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The Art of Balance

Regulating Road Salt and Heavy Metal Pollutant Impacts Using Linear Green Infrastructure and Enhanced Application Optimization Approaches

Bill Trenouth, Ph.D., P.Eng.

November 7, 2019

Why Worry so Much about Roads?

While <1% of the urban total, highways are:

– places where pollutants build up:
  - TSS >4,400 mg/L, TN = 19 mg/L

- Where they are added
  - Zn > 14,000 µg/L, Pb > 1,200 µg/L,
  - Cl^- > 30,000 mg/L, etc.

– While harmful to the environment, salt application in cold climates reduces accidents and injury:

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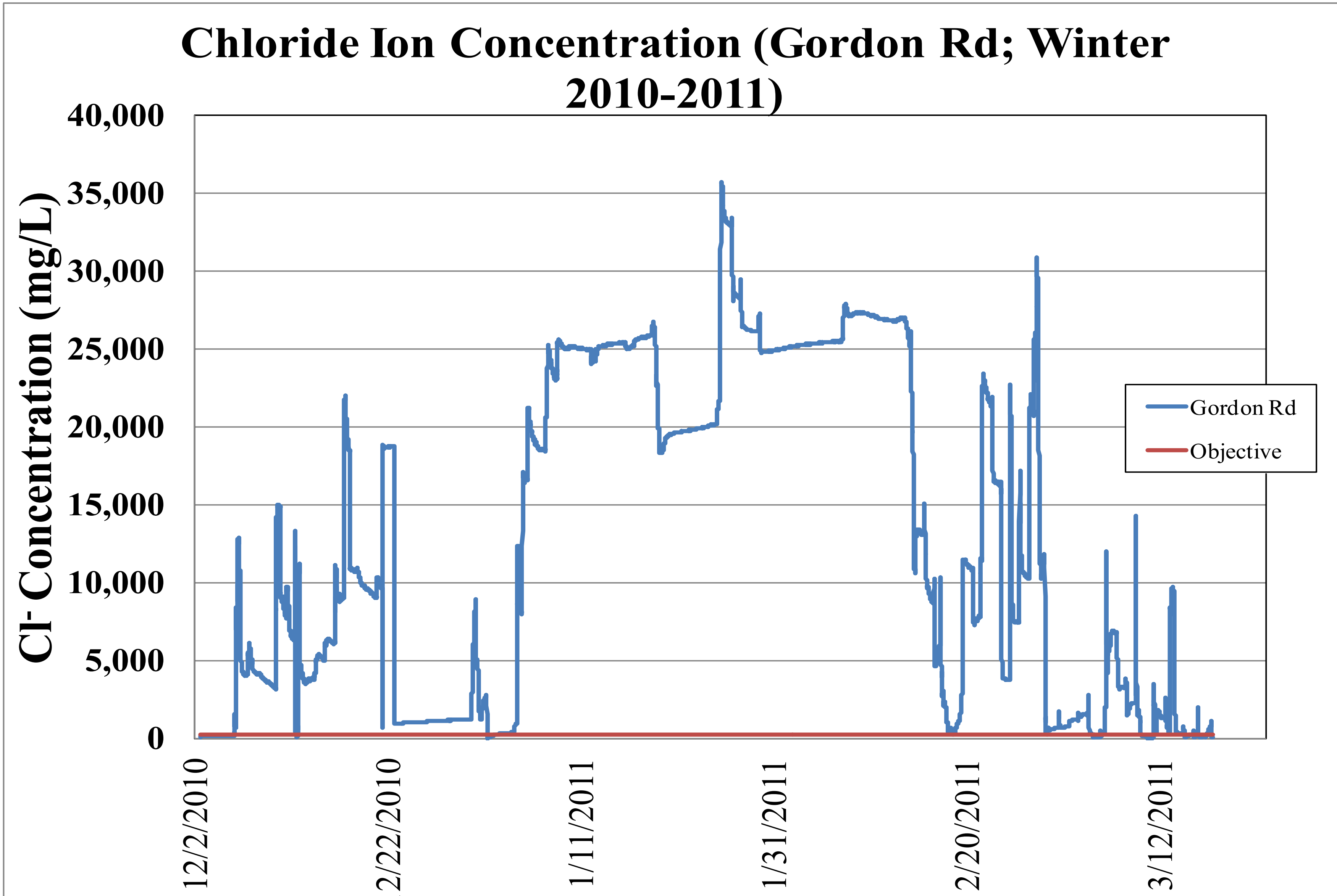

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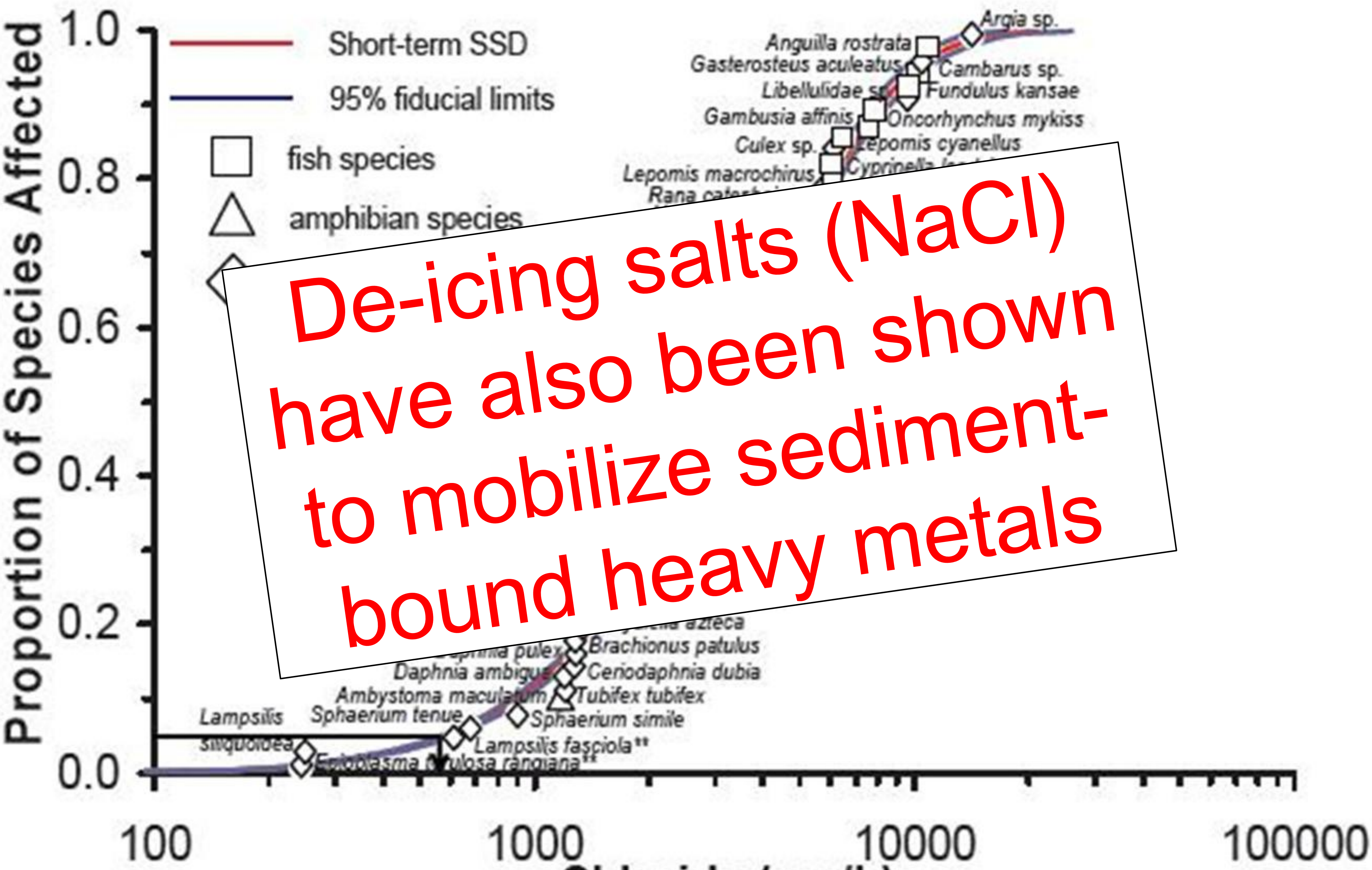

De-icing salts (NaCl) have also been shown to mobilize sediment-bound heavy metals

Source: CCME, 2011

Research Objectives

Develop and validate a **simple tool** that can **help highway maintenance** operators systematically **optimize road salt** application rates

Identify and test **cost-effective** treatment **media derived from waste materials** for their ability **to remove pollutants** from a highway stormwater analogue

Design and assess an innovative **linear treatment system's ability** to attenuate runoff and **protect groundwater and surface water**

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Addressing What Goes on the Road

Develop a **simple tool** that can **help highway maintenance** operators systematically **optimize road salt** application rates

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Road salt application planning tool for winter de-icing operations

