Colin MacLeod and **Paul H. Whitfield,** Environment Canada, 700 - 1200 West 73rd Avenue, Vancouver, British Columbia, Canada V6P 6H9

Seasonal and Long-Term Variations in Water Quality of the Columbia River at Revelstoke, B.C.

Abstract

The purpose of this study was to analyze six years of water quality data collected every four weeks from the Columbia River at Revelstoke to determine the processes controlling water quality and the presence or absence of trends. Plots versus time were used to assess seasonality, while hysteresis diagrams were used to describe processes affecting the water quality variables through the relationship of water chemistry to discharge. The major ions exhibited seasonality showing high concentrations in the winter and low concentrations in the summer, while other variables did not exhibit seasonality. The hysteresis diagrams indicate that the seasonal pattern of major ions is different from natural systems. The lack of flow relationships for metals and other sediment related variables also differs from natural systems. These differences result from impact of reservoirs on the river processes. Box-Jenkins time-series techniques were used to model and forecast future values for the variables. Revelstoke Dam has a significant impact on the water quality processes. No trends over time were found for the water quality variables.

Introduction

When attempting to assess if any trends are present in the water quality of a watershed, it is important to consider the impact of the surrounding environment, both natural and man-made.This is necessary to answer the two dominant questions in the study of water quality: (1) Why is the quality of the river as observed? and (2) Is the water quality changing over time? The presence of Revelstoke and Mica Dams significantly alters the flow regieme of the Columbia River. These impacts must be considered in any study of water quality variables downstream from these developments. Whitfield and Woods (1984) studied the impact of the construction of the Libby Dam on the Kootenai River below the dam and found that the dam regulated flow and reduced the seasonality of hydrologic and water quality variables.

Hysteresis diagrams are useful in evaluating how water quality variables behave in relation to discharge (Whitfield and Whitley, 1986; Whitfield and Clark, 1992). Plotting the concentration of a water quality variable versus discharge reveals patterns which can be compared to known classifications. Williams (1989) provides one classification which has five typical relationships which can be used to identify hydrological characteristics of a variable. In natural systems, these diagrams have been shown to be useful in determining processes which control water quality (Whitfield and Whitley, 1986; Whitfield and Clark, 1992; Bhangu and Whitfield, in press).

To determine whether a short or long term trend is present, time-series analysis is utilized. Time series analysis permits the statistical evaluation of data which are not independent and uncorrelated over time. For a time-series of dependent data, model results can be used to forecast future values, which can then be studied for evidence of a change in the mean of a series (Chatfield, 1984). Bhangu and Whitfield (in press) used both hysteresis diagrams and time-series analysis to study trends at the Skeena River at Usk; much the same process has been followed here.

This study uses six years of water quality data gathered from Columbia River at Revelstoke (Environment Canada Station Number -BC08ND0002), downstream from the Revelstoke Dam. The data, collected every 28 days from January 1986 to December 1991, were used to construct Box-Jenkins time-series models. Data from January 1992 to April 1993 were used independently to check the accuracy of the model and validate the results.

Study Area

The features of the upper Columbia watershed are identified in Figure 1. The Columbia River arises in Columbia Lake in southeastern British Columbia and flows northwest before bending

