

ROAD SALT LOADING IN THE FALL CREEK WATERSHED

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ABSTRACT

This project models the rising chloride concentrations in the Fall Creek watershed located near Ithaca, New York. Base-line salinization levels for freshwater in the northeastern United States have been increasing over the past several year and road salt has been identified as a possible primary source (Kaushal et al., 2005). Investigation is required to determine what detriment this may be causing to freshwater sources and environments. Data shows current concentrations in Fall Creek watershed to be 18.8 ppm as of 2003 (Bouldin, unpublished). By modeling Fall Creek watershed as a continuously stirred tank reactor (CSTR), it is possible to predict the increasing trends in salt concentrations in the watershed matching the data that was previously collected beginning in the 1970s. Based on data collected regarding quantities of salt purchased by local municipalities surrounding the watershed and inputs from wet atmospheric deposition, the model shows that the watershed system will reach steady state in approximately the year 2550 at a concentration of 35.4 ppm. Based on current conditions the salt concentration in the watershed could reach 30 ppm over the next hundred years. Harmful salt concentrations can range anywhere from 30 to 250 ppm as a conservative estimate, although accurate information in this area seems difficult to obtain. Though current concentrations in the watershed are below this range, continued monitoring of the area is important in order to supply data that could be used to make informed decisions regarding local salt spreading policies and management techniques.

INTRODUCTION

In recent years, it has come to light that base-line salinization of surface waters is increasing in the northeast region of the United States and posing serious ecological problems (Siver et al., 1996; Godwin et al., 2003; Kaushal et al., 2005). Salinization is defined as the increase in concentration of total dissolved solids in water, which is commonly measured by increasing anion concentrations such as chloride. The study conducted by Kaushal et al. (2005) showed that chloride concentrations up to 25% those of seawater were occurring in streams in New York, New Hampshire and Maryland during the winter time, with mean annual concentrations increasing as a function of impervious surfaces. One of the primary sources associated with the increasing concentrations is the runoff from roads that are being salted during the winter months (e.g., Peters and Turk, 1981; Siver et al., 1996; Rosenberry et al., 1999).

Sodium chloride is commonly used for deicing roads. Rock salt, or halite, which is mined from naturally occurring deposits below the ground, is the most common source of this material. Rock salt is usually considered the best chemical option because of its widespread availability, low cost, ease of application, and time-effectiveness (David Orr, Cornell Local Roads Program (CLRP), personal communication). Applying road salt to highways became a common maintenance practice in the 1940s after World War II when it was discovered that using salt was more effective than plowing alone or even plowing in combination with using abrasives such as sand (National Research Council, 1991).

Road salt works by acting to depress the freezing point of water on the ground surface and thereby melt the ice. One of the most effective salting strategies that has been developed is

termed “anti-icing.” With this method salt is applied before substantial snow or ice has accumulated on a road surface. This allows a layer of salt solution or “brine” to form on the pavement, preventing anything from bonding to the pavement surface. Snow or ice is then easily plowed from the road, or often times, simply displaced by vehicular traffic (CLRP, 2006).

Kaushal et al. (2005) also noted in their study that road salt as a contaminant in fresh water is currently not regulated in the United States (US EPA, 1988). Local municipalities have a great deal of freedom in determining the policies and management techniques that they use to spread road salt, as well as being responsible for evaluating whether or not those policies are safe and effective. In light of increasing salinity, it is, therefore, important to explore the impact that road salt is having in watersheds at local levels, especially in the northeast region.

This study focuses on one watershed near Ithaca, NY, where stream chloride concentrations have been monitored periodically since the early 1970s: Fall Creek. We hypothesize that the observed increases in salt concentration can be explained by a gradual build-up of salt in the watershed. We will test this idea by applying a simple model to the system and comparing model results with observed salt concentrations.

WATERSHED DESCRIPTION

Fall Creek is a 129 square mile watershed, mostly contained within Tompkins County, New York (Figure 1). The watershed consists of the small town of Dryden, and rural communities such as Freeville, and parts of residential areas like Cayuga Heights. Ultimately, the creek runs through Ithaca, NY before entering Cayuga Lake. The watershed is mostly rural

agricultural and forested land uses, laced with a number of roads, including an important regional conduit, Route 13.

