Trend Analyses of Selected Water Quality Constituents at Nine Locations in British Columbia

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Introduction

The BC Ministry of Environment, Lands and Parks has recently reviewed long-term water quality time series to identify any potential trends visually. Included in these time series were the data for various water quality constituents at seven water quality monitoring stations in the province. They were as follows:

· Abbotsford Aquifer Nitrate-N
· Cowichan Lake Total Dissolved Solids
· Fraser River Main Arm Average Lead (3 replicates)
· Fraser River North Arm Average Lead (3 replicates)
· Grand Forks Aquifer Nitrate-N
· Matsqui Piezometer Nitrate-N
· Osoyoos Aquifers Nitrate-N
· Osoyoos Piezometer Nitrate-N
· Quamichan Lake Fecal Coliforms

This report summarizes the statistical analyses of apparent trends of these time series data sets. Background information on each of the site locations can be obtained by contacting the BC Ministry of Environment, Lands and Parks.

Methods

Exploratory Data Analysis (EDA)

Exploratory data analysis procedures are the `initial look' at a data set, providing a researcher with tools to select appropriate statistical tests and modeling techniques. Apart from computing basic summary statistics (means, medians, minimums, maximums, number of observations), EDA procedures are best represented by graphical displays of the data. Time series plots were used in the initial data explorations.

Non-parametric Statistics

Non-parametric tests to detect trends in water quality have been used by many others in the past (Yu and Zou, 1993; Walker, 1991; Gilbert, 1987; Hirsch and Slack, 1984). The relative simplicity and minimal data assumptions of these tests make them a popular choice for analysis of water quality time series. Two different non-parametric tests, the *Kendall Test for Trend* and the *Sen slope estimator* were used to detect and determine magnitudes of any trends in the water quality data.

Kendall Test for Trend

To perform this non-parametric test, Kendall's S statistic is computed from the data (see Millard, 1997, or any good introductory non-parametric statistics text for details). The null hypothesis of no trend is rejected when S is significantly different from zero. Hirsch *et al.*(1982) note that this test is appropriate even in the presence of missing observations, and censored values.

Sen Slope Estimator

This non-parametric statistic calculates the magnitude of any significant trends found. The Sen slope estimator (Sen, 1968) is calculated as follows (Y is the variable of interest; X is the time at which the i^{th} observation was taken) :

$$D_{ij} = \left[\frac{Y_j - Y_i}{X_j - X_i}\right] \text{ for } i < j,\ X_i \neq X_j$$

The slope estimate is the median of all D_{ij} values. Hirsch *et al*. (1982) point out that this estimate is robust against extreme outliers. Confidence bounds for this slope estimator are calculated as a simple percentile of the total number of calculated slopes (Gilbert, 1987).

Parametric Modeling

Non-parametric statistics test for monotonic changes in a data series with minimal assumptions of normality and, in some instances, serial dependence. However, these methods are not very useful in constructing the forms of any detectable trends. Regression analysis has been used for this purpose and has been applied to water quality data in the past (El-Shaarawi *et al*., 1983, Esterby *et al*., 1989, Helsel & Hirsch, 1995).

Using these methods, many factors can be taken into account for explaining the variation in a water quality constituent over time, factors which include precipitation. By accounting for precipitation, it's influence on the response constituent can be removed, revealing underlying trends.

The regression model used in this report is as follows:

$$(1)\quad y_t = \hat{\beta}_0 + \hat{\beta}_1 x_t + \hat{\beta}_2 i + \epsilon_t$$

where :

y_t = Observed value of water quality variable in year t;

x_t = precipitation in year t;

ε_t = Error term assumed to follow a normal distribution with mean 0 and variance σ^2.

This regression technique is an iterative process of model parameter estimation and analyses of model residual and quantile plots.

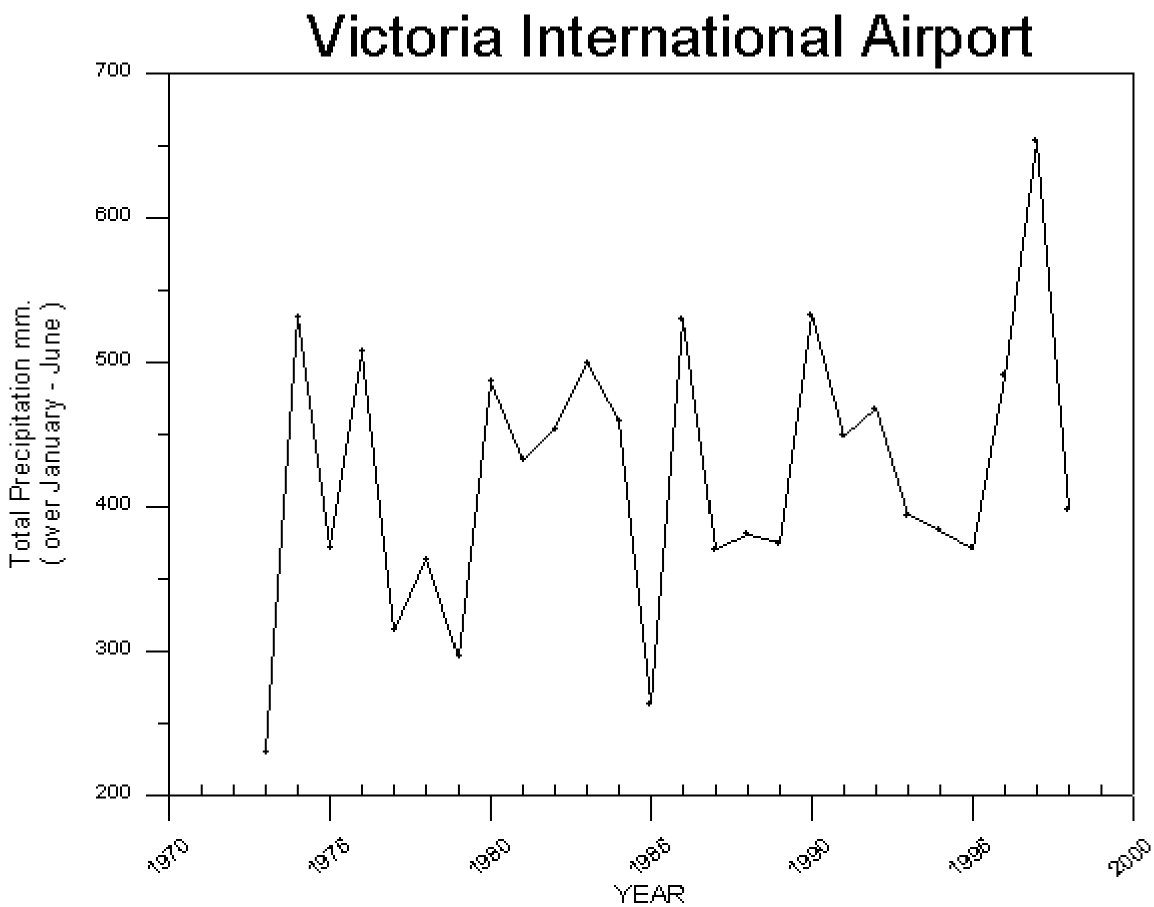
The form in equation (1) above considers only an increasing or decreasing trend with slope β_2. The presence or absence of positive quadratic (U - shaped) or negative quadratic (upside down U - shaped) trends may be determined by fitting the data to (1) with the addition of a quadratic term $(\beta_3 t^2)$. ANOVA tables may then be used to determine if the quadratic models significantly improve the linear models. Significance of the model coefficients are tested at the 5 percent level.

Results and Discussion

Consultation with the B.C. Ministry of Environment, Lands and Parks concluded that for regression modeling of fecal coliform data from the Quamichan Lake monitoring site, total precipitation data collected from Victoria International Airport (figure 1) should be used as an explanatory variable (Pommen, 1998).

The statistical results were tabulated and can be found in the appendix of this report.

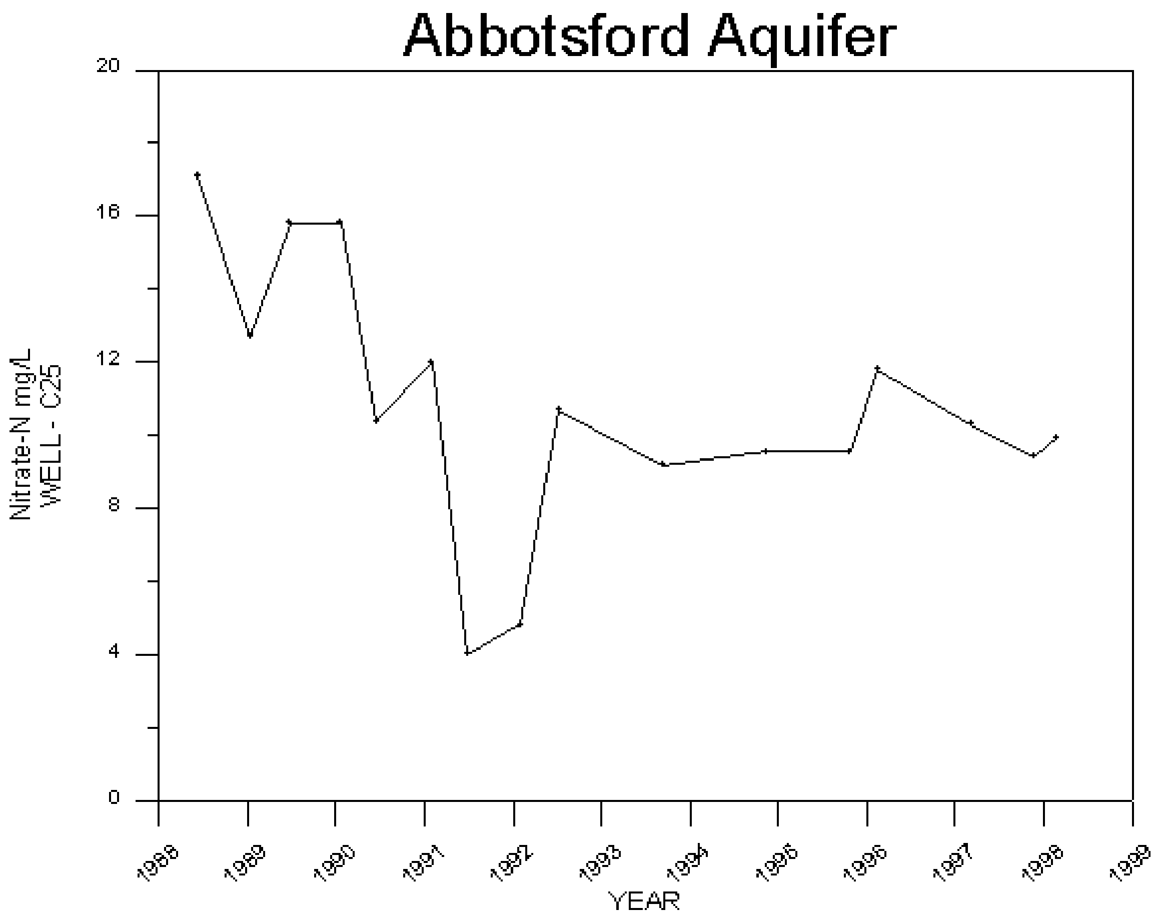
Figure 1 Time series plot of total precipitation at Victoria International Airport recorded from January to June, 1973 - 1998.



Abbotsford Aquifer

Measurements of Nitrate Nitrogen were made at two wells, well - C25 and well - C75, over a period of 11 years, spanning 1988 to 1998 (Figures 2 & 3).

Figure 2 Time series graph of Nitrate-N in Well - C25 at the Abbotsford Aquifer, 1988 - 1998.