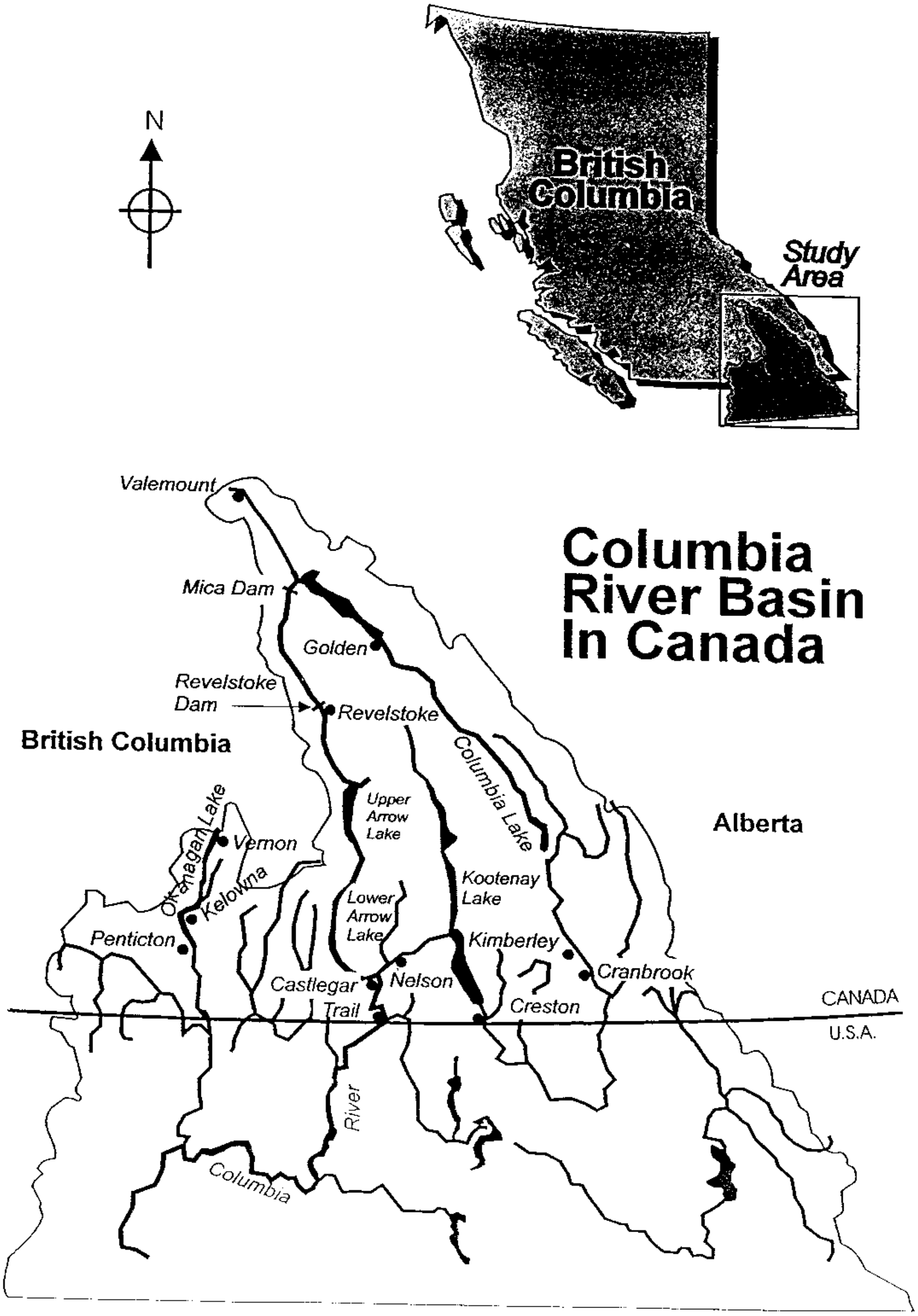

Figure 1. Columbia River basin in Canada showing the drainage area considered in this study.

south again to continue through the United States where it drains into the Pacific Ocean at Astoria, Oregon (Columbia River Treaty Permanent Engineering Board, 1992). The area of interest is the portion of the river upstream from Revelstoke, B.C., which has a drainage area of approximately 26,700 km^2.

The Revelstoke Dam is located 5 km north of the city of Revelstoke. The dam began operation in 1984 and creates a reservoir which extends north to the Mica Dam (B.C. Hydro, 1993). This reservoir, called Lake Revelstoke, provides increased energy capability. Located about 130 km north of Revelstoke Dam is Mica Dam. Drainage area above the Mica is 21,000 km^2, comprising the majority of the flow of the study area. The Dam became operational in 1973 as part of the Columbia River Treaty. This treaty, signed and ratified in 1964, is an agreement between the governments of the United States and Canada to jointly supervise and maintain the development of the Columbia River basin. This included the construction of the Mica, Duncan and Keenleyside Dams in B.C. and the Libby Dam in Idaho (Environment Canada, 1975).

Methods

i. Data Sources

The water quality monitoring station is located on the Trans-Canada Highway bridge 5 km downstream from Revelstoke Dam. This site is operated under the Canada-British Columbia Water quality Monitoring Agreement. The collection of data under this program is described by Clark and Whitfield (1993). The water quality variables were analyzed using standard methods (Environment Canada, 1979).

Six years of data were used in this analysis. Variables were eliminated from the study if there were large amounts of missing data or if there was little or no variation. Of the 55 initial variables listed, 21 had enough data and spread for examination. These were: discharge, lab pH, specific conductivity, turbidity, total alkalinity, calcium, magnesium, hardness, potassium, sodium, chloride, silicate, sulphate, copper, iron, lead, manganese, and zinc. The dissolved form of the major ions were measured, as were the total form of the trace metals. Nitrate+nitrite, total phosphorus, and total dissolved nitrogen each had three repetitions. Each of the three replicates were treated as a completely separate variable, bringing the total to 27 time series analyzed.

For each variable, a time-series plot was prepared with the water quality variable on the y-axis and time plotted on the x-axis. This gave a good representation of how water quality behaved during the time period and displayed any unusual data, or outliers, which could damage the accuracy of a forecast. These plots also displayed the degree of seasonality existing in each variable, which assists in fitting a time-series model to the data.

ii. Process Analysis

Hysteresis plots were then created to evaluate if there is a relationship with discharge. These log-log plots of water quality versus discharge for a typical year are useful in determining processes affecting water quality and the timing of peaks. A positive slope indicates a positive relationship with discharge, a negative slope indicates an inverse relationship to discharge, and no slope indicates no relationship to discharge.

iii. Trend Assessment

To utilize Box-Jenkins time-series models, the data must be stationary. In fitting a Box-Jenkins model all significant trends and seasonality are removed and in the resulting series there must be stationarity [i.e., no systematic change in the mean] (Chatfield 1984). The plots of water quality versus time are used with the autocorrelation and partial autocorrelation function of a series to determine if there is a trend present. Trends and patterns found in the series can be rendered stationary by applying a linear difference operator. For all the series considered, a seasonal model was adequate (as there was 13 observations per year the differencing was lag 13).

Afterwards, the autocorrelation and partial autocorrelation functions of the differenced series are checked to assure that all seasonality has now been removed, and are then used to identify a tentative model for the data. These models typically contain moving average (MA) and autoregressive (AR) terms. Future values are then forecasted based on the model. These values are plotted versus the observed results to visually confirm that the model is adequate. Residuals are then checked to ensure results are reasonable.

Results and Discussion

i. Process Analysis

Minimum and maximum values for each of the water quality variables observed during the study period and the Canadian Standards for Drinking Water and Aquatic Life are provided in Table 1. The variable with the largest range was iron which had a maximum value of 8.33 mg/L and a minimum value of 0.036 mg/L - a 231 fold range. Most of the other variables also show significant variation with the maximum values being from two to ten times greater than the minimum. Of the variables where a standard exists, all the variables except iron and lead were less than both the Drinking Water and Aquatic Life Standard (Table 1). Iron and lead exceeded the standard only during periods of high discharge associated with high levels of sediment.

TABLE 1. Ranges of water quality variables observed in the Columbia River at Revelstoke during the study period.