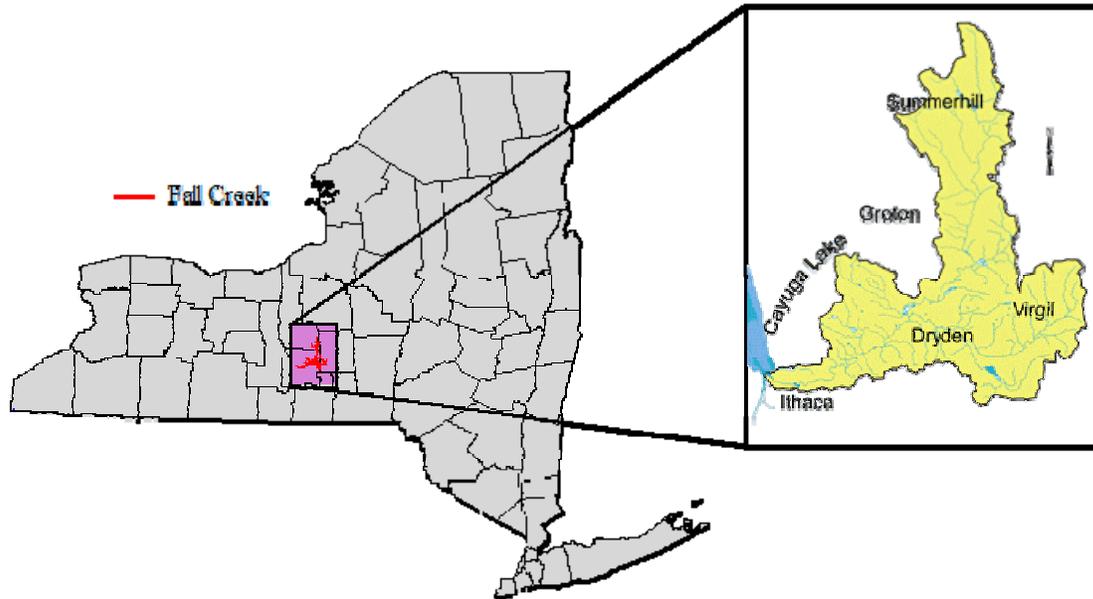


Figure 1. Map of Fall Creek watershed area located in central New York (Images from aquagap.cfa.cornell.edu and www.cayugalake.org)

Bouldin (unpublished) showed that annual flow weighted chloride concentrations in the Fall Creek watershed have been increasing since 1972, from 10.2 ppm to 18.8 ppm in 2003. Figure 2 shows a best fit line (linear model) of the flow weighted mean beginning in 1972 based on the data from that paper. This linear correlation does not explicitly account for actual loading rates of road salt in the watershed area. Thus, the goal of this project was to determine the extent to which road salt applied within the watershed during the winter months was influencing this increasing trend. Note, details about how the data shown in figure 2 were collected, analyzed and reduced are described in Bouldin (unpublished).

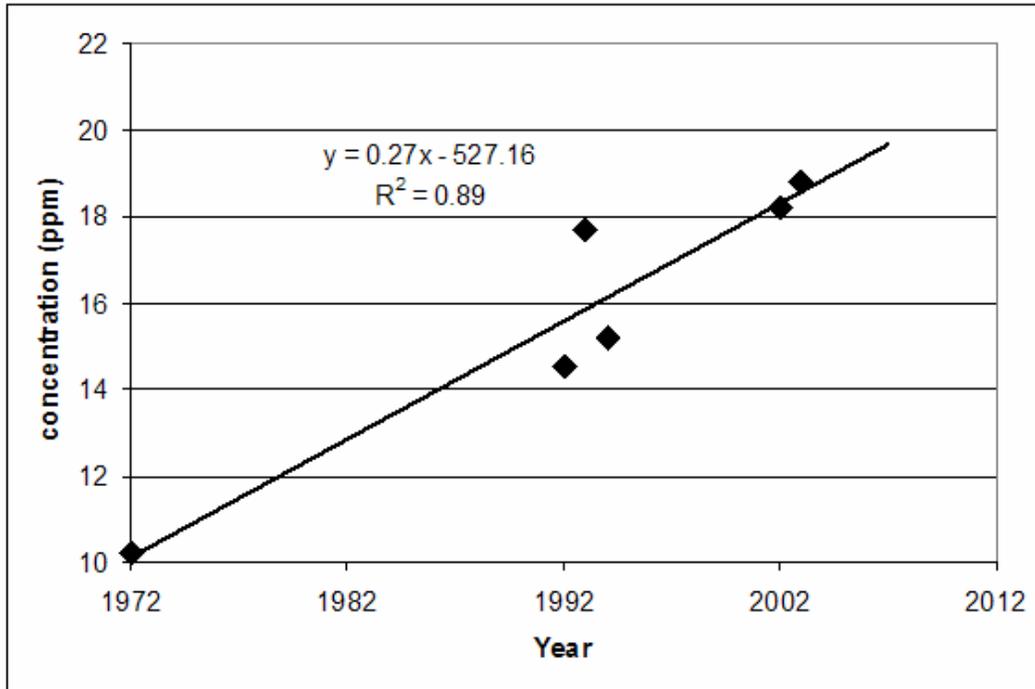


Figure 2. Flow weighted concentration of chloride in the Fall Creek watershed area from Bouldin (Unpublished). Data fitted with a linear regression. As the model later shows, a linear fit may be a reasonable approximation for short time scales.