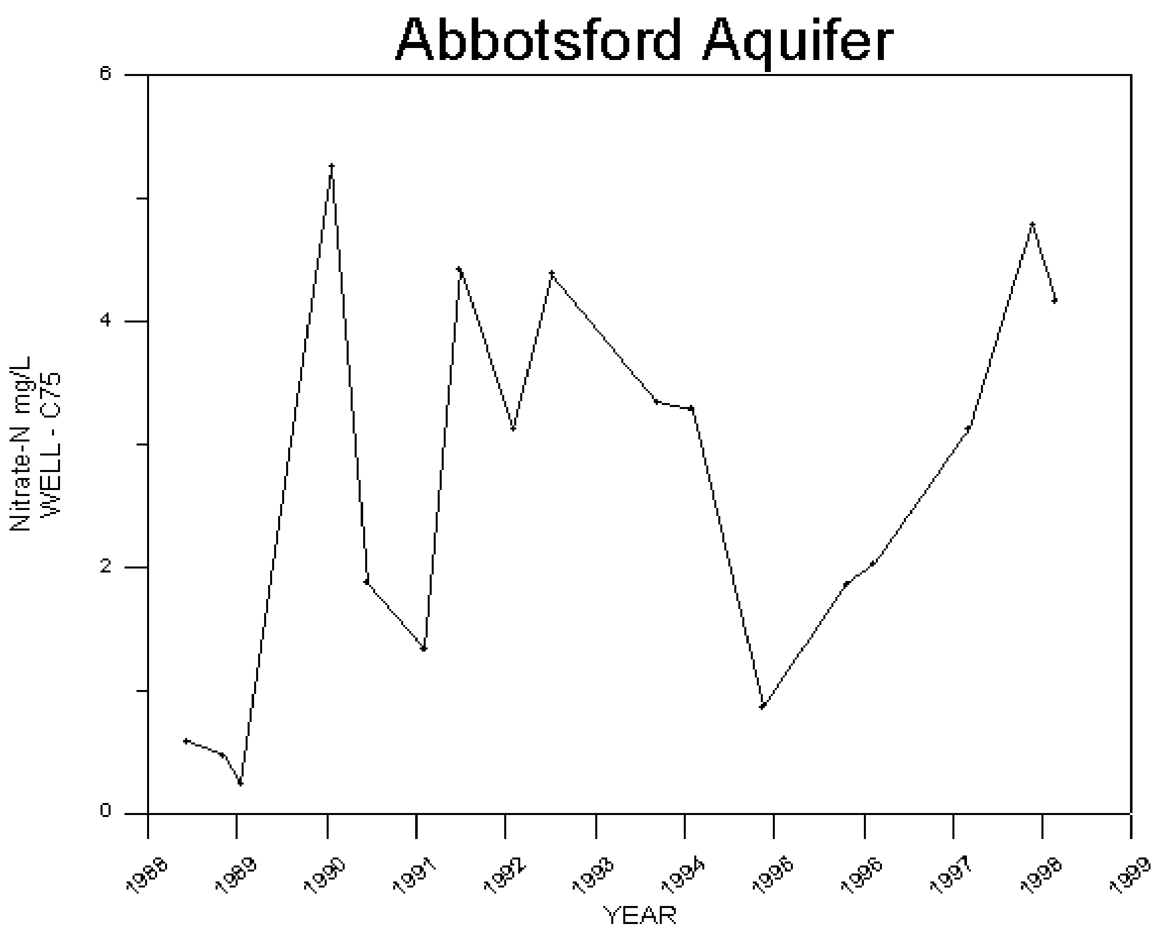


Early years of both data sets consisted of single samples taken in the winter and summer months while later years contained only single winter samples. Subsequently, it was determined that only non-parametric trend techniques were to be employed on the available data.

Statistical analysis of Nitrate-N data from Well - C25 indicated evidence of a linearly decreasing trend (see Appendix I for details).

Statistical analysis of Nitrate-N data from Well - C75 indicated no evidence of any linear trends (see Appendix I for details).

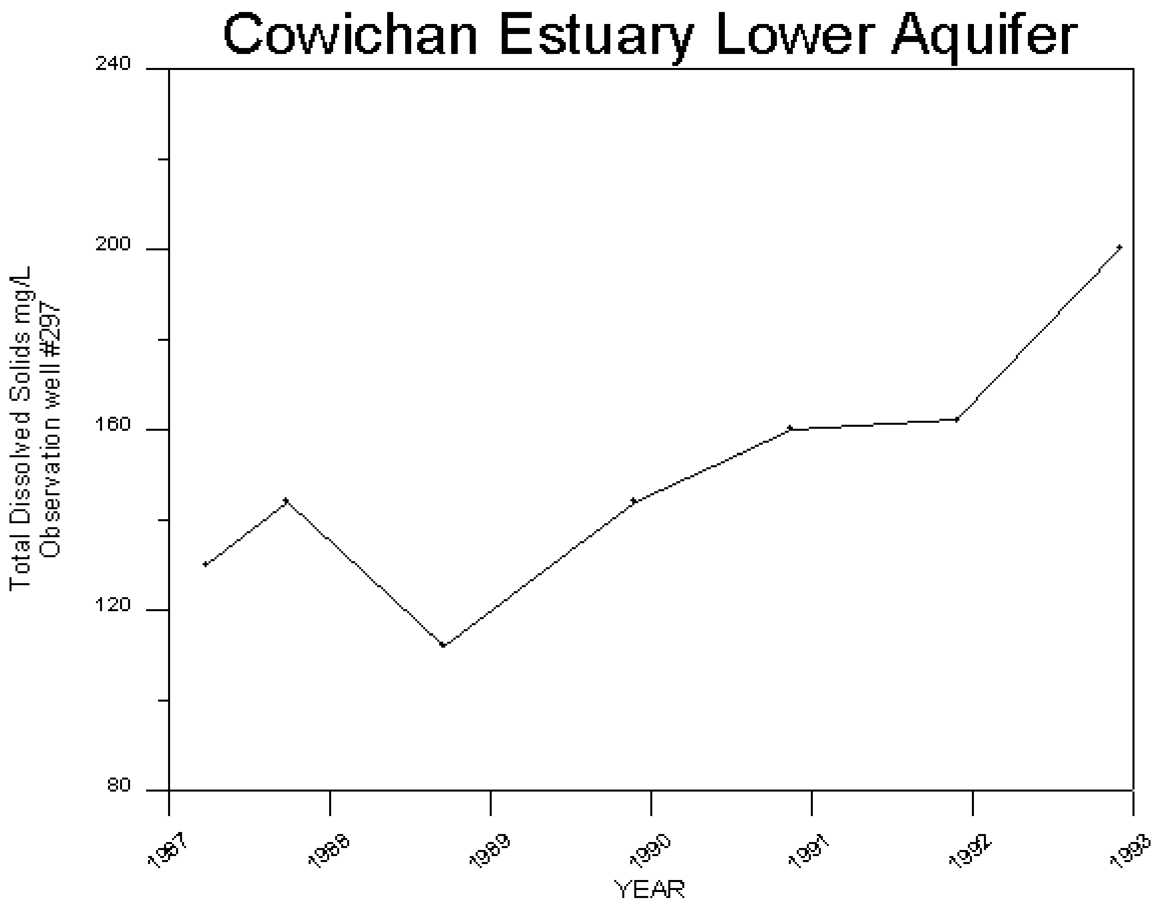
Figure 3 Time series graph of Nitrate-N in Well - C75 at the Abbotsford Aquifer, 1988 - 1998.



Cowichan Estuary Lower Aquifer

Measurements of total dissolved solids were made at two wells, observation well #297 and observation well "J", over a period of 6 and 7 years, respectively (Figures 4 & 5).

Figure 4 Time series graph of total dissolved solids in Observation Well #297 at the Cowichan Estuary Lower Aquifer, 1987 - 1992.

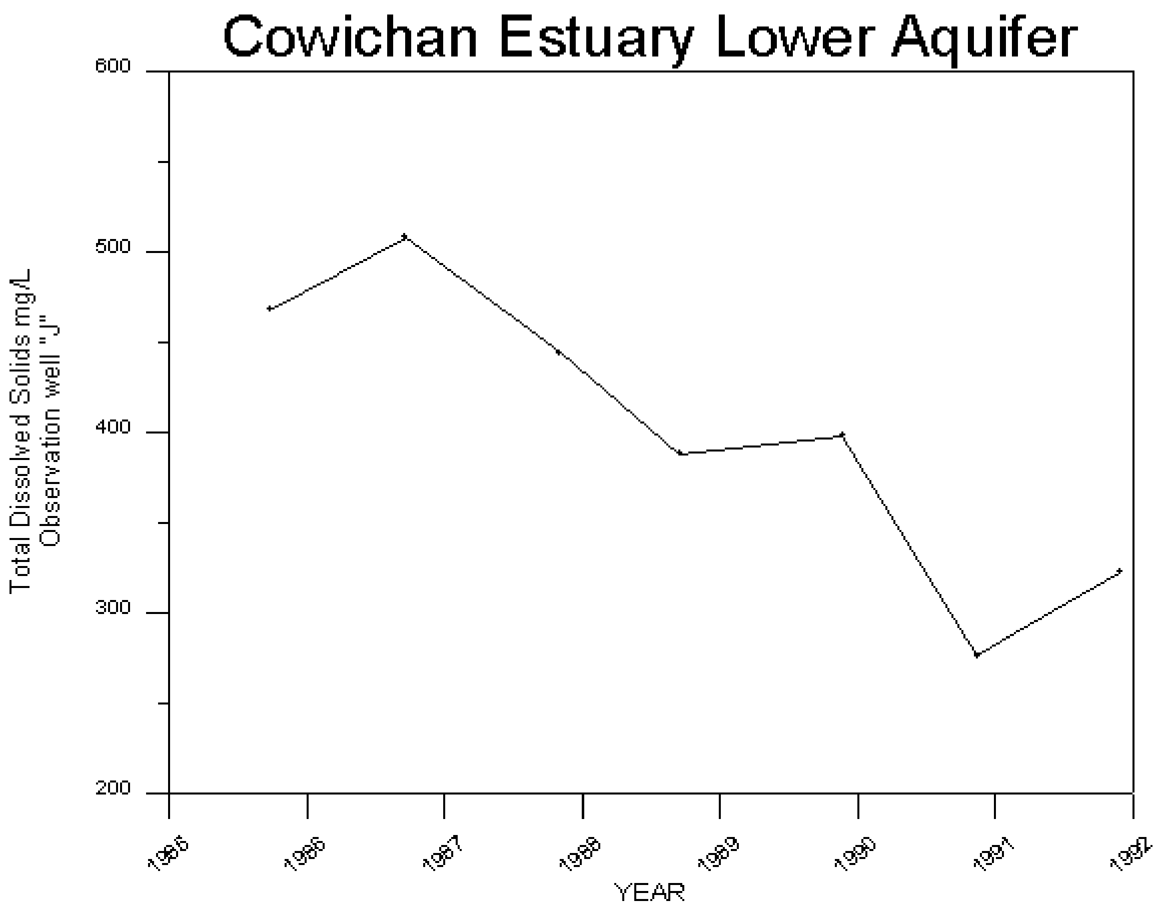


Both data sets consisted of single samples taken during the `winter' months ranging from samples taken in September to February. The relatively small amount of available data prohibited the use of the regression techniques described in the methods section of this report. Subsequently, only non-parametric trend techniques were employed on the available data.

Statistical analysis of total dissolved solids from Observation Well #297 indicated strong evidence of a linearly increasing trend (see Appendix I for details).

Statistical analysis of total dissolved solids from Observation Well "J" indicated strong evidence of a linearly decreasing trend (see Appendix I for details).

