Trend Analysis of Road Salt Impacts on Groundwater Salinity at a Long-term Monitoring Site

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ABSTRACT

A large amount of deicing salt is applied each year on highways in North America to keep the road passable and safe. There has been concern about the potential for the salt to migrate downward to contaminate groundwater quality. The University of Regina and Saskatchewan Highways and Transportation have conducted a long term salt impact monitoring study on a section of highway near Regina, Saskatchewan. This paper will present the groundwater portion of this long-term monitoring study on the environmental impacts of road salt. Salt concentration data from three monitoring wells beside the highway section are presented for initial analysis, and the data from one well is analysed to detect trends using non-parametric statistical approaches. The statistical tests show that chloride concentration has a significant upward trend with an increase of 0.2 mg/L per year at the significance level of 0.05 over more than ten years monitoring period. However, no significant upward trend is found for sodium concentration data at the same significance level.

INTRODUCTION

Rock salt (NaCl) has been used as the first choice for highway deicing for more than a half century since no alternatives have the comparable advantages of cost-effectiveness [1][2]. A study conducted in the United States showed that simply applying salt to deice highways could reduce the injury accident frequency by 88 percent as well as decreasing the cost of each accident [3]. At present, approximately 20 million tons of salt are consumed each year in the United States and Canada for deicing purposes [2]. In addition to the benefits of deicing salt, detrimental impacts of the salt are also well recognized [1][5]. Due to the important roles sodium and chloride play in a human body, one of the most obvious concerns is the possible contamination of groundwater by road salt since groundwater is a crucial source of drinking water. Deicing salt can reach groundwater by leaching from the soils and surface water directly from spring thaw runoff or from groundwater flow. In the area where intensive highway networks lie, concentrations of salt ions in wells could be increased several folds [6].

Saskatchewan Highways and Transportation was concerned about the long term impacts of salt usage in Saskatchewan, so a long-term monitoring study of environmental impacts by road salt has been in progress since 1992 [7]. A new 10-kilometer section of highway connecting the town of Balgonie on the east and Pilot Butte on the west, was selected and samples have been taken from a variety of pre-designed vadose and water sites. As some of the sampling results from the vadose sites were introduced by [8] and [7], this paper presents the sampling results and trend analysis of salt concentrations of the groundwater data. There are three monitoring wells in the study area located at the Pilot Butte access identified as Site W1 (north highway ditch property line), W2 (south highway ditch property line) and W3 (150m south on access road in west ditch at property line). All wells had the same interior diameter of 50.8mm, the depths are 13.5m, 13.7m and 11.7m respectively for the three wells [9]. After the background sampling occurred in the fall of 1992, samples were taken at the three sites in the interval of one to two months until 1997. Samples have been taken twice a year in the spring and fall since the fall of 2000. The concentration of chloride is set in laboratory by auto-analysis method (Method 4500-Cl- E in [10]). Sodium level is determined by inductively coupled plasma (ICP) method in which both ICP source and spectrometer are involved [10]. Statistical non-parametric trend detecting methods are used in trend analysis of sodium and chloride concentration data. The relative location of two of the wells is shown on Photo 1.