Data pertaining to amounts of road salt purchased by each of the primary local municipalities in the watershed, i.e., City of Ithaca, Town of Ithaca, Town of Dryden, Village of Dryden, Village of Cayuga Heights, and Village of Freeville, were obtained for the past eight years from the New York State Office of General Services (NYS OGS, 2007). On average, 6,900 tons were purchased each year by these entities combined. Although much of this salt was probably spread outside of the watershed, we also know there were entities that may have been spreading within the watershed for which we have not accounted so as first approximation, we will assume 6,900 tons were spread each year in Fall Creek.

Atmospheric deposition is the primary natural, i.e., non-anthropogenic, salt input into the watershed. Deposition data were obtained from the National Atmospheric Deposition Program site at the Aurora Research Farm (NY08) in Cayuga County, New York (2007). The average deposition rate in rain was 1.1 kg/ha*yr over the past thirty years. This is likely an underestimate of the total atmospheric deposition because substantial amounts of salt are also deposited in dry forms (Peters and Ratcliffe, 1998, Neal et al., 1988).

Stream flow partially controls the salt export from the watershed. Using data were obtained from the USGS station (04234000) for Fall Creek (USGS, 2007), the average annual stream flow for Fall Creek, which was $1.78 \times 10^8 \text{ m}^3/\text{yr}$.

MODEL

The watershed was modeled as a continuous stirred tank reactor (CSTR), with the watershed boundary functioning as the control volume. At any given time, the concentration of salt in the watershed is described by the following equation:

$$c(t) = \frac{m_{in}}{Q} + \left(c_i - \frac{m_{in}}{Q} \right) e^{-t/t_r} \quad (1)$$

Where c is the average concentration of salt stored in the watershed, c_i is the initial concentration of salt in the stream (ie., in 1972), Q is the annual discharge from the watershed, and t_r is the average residence time of salt in the watershed, which needs to be calibrated. The variable m_{in} is the mass of salt entering the watershed each year ($6.25 \times 10^6 \text{ kg/yr}$), i.e., a sum of the total mass of road salt being spread in the watershed and any chloride entering as atmospheric depositions.

RESULTS & DISCUSSION

The equation that was derived based on the CSTR model (equation 1) shows increasing salt concentrations in the watershed over the past thirty-five years comparable to the actual data that has been collected (Figure 2). Interestingly, over this 30 year time frame, the model fit is nearly linear (compare Figures 2 and 3). The salt residence time that fits these data is 79.3 years, that is, this is how quickly the salt will move, on average, through the watershed. The residence time can be envisioned as the ratio of the volume of the watershed to the average discharge, V/Q . Using this logic, V is approximately $1.41 \times 10^{10} \text{ m}^3$, which, assuming a porosity of 0.5, translates into an effective mixing groundwater depth of $\sim 80\text{m}$. This is probably somewhat deeper than would be realistically measured, possibly due to the fact that we did not explicitly account for dry atmospheric deposition or inputs from Dryden's sewage treatment plant. On the other hand, we also feel that we over-estimated road salt applications, thus, it is clear that these input fluxes need to be more carefully resolved.