CrossMark

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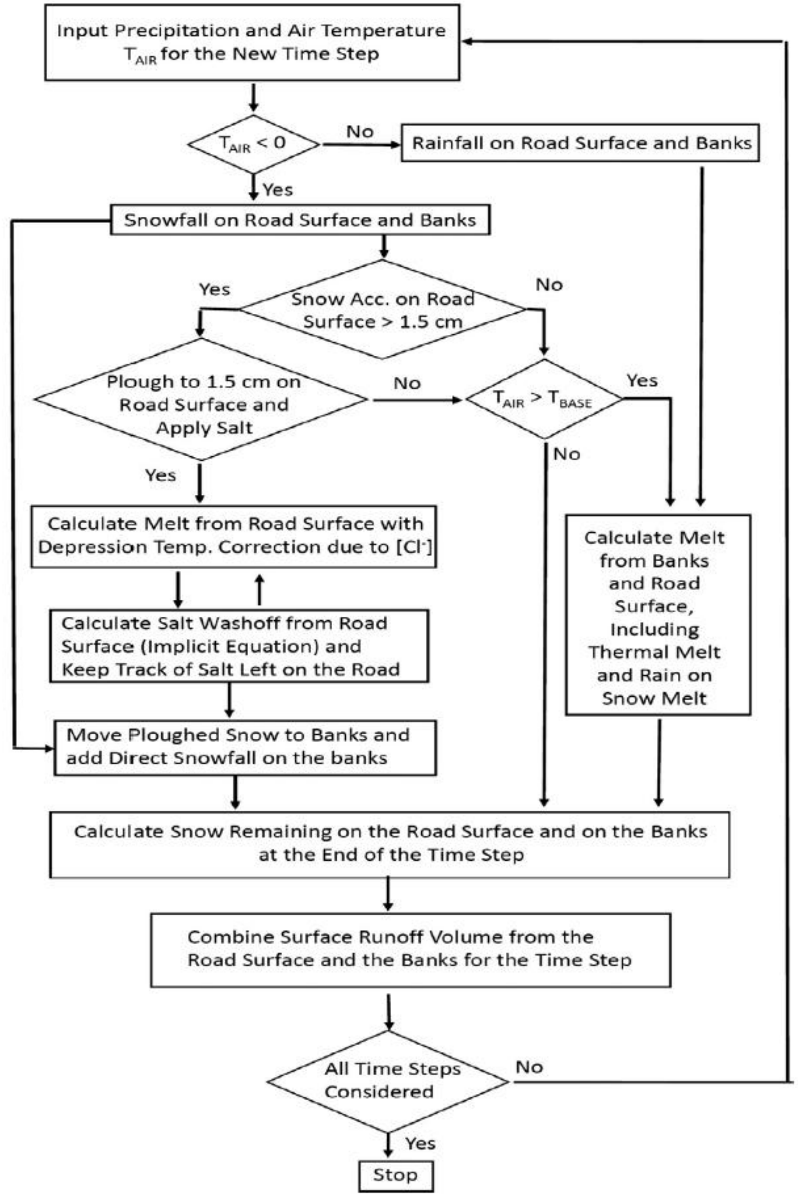
Salt-induced melt
Temperature index

SUMMARY

Road authorities, who are charged with the task of maintaining safe, driveable road conditions during severe winter storm events are coming under increasing pressure to protect salt vulnerable areas (SVAs). For the purpose of modelling urban winter hydrology, the temperature index method was modified to incorporate ploughing and salting considerations and was calibrated using winter field data from two sites in Southern Ontario and validated using data collected from a section of Highway 401 – Canada's busiest highway. The modified temperature index model (MTIM) accurately predicted salt-induced melt (R^2 = 0.98 and 0.99, RMSE = 19.9 and 282.4 m^3, CRM = –0.003 and 0.006 for calibration and validation sites respectively), and showed a demonstrable ability to calculate the Bare Pavement Regain Time (BPRT). The BPRT is a key factor on road safety and the basis for many winter maintenance performance standards for different classes of highways. Optimizing salt application rate scenarios can be achieved using the MTIM with only two meteorological forecast inputs for the storm event – readily available on-line through the Road Weather Information System (RWIS) – and can serve as a simple yet effective tool for winter road maintenance practitioners seeking to optimize salt application rates for a given storm event in salt vulnerable areas.

- Developed a conceptual model governed by simple rules – just like real life
- Ploughing routine defined using results of interviews with MTO maintenance contractors & calibration over several events
- Salt is considered at every time step and depression point adjusted accordingly



Summary of Melt Model Mechanics

Temperature Index Method:

$$M = MC(T_{AIR} - T_{BASE})$$

Where,

M = melt (mm day^{-1})

MC = melt coefficient (mm $^0C^{-1}$ day^{1}),

T_{AIR} = air temperature (^0C), and

T_{BASE} = base temperature (^0C).

Temperature Depression Pont:

$$\Delta T_m = K_m m i$$

Where,

ΔT_m = change in the melting point (^0C),

K_m = cryoscopic – or molal freezing point depression - constant (1.853 ^0K kg mol^{-1} for water)

m = molarity (mol kg^{-1}), and

i = van't Hoff factor, number of particles solute splits into when dissolved; 2 for NaCl

Summary of Melt Model Mechanics

Melt Coefficient

$$MC_{DATE} = 0.2 * sin * \left(\frac{2\pi}{365} * DATE\right) + 0.5$$

Where,

DATE = Julian Date (1 for January 1, 365 for December 31)

Ploughing subroutine

Blade height was calibrated over several events, and best fit was determined to be ~0.5 cm of snow remaining after ploughing

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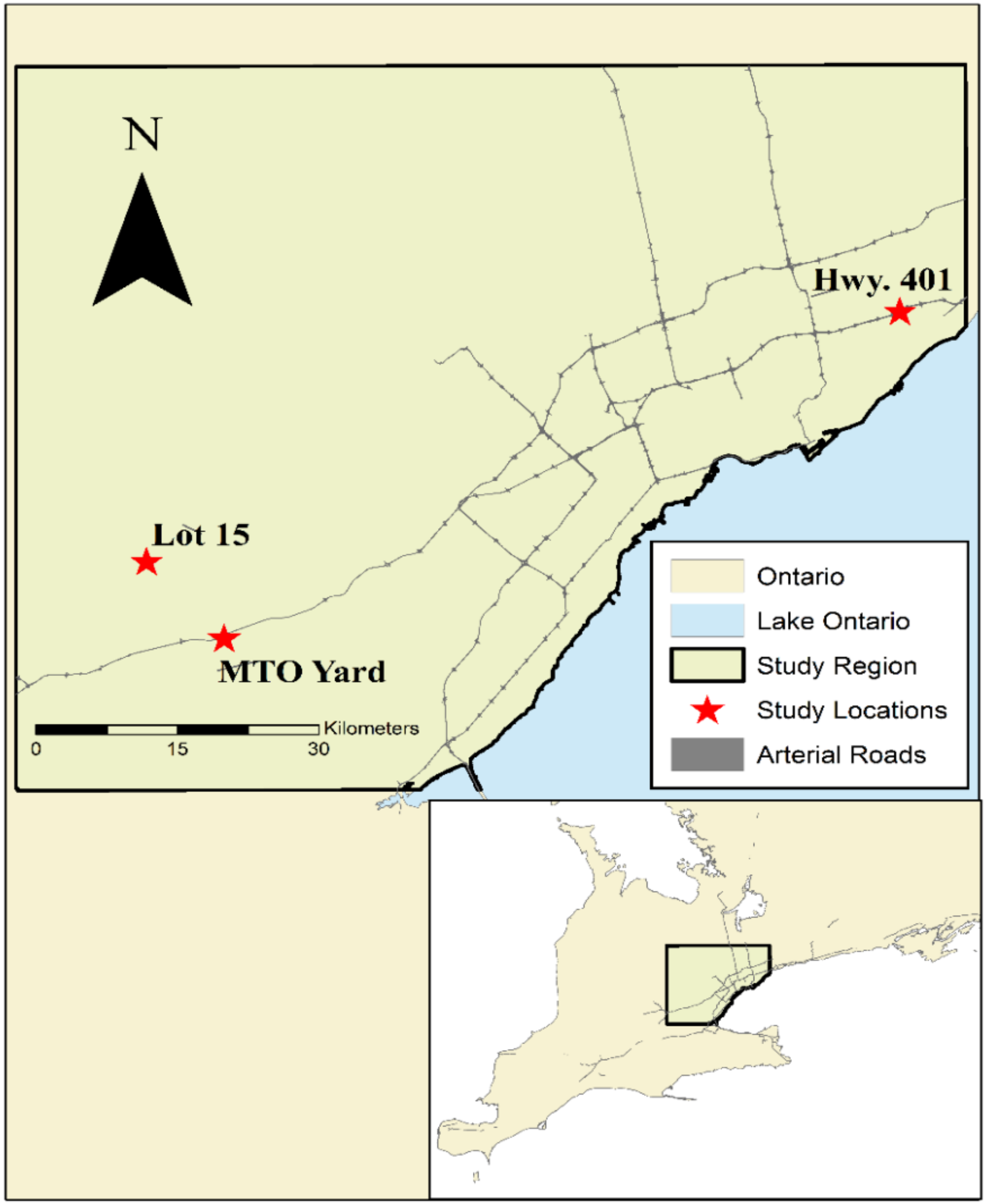
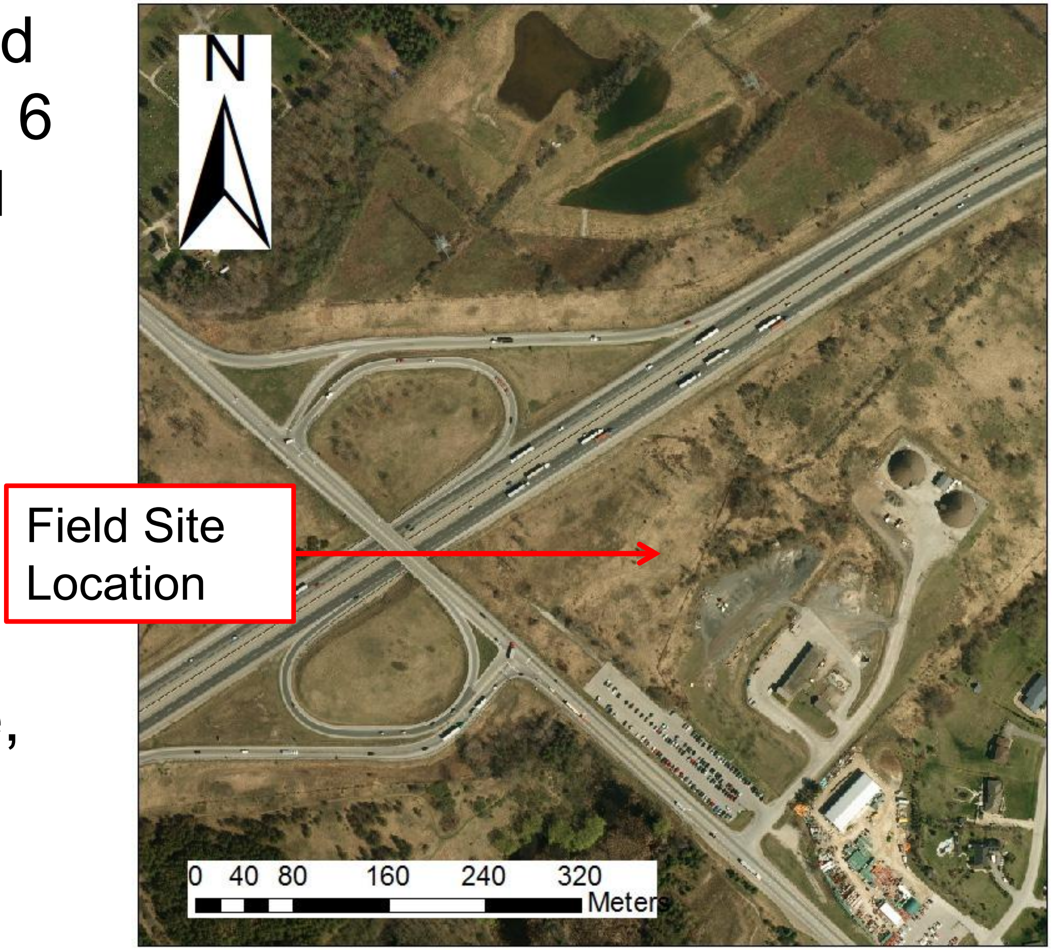
Field Site Descriptions