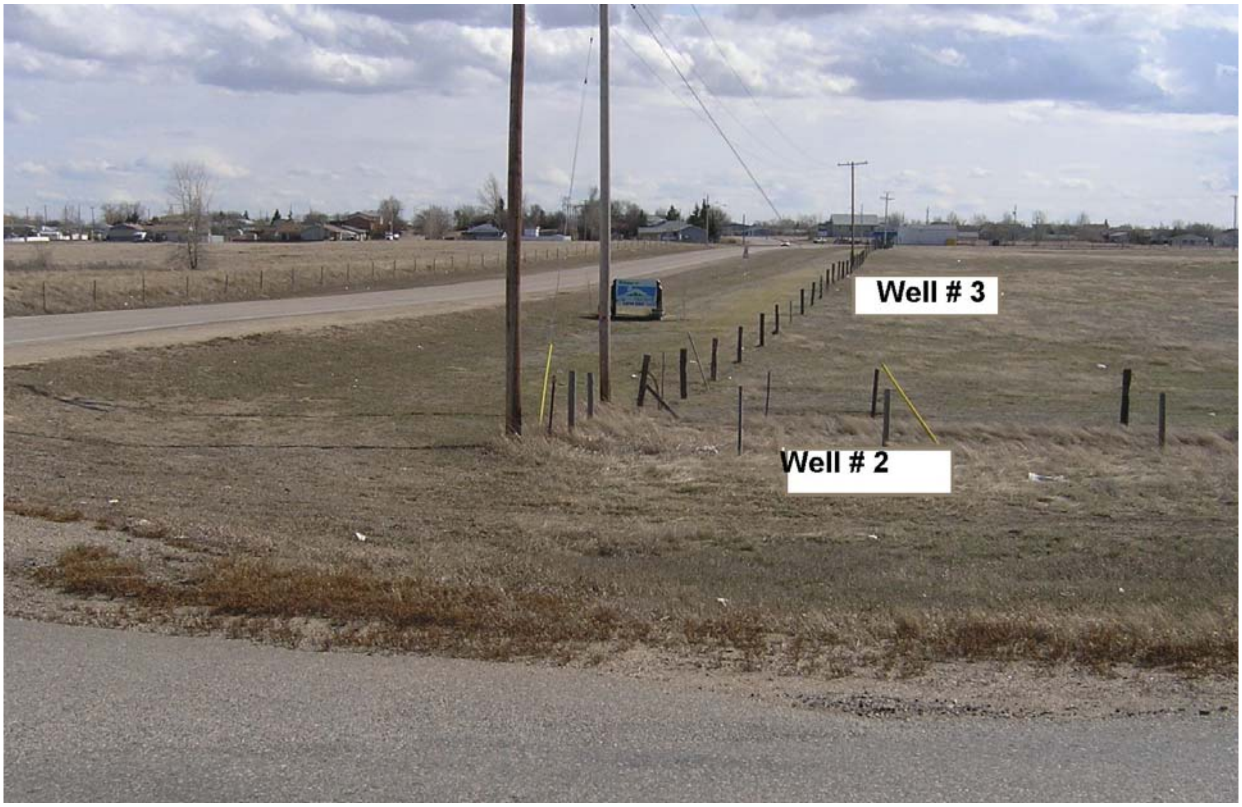

Photo 1 Showing locations of Well #2 (W2) and #3 (W3)

THE STUDY AREA

The study area lies in the Hudson Bay Nelson Drainage Basin [11]. Avonhurst Aquifer is overlain by the highway section [9] and the groundwater resources were classified as “good for town supplies” at the Pilot Butte area and “fair for farm and town supplies” for the east part by Saskatchewan Research Council [12].

Local climate belongs to the type of semi-arid to sub-humid [13]. Most frequent wind direction is southeast from January to December. The monthly and annual averages of mean daily temperatures and precipitation data for the year from 1971 to 2000 obtained from Regina A station are shown in Table 1. Annual precipitation waved from 273mm in 1984 to 586mm in 1991 with the mean of 388mm during the period [14].

Table 1 Monthly and annual mean climate data in the study area (1971 to 2000)

Parameter[a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
T_{DA} (°C)	-16.2	-11.9	-5	4.5	11.7	16.4	18.8	18	11.7	4.8	-5.5	-13.2	2.8
P (mm)	14.9	11.6	19	23.5	52.8	75.1	64.4	43.2	32.6	21.8	12.9	16.4	388
ASD (cm)	17	17	12	2	0	0	0	0	0	0	3	11	5

[a] T_{DA}: Daily Average Temperature; P: Precipitation; ASD: Average Snow Depth. Source: [14].

It can be seen from Table 1 that the mean temperatures below freezing point in the study area take place from the month of November to March. The precipitation occurs mostly from May to September and the snow events occur mostly from December to February.

Background data was collected in 1992 prior to opening the section of highway to traffic or the application of any deicing salts. Data was then collected for the remainder of the study period. Initial data analysis consisted of time series plots to determine trends as shown in Figures 1, 2, 3 and 4.