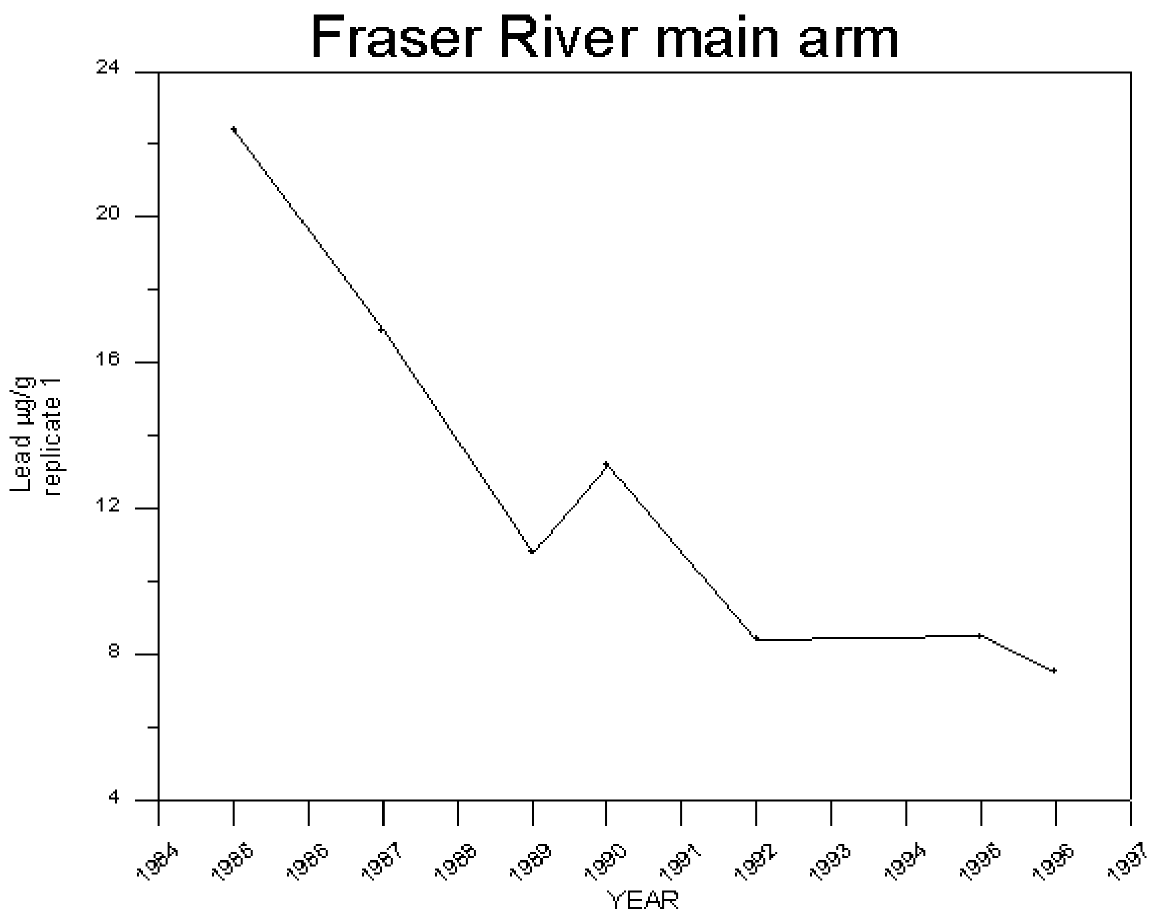
Figure 5 Time series graph of total dissolved solids in Observation Well "J" at the Cowichan Estuary Lower Aquifer, 1985 - 1991.



Fraser River Main Arm

Three replicate sediment samples were collected from the main arm of the Fraser River over a period of 12 years, spanning 1985 to 1996 and analysed for lead (Figures 6 - 9).

Figure 6 Time series graph of lead in sediments, replicate 1, in the main arm of the Fraser River, 1985 - 1996.



The data sets consisted of single observations representative of each year with several missing years of observations. Thus, the relatively small amount of available data (and missing observations) prohibited the use of the regression techniques described in the methods section of this report. Subsequently, only non-parametric trend techniques were employed on the available data.

Statistical analysis of all three replicates of lead in sediments in the main arm of the Fraser River indicated strong evidence of a linearly decreasing trends (see Appendix I for details). Analysis of the average of these three replicates also indicated strong evidence of a linearly decreasing trend (see Appendix I for details).

Figure 7 Time series graph of lead in sediments, replicate 2, in the main arm of the Fraser River, 1985 - 1996.

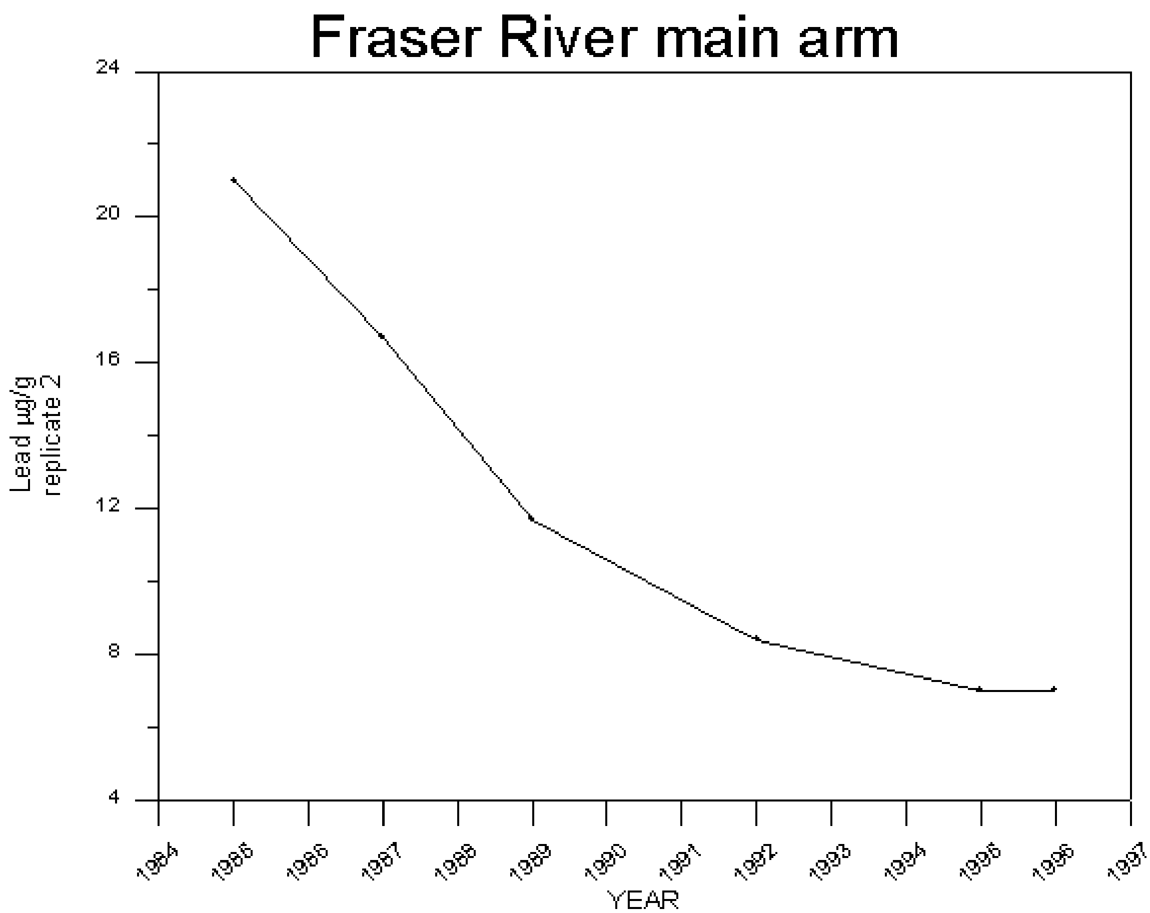


Figure 8 Time series graph of lead in sediments, replicate 3, in the main arm of the Fraser River, 1985 - 1996.

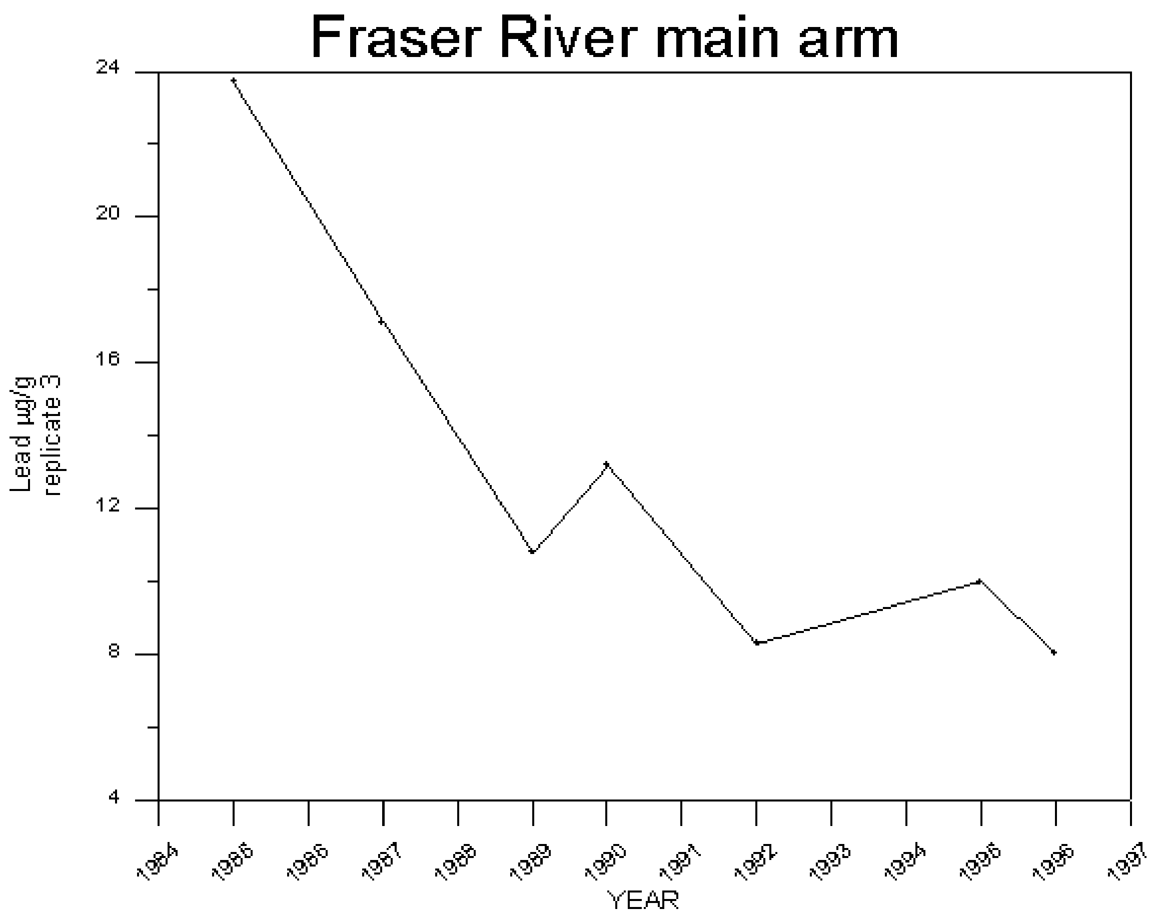
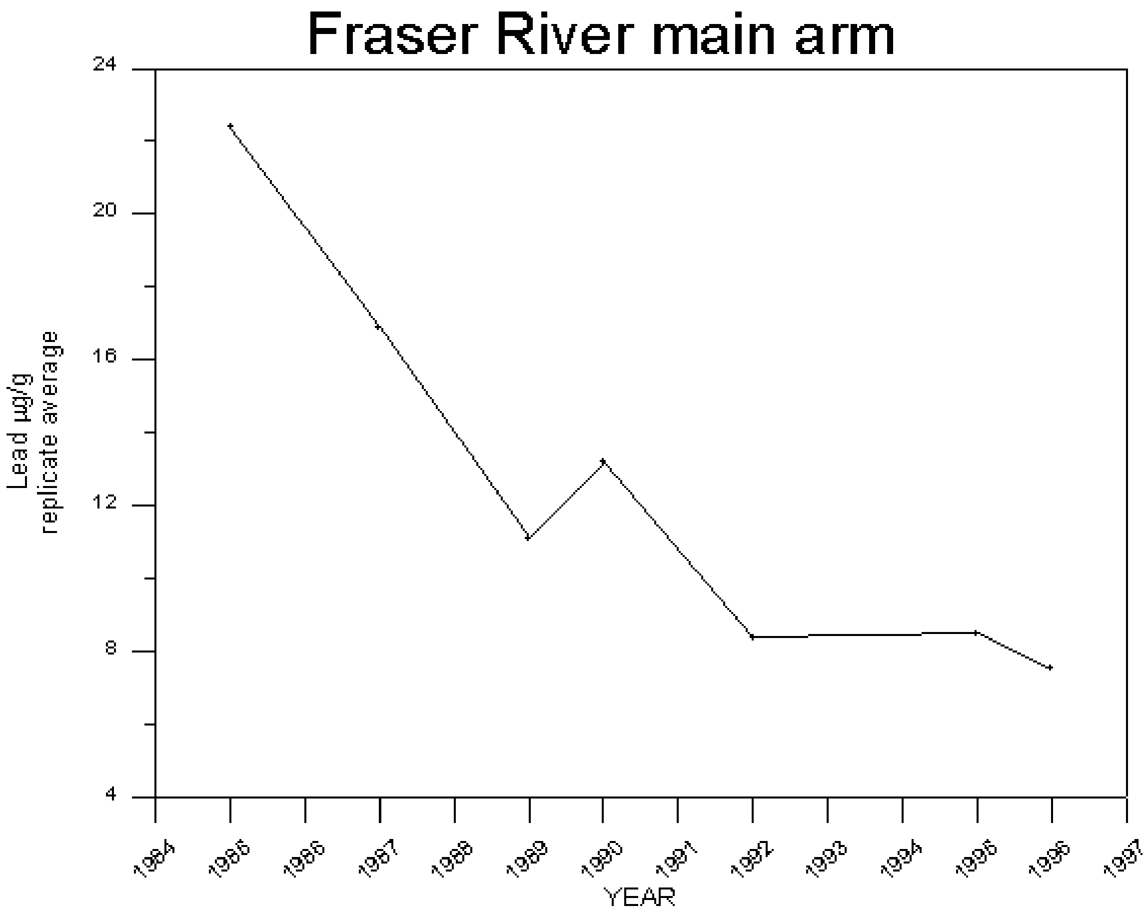