- Monitoring data from 3 locations used to modify the Temperature Index method to include salting and ploughing



Control Site Melt Monitoring

- Located at in an open field near the area of Highway 6 South and the Eastbound lanes of Highway 401
- Representative of an unploughed, unsalted snow accumulation and melt condition
- Onsite heated rain gauge, ultrasonic snow depth sensor



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Calibration of Modified TI Method

- 4.3 ha parking lot situated on the University of Guelph campus
- Salt trucks weighed before and after ploughing
- Fuel consumption was calculated

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- A stormwater outfall draining an 8.3 ha subcatchment of Hwy. 401.

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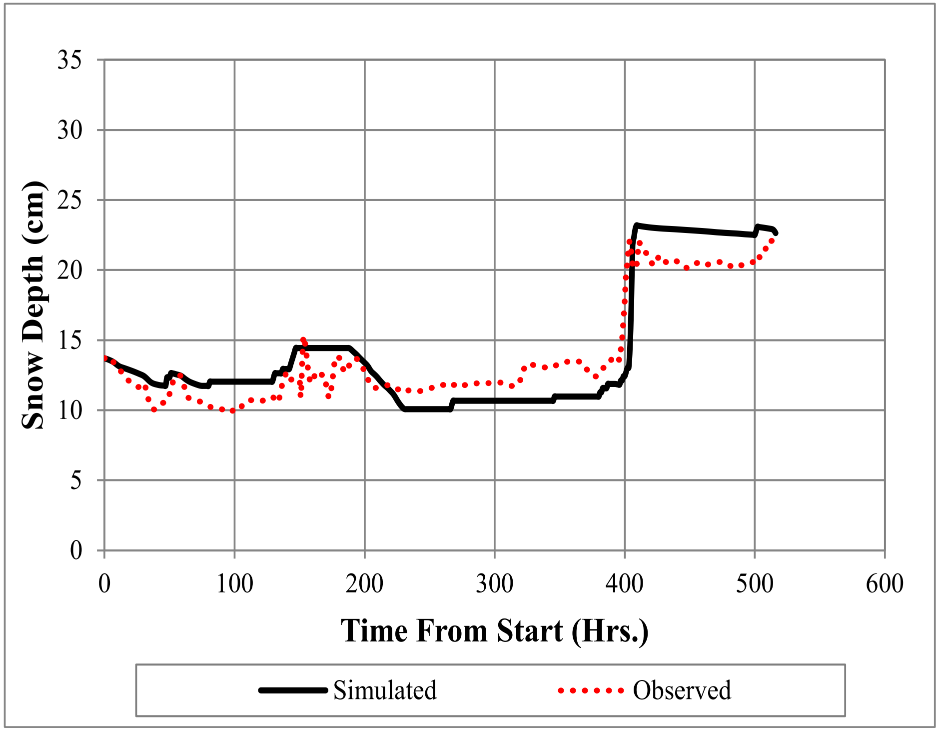
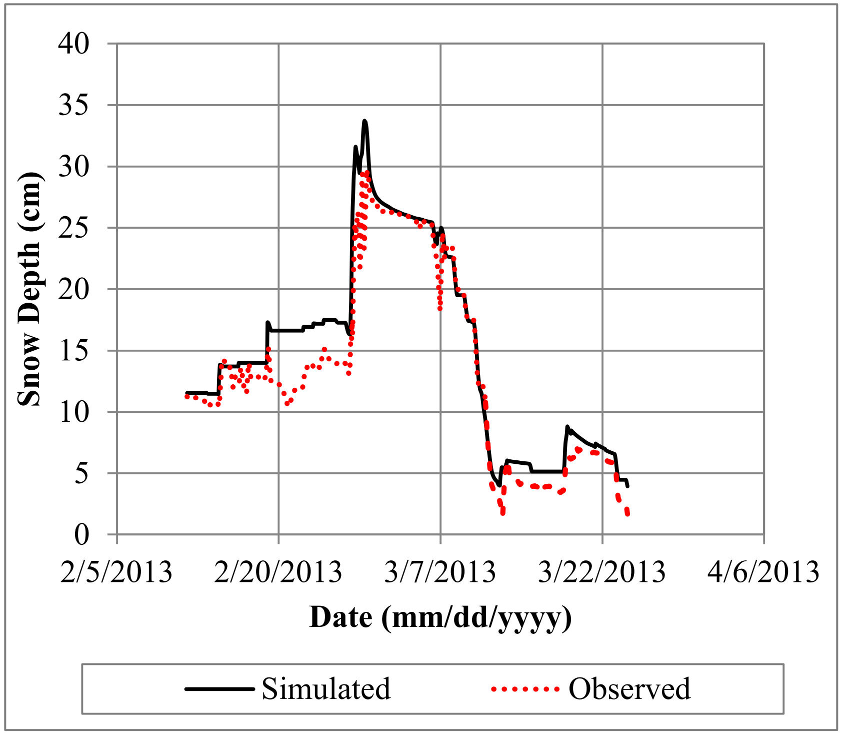
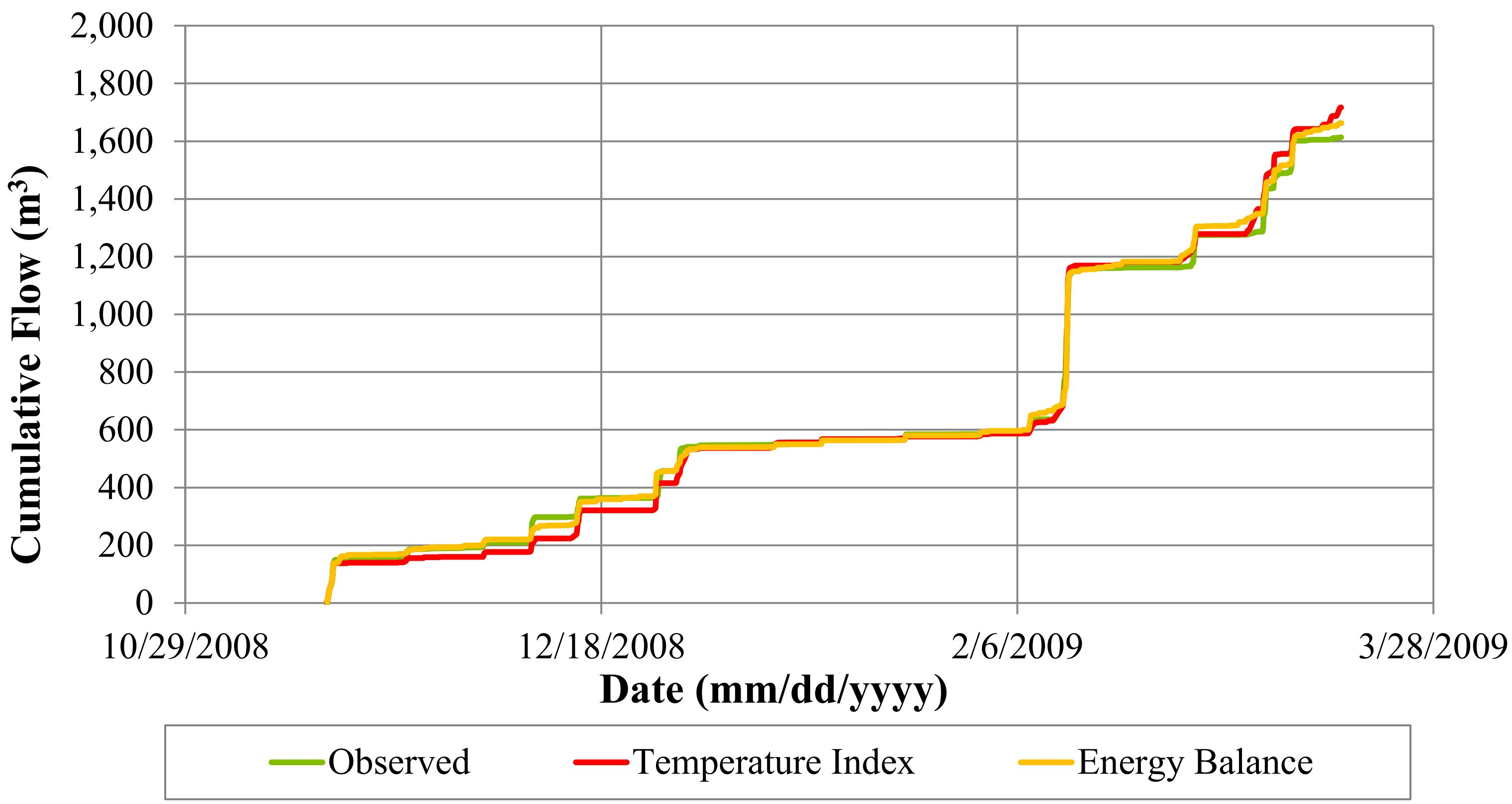
Results – Validation of Temperature Index Approach