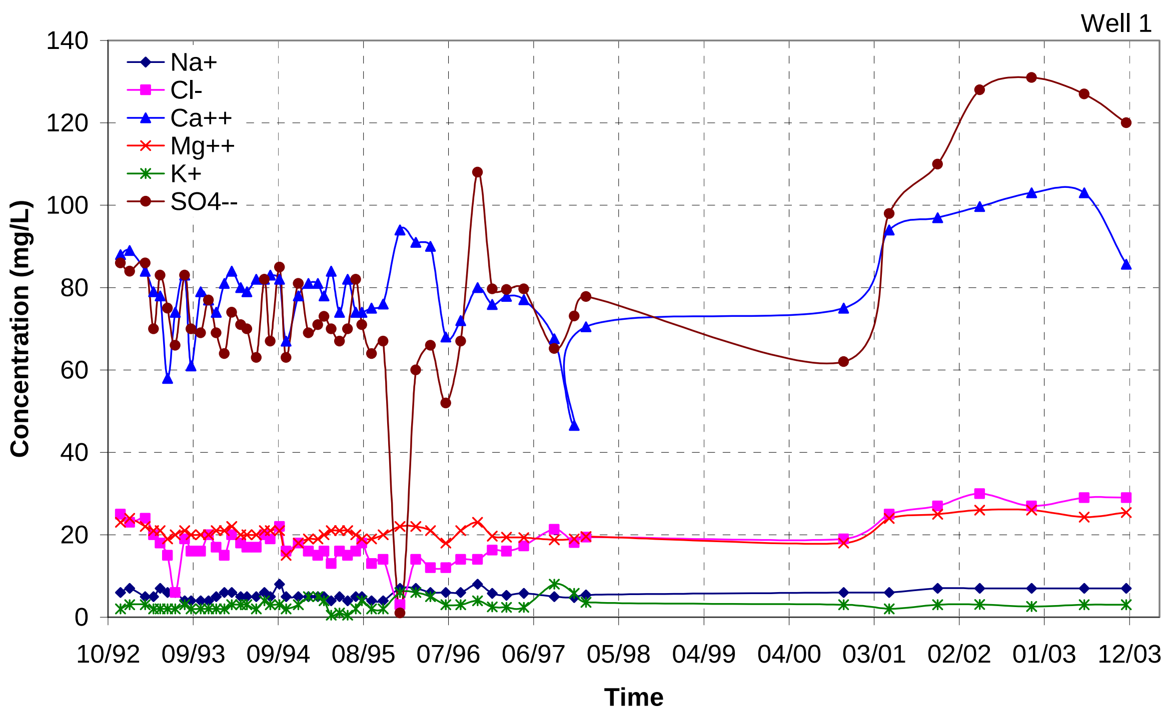

Figure 1 Time series plots of major ion concentrations W1 data

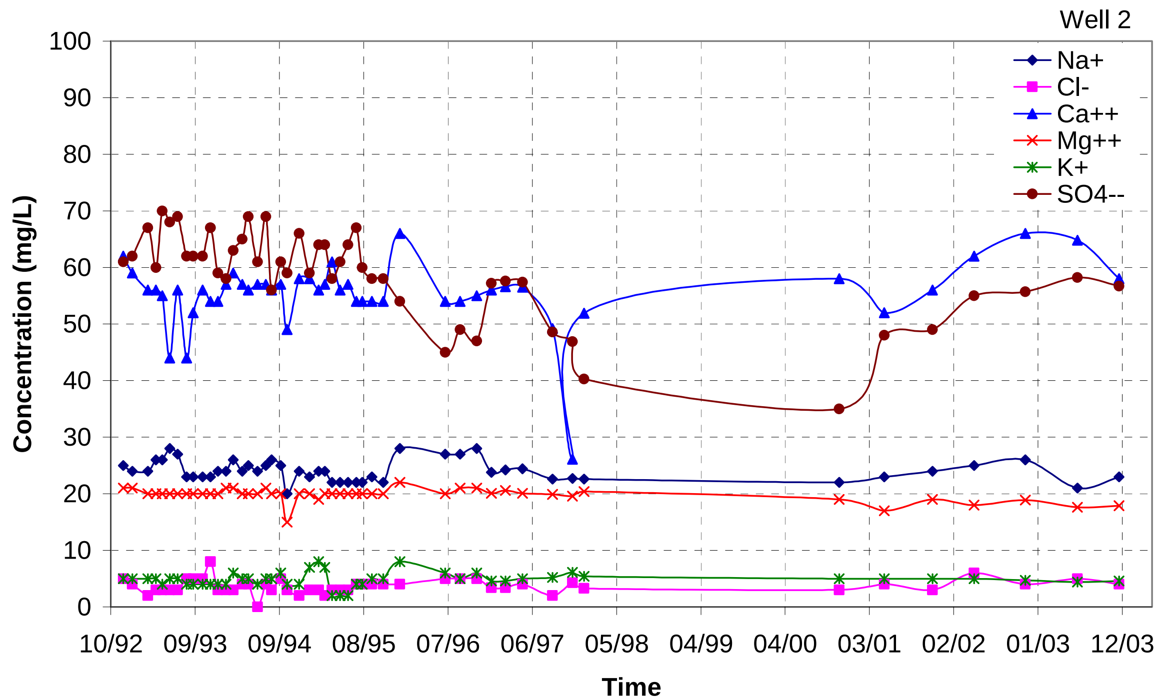

Figure 2 Time series plots of major ion concentrations W2 data

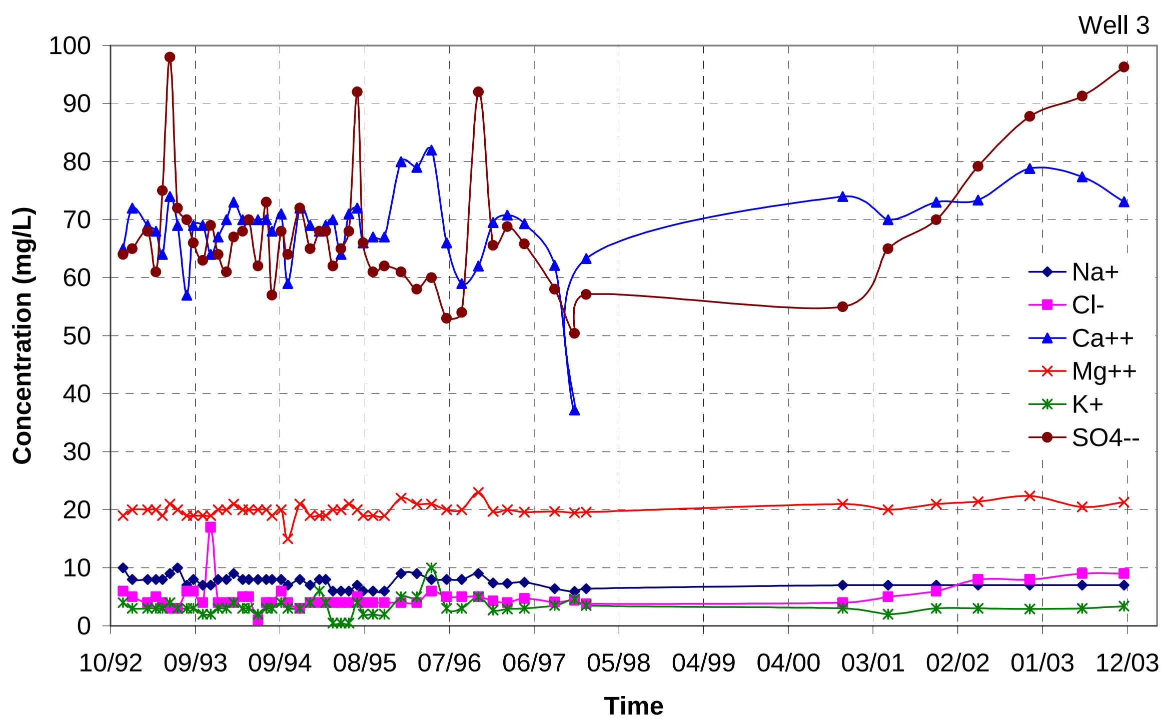

Figure 3 Time series plots of major ion concentrations W3 data

The time series plots were inconclusive in terms of determining any trends, so it was determined that a more detailed statistical analysis was required in order to determine if any trends were developing.

Figure 4 depicts the boxplots of the concentrations of sodium and chloride at all three wells although only Site W3 was used for additional statistical analysis. It can be seen clearly that outliers reside in both sodium and chloride concentration data set, which makes the non-parametric approach of trend analysis more suitable for the data.