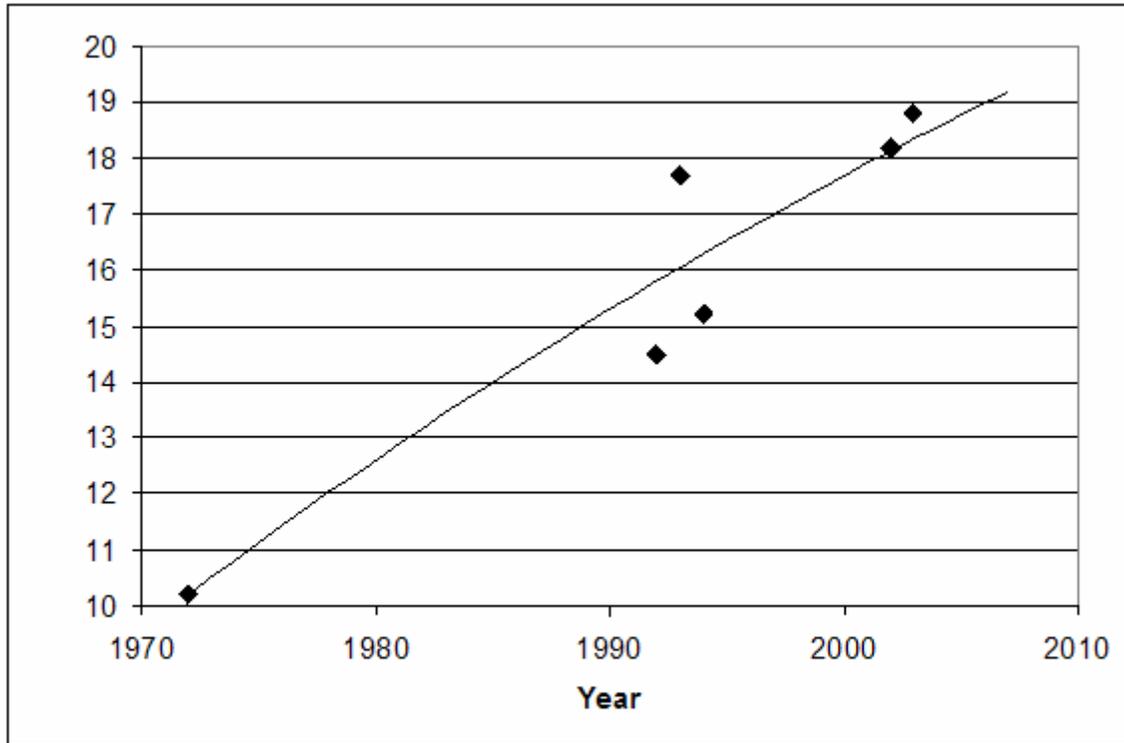


Figure 3. Concentration of salt in the Fall Creek watershed. Points are actual data. Solid line is the model.

Meanwhile, let us ignore some of the shortcomings of the models and its applications. Assuming the conditions of the system such as the annual stream flow and the quantity of salt entering the watershed do not change significantly, taking the equation to the limit as time approaches infinity, the system appears to reach steady state at a concentration of 35.4 ppm; according to the model this concentration would be reached around the year 2550 (Figure 4). However, within the next 100 years we would expect the concentration to reach 30 ppm, the point at which the salinity begins to damage terrestrial plants (Environment Canada, 2001). Note also that these average concentrations are probably spatially arranged such that there are some high concentration “hotspots” within the watershed balanced by areas of very dilute

concentrations. More work is needed to meaningfully identify the locations of these hotspots and their associated risk of salt-poisoning.

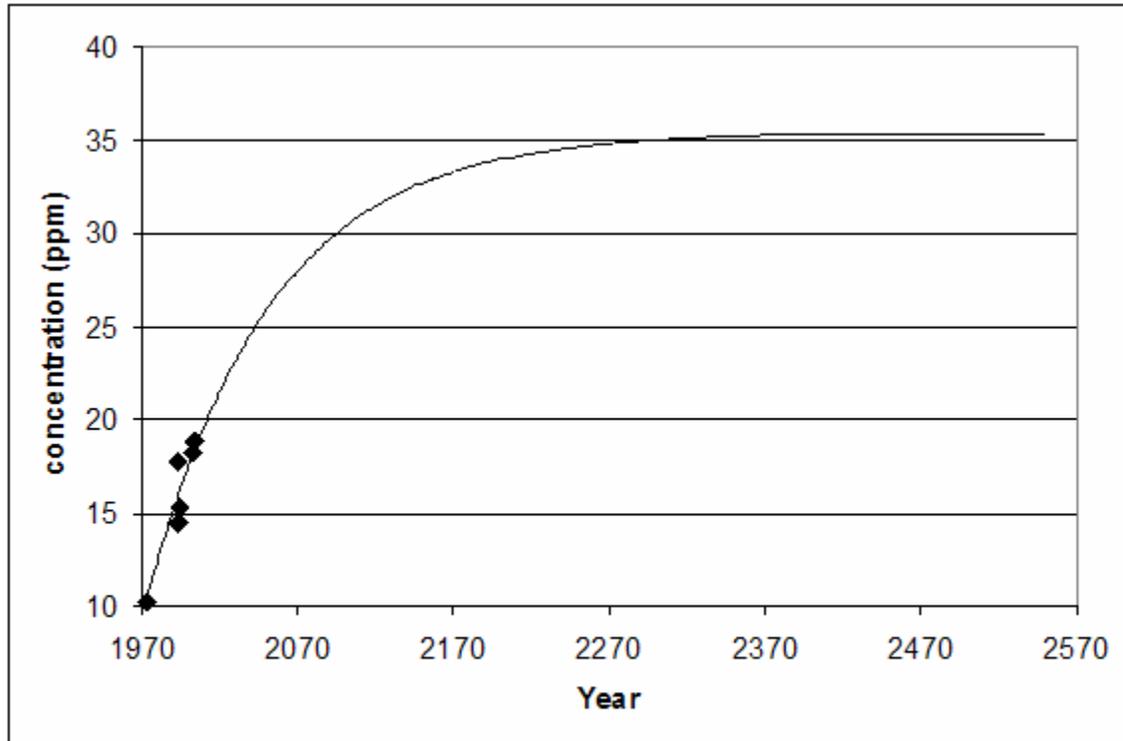


Figure 4. Concentration of salt in the Fall Creek watershed until the system reaches steady state. Points are actual data. Solid line is the model.