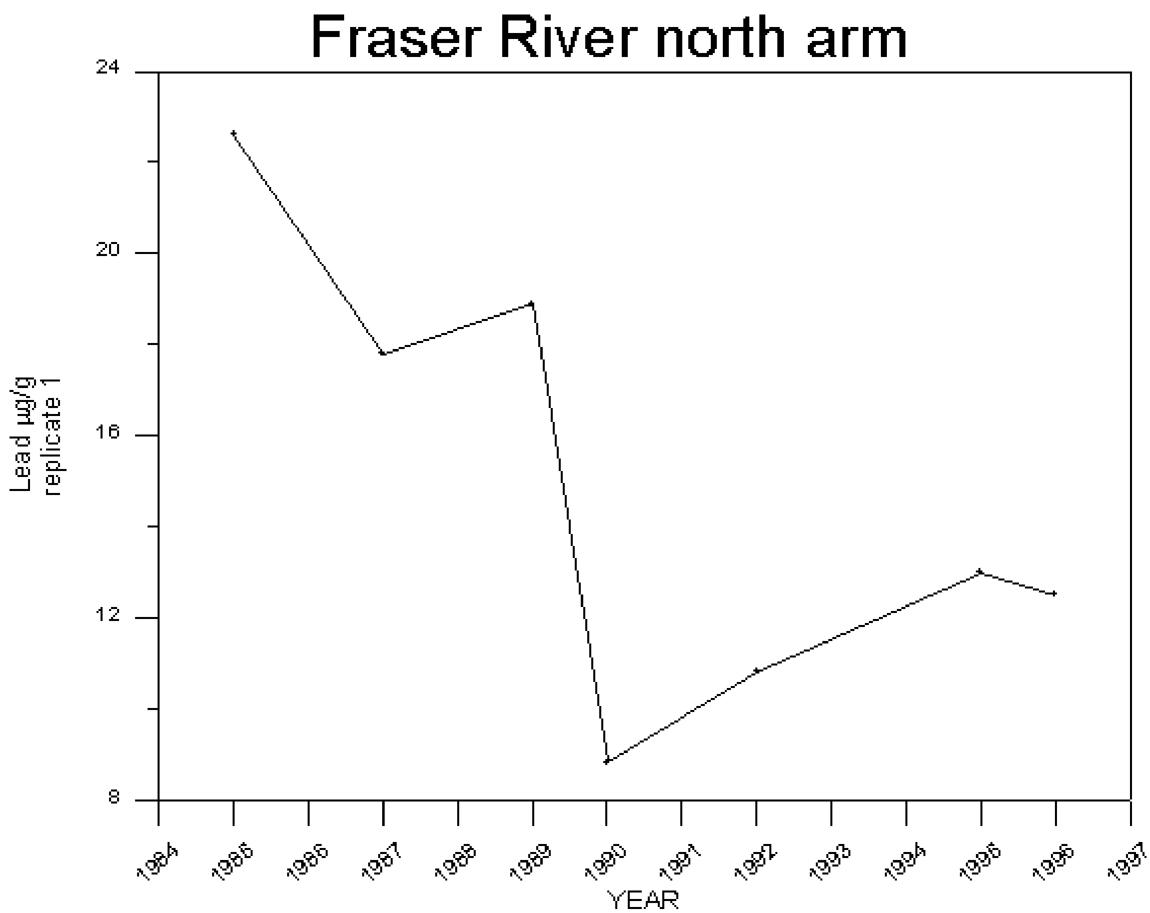
Figure 9 Time series graph of lead in sediments, average of three replicates, in the main arm of the Fraser River, 1985 - 1996.



Fraser River North Arm

Three replicate sediment samples were collected from the north arm of the Fraser River over a period of 12 years, spanning 1985 to 1996 and analysed for lead (Figures 10 - 13).

Figure 10 Time series graph of lead in sediments, replicate 1, in the north arm of the Fraser River, 1985 - 1996.



The data sets consisted of single observations representative of each year with several missing years of observations. Thus, the relatively small amount of available data (and missing observations) prohibited the use of the regression techniques described in the methods section of this report. Subsequently, only non-parametric trend techniques were employed on the available data.

Statistical analysis of replicates 1 and 2 of lead in sediments in the north arm of the Fraser River indicated no evidence of any linear trends (see Appendix I for details). However, the analysis did indicate some weak evidence of a linearly decreasing trend in the third replicate data (significant at the 9.1% level; see Appendix I for details). Analysis of the average of these three replicates indicated no evidence of any linear trends (see Appendix I for details).

Figure 11 Time series graph of lead in sediments, replicate 2, in the north arm of the Fraser River, 1985 - 1996.

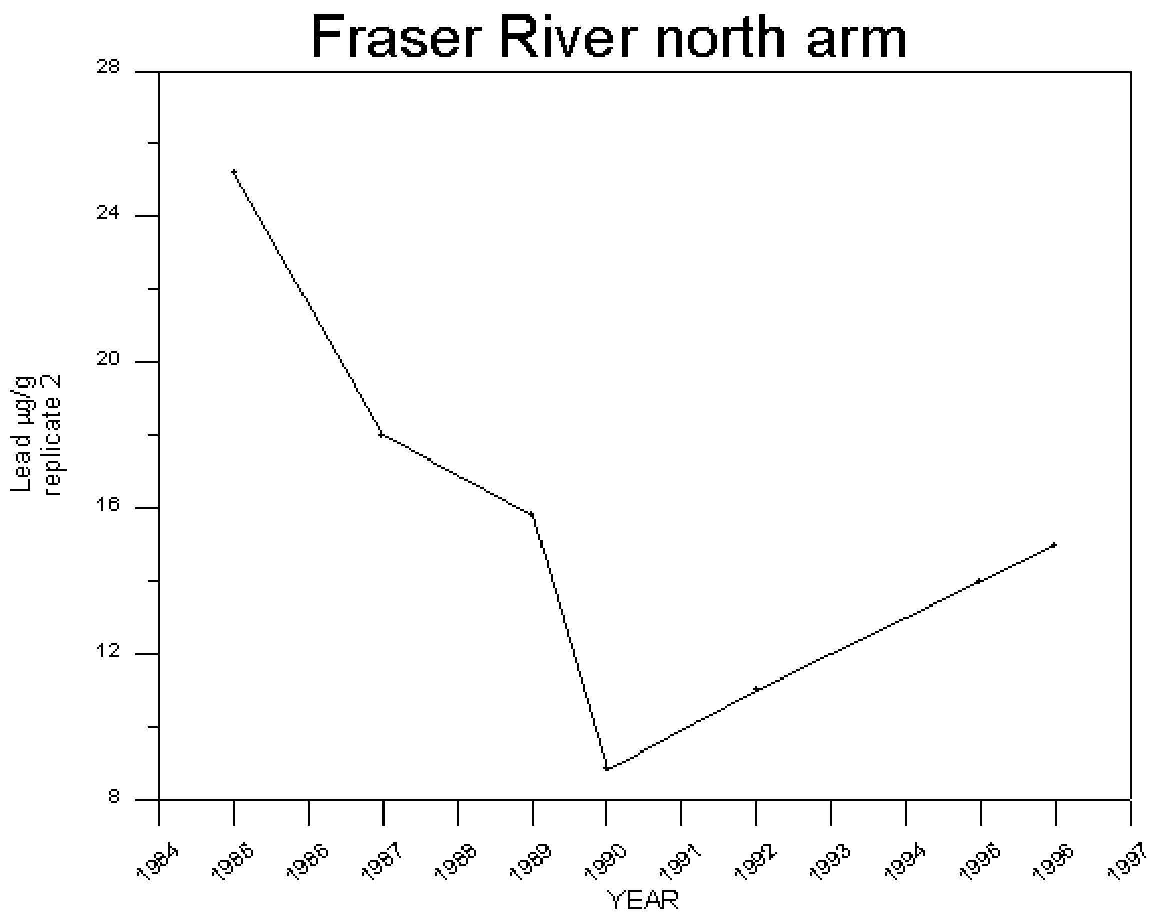


Figure 12 Time series graph of lead in sediments, replicate 3, in the north arm of the Fraser River, 1985 - 1996.