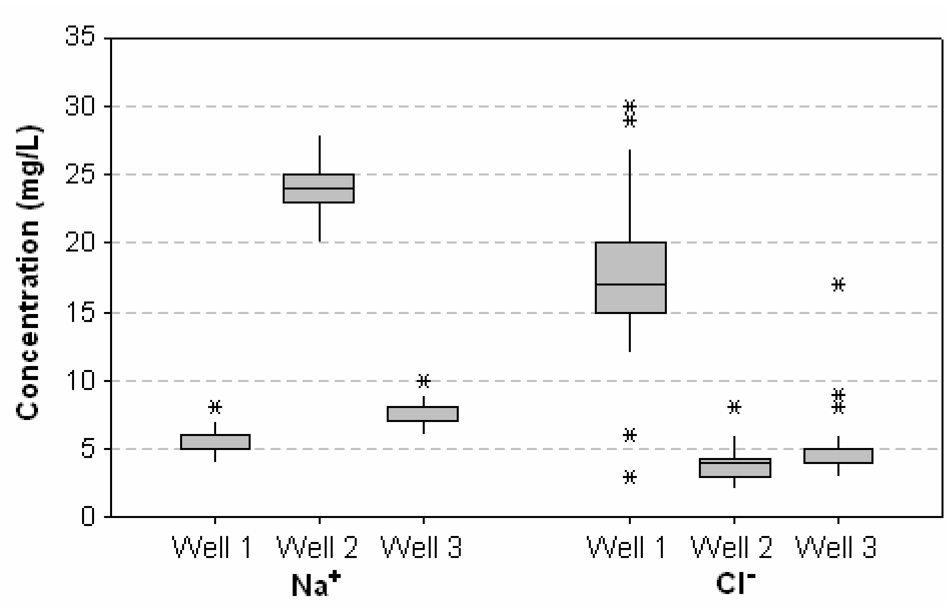

Figure 4 Boxplots of salt concentrations at Well Sites

METHODS OF TREND ANALYSIS

Trend detecting is a meaningful process for the environmental monitoring project to examine if the groundwater quality is affected by the deicing salt. For monotonic trends detection in water quality time series, the non-parametric Mann-Kendall (MK) test has been widely used as a robust tool since Hirsch et al. [15] applied the test for monthly water quality data [16] [17]. The method detects significant trend allowing existence of censored values and free of distribution. Based on MK test, seasonal Kendall trend test was developed for seasonal data set by [15]. However, van Belle and Hughes [18] demonstrated that a test for trend homogeneity is required before the application of seasonal Kendall test. If the trends in different seasons are not in the same direction (heterogeneity), seasonal Kendall test is meaningless, or even produces misleading outcomes.

Mann-Kendall Test

For the sample size n equals or less than 40, the test statistic S is defined as [19]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where x_j *and* x_k are sequential data values and

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \tag{2}$$

For n is greater than 40, the statistic Z this time is determined by

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma_S} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sigma_S} & \text{if } S < 0 \end{cases} \tag{3}$$

where

$$\sigma_S = \sqrt{\frac{1}{18} n(n-1)(2n+5)} \tag{4a}$$

When ties exist in the data set, adjusted σ_S is computed as

$$\sigma_S = \sqrt{\frac{1}{18}[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)]} \tag{4b}$$

where q is the number of tied groups and t_p is the size of the p^{th} tied group.

A positive value of S or Z may indicate an upward trend. On the contrary, negative S or Z may imply a downward trend. The null hypothesis H_0, or there is no trend, is rejected in favour of H_A in a one-tailed test if the conditions listed in Table 2 are met.

Table 2 Conditions to reject H_0 with MK test statistic

Trend	$n \le 40$ (test S)	$n > 40$ (test Z)
Upward	S is positive, significantly different from zero; The probability for the S is less than the selected significance level α.	Z is positive and $Z > Z_{1-\alpha}$
Downward	S is negative, significantly different from zero; The probability for the S is less than the selected significance level α.	Z is negative and $\lvert Z \rvert > Z_{1-\alpha}$

Seasonal Kendall Trend Test

Test statistic *S* from MK test is computed for each identified season and then the sum of all the S_i (i = 1, 2, …, m, the number of seasons in each year), S_k is determined. If n is the total number of years and the product of m and n is greater than 25, normal standardized approximation can be reached by calculating the test statistic Z_{Sk} using equation 5:

$$Z_{Sk} = \begin{cases} \dfrac{S_k - 1}{\sigma_{Sk}} & if \quad S_k > 0 \\ 0 & if \quad S_k = 0 \\ \dfrac{S_k + 1}{\sigma_{Sk}} & if \quad S_k < 0 \end{cases} \tag{5}$$

where $\sigma_{Sk} = (\sum_{i=1}^{k} \sigma_{Si}{}^2)^{0.5}$, σ_{Si} is computed as Equation 4 for each season.