Model Development – Lot 15

- After incorporating ploughing and salting, the Modified TI model did a good job simulating the parking lot melt:



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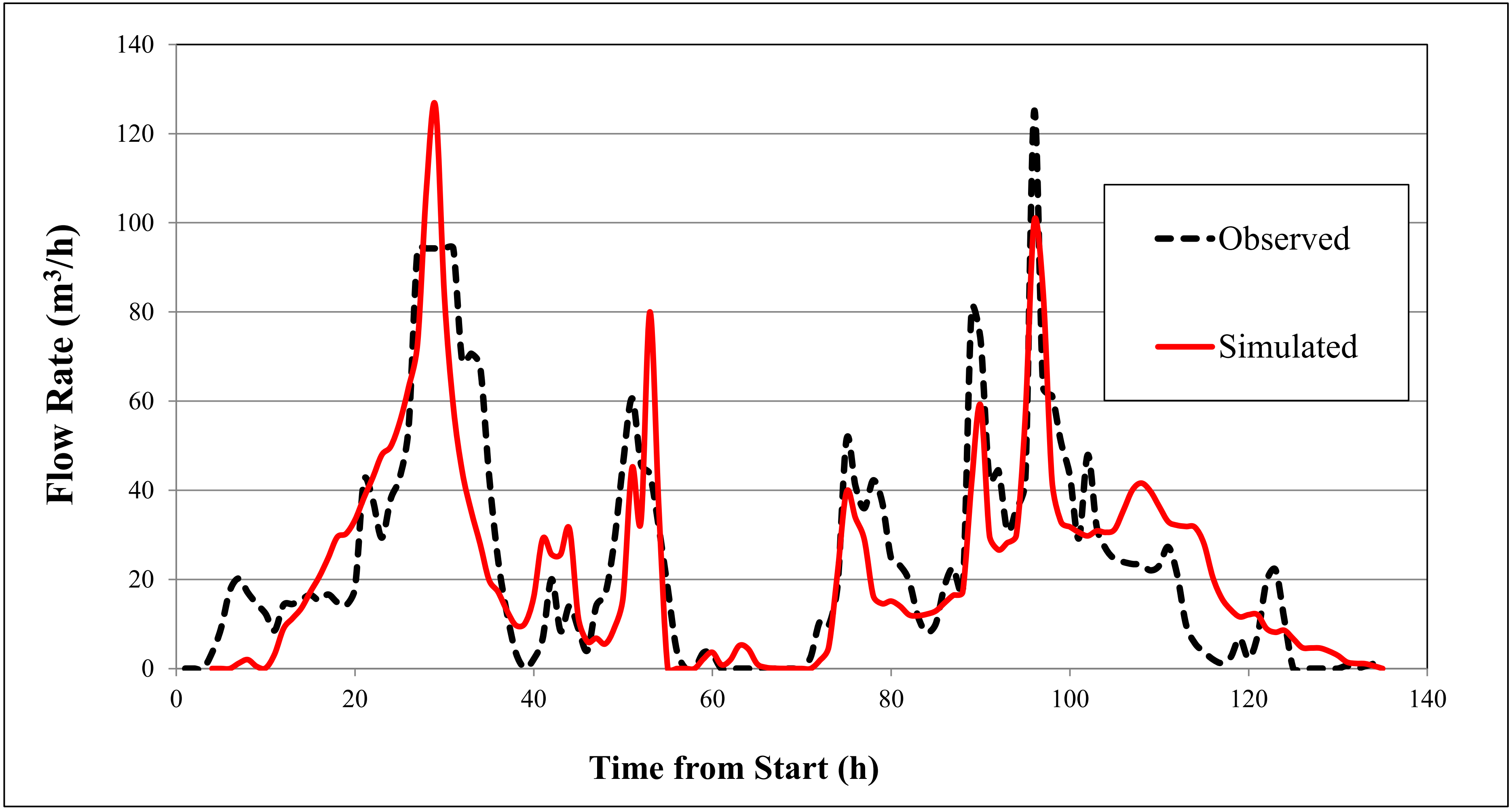
Model Validation – Highway 401



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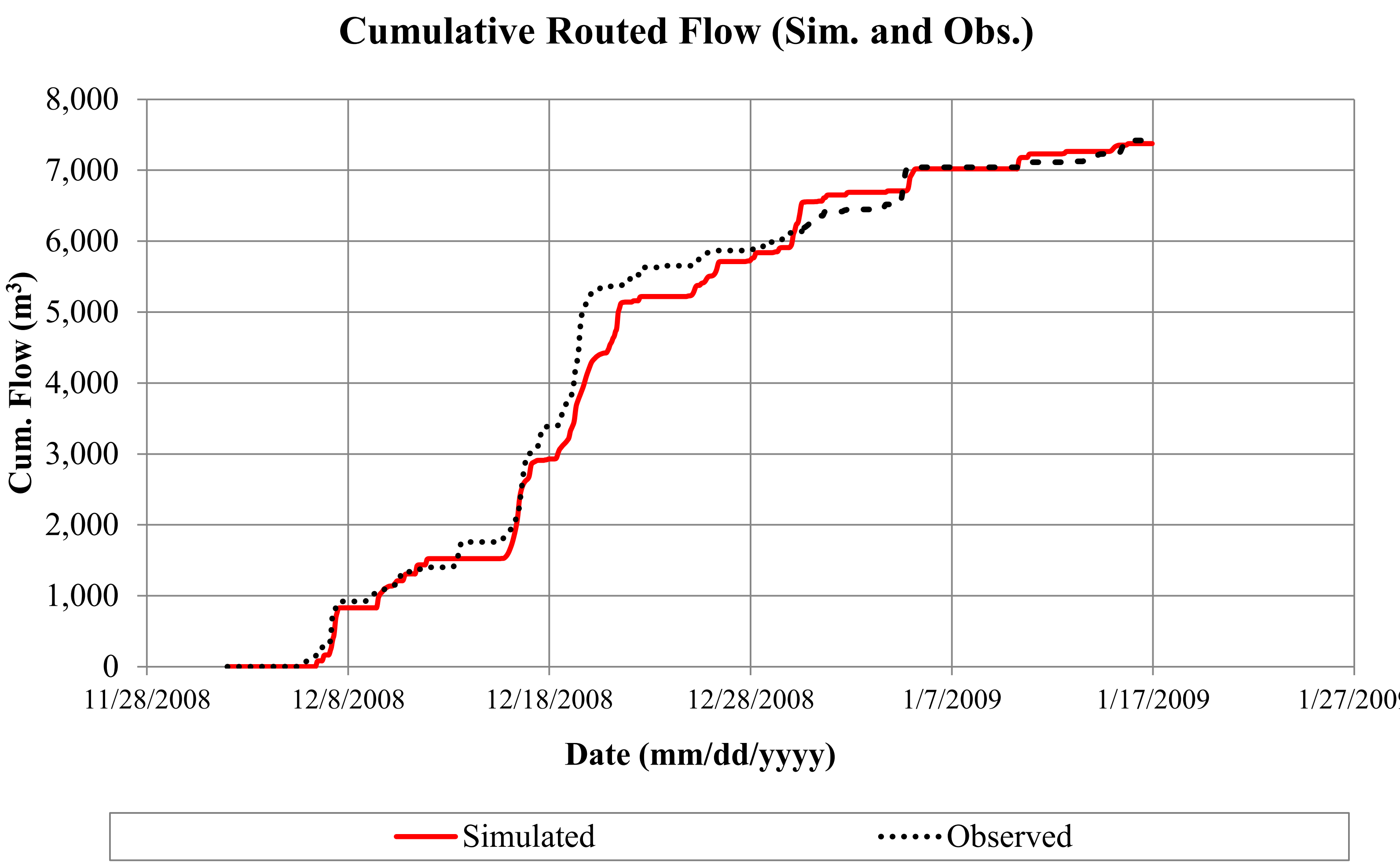
Model Validation – Highway 401