Our analysis assumed that the annual Fall Creek discharge had not been changing over the study period. Indeed, the mean annual discharge has been decreasing slightly over the period since 1970, although only very slightly and insignificantly, $r^2 < 0.001$ (Figure 5). Even so, a decrease in the average annual flow rate would result in increasing salt concentrations in the watershed, including a higher steady state concentration. A smaller Q would also mean a longer residence time for the salt in the watershed. Over longer periods (e.g. since 1950) or shorter periods (e.g. over the period of the past ten years or so), increased stream flow has been observed. Thus, it is not obvious what trends are eco-hydrologically significant, if any. It is

conceivable, though, that there is merit in further study of the impacts of potential long-term, presumably climate-change-driven, changes in watershed hydrology on stream salt concentrations.

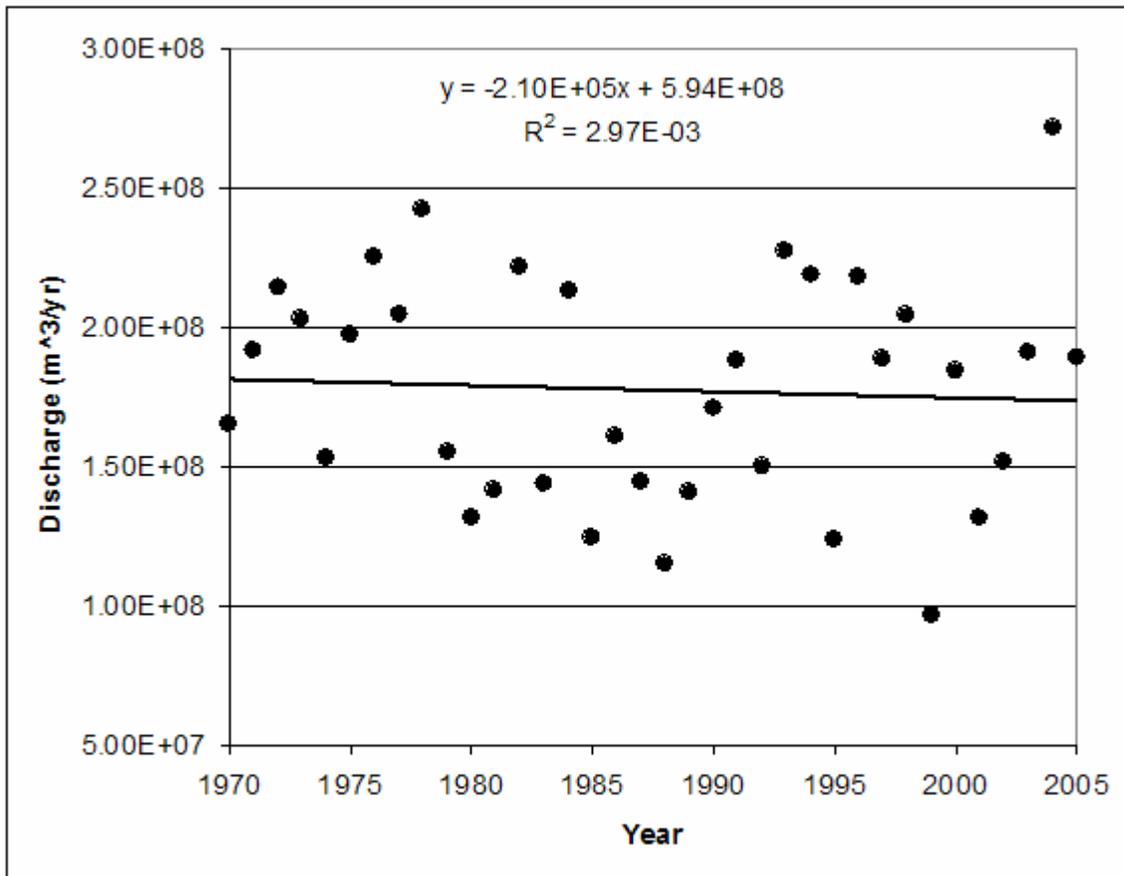


Figure 5. Average annual flow rate for Fall Creek.

We also assumed steady state road salt input loads in our analysis. However, unlike stream discharge, there is good evidence that this may not be an appropriate assumption. As shown in figure 6, the purchase of road salt has actually been increasing by roughly 10% a year over the past decade. Moreover, this past decade has brought relatively mild winters to the region and one wonders at the longer term trends in salt inputs to the watershed. Obviously,

increasing salt inputs will increase the rate at which salt levels rise in the stream and watershed and increase the long term salt levels in Fall Creek.