Test for Trend Heterogeneity

Let i = 1, …, m donates seasons. The test statistics for season homogeneity is computed by

$$\chi^2_{\mathrm{hom}o} = \chi^2_{total} - \chi^2_{trend} = \sum_{i=1}^{m} Z_i^2 - m\overline{Z}_i{}^2 \tag{6}$$

where $Z_i = S_i / \sigma_i$ for the i^{th} season and $\overline{Z}_i$ is the mean of Z values for all seasons. At a given significance level *α*, reference a Chi-square distribution table with m-1 degree of freedom (df) to test trend homogeneity. If $\chi^2_{\mathrm{hom}o}$ does not exceed the critical value in the Chi-square table, χ^2_{trend} is referred to the Chi-square distribution with 1 df to test the overall trend. Seasonal Kendall test is not meaningful unless no evidence of significance is observed.

The Monotonic Trend Slope Estimator

After a linear trend is determined, the slope of the trend is more concerned for estimating the magnitude of the trend. Without the influence of seasonality, Theil-Sen slope estimator, a non-parametric approach, can be used [19] [20]. Suppose a monotonic trend has been detected for a chemical concentration over *n* time periods. Let $i = 1, \ldots, n\text{-}1$ and $j = i\text{+}1, \ldots, n$. If X stands for the concentration values and t stands for the time periods, then all the possible slopes between two measures can be expressed as

$$Slope = \frac{X_j - X_i}{t_j - t_i} \tag{7}$$

The Theil-Sen estimator is the median of all the slopes calculated using Equation 7.

The seasonal trend slope estimator can be derived from the non-seasonal estimator. First, Equation 7 is used to determine all slopes within each season. Then all the slopes from all seasons are gathered to determine the median slope that is the final estimator of the seasonal case.

TREND ANALYSIS FOR SODIUM AND CHLORIDE DATA

Groundwater data of Site W3 (located farthest to the highway center line among the three monitoring wells) is selected for trend analysis in this paper. Based on the local historical climate data summarized in Table 1, four seasons can be identified for the data analysis. The spring sampling season consists of April and May; the summer season is from June through August; the fall season is from September to November and the winter season includes December, January, February and March.

Figure 5 shows the time series plots of the data accompanied by locally weighted scatterplot smoothing (LOWESS) with the smoothness factors f equals 0.75. LOWESS is an effective tool aiding to obtain the vision of trends [20]. It is noted that the selected smoothness factor of 0.75 is large enough not to be affected by the maximum chloride value. The visual tool in Figure 5 implies that a downward trend happened to sodium and an upward trend for the chloride data.

The outcomes of trend test are summarized in Table 3. The significance level of 0.05 is selected for all the trend tests. The outcomes of trend heterogeneity test show that at α= 0.05 there is not enough evidence to reject H_0 that states no significant trend direction difference among all the seasons. That is the condition of performing seasonal

Kendall test is satisfied. Both seasonal Kendall test and Chi-square trend test show that the concentration of Cl^- has a significant monotonic trend (p value < 0.05). The slope of this change is estimated to be 0.2 mg/L per year. Sodium concentration data does not have a significant trend at the significance level of 0.05, but showing significant downward trend at α= 0.10.