Variable	Minimum	Maximum	Standard*
PHYSICAL			
Discharge (m^3/s)	245	1600	
Turbidity (FTU)	0.1	4	
Specific Conductance (µS/cm)	95	151	
pH	6.7	8.2	6.5-8.5/6.5-9.0
Apparent Colour (relative units)	5.0	15.0	
Air Temperature (°C) (at time of sampling)	0.0	20.0	
Water Temperature (°C)	0.0	12.0	
MAJOR IONS (mg/L)			
Total Alkalinity	38.0	64.1	
Calcium	12.9	21.1	
Potassium	0.4	0.7	
Sodium	0.5	1.4	200/
Chloride	0.2	0.6	250/
Hardness	43.1	75.1	
Sulphate	7.1	13.9	500/
Magnesium	2.6	5.5	
NUTRIENTS (mg/L)			
Nitrate+Nitrite	0.003	0.73	45.0/
Total Dissolved Nitrogen	0.118	0.85	
Total Phosphorus	0.002	0.4	
TRACE METALS (mg/L)			
Total Iron	0.036	8.33	0.3/0.3
Total Lead	0.0002	0.0078	0.01/0.007
Total Zinc	0.004	0.11	5.0/0.03

* Canadian Drinking Water Standard/Freshwater Aquatic Life

Some of the observed variables, such as apparent colour, did not have enough variation to be used in trend assessment, while others showed considerable spread. This showed up more clearly in the time series plots. Strong seasonality was observed in only six of the variables: alkalinity, calcium, hardness, specific conductance, magnesium, and sulphate.

These variables were similar. Peaks were observed with the high concentrations typically occurring in the February-April range and lows in July or August. The exception was sulphate which had inconsistent high concentrations between years, but consistently had an annual low in July or August of each year. The rest of the variables showed little seasonality and no other trends. The fact that these six variables are major anions and cations seems to indicate that seasonality might occur more often in this group than other water quality variables in rivers controlled by reservoirs.

Another characteristic of these variables was the presence of one year of data which stood out from the rest. Between July 1989 and July 1990, each of the plots displayed a period with shortened peaks and less variation. This period did not seem typical and was not used for hysteresis plots and was omitted from the forecasting process when possible. Figures 2-4 demonstrate the nature of the seasonal patterns these variable demonstrate over the study period.

Hysteresis plots were prepared for each variable and each of the six years of the study. In addition, plots of the variables with discharge versus time were used to demonstrate any relationship to discharge. Figures 5 and 6 show these plots for calcium and alkalinity. The group of major ions mentioned above all exhibited a negative relation with discharge. This same result was found by Bhangu and Whitfield (in press) in the Skeena River at Usk and by Whitfield and Whitley (1986) in the Yukon River Basin. However, the pattern we observed was quite distinctive. The hysteresis diagrams show a linear portion at low flow with an open loop at high discharges.

Hysteresis plots for the other water quality variables did not reveal any measurable relationship

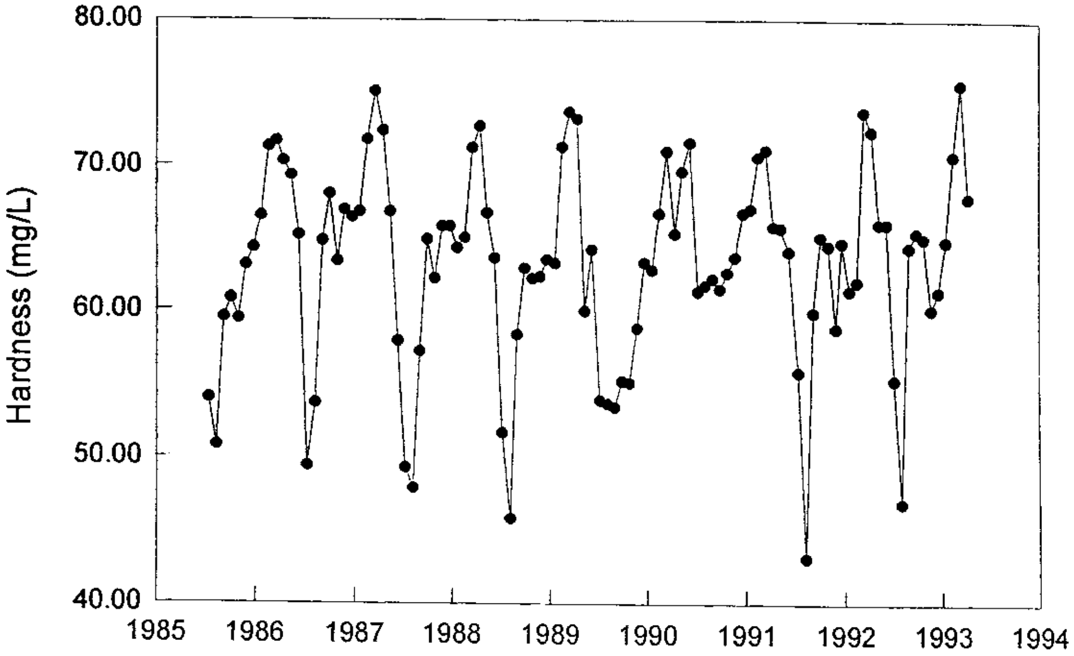

Figure 2. Time series plot of hardness (mg/L) from the Columbia River at Revelstoke.