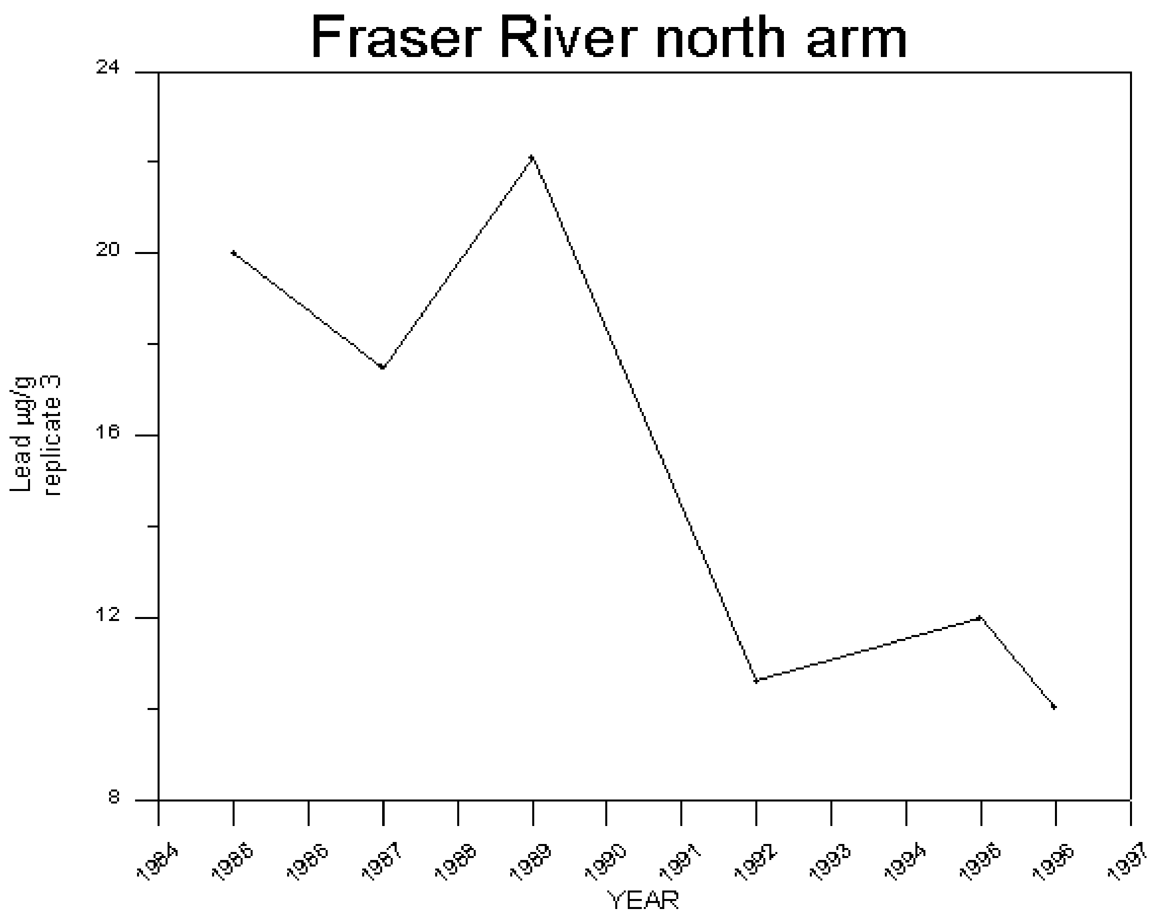
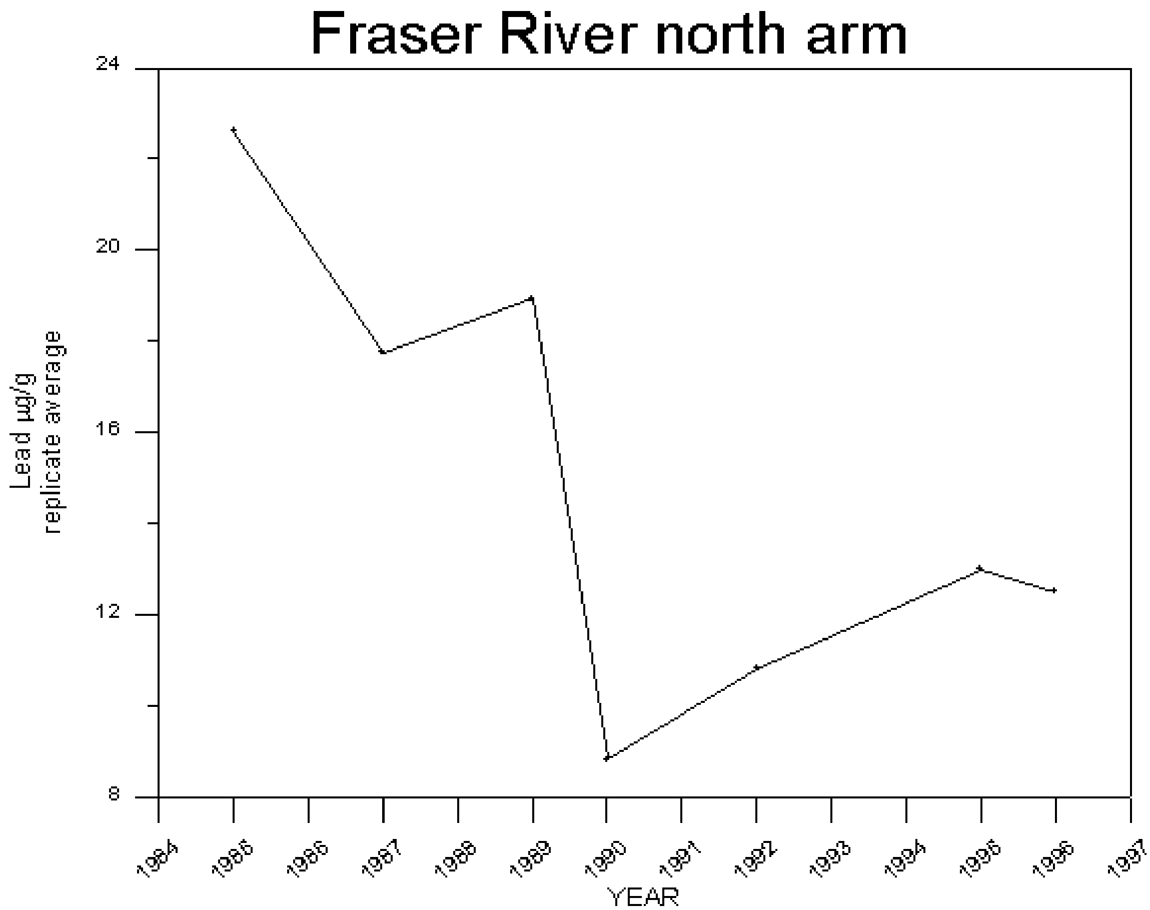


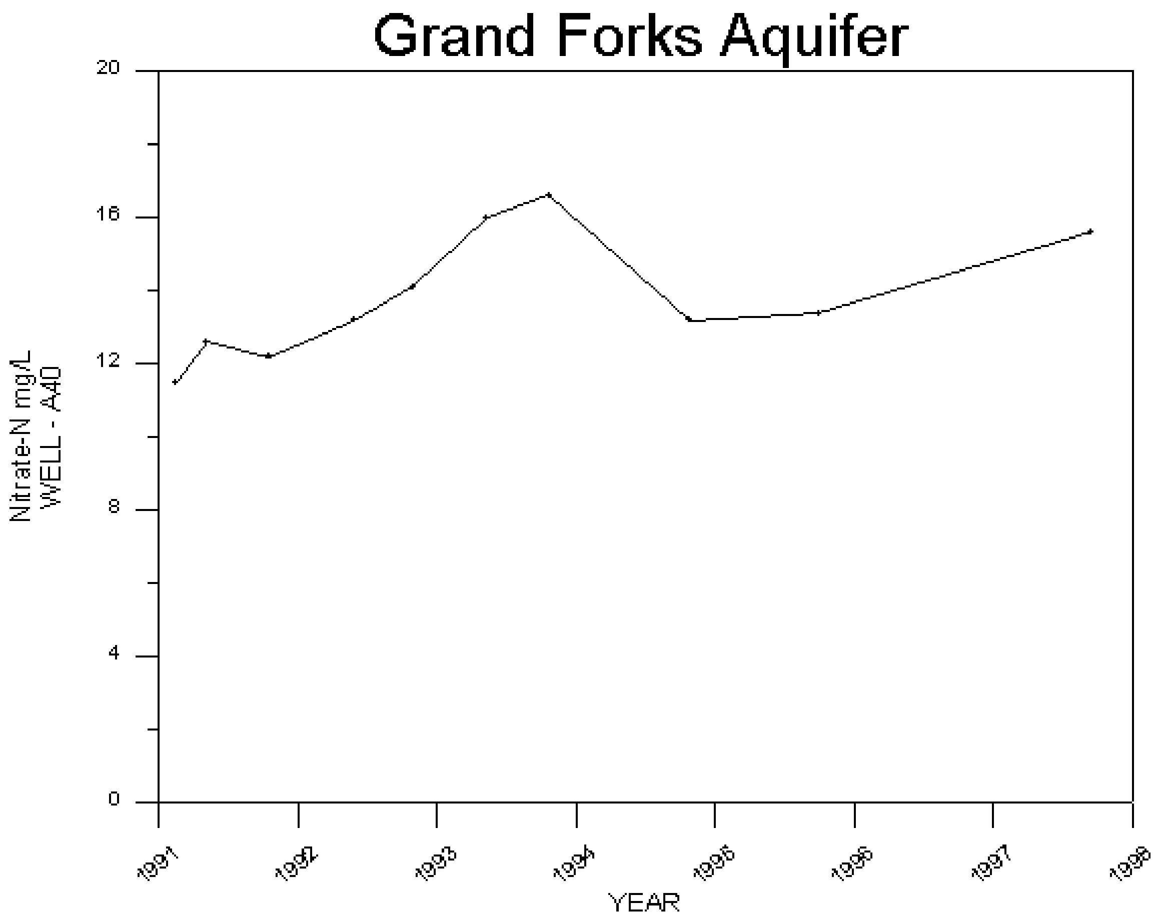
Figure 13 Time series graph of lead in sediments, average of three replicates, in the north arm of the Fraser River, 1985 - 1996.



Grand Forks Aquifer

Measurements of Nitrate Nitrogen were collected at five wells, well - A40 and well - A100, well - C100 and well-C40, and Floesser Well over a period of up to 10 years, spanning 1989 to 1998 (Figures 14 - 18).

Figure 14 Time series graph of Nitrate - N in Well - A40 at the Grand Forks Aquifer, 1991 - 1997.



Early years of all data sets consisted of single samples taken in the winter and summer months while later years contained only single winter samples (no 1996 samples were available for these data sets). Subsequently, it was determined that only non-parametric trend techniques were to be employed on the available data.

Statistical analysis of Nitrate-N data from Wells - A40, - A100, and - C100 indicated strong evidence of a linearly increasing trends (A40 & A100) and decreasing trend (C100) (see Appendix I for details).

No trends were detected for Nitrate-N in Well - C40 or Floesser Well (see Appendix I for details). At this time, it was undetermined if the low 1991 value in Well - C40 (see figure 15) was real or not. Subsequently, two analyses were performed for this well; one included the point and; one omitted the point. Both analyses indicated no significant trends (see Appendix I for further details).

Figure 15 Time series graph of Nitrate - N in Well - A100 at the Grand Forks Aquifer, 1991 - 1998.