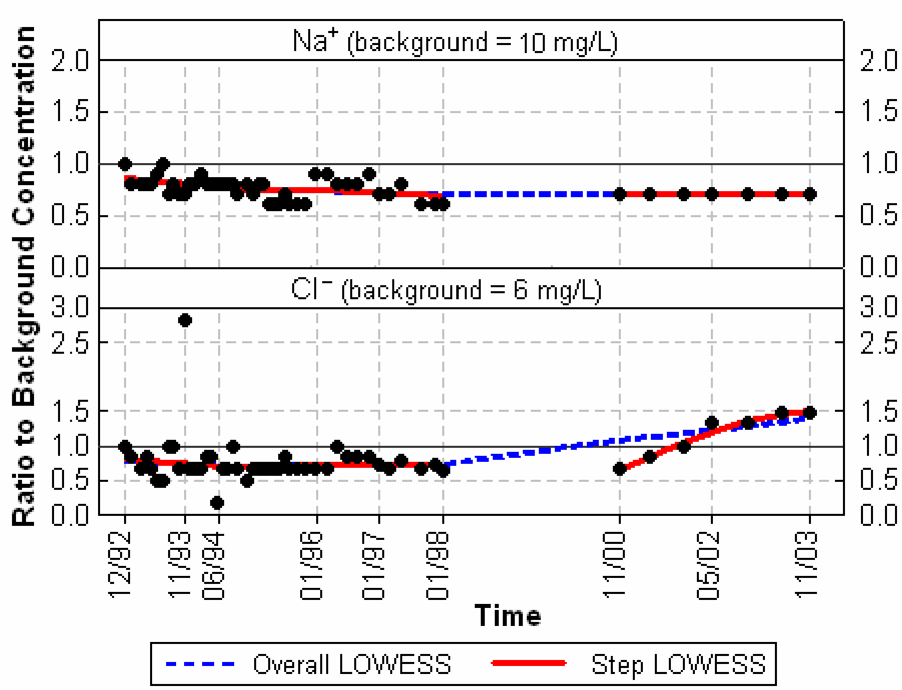

Figure 5 Time series plots of salt concentrations with LOWESS at Site W3

Table 3 Outcomes of trend analysis at Site W3

Salt ion	Trend heterogeneity test		Seasonal Kendall test	
	significance	trends	significance	Slope (unit/yr)
Na^+	Not significant	0.050<p<0.100	0.10	-0.1
Cl^-	0.050<p<0.100	0.025<p<0.050	0.05	0.2

RESULT DISCUSSION

The background salt concentrations marked in 1992 at Site W3 were 10 mg/L and 6 mg/L for sodium and chloride, respectively, which corresponding to an equivalent ratio of Na^+/Cl^- equaling 2.5. As shown in Figure 3, the amount of Na^+ keeps greater than Cl^- after the background sampling for most of the time. Such an outcome indicates that

NaCl is not the only source of Na^+ and Cl^- at the site. While KCl might be one of the sources of chloride ion, sodium ion might come from other naturally occuring salts, such as Na_2CO_3 and Na_2SO_4 [21].

Since Cl^- is much freer than Na^+ in the environment of subsurface, an upward trend should be spotted first in the chloride data. The fact that no upward trend is found in sodium data and the steep slope formed by the most recent available three year's chloride data probably indicates that salt applied in early years might have reached this groundwater monitoring site. Aesthetic threshold for chloride in drinking water is introduced as 250 mg/L by Health Canada [22]. Compared to the threshold, the Cl^- concentration at Site W3 is still quite low.

Using statistical method, chloride concentration has been found an overall increasing trend of 0.2 mg/L per year, which cannot pose an environmental concern at all. It is noted that, however, the magnitude of trend should be a dynamic value with the changing of time. When more attention is given to the most recent data available in Figure 5, the prominent increase of the slope starting from 2000 cannot be ignored. The changing rate of chloride concentration in the latest three years is approximately 1.8 mg/L per year, which is much greater than the overall rate of 0.2 mg/L per year. Considering the fact that salt is loaded on the highway section each year, it could be projected that the increasing rate of chloride concentration could be increased further with more future monitoring data.

CONCLUSIONS

As people have been concerned with the detrimental impacts of the road salt, more effective measures should be put into the environmental monitoring program. Due to the properties of environmental monitoring data, such as the existence of outliers, censored data and missing values, non-parametric approaches have more advantages than parametric methods for trend analysis. This study conducted trend analysis for long-term groundwater quality data by applying MK test, seasonal Kendall test and trend heterogeneity test. By combining LOWESS, the good visual-aiding tool, one can gain a first impression of trends that are identical to the test results in this study.

Recent monitoring data at Site W3 suggests that salt applied in early years have reached the groundwater site. The overall upward trend of Cl^- has been detected with an increasing rate of 0.2 mg/L per year, which forms no environmental concern for the time being. However, greater increase of chloride concentration at the site could be projected. More monitoring data are needed in the future.

ACKNOWDNGMENT

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