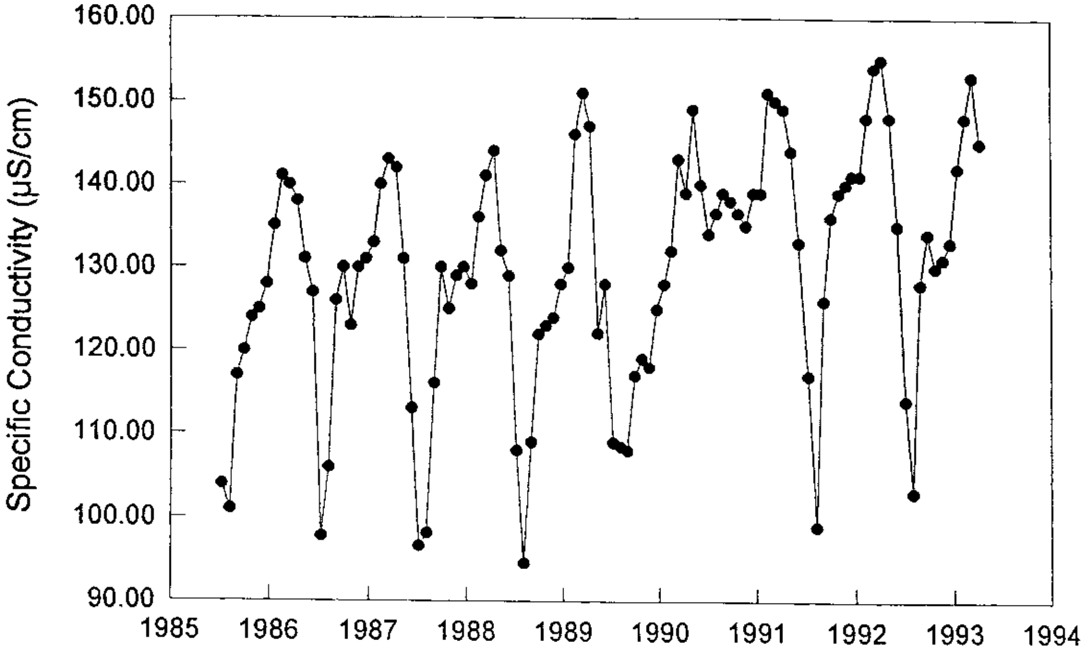

Figure 3. Time series plot of specific conductance (µS/cm) from the Columbia River at Revelstoke.

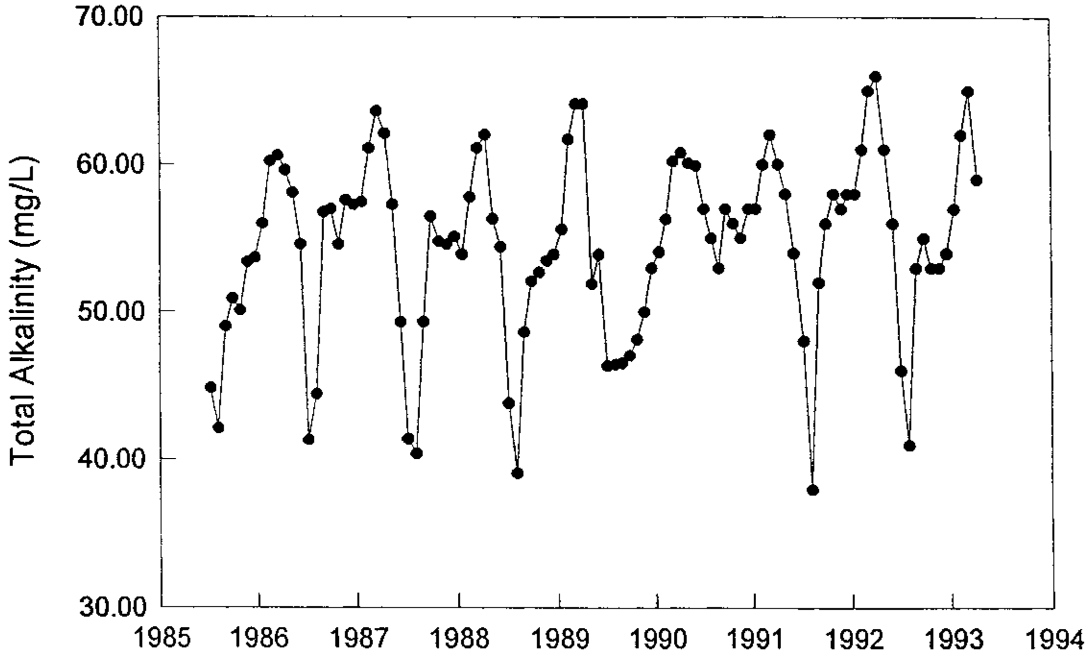

Figure 4. Time series plot of total alkalinity (mg/L) from the Columbia River at Revelstoke.

to discharge. Figures 7 and 8 show the negative relation between concentration and discharge for total alkalinity and calcium. These results are typical of all the major ions we examined. The hysteresis for these 6 major ions had a slightly negative slope, on a logarithmic scale, with a counter-clockwise loop at the end. The slope was less steep than expected. The postulated mechanism behind this, suggested by Whitfield and Whitley (1986), is as follows: snowmelt and surface runoff dilute groundwater during freshets; during post-freshet conditions concentrations increase with the increasing dominance of groundwater. The shape falls into Williams (1989) "single line plus a loop category", and signifies that during the period of the year where discharge is low and concentration is high the curves are in phase. However, during the high discharge period a loop occurs because concentration reaches a low before discharge reaches the peak. This can be witnessed by the first year in Figures 5 and 6; both calcium and alkalinity hit a low peak just before discharge hits a high peak, creating the loop observed in the hysteresis plots. Hysteresis plots for alkalinity and calcium are shown in Figures 7 and 8. In natural streams, these variables typically exhibit an open clockwise loop with no linear feature (eg. Whitfield and Whitley, 1986; Whitfield and Clark, 1992; Bhangu and Whitfield, in press). In 'natural' systems throughout British Columbia and the Yukon the hysteresis plots for anions and cations are open loops (Whitfield and Whitley, 1986; Whitfield and Clark, 1992; Bhangu and Whitfield, in press). In the Columbia River at Revelstoke these plots show linear portions (Figures 7 and 8) which are the result of the mixing of water which take place within the reservoir and causes the discharge and concentration curves to be in phase during the winter.

Silicate and pH were independent of discharge, appearing as a line which was horizontal across a range of discharges. Both these variables had a counter-clockwise loop at the high discharge end. Nitrate+nitrite, total phosphorus, total nitrogen, chloride, copper, iron, lead, zinc and manganese all had no clear shape and were independent of discharge (i.e., no slope).