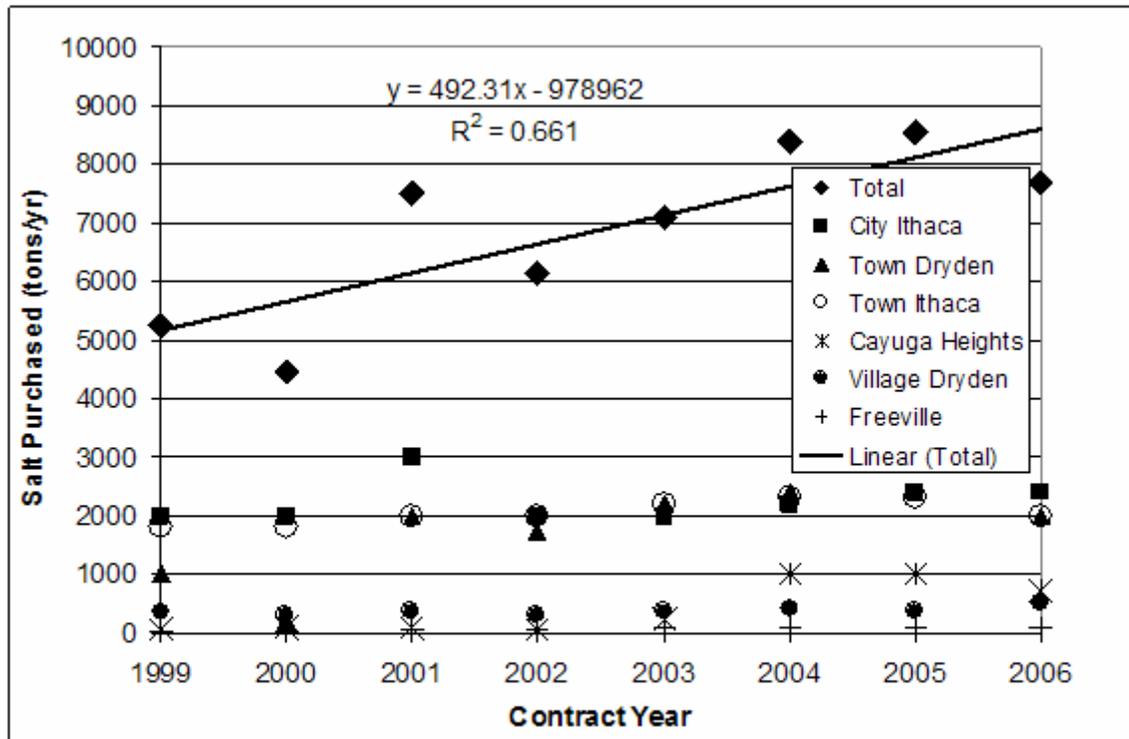


Figure 6. Quantities of salt purchased each season by local municipalities during the contract years from 1999-2000 to 2006-2007 (total and breakdown by municipality).

CONCLUSION

Based on the quantities of salt being purchased by the local municipalities in recent years and assuming that these quantities have not changed drastically over the past few decades, it seems clear that road salt is having a substantial effect on increasing chloride concentrations in Fall Creek, certainly more than can be accounted for from atmospheric deposition in rain alone. Our analysis does suggest that we have missed some additional sources, probably from atmospheric dry deposition and sewage treatment. However, even if road salt is ultimately

identified as the primary cause for the increasing chloride concentration in the Fall Creek watershed, this analysis suggests that ecologically harmful levels will not be reached for nearly a century.

In regards to concern over the possibility of fish and other aquatic wildlife being harmed by increasing salt concentrations in the creek and the lake, it seems unlikely that this would be a widespread occurrence. Sea water, for instance, contains about 30,000 ppm of sodium and an average chloride concentration of 20,000 ppm (NRC, 1991). And according to biologists from the Department of Energy's Oak Ridge National Laboratories, freshwater fish are capable of tolerating anywhere from 7,500 to 10,000 ppm of salt and perhaps even higher concentrations if the acclimatization period happens gradually enough (Salt Institute, no date). These numbers seem quite high, but that is not surprising, given that the Salt Institute has a vested interest in promoting salt use. More realistically, salt levels around 250 mg/L are likely toxic to much freshwater life and have been reported by more unbiased sources (e.g., US EPA, 1988; Environment Canada, 2001). Additional sources of data were difficult to obtain for making suitable comparisons.

Although this study was not focused on Cayuga Lake *per se* (i.e. the lake that directly receives Fall Creek's discharge) a possible impact of increasing salt concentrations is reduced lake water circulation, leading to reduced re-aeration of the lower depths in water bodies. This is because, in theory, the salt water will stratify according to salt concentration density in ways that disrupts the natural water circulation. This cycle is normally driven by annual cooling and warming of surface water but salt water densities are typically more pronounced than density

differences due to water temperature. When the cycle is disrupted the result is a decrease in dissolved oxygen levels in the water, leading to the eventual mortality of aquatic life in the surrounding environment (NRC, 1991).

When considering environmental and ecological problems associated with increasing “fresh” water salt concentrations, we must also consider the many benefits to using road salt in highway deicing. One of the obvious reasons is aiding in the reduction of traffic accidents and fatalities by improving road conditions during winter storm events (NRC, 1991). In a similar vein, properly maintained roads result in less interruption in the provision of emergency services, such as ambulance, fire and police services, which also additionally save lives. Moreover, there is the reduction of various losses in work force productivity caused by workers who might be delayed or otherwise incapable of commuting to their workplace. Other benefits stem from reducing similar disruptions in commercial traffic (trucking, etc.).

