of 2014.