In the study of discharge and water quality in the Yukon River basin, Whitfield and Whitley (1986) observed that the variables of lake-fed systems had "low-slope" relationships to discharge more noticeably than river-fed systems. As this system is fed by the Revelstoke reservoir, it is "lake-fed" and exhibits similar behaviour. The

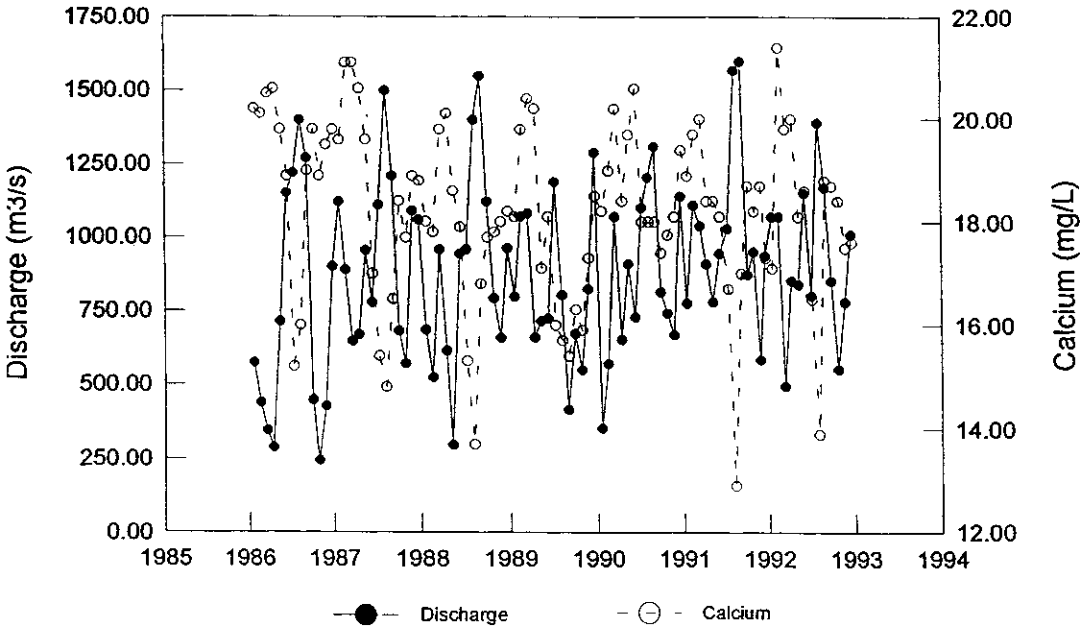

Figure 5. Time series plot of discharge (m^3/s) and calcium (mg/L) from the Columbia River at Revelstoke.

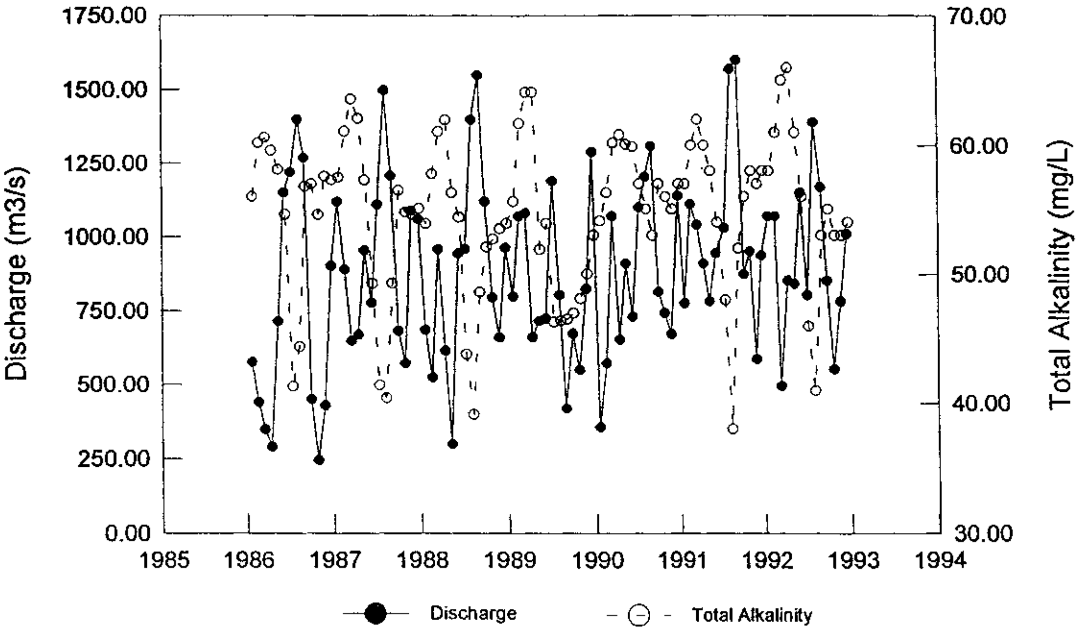

Figure 6. Time series plot of discharge (m^3/s) and total alkalinity (mg/L) from the Columbia River at Revelstoke.