Because of these benefits, it is clear that the solution is not simply to discontinue the practice of applying road salt during the winter storm season. Rather, careful and continued monitoring of the area in conjunction with and/or adjustment of local salt spreading should be emphasized and policies adjusted as localized problems emerge.

ACKNOWLEDGEMENTS

I would like to thank Dr. David Bouldin, Professor Emeritus of Cornell University’s Department of Crops and Soil Science, for sharing his data and unpublished work on Fall Creek’s salt trends.

APPENDIX A: EQUATION DERIVATION

List of symbols

$s(t)$	amount of salt in the watershed/leaving the watershed [kg]
$c(t)$	concentration of salt, $s(t)/V$ [ppm]
c_o	concentration of salt out [ppm] (same as $c(t)$)
c_i	initial concentration of salt at time zero (year 1972) [ppm]
V	volume of water in the watershed [m^3]
m_{in}	mass of salt in [kg/yr]
m_{road}	mass of salt from road salt [kg/yr]
m_{atm}	mass of salt from precipitation [kg/yr]
Q	average annual stream discharge [m^3]
r_i, r_o	rates of salt into and out of the watershed [m^3 /yr]
t_r	residence time of salt in the watershed [yr]

Model Derivation

The rate of change of salt accumulated in the watershed, $s(t) = \text{rate of } s(t)_{in} - \text{rate of } s(t)_{out}$; which can be written as an ordinary differential equation:

$$\frac{ds}{dt} = r_i c_i - r_o c_o \quad (\text{A.1})$$

The amount of salt accumulation $s(t) = c_o V$. The rate of salt accumulation $r_i c_i = m_{in}$ and the output rate $r_o = Q$. Thus, equation 1 can be written as:

$$\frac{dc_o V}{dt} = r_i c_i - r_o c_o = m_{in} - Q c_o \quad (\text{A.2})$$

Or, in words:

$$\text{rate of change} = \frac{\text{mass of salt in}}{\text{yr}} - \frac{\text{ave stream discharge}}{\text{yr}} * \frac{\text{mass of salt out}}{\text{volume of water in watershed}}$$

With units:

$$\frac{\text{tons}}{\text{yr}} = \frac{\text{tons}}{\text{yr}} - \frac{\text{ft}^3}{\text{yr}} * \frac{\text{tons}}{\text{ft}^3}$$

Because V is more or less constant on an annual basis, equation 2 can be rewritten as:

$$V \frac{dc_o}{dt} = m_{in} - Qc_o \quad (\text{A.3})$$

And rearranged as:

$$\frac{dc_o}{dt} + \frac{Q}{V} c_o = \frac{m_{in}}{V} \quad (\text{A.4})$$

This first order, ordinary differential equation can be solved via an integrating factor:

$$\rho(t) = e^{\int \frac{Q}{V} dt} \Rightarrow \rho = e^{\frac{Q}{V}t}$$

And the solution of equation A.4 will take the form: $c_o e^{\frac{Q}{V}t} = \frac{m_{in}}{V} \int e^{\frac{Q}{V}t} dt$

Which, when integrated will be: $c_o e^{\frac{Q}{V}t} = \left(\frac{m_{in}}{V} \right) \frac{V}{Q} e^{\frac{Q}{V}t} + K$

And simplified to: $c_o e^{\frac{Q}{V}t} = \frac{m_{in}}{Q} e^{\frac{Q}{V}t} + K$

Using the initial condition: @ $t = 0$, $c_o = c_i \rightarrow K = c_i - \frac{m_{in}}{Q}$, the solution to equation A.4 is:

$$c_o e^{\frac{Q}{V}t} = \frac{m_{in}}{Q} e^{\frac{Q}{V}t} + \left(c_i - \frac{m_{in}}{Q} \right)$$

If we let $V/Q_t = t_r$, the final equation can be expressed as equation 1:

$$c(t) = \frac{m_{in}}{Q} + \left(c_i - \frac{m_{in}}{Q} \right) e^{-\frac{t}{t_r}}$$

APPENDIX B: ROAD SALT, HUMAN HEALTH AND THE ENVIRONMENT

Sodium chloride is most commonly used for deicing roads. Rock salt or halite, which is mined from naturally occurring deposits below the ground, is the most common source of this material. Rock salt is usually considered the best chemical option in terms of widespread availability, low cost of material, ease of application, and time-effectiveness (David Orr, CLRP, personal communication). Applying road salt to highways became a common maintenance practice in the 1940s after World War II when it was discovered that using salt was more effective than plowing alone or even plowing and using abrasives such as sand (National Research Council, 1991). Road salt works by acting to depress the freezing point of water on the ground surface and so melt the ice. The eutectic temperature of sodium chloride, which is the lowest temperature that a concentrated solution will melt ice, is -6 °F. In practice though, sodium chloride is effective to a pavement surface temperature of 15 °F (Cornell Local Roads Program, 2006). At temperatures closest to the eutectic temperature, the melting that occurs is much too slow to be of any practical use.