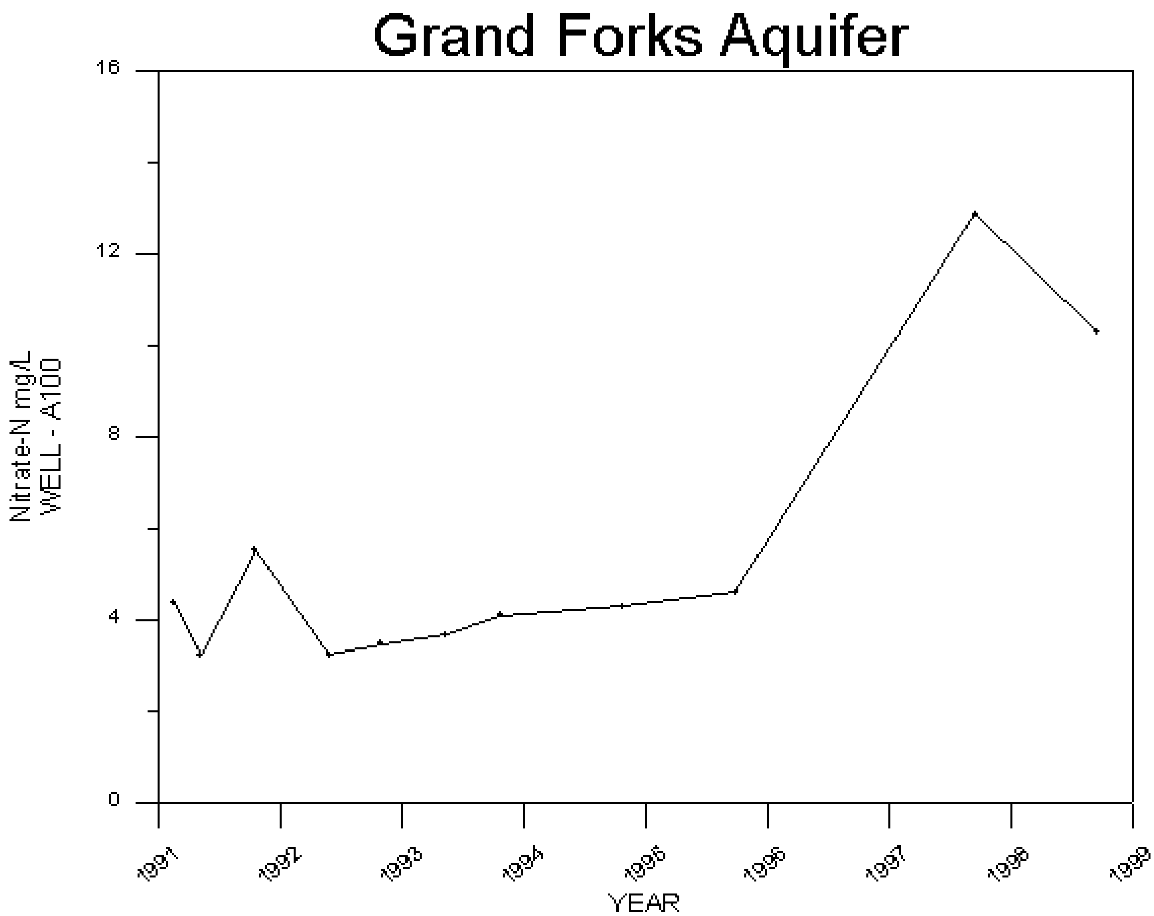


Figure 16 Time series graph of Nitrate - N in Well - C40 at the Grand Forks Aquifer, 1990 - 1998.

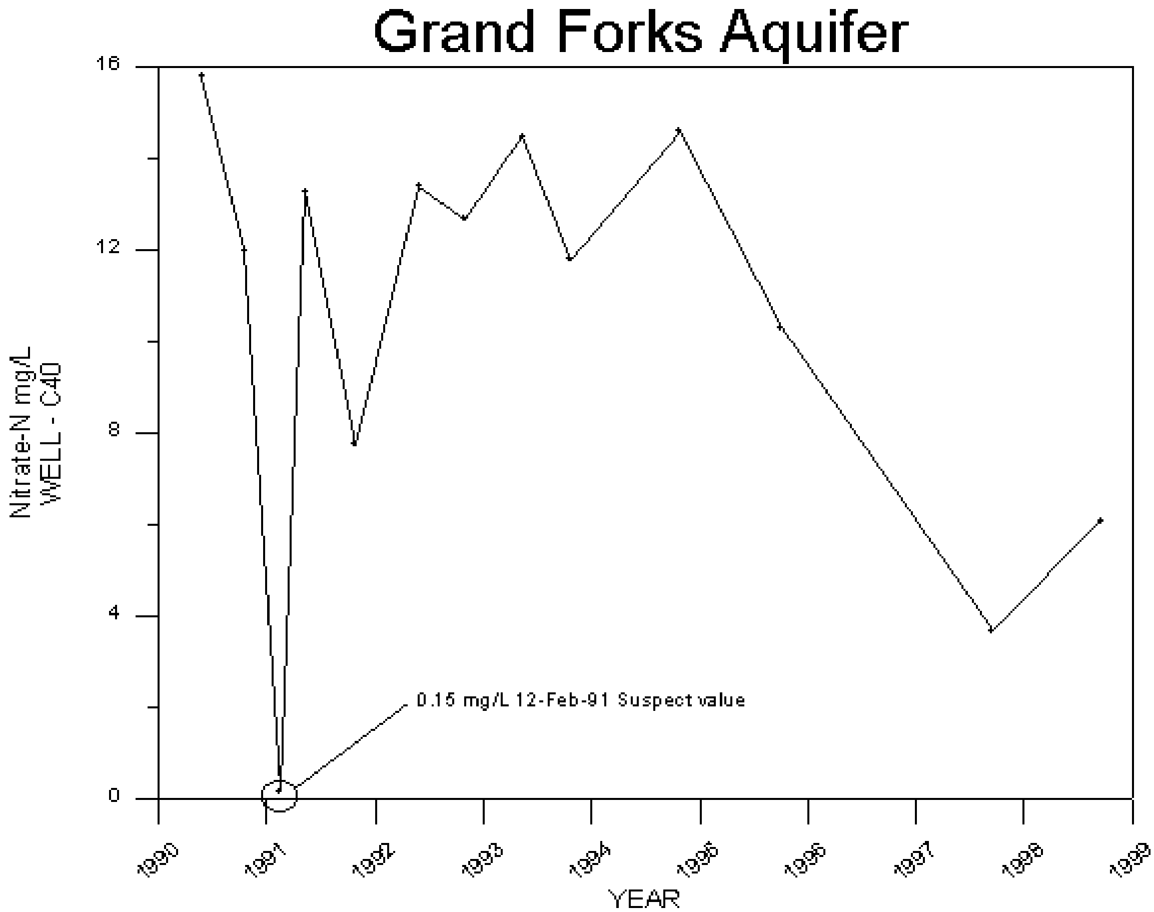


Figure 17 Time series graph of Nitrate - N in Well - C100 at the Grand Forks Aquifer, 1990 - 1997.

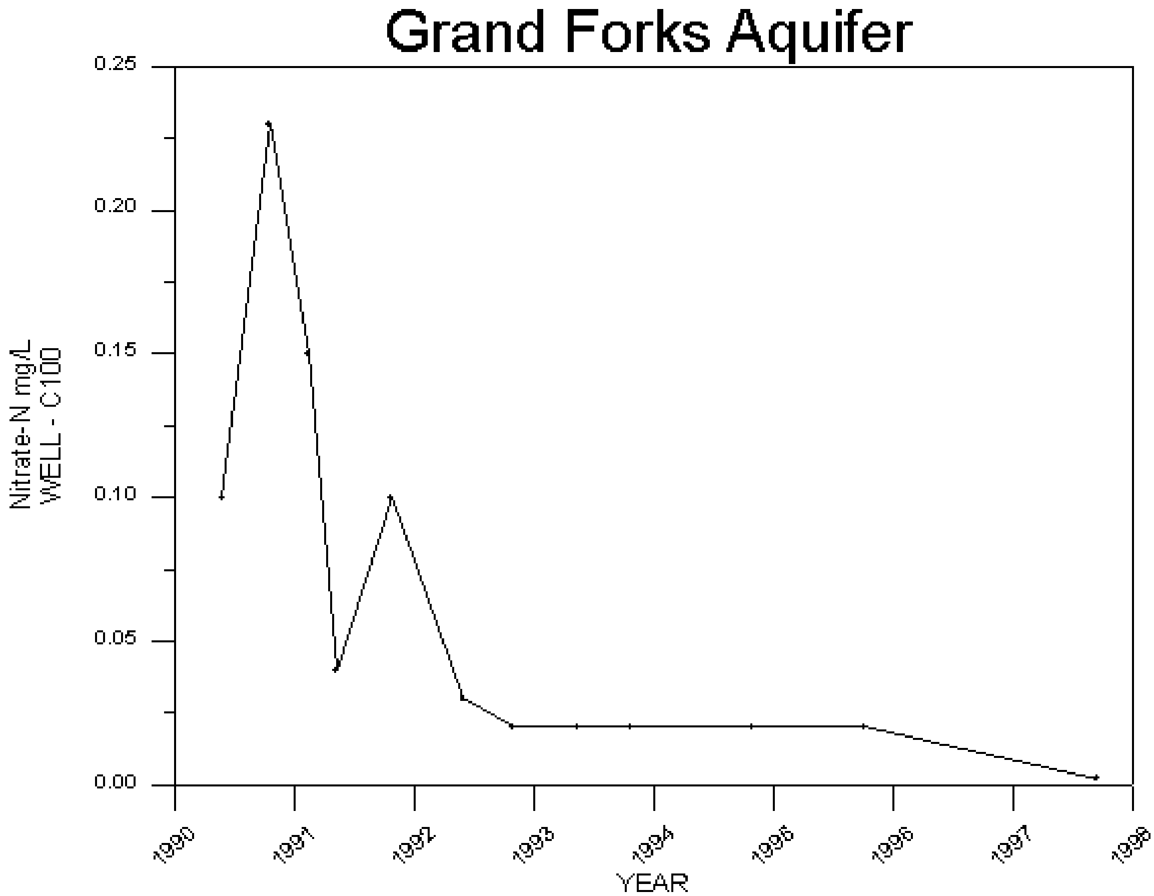
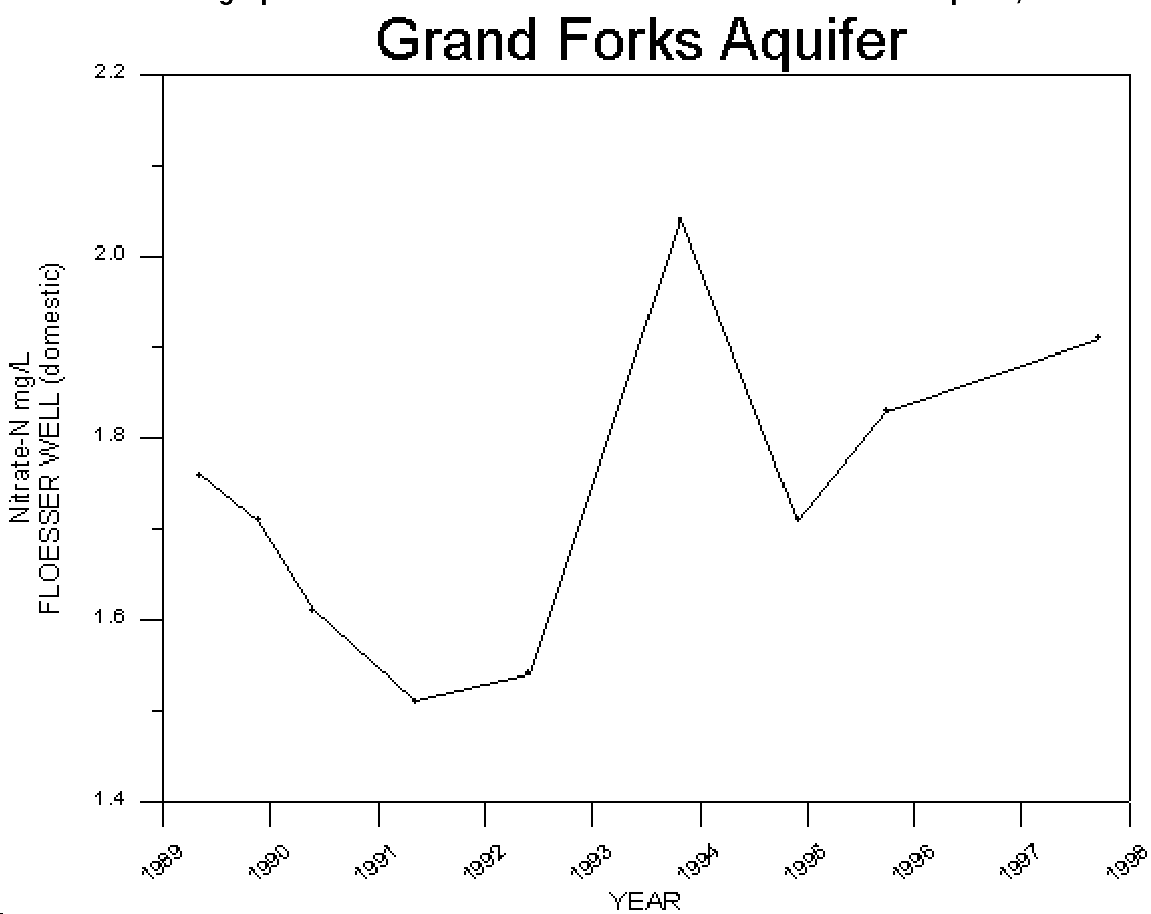