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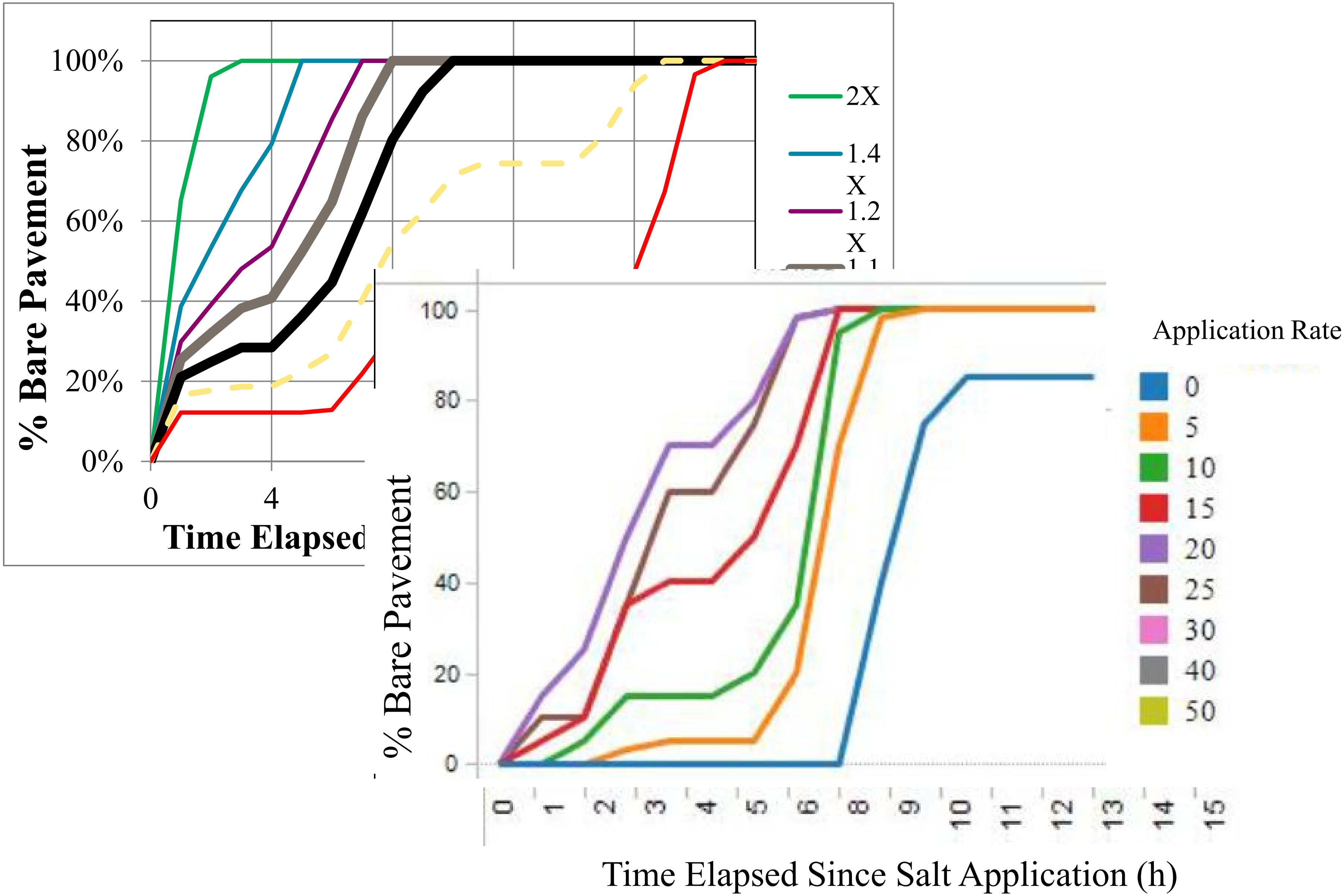
Statistical Evaluation of Model Performance

Coefficient or Measure	Variables and Associated Equations	Range of Variability	Test Result for Cumulative Runoff (401)	Test Result for Cumulative Runoff (Lot 15)
Coefficient of Determination (R^2)	$R^2 = \left[\frac{\sum_{i=1}^{n}(o_i - \bar{o})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(o_i - \bar{o})^2} * \sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2$	0 to 1	0.99	0.98
Coefficient of Efficiency (Nash and Sutcliffe, 1970)	$E = 1 - \frac{\sum_{i=1}^{n}(o_i - P_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o})^2}$	-∞ to 1	0.99	0.99
Modified Coefficient of Efficiency (Wilmott, 1982)	$E_1 = 1 - \frac{\sum_{i=1}^{n}\lvert o_i - P_i\rvert}{\sum_{i=1}^{n}\lvert o_i - \bar{o}\rvert}$	-∞ to 1	0.92	0.97
Root Mean Square Error	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - o_i)^2}{n}}$	0 to ∞	282.4	19.9
Coefficient of Residual Mass (Lague and Green, 1991; Chanasyk et al., 2003)	$CRM = \frac{\sum_{i=1}^{n} o_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} o_i}$	-∞ to ∞	0.006	-0.003

Assessing the Effects of Δ[NaCl]

– Satisfied with model performance, we next wanted to evaluate the effects that increasing or decreasing salt concentrations had on Bare Pavement Regeneration:

Event Date	EMT (°C)	Precip. (mm)	Change in BPRT from Calibrated Model Based on [Cl] Multiplication Factor (min.)				
			0.9 X Conc.	0.95 X Conc.	1 X Conc.	1.05 X Conc.	1.1 X Conc.
12/14/2008	5.3	10	0	0	0	0	0
12/23/2008	0.2	19	18	8	0	-7	-14
1/1/2009	-3.0	1	76	33	0	-27	-50
11/0/2009	-3.5	12	63	30	0	-27	-51


100%
80%
60%
40%
20%
0%
% Bare Pavement
0
4
Time Elapsed
2X
1.4
X
1.2
X
100
80
60
40
20
0
% Bare Pavement
Application Rate
0
5
10
15
20
25
30
40
50
0
1
2
3
4
5
6
8
9
10
11
12
13
14
15
Time Elapsed Since Salt Application (h)

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How Can Runoff be Treated?

Identify and test **cost-effective** treatment **media derived from waste materials** for their ability **to remove pollutants** from a highway stormwater runoff

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JOURNAL OF HYDROLOGY

Soil amendments for heavy metals removal from stormwater runoff discharging to environmentally sensitive areas

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SUMMARY

Concentrations of dissolved metals in stormwater runoff from urbanized watersheds are much higher than established guidelines for the protection of aquatic life. Five potential soil amendment materials derived from affordable, abundant sources have been tested as filter media using shaker tests and were found to remove dissolved metals in stormwater runoff. Blast furnace (BF) slag and basic oxygenated furnace (BOF) slag from a steel mill, a drinking water treatment residual (DWTR) from a surface water treatment plant, goethite-rich overburden (IRON) from a coal mine, and woodchips (WC) were tested. The IRON and BOF amendments were shown to remove 46–98% of dissolved metals (Cr, Co, Cu, Pb, Ni, Zn) in repacked soil columns. Freundlich adsorption isotherm constants for six metals across five materials were calculated. Breakthrough curves of dissolved metals and total metal accumulation within the filter media were measured in column tests using synthetic runoff. A reduction in system performance over time occurred due to progressive saturation of the treatment media. Despite this, the top 7 cm of each filter media removed up to 72% of the dissolved metals. A calibrated HYDRUS-1D model was used to simulate long-term metal accumulation in the filter media, and model results suggest that for these metals a BOF filter media thickness as low as 15 cm can be used to improve stormwater quality to meet standards for up to twenty years. The treatment media evaluated in this research can be used to improve urban stormwater runoff discharging to environmentally sensitive areas (ESAs).