One of the most effective salting strategies that has been developed is termed “anti-icing.” The way this works is that salt is applied before much snow or ice has accumulated on a road surface. This allows a layer of salt solution or “brine” to form on the pavement, preventing anything from bonding to the pavement surface. Snow or ice is then easily plowed from the road, or often times, simply displaced by vehicular traffic (CLRP, 2006). Deicing, a similar process, is what happens when ice has already bonded to the pavement surface. Once the salt is applied, the particles melt down through the layer of ice and snow and as before, begin to form a

brine layer beneath the surface. Passing traffic and the concentrated salt solution act to break the bond of ice with the pavement so that it can be plowed away (CLRP, 2006).

There are many benefits to using road salt in highway deicing. One of the obvious reasons is reducing traffic accidents and fatalities by improving road conditions during winter storm events. In a similar vein, properly maintained roads mean less interruption in the provision of emergency services, such as ambulance, fire and police services, which also potentially save lives. Then, there is the reduction of various losses in work force productivity caused by workers who might be delayed or otherwise incapable of commuting to their workplace. Other benefits stem from reducing similar disruptions in commercial traffic (trucking, etc.).

Salt is also an essential nutrient required for maintaining human health. For healthy adults and children over ten years of age it has been established that 500 mg/day is the estimated minimum required intake (US EPA, 2003). The US Food and Drug Administration (FDA) does indeed assert that most Americans consume much more sodium than they actually need. The Nutrition Facts Label lists a Daily Value of 2,400 mg per day for sodium (about 6 grams of sodium chloride, or similarly, one teaspoon of salt is approximately 2,300 mg) (US FDA, 1995). During this time, however, there are no health standards for either sodium or chloride in drinking water as put forth by the EPA. When considering such regulations, the EPA assumes that the average person drinks 2 liters of water per day and that less than 10% of their salt intake comes from drinking water (rather, most of a person's salt intake comes from the food they consume). In 1998, when the Drinking Water Contaminant Candidate List (DWCCCL) was issued by the

EPA, sodium was on the list. The list names contaminants for which maximum contaminant levels (MCLs)—which are health-based standards that must be met by public water systems—may eventually be established (NH DES, 1998).

However, as road salt usage has continued to increase since the 1950s and 1960s, various environmental concerns have been raised over the years. For example, there have been instances of roadside vegetation being harmed by the heavy application of road salt. Vegetation with low salt tolerance can be impacted by increasing salt concentrations in the soil and soil water, which interferes with the plant's absorption of moisture (Salt Institute, no date). Salt accumulation on plant foliage and branches can also result in damage in the form of leaf browning and scorching. Dying branches and inhibited shoot growth are also indications of salt damage (NRC, 1991). However, there are also other factors that have an effect, such as vehicle exhaust emissions, wind exposure or changes in drainage patterns due to construction. These factors, combined with variables such as salt exposure, species tolerance, soil texture, plant size, water availability, and of course, conditions of temperature, humidity, light and wind exposure, have an impact on whether the vegetation is adversely affected by salt. Studies have also shown correlations between salt exposure of vegetation and roadside slope. Exposure zones range from 17 to 53 feet for flat to steep downhill slopes, respectively (NRC, 1991). In some cases, it is appropriate to plant salt tolerant vegetation as a buffer near heavy salt application areas to reduce damages.

There is also concern regarding the possibility of fish and other aquatic wildlife being harmed by increasing salt concentrations in streams and lakes. Sodium ions, though, are quite common in natural waters. Sea water, for instance, contains about 30,000 mg/L of sodium.

Freshwater also contains sodium in varying concentrations, ranging from 20 mg/L to several hundred mg/L. As for chloride, concentrations ranging from 0 to 100 mg/L are possible in freshwater. Seawater has an average chloride concentration of 20,000 mg/L (NRC, 1991). And according to biologists from the Department of Energy's Oak Ridge National Laboratories, freshwater fish are capable of tolerating anywhere from 7,500 to 10,000 ppm of salt and perhaps even higher concentrations if the acclimatization period happens gradually enough (Salt Institute, no date).

The damages that occur when salt is improperly stored are perhaps more common than problems caused by over-application. Proper storage of road salt involves leak-proof shelters placed on impervious surfaces. Otherwise, precipitation falling on exposed salt stores may run off in high concentrations and leach into surrounding soils and groundwater. Appropriate storage facilities with capacities for over 1,000 tons of salt may be built for around \$100,000 (NRC, 1991). Proper management techniques also mediate many of the harmful effects of salt by reducing excessive salt use. This can be accomplished through using better spreading equipment and techniques, providing better personnel training, and also gaining more accurate and timely weather information (NRC, 1991).

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