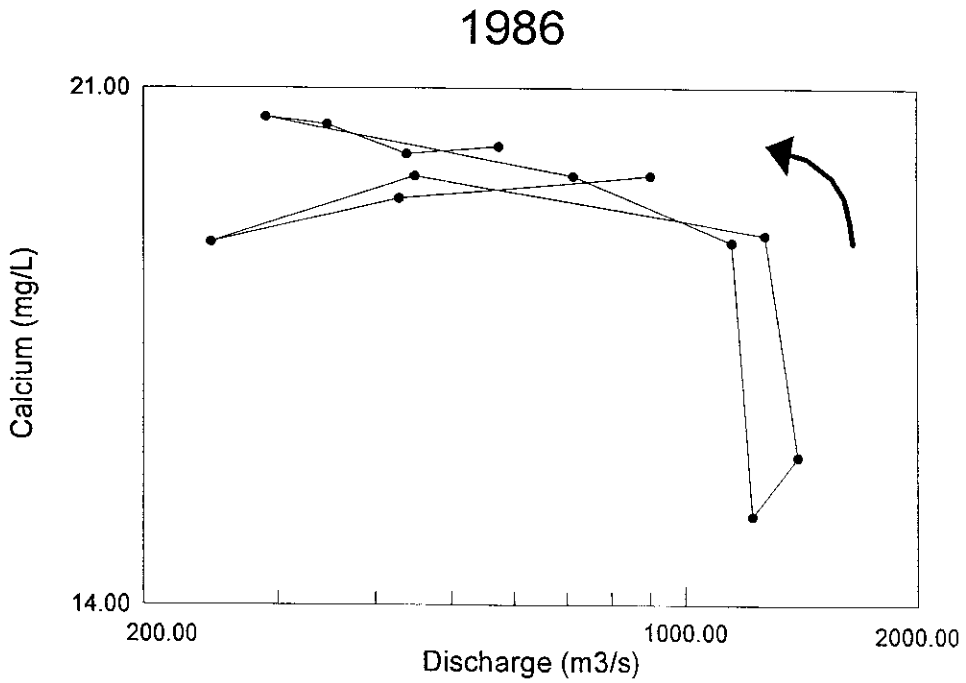

Figure 7. Hysteresis plot of calcium from the Columbia River at Revelstoke.

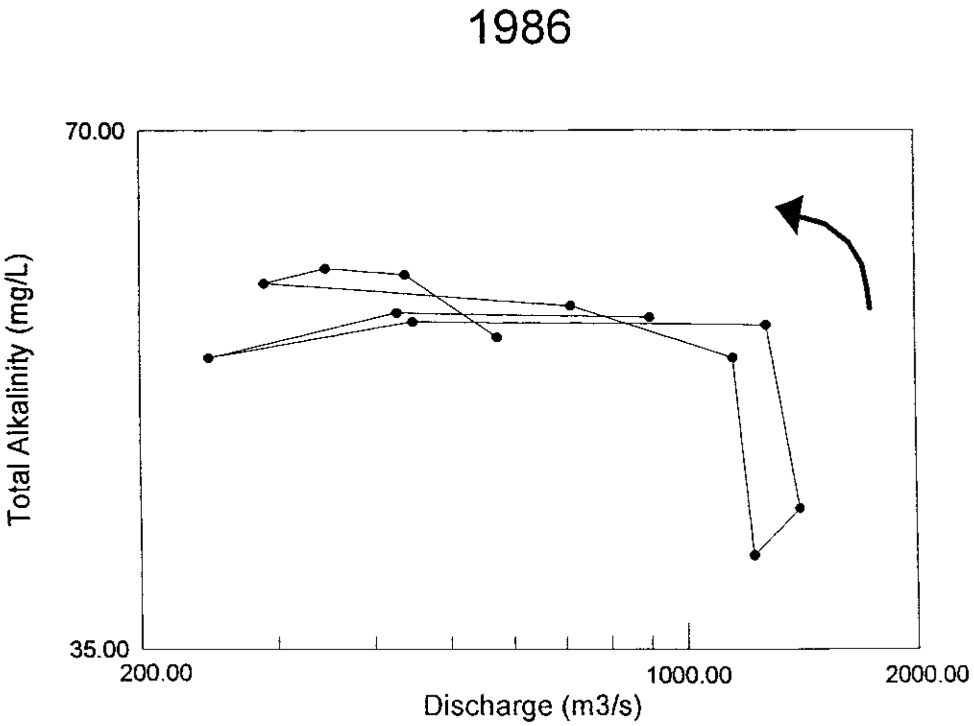

Figure 8. Hysteresis plot of alkalinity from the Columbia River at Revelstoke.

suggested reasons for this are the buffering and trapping processes in lakes, which result in the simple dilution of a uniform concentration (i.e., the lake water) as the prominent mechanism.

ii. Trend Assessment

As the first step in trend assessment we examined time series plots of water quality variables to see if there was any obvious trend which might continue into the future. None of the variables analyzed displayed an obvious trend, and the series appeared to have a stationary mean. The time series plots also showed that the data between July 1989 and July 1990 was different from other years. During this period, discharges in the Columbia were reduced through storage of runoff behind Mica Dam, altering the normal year to year flow patterns (eg. Figure 5). The result of this, for the water quality variables, is that the low concentrations normally observed during the peaks of discharge are absent from the record in this period.

Following the time series plots, Box-Jenkins time-series methods were used on the stationary series to find a model which fit the existing series and then could be used to forecast future values of a time-series and thus future trends. There were various problems which stopped models being fitted to certain variables. Total aluminum, mercury, selenium, barium, arsenic, nitrate+nitrite, total dissolved nitrogen, total phosphorus, turbidity, sodium, chloride, and fluoride all had so little variation that reliable time-series models could not be fitted. These variables could be simply expected to continue as observed. Silicate and total copper had missing data which disrupted the modelling process. The series of pH contained a period where the data obtained was known to be questionable, so a model was not fitted.

Models were fitted for the same six major ions studied previously as well as discharge. The resulting models are listed in Table 2. None of the models needed a trend component, indicating that we are currently observing no trend in the water quality. These models contain both an autoregressive component and a seasonal moving average component, indicating that over time samples which are close together in time are similar (autoregressive component) and samples which are one year apart are similar (seasonal moving average).

Alkalinity, hardness, specific conductance, magnesium, calcium and discharge were all differenced for stationarity, and then fitted with a multiplicative autoregressive model with lags at 1 and 13, indicating that each value is dependant on the previous value and the value 13 observations (one year) ago. This is the seasonal effect. The forecasts from the fitted models for alkalinity, magnesium and hardness are in Figures 9, 10, and 11. For sulphate, an autoregressive integrated moving average, or ARIMA, model with an AR term at lag 1 and an MA term at lag 13 was identified.