Blast Furnace Slag

Basic Oxygenated Furnace Slag

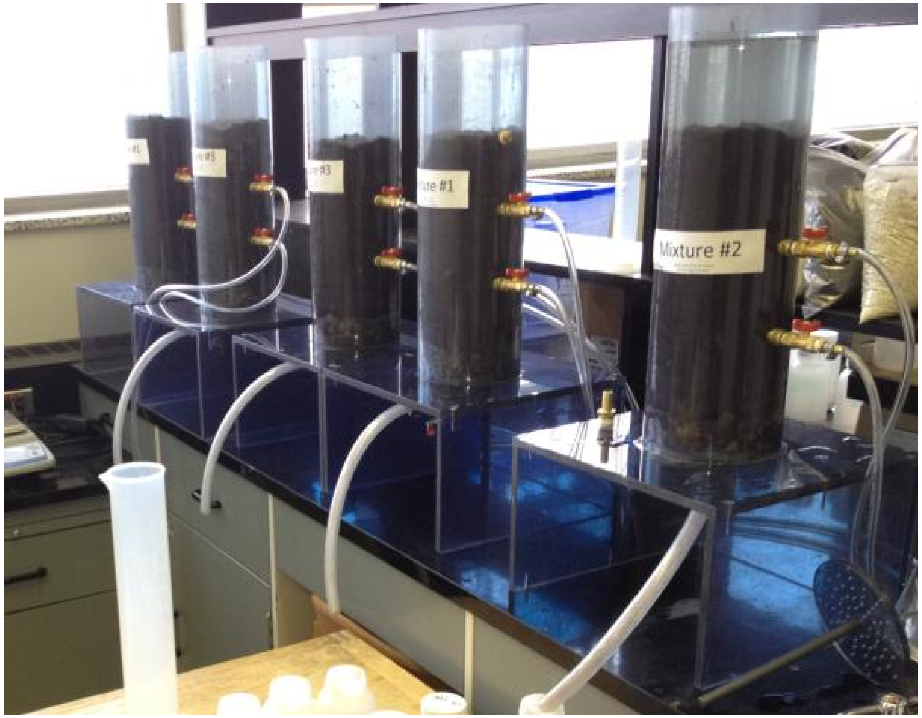
Goethite Overburden

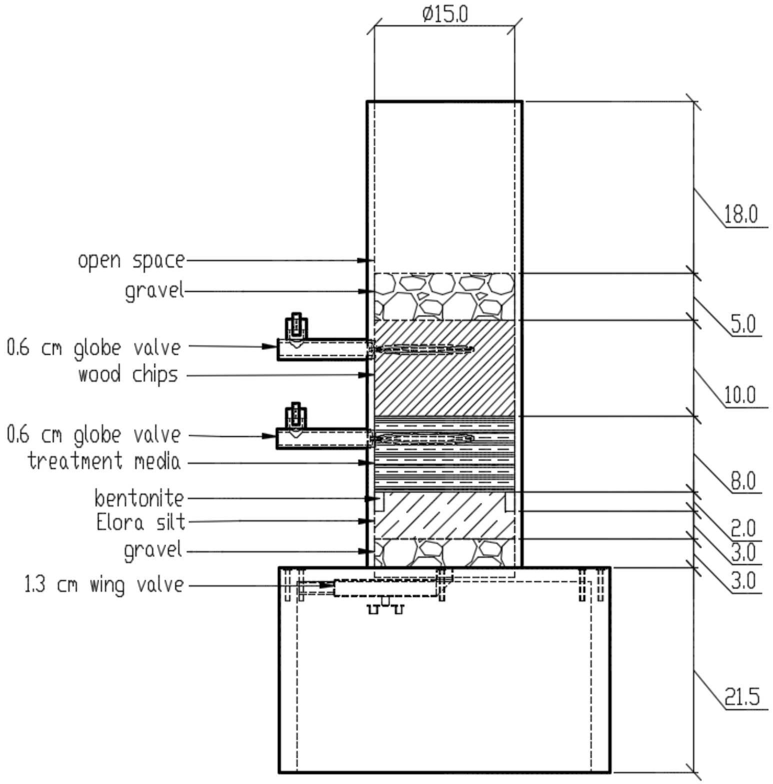
Spent Filter Alum

Column Construction

– Design based on research objectives and details available in the literature

(e.g. Safadoust et al., 2011; Starrett et al., 1996)





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Volume Added (L)	Analyte Slug Concentration (mg/L)						
	[Cl]	[Cr]	[Co]	[Cu]	[Pb]	[Ni]	[Zn]
8.0	5,000	2.08	6.64	1.24	7.44	43.4	19.1
8.0	10,000	2.88	13.1	1.62	9.05	82.7	34.9
12.0	20,000	8.26	25.7	4.76	24.6	170	73.3
8.0	30,000	18.2	63.1	10.8	60.1	416	173

Metal Species	WC		BF		BOF		IRON	
	RR (mg/g)	RE (%)	RR (mg/g)	RE (%)	RR (mg/g)	RE (%)	RR (mg/g)	RE (%)
Cr	0.4848 +/- 0.25	20.1%	1.34 +/- 0.33	71.6%	1.42 +/- 0.24	39.8%	1.36 +/- 0.07	69.2%
Co	0.2142 +/- 0.07	16.2%	0.349 +/- 0.11	40.6%	0.649 +/- 0.17	53.4%	0.479 +/- 0.03	67.3%
Cu	0.3224 +/- 0.15	19.7%	0.7385 +/- 0.15	69.3%	0.826 +/- 0.25	69.3%	0.764 +/- 0.02	72.8%
Pb	1.1348 +/- 0.57	19.1%	2.57 +/- 0.28	62.3%	3.105 +/- 0.19	80.2%	2.605 +/- 0.02	74.0%
Ni	1.924 +/- 0.58	17.3%	3.845 +/- 0.91	47.4%	6.595 +/- 1.77	63.8%	4.475 +/- 0.25	71.4%
Zn	1.564 +/- 0.68	15.9%	3.785 +/- 1.11	48.4%	5.07 +/- 0.78	68.2%	4.565 +/- 0.70	72.3%

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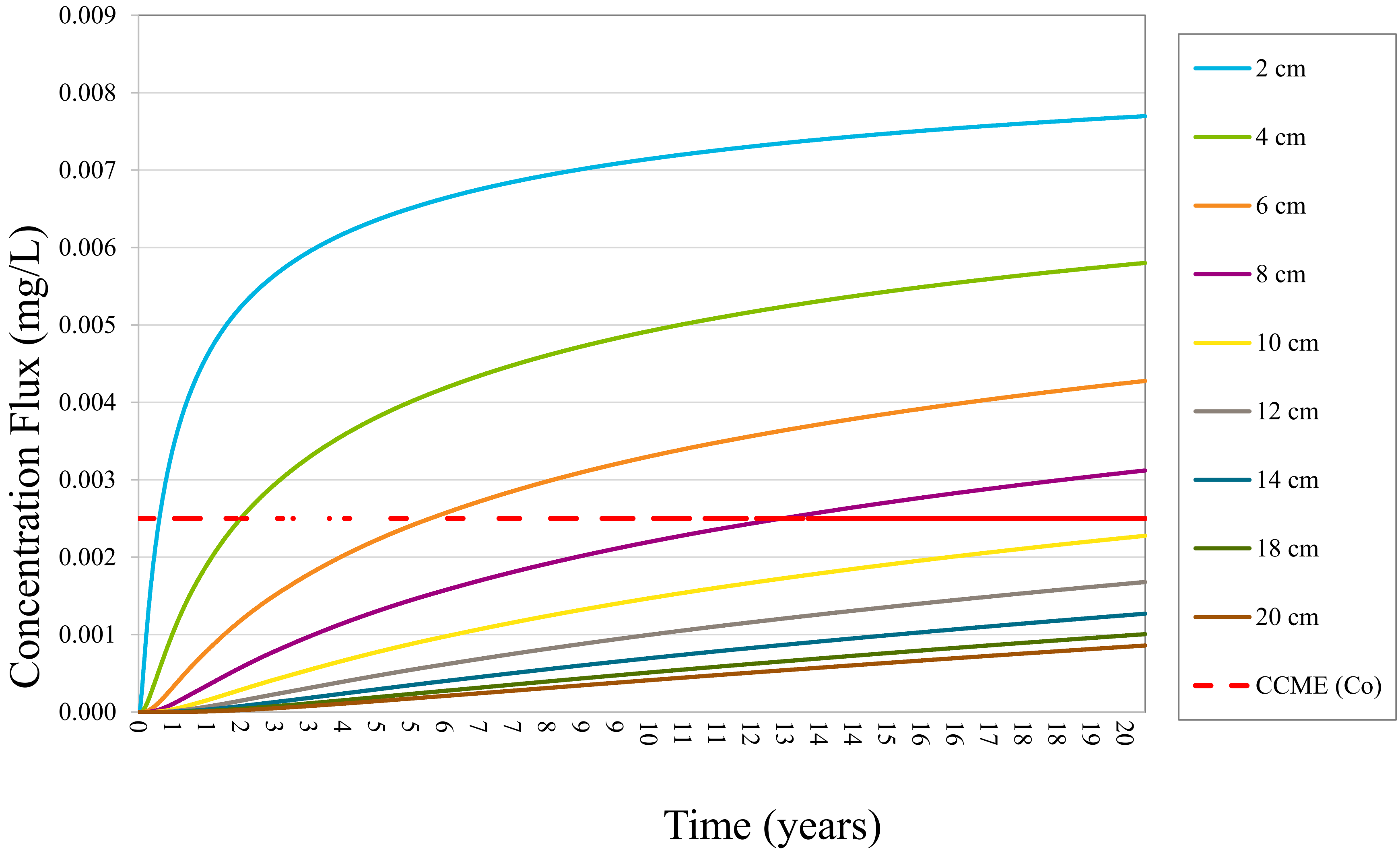

Sizing for

Metal Species	Computed Annual Load (mg)	Average Runoff Concentration (mg/L)	CCME Guideline (mg/L)	WC (cm)	BF (cm)	BOF (cm)	IRON (cm)
Cr	615	0.07[a]	0.0089	9.6	0.8	0.5	0.4
Co	86	0.0099[b]	0.0025	2.6	0.4	0.1	0.1
Cu	1055	0.12[a]	0.0020	28.0	2.8	1.7	1.5
Pb	17597	2.0[a]	0.0020	134.7	13.7	7.5	7.3
Ni	113	0.0129[c]	0.0250	N/A	N/A	N/A	N/A
Zn	4047	0.46[a]	0.0300	21.0	2.0	1.0	0.9

[a]As cited in Pitt et al., 2004

[b]Bäckstrom et al., 2003

[c]Crabtree et al., 2004

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How Can Pollutants be Detained and Attenuated?

Design and assess different **liner systems' ability** to attenuate chloride concentrations and **protect groundwater and surface water**

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Enhanced roadside drainage system for environmentally sensitive areas

CrossMark

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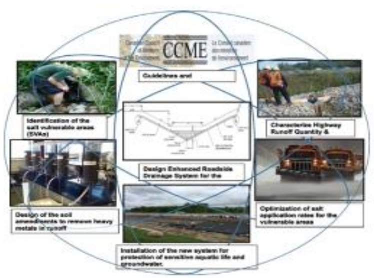
HIGHLIGHTS

- Presented a novel design for roadside drainage system to protect sensitive areas
- Presented a comprehensive scientific design framework for regulatory compliance
- Constructed, instrumented and monitored field-scale test site for three years
- The new design can be used to protect sensitive aquatic life and groundwater.