Figure 18 Time series graph of Nitrate - N in Floesser Well at the Grand Forks Aquifer, 1989 -

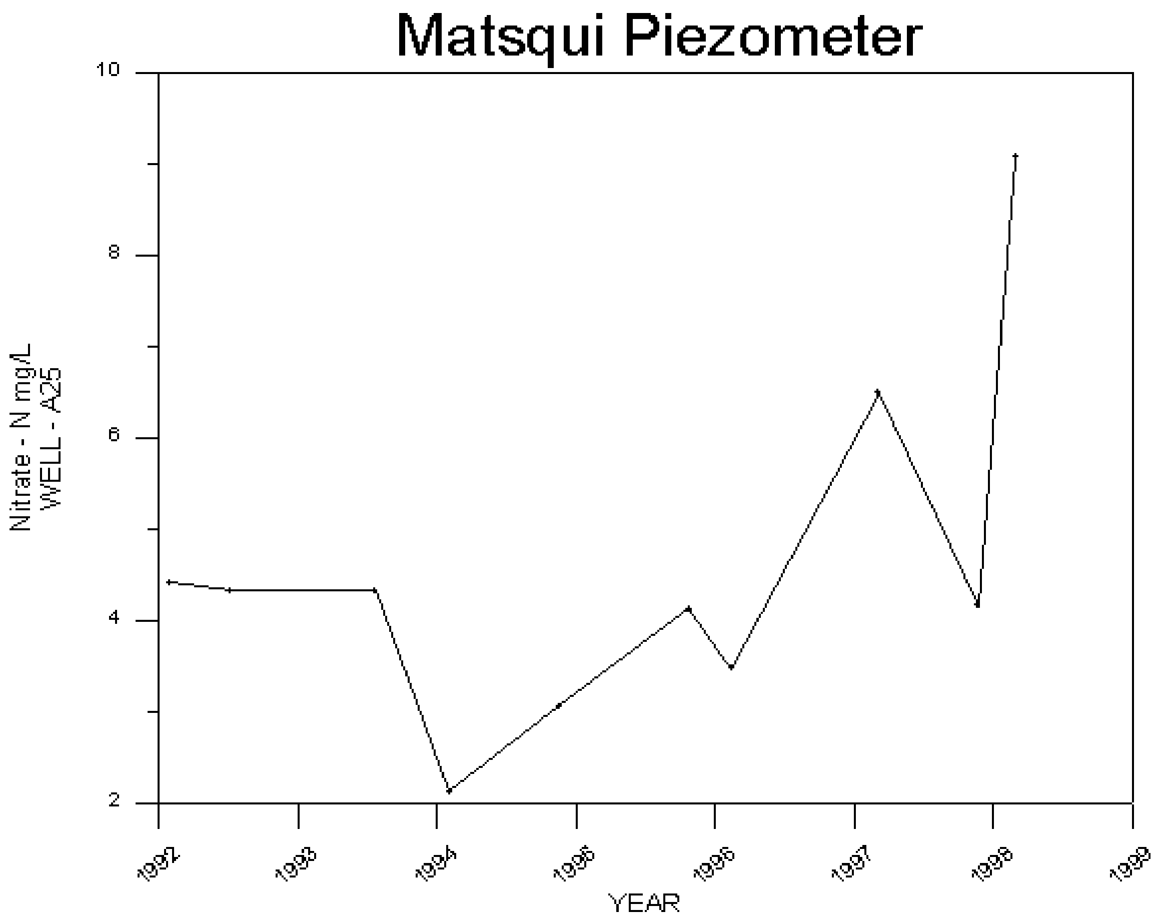


1997.

Matsqui Piezometer

Measurements of Nitrate Nitrogen were collected over a period of 7 years, spanning 1992 to 1998 (Figure 19).

Figure 19 Time series graph of Nitrate - N in Well - A25 at the Matsqui Piezometer, 1992 - 1998.



The relatively small data set and differing sample intervals prevented the use of the regression techniques described in the methods section of this report. Thus, it was determined that only non-parametric trend techniques were to be employed on the available data.

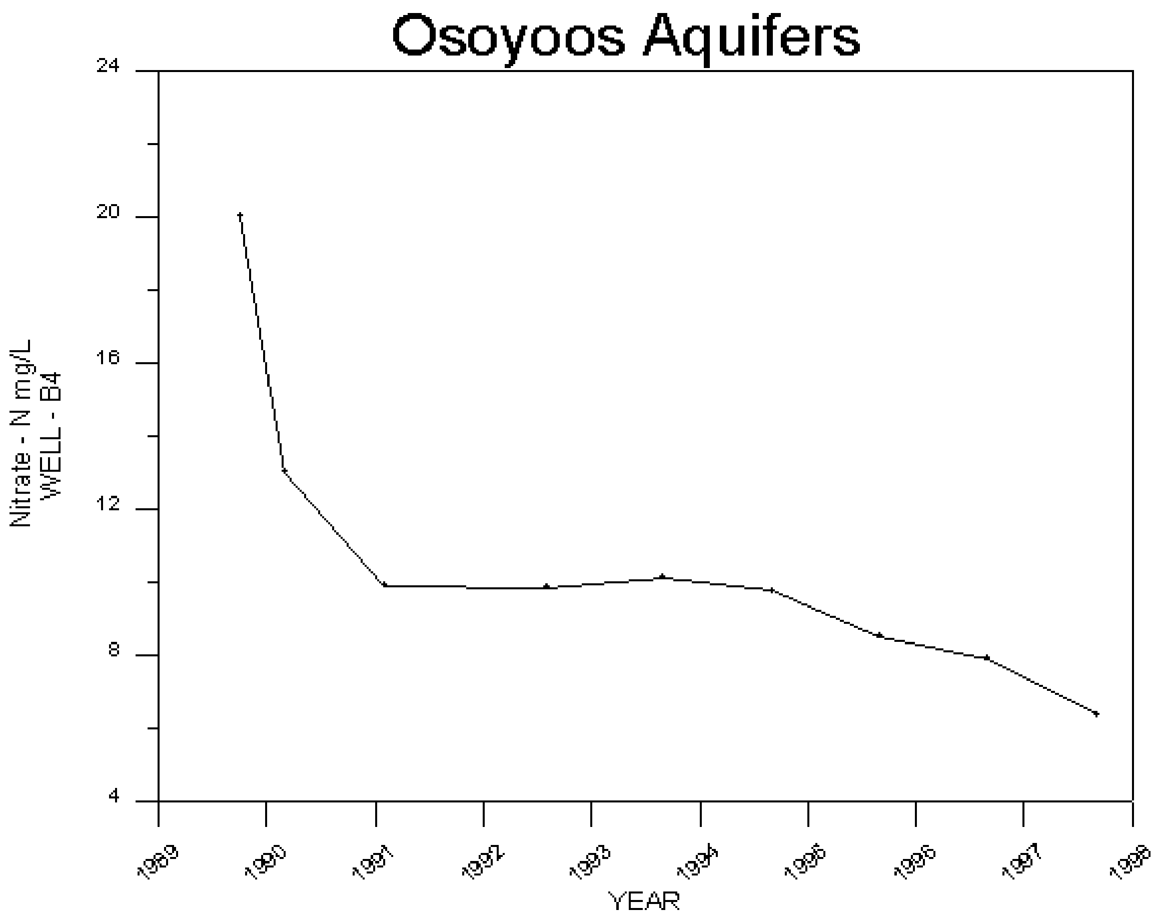
Statistical analysis of Nitrate-N data from Well - A25 indicated no evidence of any linear trends (see Appendix I for details).

However, further analysis using a data set that omitted the first three observations seen in figure 19 revealed strong evidence of a linearly increasing trend (see Appendix I for Details).

Osoyoos Aquifers

Measurements of Nitrate Nitrogen were collected at well - B4, over a period of 9 years, spanning 1989 to 1997 (Figure 20).

Figure 20 Time series graph of Nitrate - N in Well - B4 at the Osoyoos Aquifers, 1989 - 1997.



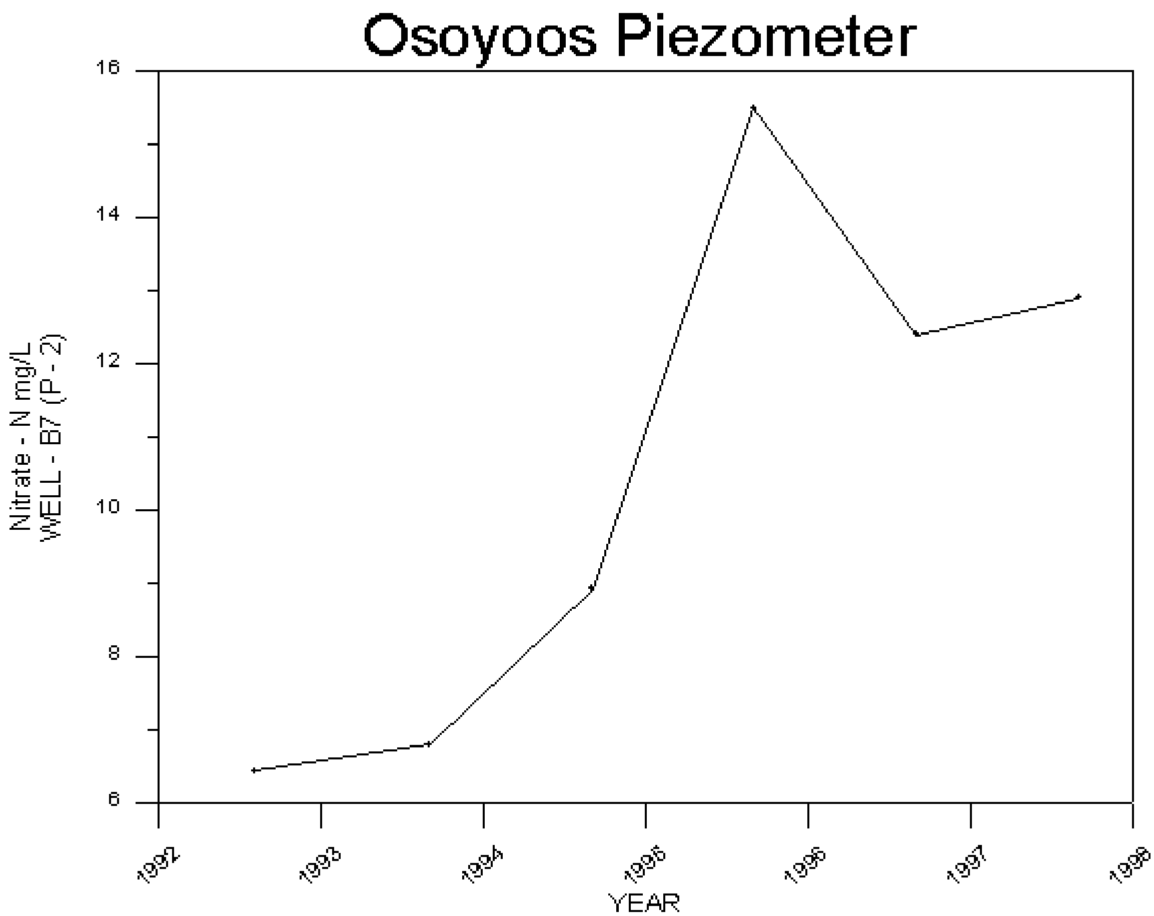
Early years of the data set consisted of single samples taken in mainly during the later winter months while the more recent years consisted of single samples taken in September. The relatively small data set and the differing sample intervals prevented the use of the regression techniques described in the methods section of this report. Thus, it was determined that only non-parametric trend techniques were to be employed on the available data.