TABLE 2. Summary of Box-Jenkins Models fitted to water quality variables from the Columbia River at Revelstoke.

Water Quality Variable	Model[1]
Sulphate	ARIMA $(1,0,0)(0,1,1)_{13}$
Alkalinity	ARIMA $(1,0,0)(1,1,0)_{13}$
Hardness	ARIMA $(1,0,0)(1,1,0)_{13}$
Specific Conductivity	ARIMA $(1,0,0)(1,1,0)_{13}$
Magnesium	ARIMA $(1,0,0)(1,1,0)_{13}$
Calcium	ARIMA $(1,0,0)(1,1,0)_{13}$
Discharge	ARIMA $(1,0,0)(1,1,0)_{13}$

[1] Model notation as described by Box and Jenkins (1976).

The plots of the forecasted versus observed values illustrate the expected inadequate fit in the 1989-90 year. After this period, however, the forecasts fit the observed values, indicating that this period of time was indeed abnormal. All forecast series showed no trends or other changes in the immediate future.

Conclusions

The Columbia River at Revelstoke exhibits distinct patterns of water quality. These patterns are the result of the modification of the natural system by the reservoirs upstream of the study site. These effects were prevalent durng the winter low flow period when the natural pattern of concentration and discharge being out of phase was changed to a pattern of being in phase. Major ions exhibited distinct seasonality and these ions varied inversely with discharge. The seasonality normally observed for variables typically associated with sediment has been dampened out in the reservoir behind the dam. The ARIMA models fitted to the series of water quality did not include a trend component indicating that no trends in water quality are occurring in the Columbia

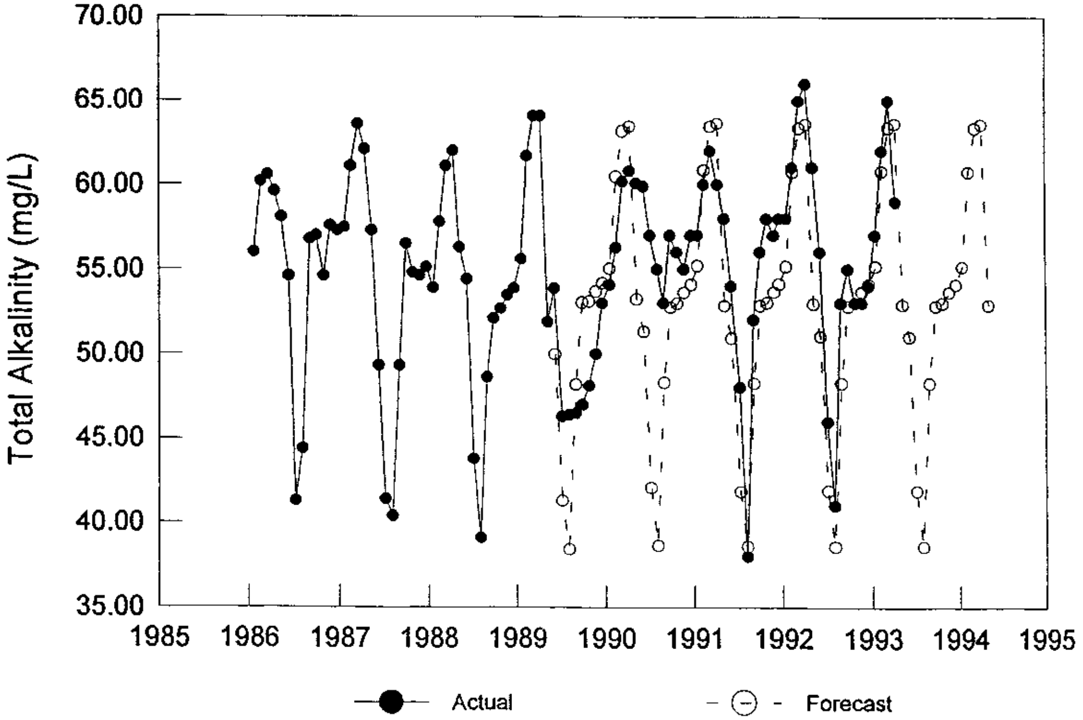

Figure 9. Actual and forecast alkalinity concentrations based on the fitted Box-Jenkins model for the Columbia River at Revelstoke.