GRAPHICAL ABSTRACT



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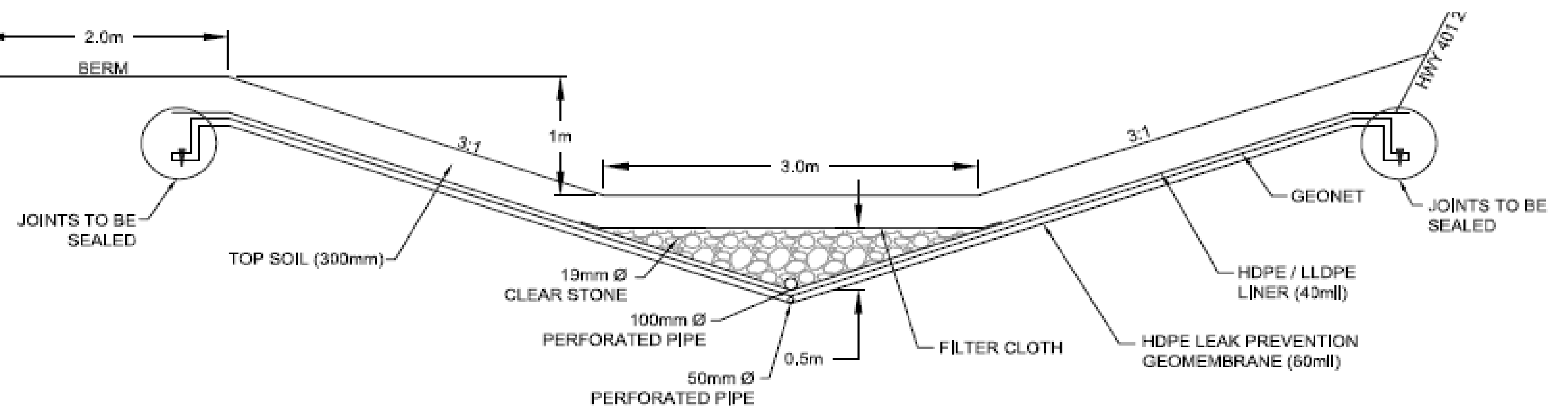
ABSTRACT

Stormwater runoff from roadways that encroach upon environmentally sensitive areas (ESAs) is one of the leading causes of degradation in urbanizing watersheds around the world. This is due to toxicity of the pollutant cocktail commonly found in roadway runoff, including heavy metals and sediments, as well as road salts from winter maintenance operations. This paper presents a novel design of an enhanced roadside drainage system (ERDS): an

Assessment of New Low Impact Drainage System

- Upscaling from the Laboratory to the Field
  - Peak dampening from diffusion, storage, homogenization & adsorption
  - Testing of Various Liners
  - Sub-surface Leak Detection



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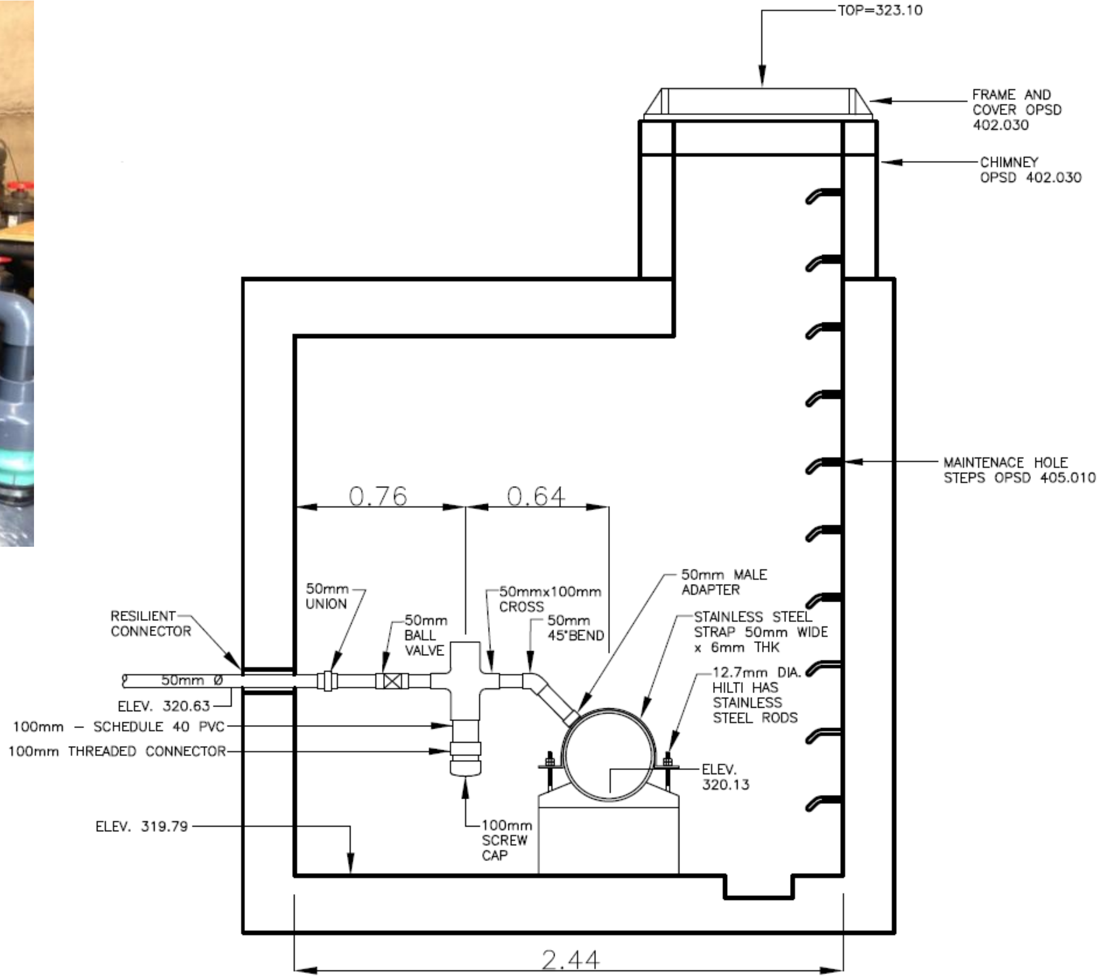
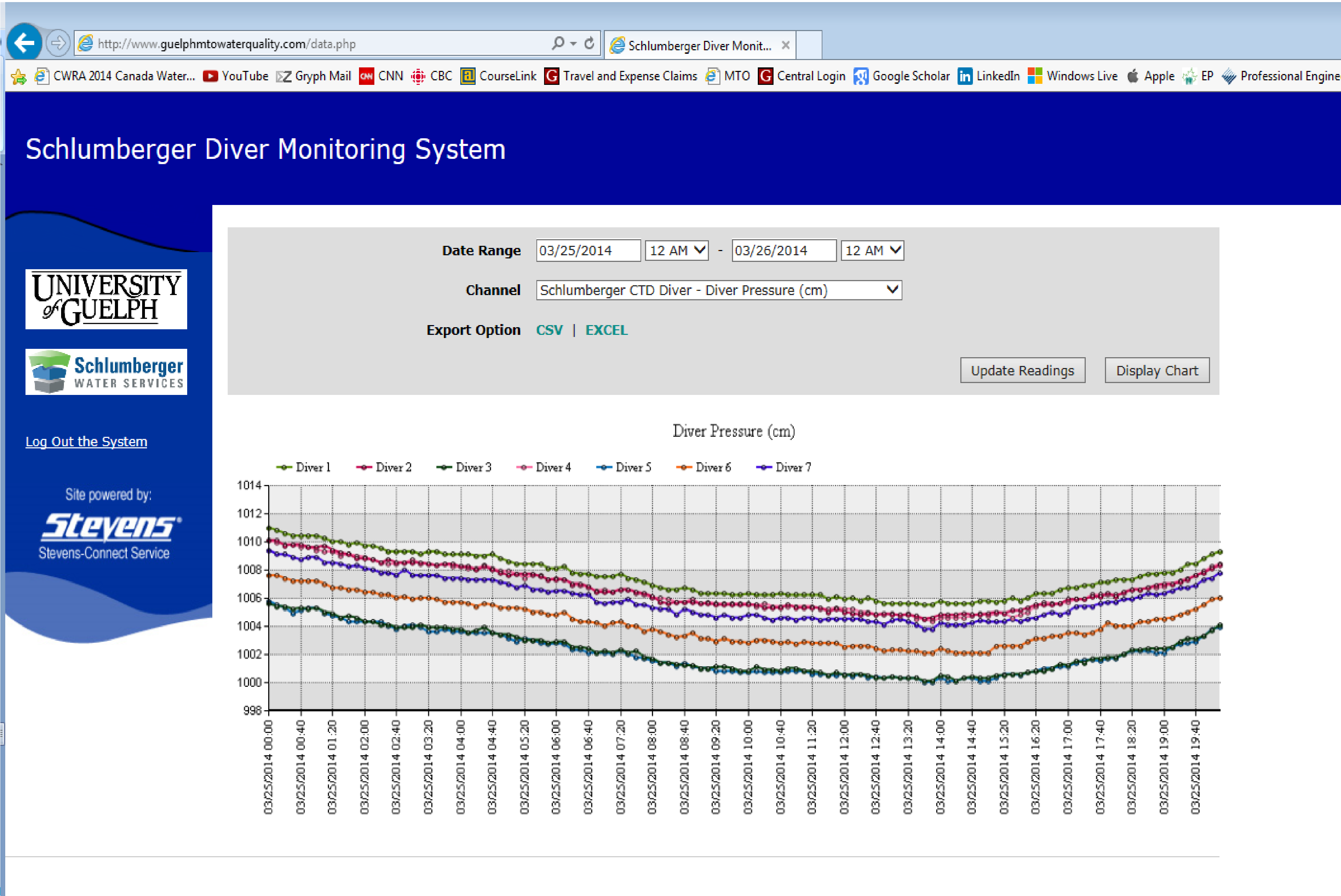
Monitoring Setup