Statistical analysis of the available Nitrate-N data from Well - B4 indicated strong evidence of a linearly decreasing trend (see Appendix I for details).

Osoyoos Piezometer

Measurements of Nitrate Nitrogen were collected at well - B7, over a period of 6 years, spanning 1992 to 1997 (Figure 21).

Figure 21 Time series graph of Nitrate - N in Well - B7 at the Osoyoos Piezometer, 1992 - 1997.



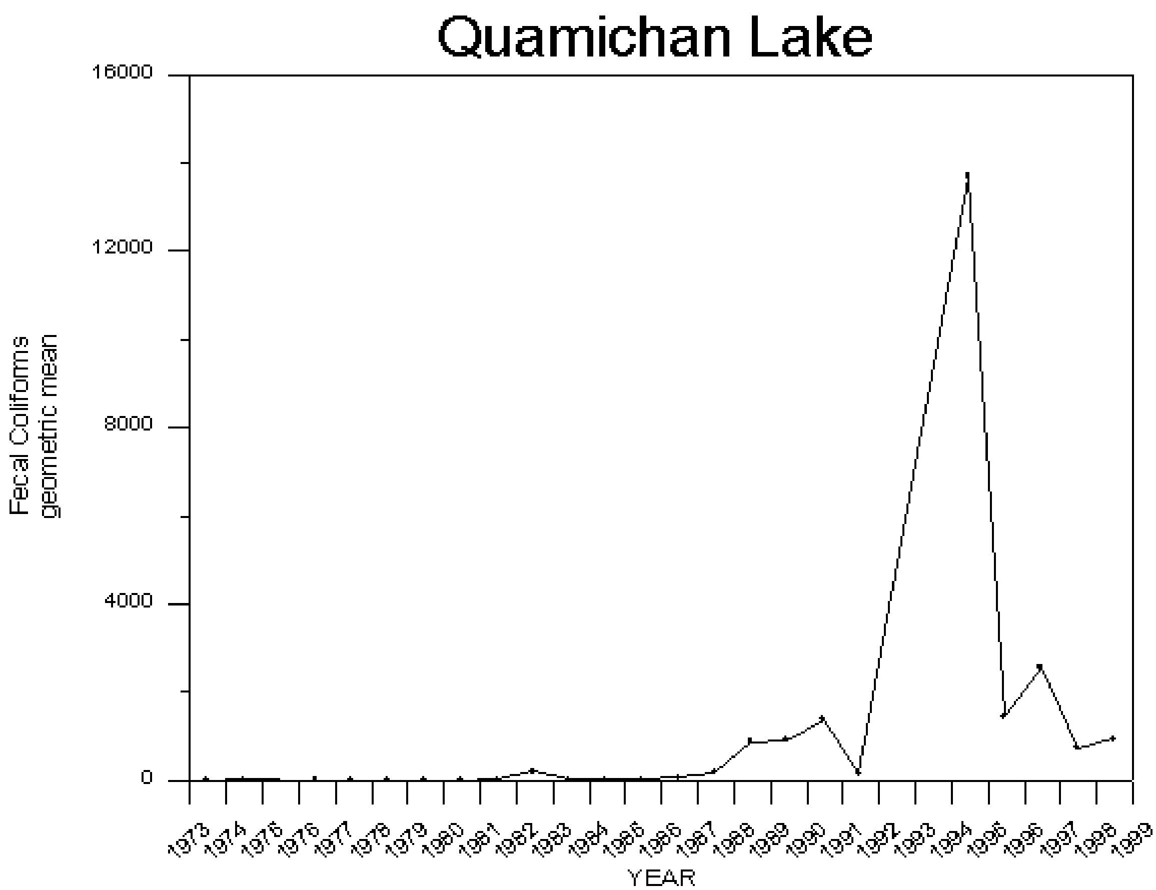
The relatively small data set prevented the use of the regression techniques described in the methods section of this report. Thus, it was determined that only non-parametric trend techniques were to be employed on the available data.

Statistical analysis of the available Nitrate-N data from Well - B7 indicated evidence of a linearly increasing trend (see Appendix I for details).

Quamichan Lake

Measurements of fecal coliforms were collected over a period of 26 years, spanning 1973 to 1998. The geometric mean of these measurements (taken in the summer) were computed and are presented in Figure 22.

Figure 22 Time series graph of geometric means of fecal coliforms sampled during summer in Quamichan Lake, 1973 - 1998.



Initial data screening indicated that although the high 1994 result was real, it should be removed for statistical testing. Non-parametric analysis of the resulting dataset indicated strong evidence of a linearly increasing trend (see Appendix I for details).

Subsequent regression modeling of the data transformed on the log scale confirmed the non-parametric result of a strong increasing trend, although it was discovered that precipitation data from Victoria International Airport *did not* help in explaining the fecal coliform data (see Appendix I for details).

Summary

Trend analyses conducted on the various data sets used in this report revealed several items of note:

· Total precipitation data collected from January to June at Victoria International Airport were not a good explanatory variable in helping to explain the variation of fecal coliform data at Quamichan Lake;

· Decreasing trends were evident in the available nitrate data at Abbotsford (well-C25), Grand Forks (well-C100), and Osoyoos (well-B4); in the available total dissolved solids data at Cowichan (well "J"); in all three replicates of sediment lead in the main arm of the Fraser River and the third replicate of sediment lead in the north arm of the Fraser River (replicates 1 and 2 exhibited no evidence of any linear trends);

· Increasing trends were evident in fecal coliform data at Quamichan Lake using both non-parametric and regression techniques;

· Increasing trends were evident in nitrate data at Grand Forks in both well-A40 and well-A100; and

· There were no indications of any linear trends in nitrate data at well-C75 in Abbotsford, nor in well-C40 and Floesser well in Grand Forks.

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Appendices

Appendix I - Statistical Results

Abbotsford Aquifer

Well C - 25
Nitrate - N non-parametric results

	statistic	p-value
KT	-0.3917	0.03816
SSE	-0.0012	NA
LCL	-0.0027	NA
UCL	0.00003	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Well C - 75
Nitrate - N non-parametric results

	statistic	p-value
KT	0.2721	0.1378
SSE	0.0006	NA
LCL	-0.0002	NA
UCL	0.0014	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator

LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Cowichan Estuary Lower Aquifer

Observation Well #297
Total Dissolved Solids non-parametric results

	statistic	p-value
KT	0.7619	0.0151
SSE	0.0295	NA
LCL	0.0056	NA
UCL	0.0605	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Observation Well "J"
Total Dissolved Solids non-parametric results

	statistic	p-value
KT	-0.7143	0.0243
SSE	-0.0947	NA
LCL	-0.1559	NA
UCL	-0.0298	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Fraser River main arm

Replicate 1
Lead non-parametric results

	statistic	p-value

KT	-0.8095	0.0107
SSE	-1.05	NA
LCL	-2.4088	NA
UCL	-0.3794	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Replicate 2
Lead non-parametric results

	statistic	p-value
KT	-0.9333	0.0074
SSE	-1.2125	NA
LCL	-2.2591	NA
UCL	-0.3939	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Replicate 3
Lead non-parametric results

	statistic	p-value
KT	-0.8095	0.0107
SSE	-1.3	NA
LCL	-2.4675	NA
UCL	-0.1319	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Averaged Replicates
Lead non-parametric results

	statistic	p-value
KT	-0.8095	0.0107
SSE	-1.05	NA
LCL	-2.4246	NA
UCL	-0.4279	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Fraser River north arm

Replicate 1
Lead non-parametric results

	statistic	p-value
KT	-0.4286	0.1765
SSE	-0.9182	NA
LCL	-2.7014	NA
UCL	0.6147	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Replicate 2
Lead non-parametric results

	statistic	p-value
KT	-0.4286	0.1765
SSE	-0.9273	NA
LCL	-3.0621	NA
UCL	1.0007	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Replicate 3
Lead non-parametric results

	statistic	p-value
KT	-0.6	0.0909
SSE	-0.9091	NA
LCL	-1.9230	NA
UCL	0.5085	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Averaged Replicates
Lead non-parametric results

	statistic	p-value
KT	-0.4286	0.1765
SSE	-0.9182	NA
LCL	-2.7122	NA
UCL	0.6147	NA

KT - Kendall Test for trend NA - Not Applicable
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit

Grand Forks Aquifer

Well A - 40
Nitrate - N non-parametric results

	statistic	p-value
KT	0.5778	0.0248
SSE	0.0016	NA
LCL	0.0003	NA
UCL	0.0048	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator

LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Well A - 100
Nitrate - N non-parametric results

	statistic	p-value
KT	0.5273	0.0293
SSE	0.0011	NA
LCL	0.0001	NA
UCL	0.0034	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Well C - 40
Nitrate - N non-parametric results

	statistic	p-value	statistic*	p-value*
KT	-0.2052	0.3601	-0.3636	0.1148
SSE	-0.0019	NA	-0.0024	NA
LCL	-0.0035	NA	-0.0042	NA
UCL	0.0018	NA	0.00001	NA

KT - Kendall Test for trend *** -** analysis with omitted 1991 value
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Well C - 100
Nitrate - N non-parametric results

	statistic	p-value
KT	-0.7424	0.0006
SSE	-0.00004	NA
LCL	-0.0001	NA

UCL	0.00001	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Floesser Well
Nitrate - N non-parametric results

	statistic	p-value
KT	0.25	0.4017
SSE	0.00007	NA
LCL	-0.0002	NA
UCL	0.0002	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Matsqui Piezometer

Well A - 25
Nitrate - N non-parametric results

	statistic	p-value
KT	0.1333	0.6534
SSE	0.001	NA
LCL	-0.0006	NA
UCL	0.0032	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Well A - 25 (first three observations omitted)
Nitrate - N non-parametric results

	statistic	p-value
KT	0.8095	0.0163
SSE	0.0033	NA
LCL	0.0009	NA
UCL	0.0072	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Osoyoos Aquifers

Well B - 4
Nitrate - N non-parametric results

	statistic	p-value
KT	-0.8889	0.0008
SSE	-0.0023	NA
LCL	-0.0047	NA
UCL	-0.0011	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Osoyoos Piezometer

Well B - 7
Nitrate - N non-parametric results

	statistic	p-value
KT	0.7333	0.0388
SSE	0.004	NA
LCL	-0.0023	NA
UCL	0.0108	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Quamichan Lake

Geometric mean Fecal Coliforms non-parametric results

	statistic	p-value
KT	0.7056	4.9e-006
SSE	0.1045	NA
LCL	0.0256	NA
UCL	0.1997	NA

KT - Kendall Test for trend
SEN - Sen Slope Estimator
LCL - Lower Confidence Limit
UCL - Upper Confidence Limit
NA - Not Applicable

Geometric mean Fecal Coliforms regression results

β_0	β_1	β_2	β_3	r^2
-496.439	NS	0.25	----	0.776

NS - non-significant ---- - term not used in model