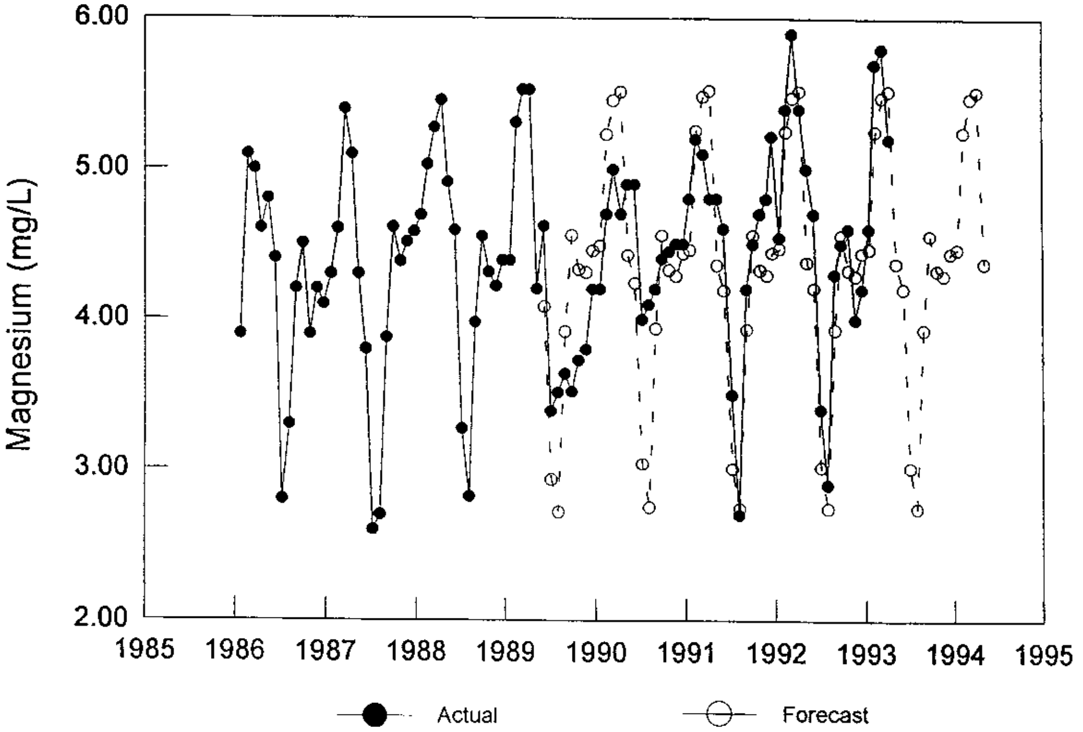

Figure 10. Actual and forecast magnesium concentrations from 1986 to 1994 based on the fitted Box-Jenkins model for the Columbia River at Revelstoke.

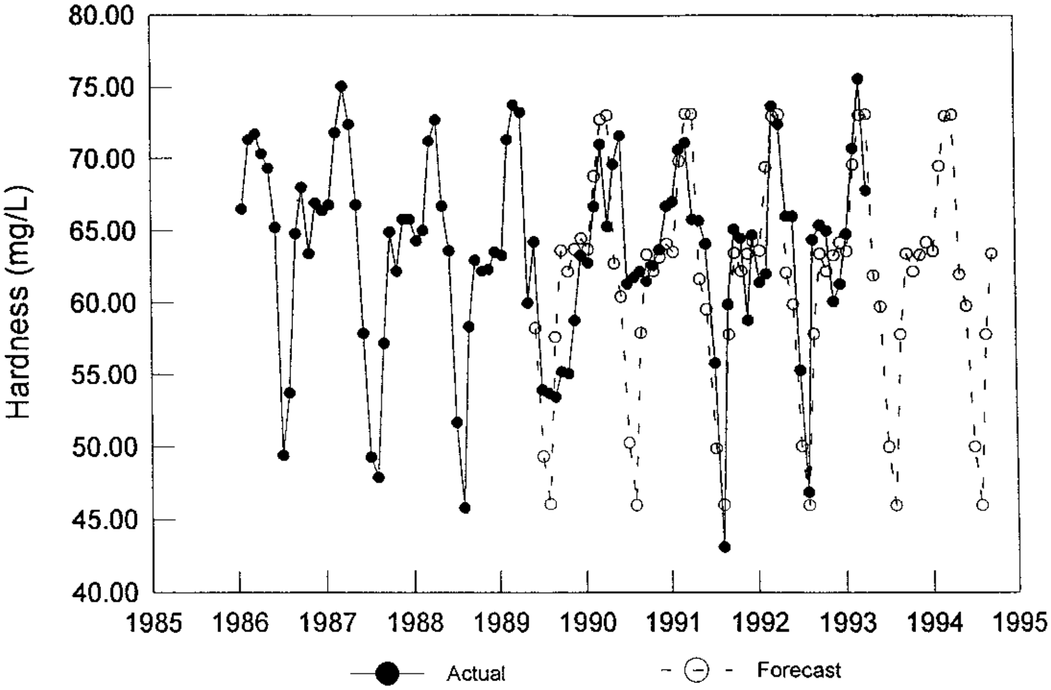

Figure 11. Actual and forecast hardness concentrations based on fitted Box-Jenkins model for the Columbia River at Revelstoke.

River at Revelstoke at present. Processes currently occurring are forecast to continue into the near future.

Acknowledgements

The authors would like to acknowledge the contributions of the staff of Environment Canada who contributed to this study: Dr. Rory Leith, Dick Boak, Norman Wade, and Indra Bhangu. We would also like to thank Larry Pommen and Julia Beatty-Spence of the British Columbia Ministry of Environment for their assistance in preparing this paper. The comments and suggestions of two anonymous reviewers were helpful in preparing this paper.

Literature Cited

BC Hydro. 1993. Making the Connection: The BC Hydro Electric System and How it is Operated. pp 41.

Bhangu, I. and P.H. Whitfield. in press. Seasonal and Long-Term Variations in Water Quality of British Columbia Rivers Skeena River at Usk, B.C. Water Research.

Box, G.E.P. and G.M. Jenkins. 1976. Time-Series Analysis: Forecasting and Control. Holden-Day. San Francisco. California.

Chatfield, C. 1984. The Analysis of Time-Series: an Introduction. Chapman and Hall, New York, New York. Third edition. pp. 12-32.

Clark, M.J.R., and P.H. Whitfield. 1993. A practical model integrating quality assurance into environmental monitoring. Water Resources Bulletin 29:119-130.

Columbia River Treaty Permanent Engineering Board. 1992. Annual Report to the Governments of The United States and Canada. pp v-vi.

Received 16 February 1995
Accepted for publication 10 August 1995

Environment Canada. 1975. Canada Water Year Book. pp. 34-38.

Environment Canada. 1979. Analytical methods manual. Inland Waters Directorate. Water Quality Branch.

Whitfield, P.H., and M.J.R. Clark. 1992. Patterns of water quality in the Rocky Mountains of British Columbia. In: Science and the Management of Protected Areas. pp 391-409.

Whitfield. P.H.. and W.G. Whitley. 1986. Water Quality-Discharge Relationships in the Yukon River Basin, Canada. In: Cold Regions Hydrology Symposium. pp 149-156. American Water Resources Association.

Whitfield, P.H., and P.F. Woods. 1984. Intervention Analysis of Water Quality Records. Water Resources Bulletin 20:657-668.

Williams, G.P. 1989. Sediment Concentration versus Water Discharge during Single Hydrologic Events in Rivers. Journal of Hydrology 111:89-106.