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Schlumberger WATER SERVICES
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Channel Schlumberger CTD Diver - Diver Pressure (cm)
Export Option CSV | EXCEL
Update Readings
Display Chart
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Diver 2
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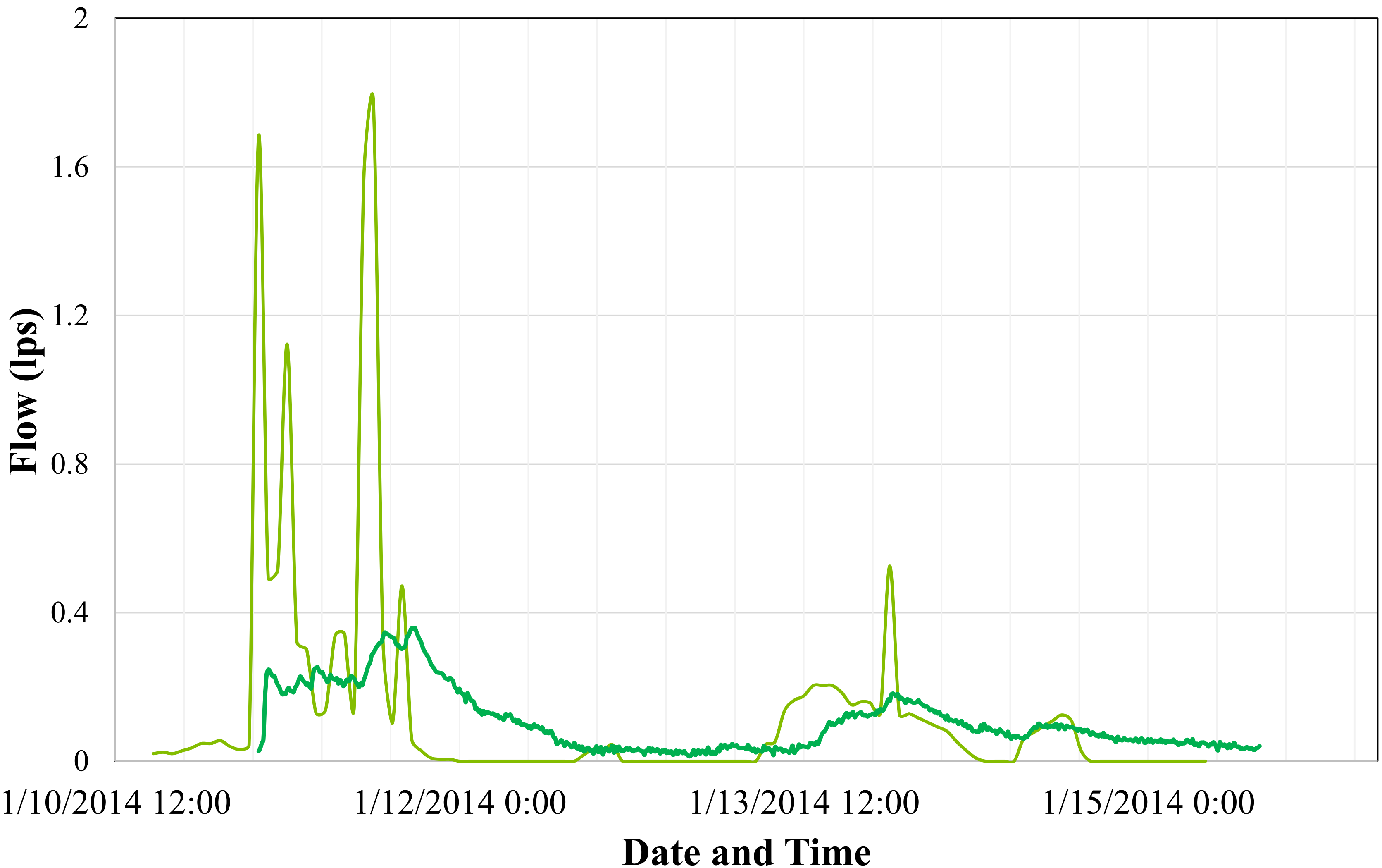
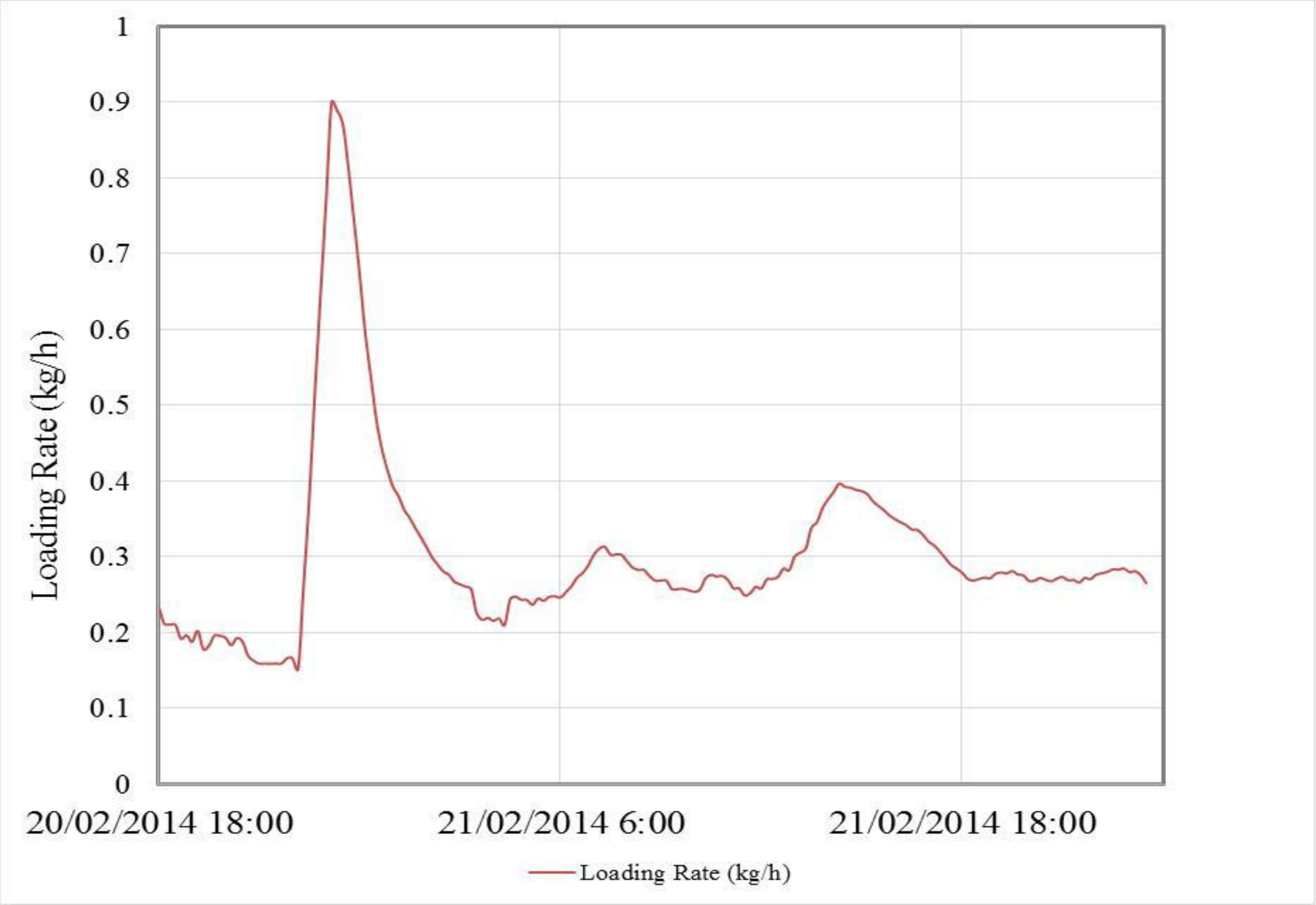
Water Quality - Attenuation



Water Quality – Peak Shaving



Numerical Simulation of Water Quality

– HYDRUS-1D model assessed for its ability to simulate outflow chloride loading rates from the field site

– Due to hourly time step of melt model, top of ‘column’ chloride load was applied instantaneously

Conclusions

– MTO Maintenance practitioners are doing a good job

– The Modified TI Method brings a clear and defensible methodology to winter maintenance decisions

– The soil amendments investigated show a clear ability to immobilize common roadway heavy metals, even when exposed to high concentrations of de-icing salts

– Computed Freundlich adsorption isotherms can be used to size treatment media thickness for pollutants of concern

– The roadside treatment system reduced the incidence of shock loadings while also protecting groundwater, with LLDPE being the most effective

Next Steps

- Initial results are promising, but further testing of the MTI Model is required
- Development of a simple UI to help with salt application calculations
- Full integration of MTO's RWIS Data
- Looking for agencies who have ESAs to protect

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Ontario

Toronto and Region Conservation for The Living City

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Thank You

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